GAW Report No. 245

An Integrated Global Greenhouse Gas Information System (IG^3IS) Science Implementation Plan

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

IG^3IS Integrated Global Greenhouse Gas Information System

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Integrated Global Greenhouse Gas Information System

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EXECUTIVE SUMMARY

The implementation of the Paris Agreement will require countries and sub-national entities to take actions to reduce emissions of greenhouse gases in an optimal way. To assist the countries in meeting their commitments the World Meteorological Organization (WMO) and its partners have initiated the development of an Integrated Global Greenhouse Gas Information System (IG3IS). IG3IS looks to serve users (decision-makers) who are able and willing to take actions to reduce emissions of greenhouse gases and pollutants that reduce air quality. This service is based on existing and successful methods and use-cases for which the scientific and technical skill is proven or emerging. The Science Implementation Plan presents the suite of the technical solutions that are available to address articulated user needs on different scales (from national to facility). It also paves the way for the development of future solutions where additional research is required.

This document presents the main principles of the IG3IS Science Implementation Plan. The choice of the objective to be implemented has to be made by the countries or sub-national implementation bodies/practitioners. For each individual objective, the plan presents the available and proven tools based on measurements and model analyses. It summarizes key elements required to implement individual solutions. The plan describes the approach to the modelling coordination activities to ensure harmonized and quality assured global implementation and compatibility of the products delivered on different scales.

The measure of success of the IG3IS implementation is the use of the provided information for valuable and additional emission reduction actions, building user confidence and practitioner skills in the value of atmospheric composition measurements as an essential part of the climate change mitigation and pollution remediation tool kits.

The IG3IS team defined four implementation objectives: 1) improve knowledge of national emissions (including reduction of uncertainties of inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC)); 2) locate and quantify previously unknown emission reduction opportunities such as fugitive methane emissions from industrial sources; 3) provide sub-national entities such as large urban source regions (for example, megacities) with timely and quantified information on the amounts, trends and attribution by sector of their greenhouse gas (GHG) emissions to evaluate and guide progress towards emission reduction goals; and 4) support for the Paris Agreement's global stocktake through the integration of these objectives.

This Science Implementation Plan documents the "good-practice" methodological guidelines for how atmospheric measurements and analysis methods can deliver valuable information under each objective area. This plan and the team that prepared it, will serve to guide WMO Members and their partners in the definition and implementation of new IG3IS projects that apply and advance these "good-practice" capabilities. The plan will evolve overtime to respond to new policy challenges and to capture emerging capabilities.

Successful application of IG3IS methods depends on intimate dialogue between scientists and users in order to ensure that user requirements are met, and so that users are introduced to previously unknown capabilities that may drive them to address challenges in new ways.

IG3IS takes a highly collaborative "Translation Atmospheric Sciences" approach to deliver science-based services to potential stakeholders/users and is well in line with the implementation plan of the Global Atmosphere Watch (GAW) Programme. The plan directly supports implementation of the WMO Strategic Plan for 2020-2023, Objective 3.2 "Advance policy-relevant science".

1. INTRODUCTION

1.1 Motivation for IG3IS

Accurate and precise atmospheric measurements of greenhouse gas concentrations revealed the rapid and unceasing rise of global GHG concentrations due to human activity. Accurate long-term observations also show a resulting rise in global temperatures, glacial retreat, sea-level rise and other evidence of negative impacts on the environment. In response to this mounting evidence, national, state, and city governments, private enterprises and individuals have been accelerating efforts to reduce GHG emissions while meeting the needs for global development and increasing energy needs. The urgency and complexity of the problem demands strategic investment in science-based information for planning and tracking emission reduction policies and actions will play a key role in the future.

The Global Atmosphere Watch (GAW) Programme of WMO was established in 1989 in recognition of the need for improved scientific understanding of the increasing influence of human activities on atmospheric composition and subsequent environmental impacts. GAW measurements of ozone-depleting gases have played and continue to play a critical role in the successful response of the Montreal Protocol to stratospheric ozone depletion and the increase of ultraviolet (UV) radiation. GHG measurements from GAW are recognized by the Global Climate Observing System as a key component of its implementation plan under the UNFCCC. Historically, GHG measurements have been made in remote locations that optimized the sampling frequency of global background concentrations. In 2016, GAW launched a new implementation plan built on the concept of "science for services" and bringing an increased user orientation to the programme.

UNFCCC requires that certain countries report their annual GHG inventories. These inventory reports are produced according to the statistical methods outlined in the 2006 Guidelines of the IPCC Task Force on National Greenhouse Gas Inventories (IPCC TFI). In 2010 the atmospheric, carbon cycle and climate change science communities produced a number of studies on the potential for atmospheric GHG concentration measurements and model analyses to independently evaluate and help to inform improved estimates of GHG emission inventories (for example, Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements (NAS 2010); GEO Carbon Strategy (GEO 2010); IPCC Task Force on National GHG Inventories: Expert Meeting Report on Uncertainty and Validation of Emission Inventories (IPCC 2010)). These studies concluded that a realization of this approach would require additional investment in research, increasing the density of well-calibrated atmospheric GHG measurements and improving atmospheric transport modelling and data assimilation capabilities.

The Seventeenth World Meteorological Congress passed a resolution initiating the development of an Integrated Global Greenhouse Gas Information System (IG3IS), based on GAW successes and progress in atmospheric measurements and modelling since 2010. A planning team comprised of scientists and stakeholders from developed and developing countries from all six WMO regions was established to develop the IG3IS Concept Paper. IG3IS will work closely with the inventory builders and other stakeholders who need to track GHG emissions to develop methodologies for how atmospheric GHG concentration measurements (the top-down) can be combined with spatially and temporally explicit emission inventory data (the bottom-up) to better inform and manage emission reduction policies and measures. GAW GHG measurement network and standards will be essential for IG3IS success, but the focus, and location of measurement sites must expand from remote locations to key GHG source regions where emission reduction is taking place or is needed. Over time, the IG3IS framework will be capable

of continually improving the quality of and confidence in the derived information from data measured in situ and the emerging satellite capabilities.

1.2 Principles – the underlying philosophy

The IG3IS plan will not be solely focused on the long-term vision for a comprehensive integrated GHG information system. Instead, the IG3IS plan begins with practical and focused near-term objectives as a way of confidence building. Some of the questions driving the formulation of IG3IS are:

- What research capabilities have demonstrated skill to meet the information needs of stakeholders at global, national, regional and local scale in a quantitative and timely way?
- How can we best demonstrate these capabilities, so stakeholders see this value and become early and active partners in this effort?
- What are the main improvements needed to strengthen the existing inventory protocols, especially the national inventory reporting system, and how can IG3IS contribute to these improvements?
- What valuable and additional outcomes will result and how can we assure that good-practice standards are established, while the delivery of services becomes scalable and available across the global North and South?

Implementation of an IG3IS requires that the lead organizations, IG3IS bodies, participating entities and individuals understand and apply the set of principles that underpin and define the vision, mission, objectives, activities and deliverables of IG3IS.

The foundational IG3IS principles that will enable the achievement of objectives and keep IG3IS on course are:

- The ultimate criterion for success is that the information produced guides additional and valuable emission-reduction actions.
- IG3IS will provide a common platform, co-developed with stakeholders, for establishing benchmarks, good practices utilizing diverse measurement and analysis approaches inside a reliable framework.
- IG3IS will take a unified approach that combines and analyses atmospheric concentration measurements together with socioeconomic data and information on natural fluxes to better quantify and attribute greenhouse gas emissions and sinks as well as their trends.
- IG3IS matures in concert with the evolution of user needs, policy and technical skills. This will enable researchers to learn the value of envisioned information products and users are introduced to previously unknown capabilities.

1.3 IG3IS objectives and tiers of activity

By themselves, accurate and consistent GAW GHG concentration measurements that are well located with respect to key GHG source regions are necessary but insufficient for IG3IS to deliver additional and useful information about GHG emission, or GHG fluxes (mass per area and time). The IG3IS analyses and resulting systematic services additionally require access to

the best available (and improving over time) information about atmospheric transport, the horizontal and vertical movement of air masses. WMO, with its combination of the GAW Programme and other WMO mandates and technical initiatives related to numerical weather prediction and atmospheric general circulation, such as the World Weather Research Programme (WWRP), make WMO the ideal organization to provide the technical leadership needed to fulfil the IG3IS mission.

IG3IS implementation planning has been underway since the endorsement of the Concept Paper by the WMO Executive Council in June 2016. The IG3IS team defined four implementation objectives in support of national governments, non-state actors, industry, and the Paris Agreement, for which the policy applications and the technical skill are to some extent already in hand and are well matched. These will be described in more detail in the following sections of this plan, but in short are:

(1) Provide information to inventory builders and national governments in support of their efforts to reduce uncertainty of national emission inventory reporting to UNFCCC and/or help guide national GHG policy and regulations.

(2) Support of non-state actor such as cities and states that represent large GHG source regions (for example, megacities) with actionable information on their GHG emissions at the needed spatial, temporal and sectoral resolution to evaluate and guide progress towards emission reduction goals.

(3) Provide information to governments and private industry that will help locate and quantify previously unknown emission reduction opportunities such as fugitive methane emissions from industrial sources.

(4) Support the Paris Agreement's global stocktake as governments and the UNFCCC define their requirements.

For each objective, IG3IS will proceed along two lines of activity: 1) the preparation of methodological guidelines and quality benchmarks that define "good practices" for the use of atmospheric measurements under each objective area; and 2) the initiation of new projects that propagate and advance these good-practice capabilities and build confidence in the value of IG3IS information with stakeholders.

IG3IS activity can also be partitioned according to three tiers of maturity, which applies across all of the IG3IS objective areas. These stages of maturity can be summarized as follows:

(1) Mapping of existing skills to decision-support needs: User needs are understood and technical methods already exist and skill is proven ("on the shelf" proven real world technical solutions).

(2) User needs are identified and understood, and partial technical solutions and skill exist with a plan to fill the gaps.

(3) User needs and the technical solutions are emerging, and both policy discussions and research and development are needed. IG3IS science team plays a role in supporting these discussions and to ensure that the policy and the technical solution converge.

In the near term, IG3IS will focus on existing-use cases in stage 1, for which the scientific and technical skill are proven and on where IG3IS information can meet the expressed (or previously unrecognized) needs of decision-makers who embrace the value of this information.

The IG3IS science team will support the identification of stakeholder needs across the different scales to ensure convergence with existing capabilities, and accounting for the geophysical constraints of the problem.

To respond to other stakeholder needs specific optimizations and developments stages have to be completed, such as, reducing costs of monitoring systems or optimizing modelling tools for specific environments. In this process, the new tools will also be subject to comparison across the scientific community, which will help to establish good practices and benchmarks.

Some mid-term goals can also represent the opportunities for which the policy application requirements and the technical readiness to meet the information needs are both incipient. For example, the Paris Agreement aims to hold the increase in global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Several independent estimates highlight the fact that the sum of the emission reduction pledges from current Nationally Determined Contributions (NDCs) does not put us on a least-cost pathway to achieve this goal (for example, UN Environment Emission Gap Report 2018, https://www.unenvironment.org/resources/emissions-gap-report-2018).

A foundation of the agreement is a "global stocktake" process every 5 years starting in 2023 with the intent, among other things, of tracking the global progress towards achieving the aforementioned goals. The IG3IS methods (atmospheric measurements, remotely sensed and in situ activity data, and modelling systems) will be able to deliver additional information on greenhouse gas emissions as one possible input to the global stocktake process.

The achievement of the long-term goal of a comprehensive integrated system akin to the maturity of numerical weather prediction and the successful response to the most complex and challenging of stakeholder needs falls under the fundamental research, which will be required. This research will be guided by the practical (current and future) questions of stakeholders, as well as be in line with the overall research agenda of WMO Members. The research and development projects conducted will also push the state-of-the art and help advance the benchmarks and good practices within IG3IS.

Two research and development needs already identified for IG3IS are:

(1) Advancing atmospheric transport modelling and improved quantification and benchmarking of inverse modelling skill, both of which are covered in the IG3IS modelling cross-cutting activity (See section 6).

(2) Improved technical capacity to establish the source attribution, for example, the way to disentangle the relative contributions of fossil fuel CO_2 and biospheric CO_2 in atmospheric concentration measurements of CO_2 such as through improved measurement capability for radiocarbon ($^{14}CO_2$) and advancing inverse model analyses of co-emitted, co-varying atmospheric constituents.

1.4 IG3IS science team

To achieve the vision and mission of IG3IS, WMO will maintain a science team (established 2015) to serve as the key technical body in support of IG3IS implementation and the maintenance of "good-practice" science-based methodologies and in support of the development and evaluation of projects. The IG3IS Science Team will:

- Evaluate, endorse, and advise on the technical merits of project proposals looking for IG3IS endorsement and partnership.
- Guide implementation, provide expert support/partnership to IG3IS projects.
- Lead IG3IS cross-cutting activities, research and development activities, and updating the IG3IS Science Implementation Plan.
- Keep informed of and evaluate the scientific developments in the fields of greenhouse gasses and co-emitted species (such as, aerosols and reactive gasses), advances in atmospheric measurement techniques, inverse modelling techniques, data assimilation and other scientific aspects relevant to the IG3IS, and share this information with other members of the IG3IS governance and management structure as appropriate.
- Establish, publish and promote best practices for individual IG3IS activities (observations, inverse modelling techniques, data assimilation).
- Promote IG3IS within scientific community and solicit inputs to IG3IS activities.
- Promote and facilitate research relevant to IG3IS objectives.
- Contribute to the organization of technical/expert meetings on IG3IS objectives.

1.5 IG3IS multi-tiered observational strategy

As stated above, IG3IS success will depend on the creation of new measurement networks in key GHG source regions where emission reduction is taking place or is needed. In addition, IG3IS success will depend on a multi-tiered observing strategy, involving satellite, aircraft, and mobile and tall tower surface measurements. This approach has proven to be effective in many of the emerging IG3IS capabilities that will be documented in the following sections of this plan, such as the identification of large point source (super-emitters) of methane at regional scales (Kort et al., 2014; Frankenberg et al., 2016). A multi-tiered observing network has the potential to inform and unlock potential for cities to achieve advanced emission reduction strategies (Duren and Miller, 2012).

Earth’s carbon-climate system is undergoing profound and unprecedented change. This change is driven by fossil fuel and land-use change emissions that increase atmospheric concentrations of CO_2 and other GHGs. During the last decades, the effect of emissions on the increase of atmospheric CO_2 has been strongly attenuated by the response of the natural carbon cycle, with ocean and land carbon sinks absorbing on average approximately half of the emissions. Future climate change is projected to weaken the capacity of natural sinks and diminish their capacity to absorb CO_2. This combination of complexity across many space-timescales and controlling processes has some parallels with well-established weather and other environmental extremes. However, unlike weather and extreme events, society currently has limited "situational awareness" of the coupled human-natural carbon system.

While IG3IS has near-term objectives and deliverables that will guide improved knowledge on emissions and inform new emission reduction opportunities, the long-term payoff is to enable the provision of decision-relevant carbon situational awareness through comprehensive, reliable, sustained, frequent assessments of greenhouse gas fluxes.

The long-term vision for IG3IS capabilities is similar in some respects to aspects of modern weather services – primarily the rapid delivery of current and recent carbon fluxes and controlling activity (on timescales of weeks rather than years). As with modern weather services, the transition between research-driven and operational GHG observing and information systems presents a number of challenges and will be decades in the making.

Studies sponsored by the European Commission examined the requirements for an operational observing system able to monitor fossil fuel CO_2 emissions (Ciais et al., 2015; Pinty et al., 2017). The focus was within the European domain and builds upon the Copernicus programme. These reports are relevant for defining the requirements for an IG3IS approach to yield valuable new constraints on fossil fuel CO_2 emission inventories, and on the long-term IG3IS goal of a more systematic operational approach. To achieve its long-term vision, IG3IS must help to build upon, integrate and improve existing and planned surface-based measurement networks, airborne and satellite observations, modelling frameworks and data assimilation systems, and help fill key gaps in those systems.

As the providers of the modern weather services, WMO, its Members and partners have the experience and technical knowledge essential for building IG3IS and sustaining it in its future construction, deployment and operational phases. By leveraging existing skills from weather services and ongoing atmospheric and carbon cycle research, WMO can provide the leadership and structure needed to build and deliver IG3IS and decision-relevant carbon situational awareness and help society to avoid the unmanageable impacts of climate change.

2. OBJECTIVE 1: IG3IS IN SUPPORT OF NATIONAL STAKEHOLDERS AND NATIONAL INVENTORY PREPARATION

2.1 Overview

Through Article 4 of the UNFCCC, Parties to UNFCCC have the responsibility to report anthropogenic greenhouse gas emissions and sinks either as annual National Inventory Reports (NIR) or, in case of developing (Non-Annex I) countries, as less demanding and frequent National Communications (NC). Data for the annual NIR are estimated and reported according to guidelines developed by the IPCC Task Force on National GHG Inventories (IPCC TFI), and usually involve combining source-specific emission factors with activity data, a process often called "bottom-up". This process requires a major effort to collect the underlying statistical data and may be prone to errors due to uncertain and incomplete information or simply due to mistakes. Furthermore, it entirely relies on self-reporting and hence on the capabilities of the country to collect the necessary information, which challenges the goals for transparent, accurate, complete, consistent and comparable (TACCC) reporting. The quality of the reports is assured through reviews by third parties, but these reviews only check for consistency of the applied procedures with the guidelines but do not provide an evaluation against independent information.

Under the Paris Agreement, the previous separation into Annex I and Non-Annex I countries has been replaced by a differentiation between developing and developed countries, and all Parties will have to provide an NIR on a regular basis. This will greatly challenge the capacity of developing countries in establishing the necessary infrastructure for data collection, reporting, and quality assurance.

Furthermore, the Paris Agreement requires all Parties to put forward their best efforts through NDCs, and to contribute to the global stocktake every five years to assess the collective progress and inform further individual actions by Parties. Currently, many national inventory reports have a latency of about two years (emission estimates for year Y become available in year Y+2), which limits the ability of the Parties to monitor progress towards the targets of their NDCs in a timely manner.

Atmospheric inverse modelling that incorporates information from measurements of atmospheric greenhouse gas concentrations can support this process by providing a top-down quantification of emissions. Due to the integrating nature of the atmosphere, the top-down approach has the advantage of accounting for the net real world emissions and cannot forget or double count any sources. At the same time the approach can represent a challenge in distinguishing individual contributions to the estimated fluxes as reflected in the research priorities.

The United Kingdom, Switzerland and Australia already successfully include top-down analyses to guide improvements to their NIR reporting. Other Annex 1 countries have comparable measurement and modelling capacities and could follow these examples. Due to the limited capacity of developing countries to collect all statistical data that is necessary for developing accurate emission inventories, these countries could greatly benefit from independent top-down estimates to guide this development. In most countries, but especially in developing countries, this will require setting up additional measurement and modelling infrastructures. Given the widely varying existing infrastructures and needs in the different countries, IG_3IS employs a tiered approach to help address those needs ranging from basic to most detailed emission information.

An IG_3IS near-term objective is to propagate good practices and establish quality metrics for these top-down methods, how they can be compared to GHG inventories developed from bottom-up methodologies, and how the results can be used to target improvements in bottom-up inventory data inputs. The IG_3IS initiative has already made progress on this objective through participation in a recent IPCC TFI Expert Meeting. This near-term IG_3IS objective was presented to the IPCC TFI members who recommended that more information on top-down approaches such as IG_3IS be incorporated as part of targeted updates to the 2019 Refinements to the methodology report updating the IPCC 2006 Inventory Guidelines.

2.2 User information requirements, current capabilities and gaps

The needs for applying top-down methods will differ country-by-country, as each nation develops its own NDCs and priorities, and since the mixture of relevant GHG sources is specific to each country.

Although in most countries the emissions of CO_2 are the dominant contribution to the national GHG budget, they are not necessarily the largest source of uncertainty. CO_2 emissions from fossil fuel use, for example, are often well-known, but large uncertainties exist in the agricultural and land use emissions and uptake. Emissions of CH_4 and N_2O occur from mostly diffuse, complex and time-varying sources and are, in relative terms, much more uncertain than those of fossil fuel CO_2 emissions. To understand the needs of individual countries to improve their emission inventories, it is thus important to identify the emission categories with the largest uncertainties.

Atmospheric inversions have a great potential to provide independent quantification of a country's total and sectorial emissions, to identify shortcomings, and to build confidence in the national reporting. This is particularly true for non-CO_2 greenhouse gases as demonstrated by the examples from UK, Switzerland and Australia. These countries already include top-down emission estimates in Annexes to their annual NIRs following the IPCC 2006 guidelines that explicitly mention the comparison with atmospheric measurements as a means of independent verification. UK includes estimates of fluorinated gases, CH_4 and N_2O based on measurements at Mace Head on the west coast of Ireland and, since 2013, additional sites on the main British island. The measurements are combined with Lagrangian backward transport simulations and an inversion approach described by Manning et al. (2003, 2011). The inversion results, which cover all years since 1990, are broadly consistent with the NIR numbers for N_2O but show significantly smaller negative trends for CH_4. For the hydrofluorocarbon HFC-134a, a large discrepancy of almost a factor of two was found which led to a revision of UK's inventory by correcting the emission factor for HFC-134a losses from mobile air-conditioning (Say et al., 2016). Similarly, the Swiss NIR includes a comparison with top-down estimates for fluorinated gases based on measurements at the high Alpine site Jungfraujoch and applying a simple tracer-ratio method. Since 2016, it additionally covers top-down estimates of CH_4 emissions based on a network of sites established in 2012/2013 and a transport and inverse modelling system similar to that applied in UK. The comparison with the bottom-up numbers showed excellent overall agreement (Henne et al., 2016). It helped reduce the overall uncertainty, suggested a minor overestimation of agricultural emissions, and confirmed the low leakage rates from the natural gas distribution system assumed in the NIR.

There is a growing number of scientific studies revealing the potential of top-down emission estimation at the country level especially for CH_4. Ganesan et al. (2017), for example, reported good agreement between top-down estimates for India with the numbers officially reported to UNFCCC, whereas the study of Miller et al. (2013) suggested a major underestimation of CH_4 emissions by the official inventory in the United States, especially from agricultural sources.

Top-down estimation of anthropogenic CO_2 emissions is likely not a priority for uncertainty reduction since the top-tier inventory methods already have a low uncertainty in most countries. However, atmospheric inversions are likely the most robust method for determining net CO_2 fluxes due to land use and land-use change and forestry (LULUCF) and may thus make a valuable contribution even if the fossil fuel emissions are accurately known. In New Zealand, inverse model analysis of atmospheric measurements indicates that the terrestrial biosphere was a net annual CO_2 sink removing from the atmosphere 98 $TgCO_2\ yr^{-1}$ on average during 2011–2013. This sink is much larger than the 27 $TgCO_2\ yr^{-1}$ reported in the national inventory for the same time period. New Zealand is supporting an ongoing collaboration of atmospheric scientists and inventory builders to refine both approaches and provide best estimates of land carbon exchange.

Not only the needs but also the capabilities differ country-by-country both with respect to bottom-up data collection and with respect to the measurement infrastructure available for applying top-down methods. A close analysis of the respective gaps is required to identify the opportunities for top-down methods and to guide the development of appropriate measurement and modelling capabilities.

In order to respond to the different needs and capabilities of the countries, IG_3IS follows a tiered approach as shown in Figure 1, which differentiates between different levels of sophistication in terms of measurement and modelling infrastructure. Some countries may need a first rough estimate of emissions and their trends, for which a low tier would be sufficient. Other countries may need more accurate information not only on country totals but

also on sector-specific emissions, which will require a higher tier. Distinguishing between anthropogenic and biospheric fluxes of CO_2 will always require the highest tier for the measurement infrastructure, that is, measurements of additional tracers such as radiocarbon, stable isotopes, and co-emitted species.

Increasing model complexity →

Increasing measurement complexity ↓

		Tier 1 Use established (global) model and inversion system, operated by external experts	Tier 2 Use established (global) model and inversion system; develop local expertise to operate the system	Tier 3 Taylored high-resolution modeling and inversion system, operated by local experts
Tier 1	Single representative station in country or station every 500-1000 km	Trend in total emissions in area of influence of site(s)	Total emissions and their trend in area of influence of site(s)	Total emissions and their trend with higher accuracy in area of influence of site(s)
Tier 2	Network of sites covering all parts of country, simple measurement infrastructure	Trend in country total emissions, no separation between anthropogenic and biospheric fluxes	Total country emissions and their trend, no separation between anthropogenic and biospheric fluxes	Total country emissions and their trend with higher accuracy, no separation between anthropogenic and biospheric fluxes
Tier 3	Network of sites covering all parts of country, additional tracers (radon, radiocarbon, isotopes)	Trend in country total emissions, separation between anthropogenic and biospheric fluxes, sector-specific information	Total country emissions and their trend, separation between anthropogenic and biospheric fluxes, sector-specific information	Total country emissions and their trend with higher accuracy, separation between anthropogenic and biospheric fluxes, sector-specific info.

Figure 1. Tiers of sophistication of the measurement network and modelling infrastructure and questions that can be addressed for a given combination.

Source: WMO

2.3 Measurement network design

The objective of this section is to provide guidance on the observational network required for the assessment of the national GHG emissions. A first analysis should address the existing infrastructure in a country and identify the most suitable sites by considering the local environment, spatial coverage, and also practical aspects. The suitability of a site depends on the height of the sampling above surface, the local environment including topography, proximity to significant sources, buildings, and vegetation, the proximity to other sites, as well as practical considerations such as accessibility, power, internet, etc. A site should capture the integrated signal from a source region, and therefore not be too close to individual sources where the signal is complex, but also not too far so that the signal is robustly seen.

Tall towers are preferred locations, as they offer a high-spatial coverage and are least susceptible to local influences. This is particularly relevant in the case of CO_2, which may be strongly affected by exchange fluxes with the local vegetation. Locations in complex topography should be avoided, since the ability of atmospheric transport models to represent small-scale topography-driven circulations is still limited. Mountain sites may be valuable if the corresponding measurements have similar properties as a tall tower, but often this is not the case or the measurements have to be strongly filtered for suitable conditions.

The set-up of a greenhouse gas measurement network may benefit from existing air pollution monitoring infrastructure, but the needs for representative greenhouse gas observations are different from those of air pollution monitoring networks, which often focus on polluted locations with strong local influences and correspondingly poor representativeness.

Starting from the available infrastructure, a network design study based on observing system simulation experiments (OSSE) should identify gaps and the optimal placement of additional sites.

Such OSSEs should build on backward Lagrangian Particle Dispersion or similar simulations that are able to calculate the sensitivities of the measurements to upstream sources. The main tool of the OSSE are inversion simulations with synthetically generated observations, a priori emission inventories and natural fluxes, and global background model fields. The inversion simulations should compute national/regional/sectoral uncertainty reductions based on various network configurations.

The OSSE should be set-up for a minimum period of one year to cover a wide range of weather conditions and a complete seasonal cycle of GHG. It should account for the sources and sinks of the target gases as realistically as possible, since the optimal configuration of the network will be sensitive to these choices. A priori anthropogenic emissions may be obtained from global databases (for example, EDGAR) and natural biospheric fluxes of CO_2 and CH_4 from terrestrial ecosystem models (for example, DGVM-TRENDY model intercomparison; WETCHIMP for methane).

The network design should not only be based on the requirement of capturing a major proportion of the emissions of a country, but should also consider the possibility to distinguish between different types of emissions. The sites should therefore cover a wide range of sensitivities to different source categories.

To successfully capture the influence of the orography and of the heterogeneous landscape and sources on the measurements, the OSSE should be based on high-resolution simulations provided either by a regional model or driven by high-resolution global meteorological analyses, which are now becoming available at resolutions down to about 10 km x 10 km. Regional models need to be embedded in global models, which must be able to describe background concentrations without significant biases.

Due to the limited resolution of the atmospheric transport models used in such OSSEs, local influences are not well captured and should be addressed by other means such as, by analysing the dominant wind sectors and identifying potential disturbances such as nearby sources in those sectors.

2.4 Measurement network development

The measurement network should build on well-established equipment and procedures and should be as uniform as possible to limit the costs for maintenance and training of technicians. Auxiliary measurements of co-emitted species such as NOx, CO, hydrocarbons and of isotopes should be considered, as these will help to attribute the measured enhancements to specific sources. Regular flask sampling and subsequent analysis in the laboratory may be a valid alternative when measurements for the more challenging species such as isotopes are not possible on site.

The following considerations should be included in the instrumentation set-up:

- Selection of adequate greenhouse gas analysers with necessary precision and accuracy and with stable performance and low needs for interventions.
- Selection of peripheral equipment (data acquisition, valves, pumps, flow control, water removal, calibration units etc.).
- Selection of instrumentation for auxiliary measurements, for example, for co-emitted air pollutants like NOx, CO, hydrocarbons, for isotopes, radon, flask sampling.
- Selection of equipment for standard meteorological parameters (wind, temperature, humidity, pressure) and for more advanced parameters such as turbulent fluxes or planetary boundary layer height.
- Measurement set-up, that is, installation of all equipment on site, mounting of inlets and sampling lines, air conditioning, etc.
- Definition of standard operation procedures, that is, responsible personnel, frequency of station visits, interventions and maintenance, etc.
- Development of a quality assurance / quality control framework (for example, calibration strategy, selection of reference gases, reference scales, traceability to WMO, network compatibility, linearity, blanks, drift correction, determination of overall measurement uncertainties), procedures for troubleshooting in case of instrumental issues.
- Design of data management (data visualization, review, processing, archiving and dissemination).

Some guidance on the quality assurance procedures within the GAW Programme can be found in the WMO Greenhouse Gas Measurement Techniques (GGMT) recommendations available at https://library.wmo.int/opac/doc_num.php?explnum_id=3074.

2.5 Model development

A large number of atmospheric inversion systems have been developed in the past based on different flavours of the Bayesian principles (analytical, variational and ensemble formulations). These techniques sometimes involving technical developments have delivered information on greenhouse gas emissions mostly within the context of scientific research. They have allowed the demonstration studies that support the vision of IG_3IS.

In order to orientate these systems towards policy applications, a community effort is needed to greatly enhance the traceability and transparency of the process. Inversion results should be reproducible on various systems, not only for different target applications but also for the same target but by different users, possibly with a different set-up. This calls for a community framework that should be modular, documented, free and open-sourced. Furthermore, it should be flexible to support different transport models, control vectors, and inversion techniques. Such a well-documented community framework would greatly simplify the access for new users and enhance the acceptance by policymakers.

The set-up of an operational inversion system is a significant investment that needs to go hand in hand with the implementation of the measurement network. National weather services are often experienced in running numerical models, but inverse modelling requires adjoint

techniques that are usually beyond their expertise. Operating an inversion system will thus require specially trained persons that are familiar with the concepts and able to interpret the results. Lagrangian particle dispersion models (LPDMs) have the advantage that they can be run easily in backward mode, driven by the output of a numerical weather prediction (NWP) model. LPDM simulations could thus be integrated into the operational model chain of a weather service without a major effort. Ensemble Kalman filter approaches require only forward model simulations that may be realized with standard NWP models, but the model needs to be able to transport passive tracers and the investment in computation resources for running the ensemble may be significant.

Other approaches require an adjoint code, which is often not available for the NWP models used by weather services. Running such a code thus requires setting up additional modelling infrastructure. Alternatively, the simulations could be carried out externally by a specialized company or modelling center.

It should be acknowledged that while atmospheric inversions are necessary to quantify national fluxes, much information can already be obtained from examination of observations before models are added. Examples are trends in concentration peak amplitudes, which are closely related to real emission trends, tracer-tracer ratios, or the partitioning of sources using isotopes and ancillary tracers. This is of particular importance for low and medium income countries where resources and expertise may be hard to come by. Showing pathways to build a national GHG observing system over time will be essential.

2.6 Communications and technical support for inventory builders

As inventory builders work with emission factors and activity data, the outcome of inverse modelling/top-down regional emission estimates should not only address total emissions but should be broken down into activity categories. The joint work with inventory builders at national and international (IPCC TFI) level is needed to address the requirements of inventory builders.

2.7 Capacity building and outreach

Good-practice greenhouse gas observations, associated data processing and management, as well as meteorological and inverse modelling require sound scientific and technical expertise available in country at a given project location.

The identification of existing knowledge and the development of appropriate know-how are key to maintain a sustainable infrastructure and to retrieve long-term high-quality outcomes; therefore, capacity building and training are central to implementation.

3. OBJECTIVE 2: IG_3IS IN SUPPORT OF MITIGATION EFFORTS OF CITIES AND OTHER NON-STATE ACTORS

3.1 Overview

The Lima–Paris Action Agenda of the Paris Agreement has formalized a role for "non-state actors" including cities (and other sub-national stakeholders) as leaders in greenhouse gas mitigation and climate adaptation. Due to their concentration of population and economic intensity, cities account for roughly two-thirds of energy-related greenhouse gas emissions. In order to provide a diagnosis of urban emissions at policy-relevant scales and identify low-carbon or carbon mitigation opportunities, stakeholders need to understand their emitting landscape due to both natural and human activities. Given the widely varying existing knowledge and needs, IG_3IS employs a tiered approach to help address those needs ranging from basic to most detailed emission information. This information must be generated in a timely manner by scientifically accurate methods, reflect space and timescales relevant to urban decision-making, and if possible, include attributions that are consistent with information categories cities often manage such as economic (sub-) sector and fuel types.

A number of research and development projects around the world, such as the Indianapolis INFLUX project, the Los Angeles and Paris testbed systems (described below), have developed and tested methods for integrated/innovative estimation of greenhouse gas emissions. This work has established a framework for urban greenhouse gas information systems that combine atmospheric monitoring, data mining and model algorithms. IG_3IS will provide an overview of the scientific basis, principles and components available to provide information at various tiers of detail, particularly in response to a large, urgent need for GHG management for the low- and middle-income countries where GHG information needs are greatest, capacity is limited and emissions are still expected to increase.

IG_3IS goals include short feedback loops to demonstrate the positive impact of mitigation activities (faster than the current 1-2 year lag in producing national inventories). This will offer the opportunity for "course-correcting" action in a timely manner. The integrated greenhouse gas framework aims to be relatable to socioeconomic data at commensurate space and timescales to enable analysis of co-benefits and trade-offs such as air quality improvements, traffic management, quality of life.

3.2 User information requirements, current capabilities and gaps

IG_3IS aims to determine the expectations and needs of stakeholders through direct connection with city authorities and through creation of an advisory group of interested stakeholders and pilot cities. Especially beneficial are interactions with city networks such as C40, ICLEI and the Global Covenant of Mayors as well as state agencies like the California Air Resources Board (CARB), Bay Area Air Quality Management District (BAAQMD), Companhia Pernambucana de Controle da Poluição Ambiental e de Administração de Recursos Hídricos (CPRH) and regional governments. For many of these activities natural partnerships will be with climate-KIC, the Carbon Disclosure Project (CDP), the World Resources Institute and CO_2-USA that have previously performed demand assessment studies. Direct entrainment of urban stakeholders is critical to success as each city has unique priorities, which are potentially changing over time, in addition to acting as partners in discovering and assessing relevant local data.

IG_3IS aims to match existing R&D and pre-operational urban scale monitoring and modelling systems to the information needs of stakeholders for example, whole city emissions, trend analysis, space/time/sector quantification, sector specific analysis of emissions, co-benefits

and trade-off with air quality inventories and biosphere exchange. The science team will identify where current knowledge and techniques are insufficient to meet stakeholder needs and outline a pathway to resolve them.

Identified needs and examples of relevant tiers of information

Information can be provided for each need, with different levels of robustness from the most readily implemented approaches to the more complex approaches. The available tools and expertise as well as urban typology will determine the most appropriate level for a given case. Examples of already identified need and demonstrated, theoretical and future solutions are outlined on Figure 2.

Level of sophistication of urban stakeholder needs →

Complexity of solution ↓

Identify major emitters and anomaly detection	Quantification of total GHG emissions	Assessment of GHG emissions per sector	Tracking annual and long-term emission changes	Understand short-term emission changes and spatial patterns	Process understanding of emissions and tracking of mitigation impacts
Inventory validation (A1)	Inventory or emission model (A2)	Sector-specific inventory or emission model (A3)	Continuously updated inventory or emission model (A4)	Temporally and spatially disaggregated inventory or emission model (A5)	Process-based emission model using real-time emission data (A6)
Mobile surveys (B1)	Mass-balance (B2) Radon tracer method (B3)	Multi-tracer ratio observations (B4)	Radon tracer method (B5) Multi-tracer observations (B6)	Mobile surveys (B7) Urban flux towers (B8) Repeated mass-balance (B9)	Urban flux towers (B10) Dedicated field campaigns (B11)
Remote sensing (C1)	DAS using short-term observations (C2)	*DAS using dense observations (C3)* DAS using multi-species data (C4)	DAS using long-term observations (C5)	*DAS using dense observations (C6)*	FFDAS DAS using multi-species (C7)

Demonstrated skills
Theoretically tested skills
Future potential skills

DAS = data assimilation system

Figure 2. Tiers of sophistication of the measurement and modelling systems and stakeholder questions that can be addressed for a given combination.

Source: WMO

Case studies on user needs

For more than 30 years, the trend in the fossil fuel CO_2 ($ffCO_2$) concentration has been monitored in Heidelberg, Germany by the Institute of Environmental Physics of Heidelberg University. Fortnightly measurements of the radiocarbon content in atmospheric CO_2 allow the separation of biogenic from fossil CO_2 components by comparing them to radiocarbon measurements at a background site.

The city of Heidelberg as well as the rest of Germany have reduced the $ffCO_2$ emissions as part of the Kyoto protocol. Sustained $_{14}C$ measurements when accompanied by continuous CO_2 and $_{222}Rn$ measurements allow for (see Figure2 for the used solution codes):

- Detecting emissions trends (B5);
- Separating biogenic and fossil CO_2 contributions (B4);
- Independently quantifying CO_2 emissions (B3).

Figure 3 compares the trend observed in atmospheric $ffCO_2$ contributions to bottom-up emissions for the state of Baden-Württemberg, all values normalized to 1996=100%.

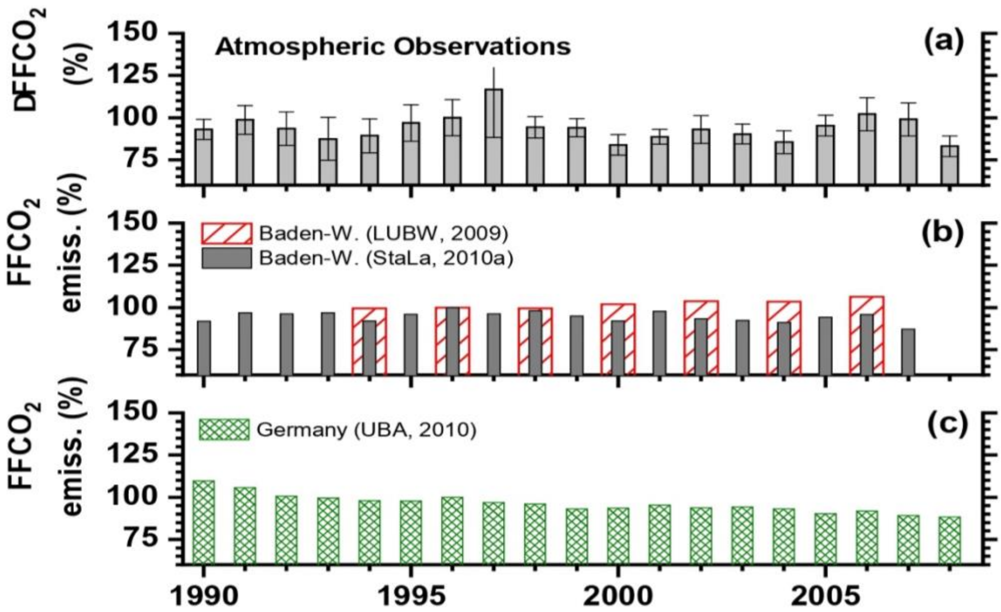

Figure 3. Comparison of the bottom-up and top-down estimates of CO_2 emissions related to the fossil fuel combustion (for the state Baden-Württemberg, Germany).

Source: Ingeborg Levin, Samuel Hammer, Elke Eichelmann and Felix R. Vogel (2011)

Bottom-up emission statistics for the state of Baden-Württemberg reports a reduction of 15% compared to 1994-1996. Atmospheric top-down estimates confirm the magnitude as well as the timing of this decrease.

The Recife Project was an extension of the CarboCountCity projects conducted in Paris, France (Bréon et al., 2015, Staufer et al., 2016, Wu et al., 2016). Through funding by the air quality agency of the State of Pernambuco, Brazil (CPRH) and the Climate KIC European Institute of Innovation and Technology (EIT) a project was launched to demonstrate the commutability of the approach used in Paris. The Recife urban area in Pernambuco, Brazil houses ca. 4 million people but did not have any atmospheric monitoring of GHGs prior to 2015. Within the project a sector specific emission inventory for CO_2 (A1, A3) based on publicly available data was created and two atmospheric measurement stations deployed for several months to estimate GHG emissions using data assimilation system DAS (Figure 4), and support improvements of the inventory and identify emission anomalies (C2, B1).

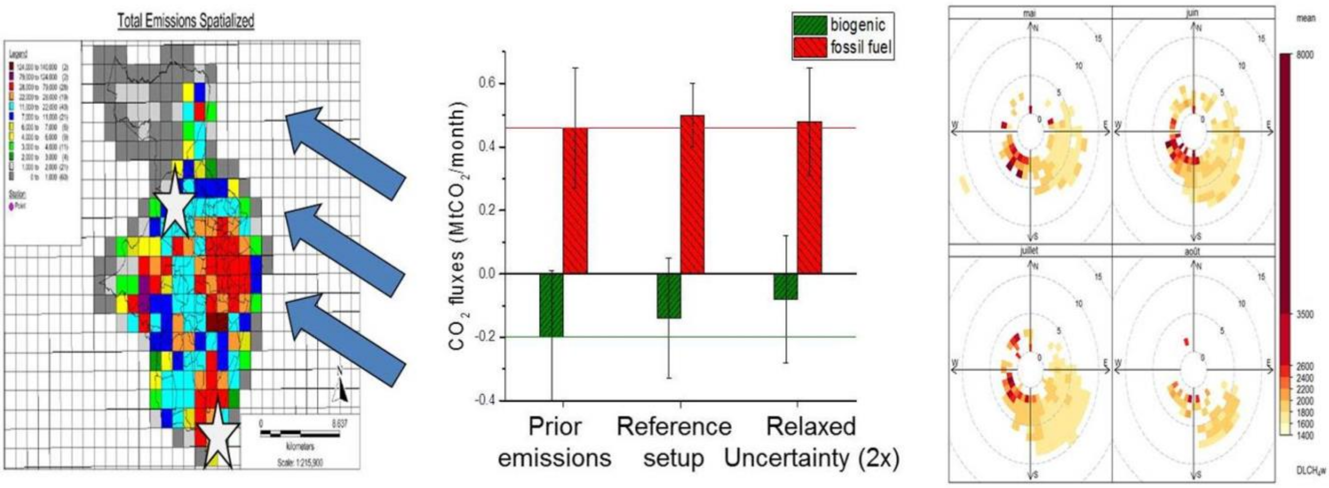

Figure 4. CO_2 emission inventory for the Recife region with locations of measurement stations and main wind direction (left), comparison of inventory estimates and inversion results (center), pollution rose of observed CH_4 concentrations (right).

Source: Recife Project - CarboCountCity

The inventory estimated annual emissions of 5.52MtCO_2 for the region and the inverse modelling system confirms emissions at the level of 6.0±1.2MtCO_2. After creating confidence in the CO_2 inventory, it is now being used to establish a spatialized inventory for criteria air pollutants for the region. The co-located measurements of CH_4 helped to identify strong local emissions from the city and the mangroves, likely due to significant amounts of untreated wastewater, signalling a large potential for future GHG mitigation for Pernambuco and Recife.

The Indianapolis Flux Project (INFLUX) aims to develop and assess methods for quantifying greenhouse gas emissions from urban areas, using Indianapolis as a testbed. INFLUX has run since 2010 and has 12 instrumented towers (in situ CO_2, CO and CH_4 and ~weekly flask sampling for 50 species including $^{14}CO_2$, CO_2, CO, halocarbons and hydrocarbons), regular flights by instrumented aircraft, a high-resolution bottom-up data product (Hestia), CO_2 flux towers, and mesoscale modelling (WRF/LPDM (Davis et al., 2017; Lamb et al., 2016; Lauvaux et al., 2016; Turnbull et al., 2015, Gurney et al., 2012). In addition, INFLUX provides a testbed for novel techniques, either long-term or short-term experiments, such as column observations, and novel tracers and isotopes (Vimont et al., 2017). INFLUX has thus by far demonstrated the utility of IG_3IS at several levels (for example, Figure 5):

- Atmospheric observations of an unexpected CO_2 plume subsequently identified a missing coal-fired power plant in the bottom-up dataset; this was one of a number of power plants that were misidentified in the USA point source catalogue and the bottom-up dataset was rectified not only for this single power plant but for many more around the USA (Figure 2, A1).
- Indianapolis includes a large electricity generation plant and atmospheric observations have documented the reduction in emissions as the plant shifted from coal to natural gas between 2014 and 2017 (Figure 2, C4).

- The Hestia high-resolution bottom-up data product, atmospheric inversion based on tower data, and aircraft mass balance all produce whole-city CO_2 flux estimates that agree to better to 10% (Figure 2, A2, B2, C2).
- Flask-based measurements have separated the fossil fuel and biogenic fluxes, showing that even in the cold Indianapolis winters, biogenic sources contribute ~20% of the urban CO_2 emissions (Figure 2, B4).
- The time-varying ratio of $CO:CO_2$ has been used to evaluate the mixture source sectors contributing to CO_2 emissions and shows that the Hestia data product has the source sector mix approximately correct except during the night-time when it appears that traffic CO_2 emissions may be underestimated (Figure 2, A3, B4).
- The total urban CH_4 emissions for Indianapolis have been evaluated by developing a process-based inventory, which underestimates emissions relative to aircraft-based mass balance and tower observation based data assimilation system and signals that diffuse natural gas leaks are the most likely reason for the inconsistency (Figure 2, A1, A2, B1, B2, B7, C2).

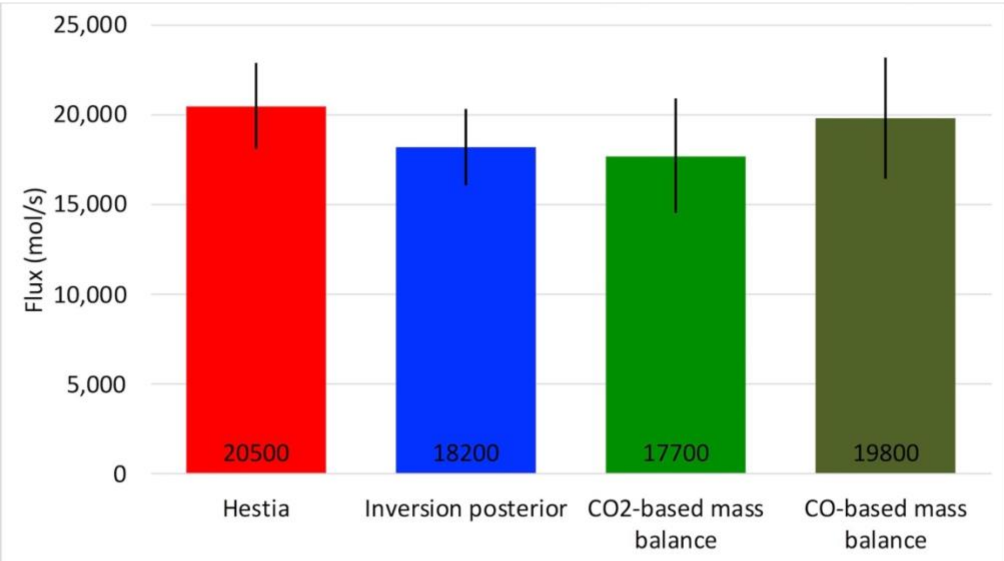

Figure 5. Indianapolis CO_2ff flux comparison utilizing different approaches

Source: Jocelyn C. Turnbull (2019)

3.3 Urban typology

Urban regions (cities and connected urban regions) vary widely in human-dominated dimensions including their per capita energy use, urban density, age of infrastructure, dominant commercial sectors, GDP. These factors significantly influence emission profiles and can determine future mitigation potential (Creutzig et al., 2016). Understanding how particular cities respond to changing drivers such as climate change, urbanization or novel technologies could allow grouping them, so that climate solutions for similar cities can be identified (Nangini et al., 2019).

Other dimensions critical to understanding GHG emissions are given by the geophysical features of a city, its topography, availability/proximity to water, climate and weather. For example, two broad typologies based on meteorological conditions have already been identified: plume and dome cities (Hutyra et al., 2014). In plume cities, the urban emissions are transported downwind in an identifiable plume, which may be sampled to characterize emissions. Dome cities are often constrained by topography so that the emissions build up in a "dome" over the city, flushing out only irregularly. The buildup of emissions in the dome can be tracked.

The creation of a more detailed urban typology to identify commonalities and differences between urban areas will ensure that new urban studies take advantage of existing knowledge relevant to their own typology. Here a strong connection to previous work within GAW Urban Meteorology and Environment (GURME) project and the Global Carbon Atlas will help accelerate our progress.

3.4 High spatial and temporal resolution bottom-up emission products

A new approach to traditional bottom-up inventories has emerged in the last decade. These new emission data products utilize combinations of remote sensing, data mining and modelling to provide space and time-resolved estimates of emissions at multiple scales (global, national, urban). Often built from information about individual emission processes, these data products have shown greater consistency with atmospheric monitoring and deliver more functional detail than traditional or "regulatory-based" inventories.

At the global and national scales these are typically built from some combination of national GHG reporting, night-time lighting, population distribution, power plant databases, air quality reporting and traffic data (Oda and Maksyutov, 2011; Oda et al., 2017; Rayner et al., 2010; Asefi-Najafabady et al., 2014; Gurney et al., 2009; Jones and Kammen, 2013). These efforts provide 1-10 km resolution and are a "basic" or tier-1 starting point for urban areas where little information currently exists, and limited effort has been made to acquire city-specific emissions-related information.

At the urban scale, recent research has demonstrated the ability to quantify emissions at the scale of individual building and street segments, characterizing the emissions process at the individual emitter scale. An example is the Hestia effort in the USA for which four USA cities (Baltimore, Los Angeles Basin, Salt Lake City, Indianapolis) have achieved a complete building/street scale emissions estimate for multiple years (Gurney et al., 2012). These urban data products are constrained by the national Vulcan data product and use additional data unique to a given city to further refine the magnitude and space/time detail of emissions.

These scientific efforts, typically focusing on direct emissions, are distinct from the many cities that have performed GHG footprinting with the assistance of city networks such as ICLEI. These more traditional footprints are useful where no alternative exists but necessarily use simpler, more approximate methods and can be incomparable to other cities due to the lack of a common metric or linkage across scales.

These scientific emission data products are used as a prior constraint for the integrated data assimilation system approach using atmospheric measurements. The emission data products offer an important constraint to the space and time distribution of fluxes and in return are strengthened by the integrating accuracy of the atmospheric monitoring, providing constraints at the whole-city scale. Integrated, the combined approach offers the most accurate, information-rich emissions estimation possible for an urban domain.

A novel next step would be process-oriented city-scale emission models, which include emission processes that have been calibrated (fine-tuned) for the specific city using atmospheric observations. For example, determination of heating emissions in response to ambient temperature variations or traffic sector emissions based on vehicle consumption/efficiency models. Such a system could allow for better prediction of the impact of reducing emissions in a specific sector due to mitigation policies or regulations.

Whereas CO_2 emissions are often a direct product of human activity and therefore correlate and can be modelled as described above, methane emissions are often representative of unintended loss processes, and it is thus more difficult to construct high-accuracy inventory representations. For methane, this is part of why atmospheric observations contain such high value. Some efforts have made headway in creating bottom-up emissions products using publicly available data and geospatial mapping techniques, most notably the Vista-LA project in Los Angeles (Carranza et al., 2018).

The majority of nations plan to invoke Land Carbon Credits as part of their NDCs and cities are also interested in how urban ecology may mitigate their emissions. While considerable effort has been taken to evaluate biogenic carbon fluxes globally and regionally, urban biogenic fluxes remain almost entirely unconstrained. While highly urbanized city centres may have little vegetation, suburban and exurban regions typically have a large fraction of vegetative cover that is heavily managed (irrigation, fertilization, removal of green waste, and so forth) and often support ecology dissimilar to the surrounding regions. Thus, urban regions could have very different biogenic carbon fluxes than the surrounding regions, in both magnitude and seasonal cycle and recent research hints that this may lead urban areas to sequester substantially more carbon than the surrounding rural areas (Reinmann and Hutyra, 2017).

IG_3IS methodologies address both anthropogenic and biogenic carbon fluxes. Bottom-up biogenic carbon flux process models are being developed specific to urban areas, including estimates of impervious surface area, effects of the urban heat island, and the differing vegetation in cities (for example, Hardiman et al., 2017). Eddy CO_2 flux measurements allow evaluation of the net ecosystem fluxes for small areas and specific land cover types in a given region and have been systematically used in urban areas since within FLUXNET (Grimmond and Christen, 2012). Multi-tracer approaches allow partitioning of CO_2 fluxes. $^{14}CO_2$ is widely used to partition the urban CO_2 flux into fossil fuel and net biogenic fluxes (Turnbull et al., 2011; Levin et al., 2003; Newman et al., 2016; van der Laan et al., 2010) and carbon monoxide (CO), with careful calibration for a given urban area, can also be used (Vogel et al., 2010; Turnbull et al., 2015; Levin and Karstens, 2007). Carbonyl sulphide (COS) has the potential to separate photosynthetic and respiration fluxes (Hilton et al., 2017) and oxygen isotopes in CO_2 have been used to further separate the respiration flux into above and below ground respiration (Djuricin et al., 2010).

3.5 Measurement design

Various urban measurement and modelling systems have already been deployed and new techniques are rapidly evolving. The choice of technique will depend on stakeholder needs, which GHG is being targeted, the urban typology, and the availability of equipment and expertise for the city of interest. For the techniques already deployed in the field efforts should be undertaken to identify existing and known methodological challenges to avoid duplicating errors/problems in future studies. Efforts are underway to critically assess the current techniques and available skills and determine where future developments should be directed to meet the needs of stakeholders. Nonetheless, some generalities apply: measurement networks will typically include a network of in situ GHG sensors, co-located measurement of ancillary

trace gases and isotopes, and local meteorological information. These may be deployed at fixed sites and/or on mobile platforms.

A large amount of information at the whole city scale can be obtained from direct analysis of atmospheric observations and bottom-up data products, by using a ratio approach. That is, when any two tracers are co-emitted or their emissions are co-located at the spatial scale of interest, the ratio of the local concentration enhancement of those two tracers is largely independent of atmospheric transport, as long as both tracers are stable in the atmosphere and mixing with background can be accounted for. Thus, as long as the footprint is approximately known, the emission ratio of two tracers can be directly evaluated from atmospheric observations of both species. Where the flux of one tracer is independently known then the flux of the other can be simply derived, such as, using ^{222}Rn and CO_2 measurements together (van der Laan et al., 2010). The relative partitioning of CO_2 into source sectors can also be achieved through the ratio technique, such as, splitting the total CO_2 flux into fossil and biogenic components using $^{14}CO_2$ and total CO_2 observations (Levin et al., 2003; Turnbull et al., 2011). These techniques can provide straightforward, reliable diagnostics of long-term changes in emissions, even though they may not provide absolute emission flux rates. Mass balance techniques can determine whole city fluxes using aircraft measurements, combining CO_2 observations and meteorological data with some assumptions about atmospheric mixing processes. A modest number of aircraft flights can provide a reasonable whole city flux estimate, but this method may be limited or biased by flight constraints such as weather and air traffic restrictions. Nonetheless, mass balance can be quite effective in "plume" urban typologies, as highlighted in the Indianapolis Flux Project (for example, Heimburger et al., 2017; Cambaliza et al., 2014).

Quasi-continuous in situ measurements from towers or other locations within and around cities provide a wealth of information. Large point sources may be identified from the observations alone, and in combination with DAS, may be used to estimate total emissions (CO_2, CH_4 and other species), track trends through time, quantify the impact of external drivers (for example, ambient temperature), etc. (Figure 2, C2,3,4,5,6,7). The main sensors used for GHG measurement are high precision (<0.1 ppm uncertainty for CO_2, <4 ppb for CH_4), typically providing observations at a native time resolution of a few seconds that may be averaged to time periods of up to one hour. For urban areas which have large signals or stakeholder questions that require only a limited precision, instrumental requirements may be less critical than for other urban or national-scale studies. Yet data quality must still be assessed, particularly persistent biases in instrumentation. Offsets between instruments within a network are of particular concern, and in most situations, the instrumentation should be calibrated to the same scales as used by the wider greenhouse gas community (see GGMT recommendations available at https://library.wmo.int/opac/doc_num.php?explnum_id=3074), to ensure consistency. This is particularly important when other data streams (such as background observations from other networks) will be incorporated.

Sensor types for additional tracers (carbon monoxide, ethane, oxygen, air quality gases, particulates, hydrocarbons and halocarbons) and isotopes (primarily ^{14}C and ^{13}C) vary for each species. Some species can be measured in situ but in many cases, it may be necessary (for example, ^{14}C) or advantageous to collect air for offsite analysis. A large suite of gases and isotopes can be measured from a single flask of air in a single laboratory, substantially reducing costs relative to deploying multiple in situ instruments and ensuring that the suite of tracers are all measured from the same parcel of air. Flask measurements are also a key diagnostic for ensuring consistency across multiple in situ instruments at different sites. In the highly variable urban environment, time-integrated flask sampling (over ~ one hour) is beneficial to avoid sampling short-term variability that is difficult to interpret. Offsite analysis

requirements necessarily limit the measurement frequency of these measurements. For long-term monitoring, samples taken once or twice per week may be sufficient, but shorter campaigns may require denser sampling. Samples are commonly taken during mid-afternoon to maximize the ability to interpret the data with atmospheric transport models but diagnosis of diurnal cycles will require sampling across a range of time periods. A combination of in situ measurements and flask collection can be useful. For example, in situ CO measurements can be used to determine fossil fuel CO_2 when regular paired $_{14}C$ and CO flask measurements are used to diagnose the CO to fossil fuel CO_2 ratio at a given location (Levin and Karstens, 2007).

Lower-cost sensors, total column and open-path sensors are emerging new technologies that are still being assessed in established urban testbeds such as, Paris, Indianapolis and Los Angeles. They provide an opportunity to obtain much denser spatial information at lower cost, but this is traded for lower precision and potential biases that present as-yet-unresolved challenges in flux determination. A wide range of lower-cost sensors is available, with a commensurate range of data quality. Medium precision CO_2 sensors may have 1-2 ppm long-term repeatability, and lower precision sensors may have 5-50 ppm repeatability. Users will also want to consider the full cost of the observations that is, cost per valid and useful data point, as low investment costs may be offset by high maintenance and calibration costs.

It has been suggested that integrated column measurements of the urban dome of CO_2 are less sensitive than surface point measurements to the redistribution of emitted CO_2 by small-scale processes and thus may allow for more precise trend detection of emissions from urban regions (McKain et al., 2012).

The choice of sensor location will determine the ability to provide useful information about the regions/processes to be monitored; in general, locations should be well above ground so that they are not unduly influenced by very local sources and have a footprint commensurate with the area of interest. Telecommunications towers are commonly used, and rooftops are often practical sites but consideration of direct building emissions is needed. Existing high precision but low-density networks typically use high altitude (50 – 200m) locations so that each sensor observes a large area. This also has the advantage that the highly heterogeneous urban emissions are at least partially mixed before reaching the observation site, making interpretation more straightforward. Lower altitude sites will have a much smaller footprint that may be appropriate for high-density networks, but careful consideration must be given as to how these small footprint signals can be scaled up to represent the whole city.

When the objective is to constrain urban CO_2 emissions, the up-wind or background CO_2 (and tracer) concentration must be appropriately quantified to isolate the signal of the urban region. The objective of these reference measurements is to determine what the signal at the downwind site would have been in the absence of the urban emissions. In practice, this background is typically determined from observations upwind or on the edges of the urban area, sometimes in combination with sophisticated regional atmospheric transport modelling. Continental background sites are often insufficient to isolate the signal of an urban area but may be useful in combination with other methods. For urban areas with other emission sources nearby, multiple observational sites may be required to adequately constrain the background and its spatial and temporal variability, and these critical observations may require a significant investment.

Meteorological information including wind speed and direction and boundary layer height will be needed in most cases. For some urban topographies, data from existing meteorological stations may provide sufficient detail, but more complex topographies may require meteorological measurements co-located with the greenhouse gas observation systems.

3.6 Model development

More complex modelling frameworks utilize atmospheric transport modelling. Forward and backward atmospheric transport models are used to describe the movement of the air and relate observed atmospheric concentrations to the emission flux. Mesoscale transport models with horizontal resolution of around 1 km and hourly time step run in forward mode are typically used to describe the meteorology; some urban typologies will need much finer resolution. Lagrangian particle dispersion models are commonly used for the backward modelling. Recent innovations that are still under development include higher-resolution plume and eddy models that may be run independently or embedded within the other models.

Atmospheric inversions use this modelling framework in conjunction with observations to provide a highly detailed analysis of urban emissions, ultimately allowing for improved estimates of the emission flux sector-by-sector, at hourly time step and fine spatial resolution. They incorporate spatially explicit bottom-up data products as a prior "first-guess" constraint, and use an atmospheric transport model to predict the concentrations at observing sites and times. They then apply statistical tools to adjust these fluxes to obtain the best match with the atmospheric observations, providing improved flux estimates that incorporate both the process-based information in the bottom-up data products and the atmospheric "truth" that integrates across all sources. The quality of atmospheric inversions is dependent on the model fidelity and on the quality and density of the observations that drive them. Urban-scale CO_2 inversions are relatively common, but are still novel for CH_4 emissions quantification, in part because bottom-up data products less well-developed for CH_4 than for CO_2.

It is important to recognize that different techniques (see Table 1) assess emissions in different ways. Comparison of different methods requires understanding of this "apples and oranges" problem. For example, bottom-up methods generally evaluate only anthropogenic CO_2 emissions, whereas top-down observations that rely on CO_2 observations alone will incorporate both anthropogenic and biogenic CO_2 sources. By adding isotopic or other fossil CO_2-specific observations, this inconsistency can readily be resolved. Bottom-up methods will estimate emissions for a specified domain, which may include only specific political boundaries, whereas atmospheric observations will evaluate emissions for the footprint of the particular observational strategy (which may be smaller or larger than the bottom-up domain). Depending on the observational strategy and modelling methodology, atmospheric inversions may be more or less strongly linked to the initial prior emission estimate. For example, most atmospheric inversions currently assimilate only afternoon observations, so they have very little sensitivity to night-time fluxes.

High-resolution modelling, particularly in the highly heterogeneous urban emissions landscape, can still benefit from refinement and further understanding of the biases and uncertainties in the modelling systems.

Areas of particular interest for urban scale include:

- The impact of the chosen atmospheric transport model. This includes consideration of different types of models (Lagrangian, Eulerian, large eddy simulations, computational fluid dynamics, etc.) and even differences amongst models of the same class due to different assumptions and parameterizations.
- The robustness of different data assimilation approaches for atmospheric inversions (analytical Bayesian, variational Bayesian, Kalman filter, and so forth).

- Novel data streams used to create prior emission inventories (such as, cell phone data, high-resolution satellite imagery, biogenic flux models, local level demographic data, city/company reported emission inventories, point source information).
- Novel inversion systems such as those without spatially explicit prior (bottom-up) flux information, fossil fuel data assimilation systems (FFDAS), and multi-species inversions.

Data processing and management routines

Whatever measurement and data analysis strategy is used, the information must be archived. This is essential to ensure transparency and to allow re-analysis as both the scientific tools and stakeholder needs evolve.

Observations, metadata, model code, and model outputs must be archived at one or more levels. Raw observational and calibration data is designated level 1, with higher levels for data that has been parsed into subsets designed for specific uses (for example, different wind directions), and/or additional calculations such as enhancements over background or additional information (for example, fossil CO_2) calculated from initial observations.

3.7 Existing projects

Some existing projects have already adopted the IG_3IS principles and many more projects are moving towards embracing the concept. Besides the stakeholder-oriented projects, novel measurement and modelling techniques, critical for future solutions, are being developed in R&D focused projects.

Stakeholder driven IG_3IS related projects

The Auckland Carbon Emissions (ACE) project is focused on providing information to end users, in this case the Auckland City Council. ACE will provide spatially and temporally explicit fossil fuel CO_2 emission maps based on bottom-up information, extending the already-available city total emissions derived from downscaling of national totals. A key output from the council's perspective is the urban biogenic CO_2 flux, since this is currently unconstrained. Any demonstrated land carbon sink could be included in the city's reported net emission budget, and council policy tools might realistically be used to drive urban land use change to reduce net emissions.

Thus, ACE will produce a first, spatially and temporally explicit modelled biogenic CO_2 flux estimate for Auckland. Atmospheric observations of CO_2 and $^{14}CO_2$ will be used to partition the observed CO_2 flux into fossil and biogenic sources, providing a first evaluation of the bottom-up modelled emissions. Proposed future work will expand the observational network to further improve the source partitioning to specific fossil fuel CO_2 source sectors (traffic, industry, and so forth) and biogenic sources and sinks (photosynthesis, respiration, biomass combustion). Predictions of future emissions from the various sources will be developed using the bottom-up fossil and biogenic models (by then validated by atmospheric observations) and growth scenarios.

The city of Toronto has committed to reducing its GHG emissions relative to 1990 by 30% in 2020 and 80% in 2050, so significant changes should be expected. Another key partner for the project is "the atmospheric fund" (TAF) which invests in urban solutions for the Greater Toronto and Hamilton Area (GTHA). The GTHA testbed for atmospheric observations has been established in 2010 with continuous observations of all major GHGs (CO_2, CH_4, N_2O) as well as

carbon isotopes (^{14}C and ^{13}C). Previous publications have revealed significant deviations of totals and spatial patterns of reported and observation-based emissions of CH_4 and N_2O (Vogel et al., 2012) in this region for 2006-2009. In the current project stage, ongoing high-precision measurements will be used to track the decadal emission trends for CH_4 and N_2O since 2006, while intensive measurements campaigns will be conducted to identify down-stream CH_4 emissions in the GTHA within a Climate and Clean Air Coalition (CCAC) project, cross-cutting to IG3IS objective 3 (see sections below). The recently established CO_2 modelling framework (Pugliese et al., 2017) for the region has already been linked with the official air quality inventory of Environment and Climate Change Canada (ECCC), which will be updated based on the finding (suggested improvement) from analysing the model-data mismatch found for CO_2. Sectorial emission behaviour is being monitored using continuous observations of carbon isotopes (Vogel et al., 2013; Pugliese et al., 2016), and novel measurement techniques based on ground-based total column instruments are being also deployed (Gisi et al., 2012). The ability to track sectorial emissions will be key as this project also aims to assess the impact from infrastructure investment in the transport sector.

Emerging projects with R&D for novel measurements and modelling systems

New and novel techniques for GHG observing systems are evolving rapidly, and some of the innovations that current projects are investigating include: a) Dense low-cost in situ sensor networks; b) Open-path measurements in the horizontal and vertical; c) Satellite observations - algorithms to transform existing remote-sensing data products to flux-related information; d) Novel tracers and isotopes (^{14}C, O_2/CO_2 ratios, CO, stable isotopes, COS, SIF, etc.); and e) Air-quality tracers: co-varying species for attribution and co-benefit of pollutant inventories.

Table 1. Overview of the urban projects and the utilized emission estimate techniques

Domain	*Framework, Scope, Boundary*	*Established Estimation Technique*	*Sectors Estimated*	*References*	*Novel techniques tested*
Indianapolis	In-boundary emission	Atmospheric measurement w. inverse modelling; mass balance; bottom-up data products (fossil fuel and biogenic); eddy CO_2 flux	All ffCO_2, CH4	Davis et al., 2017; Lauvaux et al., 2016; Turnbull et al., 2015; Heimburger et al., 2017; Miles et al., 2017; Richardson et al., 2017; Vimont et al., 2017; Gurney et al., 2012; Gurney et al., 2017; Nathan et al., 2018; Deng et al., 2017; Lamb et al., 2016; Cambaliza et al., 2014; Cambaliza et al., 2015; Mays et al., 2009; Sarmiento et al., 2017; Oda et al., 2017; Gaudet et al., 2017; Cambaliza et al., 2017; Turnbull et al., 2012	^{14}C (flasks) and in situ CO for fossil fuel CO_2 partitioning; multi-species flask measurements (halocarbons, hydrocarbons); CO stable isotopes; Some of the work is space/time explicit; multi-species inversion; driving studies to determine spatial patterns of emissions
Paris	In-boundary emissions	Atmospheric measurement w. inverse modelling	All fossil fuel biosphere	Bréon et al., 2015 Staufer et al., 2016	Total column GHG (FTS) Horizontal scanning GHG observations Low-cost sensors Satellite-based GHG estimates ^{13}C and ^{14}C observations
Los Angeles	In-boundary; embedded in buildings	Atmospheric measurement; activity-Emission Factor	All fossil fuel, on-road transporta-tion; buildings	Feng et al., 2016; Kort et al., 2012; Newman et al., 2016; Reyna and Chester 2015; Wong et al., 2015; Wunch et al., 2009	Some of the work is space/time explicit; atmospheric monitoring includes $^{14}CO_2$, CO, and CH_4

Salt Lake City	In-boundary; consumption	Atmospheric measurement; direct flux/activity-Emission Factor/fuel statistics; forest growth modelling/eddy flux	All fossil fuel; biosphere	Patarasuk et al., 2016; Kennedy et al., 2009; McKain et al., 2012; Pataki et al., 2009; Pataki et al., 2006	Some of the work is space/time explicit
Baltimore	In-boundary	Eddy flux atmospheric monitoring; atmospheric monitoring/inversion	All fossil fuel and biosphere Onroad; pipeline leak; pipeline leak; biosphere respiration	Crawford et al., 2011; Brondfield et al., 2012; Decina et al., 2016; McKain et al., 2015; Phillips et al., 2013	Some of the work is space/time explicit; includes some CH_4.
Boston, Seattle, New York City, Toronto	Scope 1,2 (some scope 3 included); scope 1 in lowland area	flux chambers/remote-sensing	Excludes some sectors; biosphere carbon stock change	Hutyra et al., 2011; Kennedy et al., 2012	
Chicago	Measuring CO_2 fluxes in Chicago to understand urban CO_2 fluxes (all sectors combined including biospheric); scope 1, neighbourhood scale observation of fluxes	Micrometeorological measurements: Eddy covariance measurements	not separated: overall net flux observed	Grimmond et al., 2002	One of the first attempts to test eddy covariance for urban CO_2 flux measurements
Mexico City	In-boundary	Eddy flux	All fossil fuel and biosphere; on-road	Velasco et al.; 2009; Chavez-Baeza and Sheinbaum-Pardo 2014; Velasco and Roth, 2010; Velasco et al., 2005	Footprint of single monitoring location; whole-city inventory
Vancouver	In-boundary	Eddy-flux	All fossil fuel and biosphere	Crawford and Christen, 2014	

Use of satellite platforms

Observations of GHG from the satellites (GOSAT, OCO-2) are often used in multiple locations and are thus not associated with one specific urban area. Japan's Greenhouse Gas Observing Satellite (GOSAT) observations are increasingly being used to study urban anthropogenic emissions. Interannual emission changes from the megacities of Los Angeles and Mumbai were detected using GOSAT column CO_2 observations in a study that used minimal modelling (Kort et al., 2012), while comparisons between model simulations and GOSAT CO_2 enhancements have indicated potential under-reporting of CO_2 emissions from Chinese cities (Janardanan et al., 2016). Although GOSAT measures both CO_2 and CH_4, it is actually quite limited in its potential to quantify urban GHG emissions compared with some other current and proposed mission, since it has sparse sampling with a large spatial footprint (10.5 km diameter).

NASA's Orbiting Carbon Observatory 2 (OCO-2) offers much denser coverage by imaging column CO_2 with parallelogram-shaped footprints of $\leqslant$1.3x2.3 km^2. This improved horizontal resolution enabled one study to distinguish the urban core, suburbs and countryside of the Los Angeles region (Schwandner et al., 2017) but OCO-2 does not observe all cities of the globe, missing a large fraction due to its narrow swath or cloud cover. China's Tansat has the potential for quantifying urban emissions by imaging CO_2 at 2x2 km^2 (Cai et al., 2014).

Future missions, like NASA's planned OCO-3 mission (Eldering et al., 2016) could increase CO_2 imaging capacity from space over lower latitude regions with similar capabilities to OCO-2 focused on targeting cities and other anthropogenic emission sources. However, much larger gains in quantifying urban CO_2 emissions from space would come from future missions such as the city mode of Centre National d'Études Spatiales (CNES) MicroCarb, the Sentinel-7 CO_2 monitoring constellation now being prepared by the European Union in partnership with European Space Agency, NASA's upcoming GeoCarb mission and a number of other proposed CO_2 imaging concepts. The combination of CO_2 imaging from multiple satellites in different orbits from this next generation of missions forming a virtual-constellation, could lead to major advances in quantifying urban CO_2 emissions from space with the accuracy, precision and spatial scales relevant to climate policy.

3.8 Capacity building and outreach

Good-practice GHG observations, associated data processing and management, as well as bottom-up data product development and meteorological and inverse modelling all require sound scientific and technical expertise. IG_3IS therefore supports the building of local capacity through knowledge transfer and training, and links to existing international standardization organizations such as GGMT including established intercomparison activities. After more operational methods have been adopted working with international standardization organizations like ISO or Gold Standard would be beneficial to assure coherence of private sector standards/methods with the WMO IG_3IS findings.

4. OBJECTIVE 3: ANTHROPOGENIC METHANE EMISSIONS: DETECTION, QUANTIFICATION, AND MITIGATION OPPORTUNITIES

4.1 Overview

While carbon dioxide is 200 times more abundant than methane in the atmosphere, methane has a 120 times higher global warming potential (GWP) relative to CO_2 (kg per kg upon release to the atmosphere), >80 times higher over 20 years after it is released. Atmospheric concentrations of methane have almost doubled since the preindustrial revolution, and after a decade of relatively stable concentrations, they started increasing again in 2007, the cause of which is still uncertain. Methane is emitted by natural processes (wetlands, geological seepage) and human activities (oil, gas and coal value chain, ruminants, rice production, landfills, and other organic waste management). Given that different methane sources spatially overlap, a key aspect of ongoing research has been attributing existing emissions to specific sources. Methane's high GWP makes it a key influence on the climate, currently anthropogenic emissions account for ¼ of net radiative forcing from GHGs, while its short atmospheric lifetime makes mitigation impactful much more quickly than does long-lived GHGs. Focusing on methane mitigation needs to be done in tandem with efforts to reduce carbon dioxide.

Understanding and managing methane’s atmospheric burden requires correctly accounting for a diverse mix of sources in inventories. Unlike CO_2, combustion is not the primary emission source of methane, and so simple emission factors based on fuel use and composition are not sufficient to understand emission patterns. In contrast, most methane emissions are from direct leaks and releases, whether from anthropogenic, or natural sources. In addition, because of its high GWP, controlling emissions of methane even from renewable sources, (for example, anaerobic digesters) is important (for instance, significant emissions of biogenic methane can potentially offset any net negative emission from biofuels). The wide range of emission source categories, with markedly different emission characteristics means that direct measurement, whether directly used for reporting or for improving source specific emission factors, is critical.

Regardless of the degree to which specific sources drive the recent increase in atmospheric methane concentrations, anthropogenic methane sources constitute a large contribution to the total methane budget and are a prime opportunity for impactful GHG emission reductions. Initial emission reduction efforts are easiest for those sources where cost-effective, readily available control technologies already exist. Two particular sectors where atmospheric observations have directly influenced mitigation strategies are oil and gas and the waste sector. Table 2 presents relevant examples (that is, case studies) where atmospheric information influenced decision-making from diverse stakeholders.

Table 2. Summary of successful case studies where atmospheric observations have directly responded to stakeholder needs

Source	*Category*	*Case Study*	*Summary*	*Relevant Stakeholders*	*Outcome*
Oil and gas	Guide decision-making from diverse stakeholders	Aliso canyon	In October 2015, 100,000 tons of methane leaked from storage field in California. Rapid response to quantify the leak using in situ airborne-based measurements motivated methane action across the state.	California government, affected communities, private sector, NGOs	Additional atmospheric observations corroborated the magnitude of the leak. The leak shed light to weak regulations that since then have been improved. Operator responded to repair and fix the leak. California has now passed the strongest methane emissions regulations from the oil and gas sector in the entire USA.
Oil and gas	Guide decision-making from diverse stakeholders	Four corners	A large hotspot of emissions in New Mexico, USA was located and quantified using satellite-remote sensing. Follow-up studies provided a more detailed characterization of the emissions with the use of multiple methodologies. Atmospheric information was used to detect high-emissions- which catalysed action from affected communities and regulators.	Affected communities, research community, local government	Additional atmospheric observations -at different scales- provided more details about the sources of the emissions and magnitude. Local government and local communities started conversations to mitigate oil and gas emissions in the region.
Oil and gas	Improvement of inventories	EDF's USA Natural gas supply chain studies	Revision of emission factors for different stages of the supply chain as a consequence of several studies that collected emissions data.	USA EPA	Several categories from the oil and gas system within the US National GHG inventory have been revised based on empirical data.
Oil and gas	Design, implementation of regulations	North American countries pledge to reduce oil and gas methane emissions by 40-45%	USA, Canada and Mexico announced a goal to cut their oil and gas methane emissions by almost half. USA and Canada have already announced regulations, Mexico is still in the design process. Regulations incorporate relevant characterization of emissions from several recent studies.	Federal and state/provincial governments	USA federal (for example, Bureau of Land Management) and state (California, Colorado, New York, North Dakota, Wyoming) regulations, as well as Canadian federal regulations have incorporated elements derived from empirical data (that is, including atmospheric observations) and critical emissions characteristics in order to

Source	*Category*	*Case Study*	*Summary*	*Relevant Stakeholders*	*Outcome*
					design effective mitigation strategies. For example, the need of frequent leak detection and repair programmes.
Oil and gas	Mitigation efforts from operators	Methane detectors challenge	Partnership between EDF, oil and gas operators and mitigation technology providers to accelerate the development of sensors that can detect methane leaks.	Oil and gas operators, developers of mitigation technology	California's PG&E, Statoil, and Shell have been testing the top performing sensor systems in active facilities. These technologies provide operators low-cost options to detect and fix leaks in real time.
Oil and gas	Mitigation efforts from operators	Pledges to reduce methane emissions	XTO Energy, a subsidiary of Exxon recently announced commitments to significantly reduce methane emissions from their supply chain.	Oil and gas operators	Commitments include several actions that are based on conclusions from recently published studies, such as: phasing out venting equipment, installing zero emitting devices, enhancing leak detection and repair to locate high emitters. Atmospheric information will play a central role in assessing implementation and success of these commitments.
Waste sector	Mitigation efforts from operators	Pledge to help customers reduce emissions by 60MTCO2e/a and increase renewable energy production by 10%)	Vehicle-based surveys and source strength estimates have been performed for landfills to quantify emissions and impact of mitigation activities (improved capture and additional geomembrane)	Global service provides in waste sector	Emission rates were successfully determined, and emission reductions found for level 1 and level 2 mitigation interventions were 38% and 65%, respectively. The additionally captures landfill gas also increased the amount of renewable energy generated on site. Based on the vehicle-based survey technique SUEZ has developed a quick scan survey service for (other) landfills to identify GHG mitigation potentials.

Given the criteria of seeking out sectors with high emissions and well demonstrated cost-effective technology for their mitigation, the oil and gas supply chain is a logical place to focus effort. A system that in comparison with other anthropogenic sources (such as, agriculture) is more physically concentrated and the number of actors is also relatively limited, facilitating the implementation of mitigation strategies. According to the International Energy Agency's (IEA) most recent World Energy Outlook (2017), global oil and gas methane emissions could be reduced by 75% using currently available technologies, with roughly two thirds of these reductions at zero net cost. Furthermore, mitigating methane emissions from the oil and gas sector presents additional co-benefits such as reducing emissions of ozone precursors and air toxics that are co-emitted by some of the supply chain sources (such as, upstream sources).

There are also significant uncertainties in the overall estimates of these emissions. In the case of CO_2 emissions from the power sector for example, a simplistic sanity check against bottom-up calculations can be done by comparing to emissions based on a countries total fuel use (that is, the IPCCC non-source specific reference approach). Such top-down order of magnitude comparisons are not possible for the methane inventory, and so comparisons must be made against levels of methane in the atmosphere. However, as described above, the disparate emissions sources and short lifetime of methane make this a complicated set of measurements to make, but one in which IG_3IS can contribute effectively.

A key lesson can be drawn from the recent experience in the USA. As the USA was embracing the shale gas revolution, there was a growing recognition of the uncertainty in the understanding of methane emissions from oil and gas production, transport and use, and in turn the climate implications of fuel switching from coal or oil to natural gas. Methane leakage during the production, processing, transport and use of natural gas erodes the climatic advantage when compared to other fossil fuels (Alvarez et al., 2012). To address this uncertainty, a large coordinated scientific effort was undertaken starting in 2012 and focused on characterizing the magnitude and sources of methane emissions from the natural gas supply chain in the USA.

The information products derived from this scientific effort have directly influenced decision-making processes from a diversity of stakeholders, including the development of integrated inventories and flux estimates (that is, reconciliation between top-down and bottom-up approaches and improvement of emission factors that directly affect national inventories), design and implementation of regulations at federal and state level, and design of mitigation strategies to detect and control leaks by operators.

Another major potential for added value of atmospheric information to identify mitigation potentials, that can be easily unlocked, lies in the waste sector. Currently landfill methane emissions are estimated using IPCC default calculation schemes or methane generation models. While the emission models like SIMCET are partly based on measurements in the past, no actual measurements are involved in estimating and reporting from most landfills today. However, recent research shows that landfill gas capture efficiencies can vary between 10% and 80% but the reasons for this large variation are often poorly understood. The consequences are that estimated GHG reduction potential for landfills on the basis of standard calculation methods and real-world emissions can be dramatically different. According to USA EPA emission reduction potential is 50% for 30$/t$CO_2$e (compared to 33% in oil and gas sector). The investment cost for improved landfill gas collection can often be offset by co-generation of renewable energy on-site with the additional gas. Furthermore, reduced gas leakage rates of landfills have significant co-benefits for the air pollution and odorant exposure of surrounding communities.

In summary, this objective focuses on the opportunity to link atmospheric observations to the detection, quantification and mitigation of anthropogenic methane emissions. In particular, we underscore how multiscale methodologies -that range from direct measurements at the component level (for instance, valves at the production well sites) to top-down inversion modelling techniques- have already reduced the uncertainty of oil and gas and waste sector emissions and have triggered mitigation actions from regulators as well as operators.

This IG3IS objective intends to extend the significant successes in characterizing methane emissions from the oil and gas supply chain in the USA to the world. This effort has excellent potential to produce empirical data to improve inventories and provide oil and gas operators with relevant data that will allow them to increase methane mitigation cost effectively. We have identified an initial activity that builds on the significant successes in estimating and characterizing methane emissions from the oil and gas supply chain in the USA and how it has been translated to concrete improvements in terms of emissions reporting and effective mitigation strategies from a diversity of stakeholders (such as, regulators, operators). If acted upon, significant methane emissions reductions are achievable. Exploring these solutions and applying them to new types of sites or emissions profiles, for example offshore platforms or the Liquefied Natural Gas sector, can potentially provide additional reductions.

Based on the experience gained from the work on oil and gas supply chain, and integrating expertise (within IG3IS and externally) in other sectors, IG3IS intends to extend these approaches to other methane emitting sectors (for example, rice production, waste and wastewater) and develop sector-appropriate methodologies. All of these sectors have close links with urban methane emissions as they are often co-located.

4.2 User information requirements, current capabilities and gaps

A key driver from the user base is to identify the main improvements required to increase the accuracy and precision of existing inventories and identify the main opportunities to reduce emissions. In Table 3 we summarize customer-based information requirements and examples.

Current best practices for inventory building according to IPCC guidelines for methane is the use of industry/country specific emission factors. Historically in most cases these have been relatively coarse (such as, emission factors for venting and flaring based on gas production volumes). More recently, there has been interactions between inventory builders and the atmospheric measurement community, with continuous improvements to the inputs that create the inventory. This work has mainly taken place in North America and must be expanded internationally, with the objective of understanding differences and similarities of emission sources across regions and technologies (such as, site configurations, equipment used, age of infrastructure and operation practices, capital expenditure).

Most regional models are configured and/or validated against source terms derived from the EDGAR global emission database. EDGAR uses harmonized emission factors with 0.1 degree spatial resolution for source locations, resulting in a product of unknown and uneven accuracy. Whilst this is appropriate for large-scale modelling, it does not provide the resolution for local assessment or for sector mitigation activities. In contrast, recent work has produced spatially explicit inventories at the national scale that provides a much more resolved starting point for modelling practices (Maasakers et al., 2016).

Table 3. Customer-based information requirements

Customer	*Requirement*	*Example of atmospheric data available*	*Gaps*
Regulators	Integrated, spatially explicit and temporally resolved flux estimates at different scales (for example, national, regional) that can be used by regulators to assess if methane reduction pledges and commitments are being met.	Recent studies have demonstrated how integrated, multiscale emission estimates can be assembled by using top-down approaches (such as, tower networks, in situ airborne-based measurements, satellite remote sensing) and bottom-up approaches (such as, ground-based, facility wide measurements, on-site measurements). In addition, recent development of spatially explicit oil and gas methane emission inventories provide a framework to assess regional differences and track mitigation efforts.	Future work should focus on assessing temporal variability of emissions, which is not currently well characterized. Long-term atmospheric monitoring can provide this additional layer of information, in contrast with the field studies and campaigns that have been the main source of information in recent years.
Inventory builders	Empirically derived emissions data to improve inventories and reporting schemes.	Ground-based, downwind measurements have demonstrated how atmospheric measurements can improve emission factors for the oil and gas upstream and midstream sector. In particular, the gathering sector was almost entirely excluded from the USA national GHG inventory until information derived from the recent studies was incorporated to the national inventory. In addition, regional and sub-regional top-down studies have provided additional information to assess accuracy of reporting and reduce uncertainties in inventories.	Similar improvements should be applied to inventories globally.
Oil and gas operators	Implement mitigation strategies, find sites/facilities with unintended high-emissions related to abnormal operating conditions (for example, malfunctions).	Development of fence-line sensors in conjunction with inverse modelling techniques can help operators monitor individual sites and detect leaks, high-emitters.	Development of new technologies will reduce cost of monitoring systems and will provide real-time information to detect episodic and persistent emissions.

4.3 Measurement network design and modelling framework

Numerous studies have relied on top-down approaches to estimate methane emissions at regional scales, including airborne mass balance techniques. For top-down methods, one of the key challenges is attributing emissions of methane to one of the many possible sources, including oil and gas infrastructure. Methodologies to enabled attribution have greatly improved over the past few years through a combination of isotope and/or hydrocarbon ratios and, inverse modelling.

Multiple top-down studies have found larger methane emissions than estimated with bottom-up methods (inventories) (Brandt et al., 2014), which until recently tended to deploy dated emission factors, unrepresentative sampling methods and inaccurate facility/component counts. Research efforts have focused on closing the gap in overall methane emissions estimates between top-down and bottom-up methods.

Zavala-Araiza et al. (2015) synthesized the results of a coordinated measurement campaign that involved a dozen research teams in the Barnett Shale production region (Texas, USA; oldest production basin to apply hydraulic fracturing and horizontal drilling), where multiple multiscale methodologies were deployed resulting in convergent top-down and bottom-up emissions estimates. Bottom-up approaches have historically relied on on-site component by component direct measurements or engineering calculations. However, this study incorporated down-wind measurements and inverse modelling (for example, Gaussian dispersion modelling) to estimate emission factors. In addition, the improved bottom-up inventory produced during this study also relied on a thorough review of activity data, finding that omission of numerous facilities is a common cause for inventories underestimating emissions. This measurement/modelling strategy provides a roadmap through which it should be possible to constrain estimates of global oil and gas associated methane emissions.

An important feature of the observed patterns of methane emissions found across the USA oil and gas supply chain is the presence of skewed distributions or fat-tails, where a small fraction of sources disproportionately account for the majority of emissions. The presence of these "super-emitters" offers the potential for effectively locating and then controlling a large fraction of methane emissions through a tiered suite of atmospheric observations: aircraft-based, ground-based in situ or on vehicles, towers, and models. Currently these "super-emitters" are stochastic, but there is very expectation that with more and better data the patterns will become increasingly probabilistic. The ubiquitous presence of a fat-tail possesses the challenge of designing sampling strategies that can effectively observe low-probability, high-emitting sources.

There are several scales in which empirical data can be collected to characterize methane emissions from the oil and gas system (Table 4). As described above, previous work has shown the value of incorporating several layers of data as a way to fully understand the emission patterns.

Key issues in utilizing and combining both bottom-up and top-down methane data are related to source apportionment, heterogeneity of background levels, multiple source characteristics, and the disambiguation of anthropogenic and natural sources.

Table 4. Summary of available measurement and modelling techniques specifically used to constrain oil and gas methane emissions, classified by scale of measurement and expected purpose of the output.

Scale of measurement	*Size of measured element*	*Measurement and model methods*	*Purpose/ use of data*
Regional	100's km	Satellite, towers, airborne, ICOS, regional inverse models	Detect oil and gas methane emission hotspots, estimate regional fluxes
Sub-regional	10's km	Airborne (in situ and remote sensing)	Source detection, basin-wide estimates (for example, mass balance techniques).
Facility	100's m to 1 km	Airborne (in situ or remote sensing), ground based, mobile surveys, optical remote sensing, inverse dispersion models.	Identify super-emitters, facility-wide emission factors.
Site area/unit	100's m	Optical sensing techniques	Emission reporting, input to facility scale reporting, leak identification.
Component	<1m	Sniffing, optical gas imaging, Hiflow	Individual leak quantification, mitigation – leak detection and repair programmes. Component scale emission factor development.

4.4 Capacity building and near-term plans

Good-practice greenhouse gas observations, associated data processing and management, as well as meteorological and inverse modelling require sound scientific and technical expertise available in country at a given project location. The development of such knowledge is key to maintain a sustainable infrastructure and to retrieve long-term high-quality outcomes therefore; capacity building and training are central to implementation.

From measurements to mitigation

Recent studies in the USA have identified effective emission mitigation strategies (for example, leak detection and repair programmes, replacement of high-emitting equipment, reduce venting). These cost-effective mitigation options can significantly reduce emissions at multiple points along the natural gas supply chain. In this case, it becomes critical that oil and gas operators -as end users- are able to adopt and apply mitigation strategies identified by the different research teams. In the case of the USA studies, partnerships between researchers and operators during the field measurements allowed an efficient transfer of relevant information. As a consequence, operators in the USA have successfully adopted some of the identified emission control strategies.

As additional research focuses on the global oil and gas supply chain, it becomes important to understand how the sources of emissions vary geographically and by sector. A better characterization of the global oil and gas system will allow to transfer mitigation practices and pinpoint new ones.

As part of capacity building, it is crucial to create a bridge between science and regulators. In the USA, the recent studies have directly influenced federal and state regulations as well as operator practices, all targeting reduction in oil and gas methane emissions. In a similar way, there are also international examples, with Canada currently working on federal and provincial regulations, Mexico having announced a reduction goal, and additional countries announcing pledges to reduce emissions.

Near-term plans

A number of activities are underway to improve the understanding of methane emissions from sectors in order to improve inventories, and with sufficient detail to have the potential to inform mitigation activities. Here we describe two of these projects that represent an opportunity to further expand the IG_3IS methane objective.

$MEMO_2$

The European $MEMO_2$ project "MEthane goes MObile – MEasurements and MOdelling" (http://h2020-memo2.eu) is one activity currently underway to address some of the future needs linking the large-scale measurements at regional scales to site scale emissions. This project is a European Training Network (MSCA-ETN) with more than 20 collaborators from 7 countries, which include a number of experts and institutions involved in IG_3IS. The aim of the project is to identify and evaluate methane emissions and support mitigation measures by supporting the development of new and advanced mobile methane measurements tools and networks, isotopic source identification, and modelling approaches at different scales. The project aims to educate a new generation of scientists, able to effectively implement novel measurement and modelling tools in an interdisciplinary and intersectoral context. $MEMO_2$ aims to bridge the gap between large-scale scientific estimates from in situ monitoring programmes and the bottom-up estimates of emissions from local sources that are used in the national reporting.

CCAC International Oil and Gas Methane studies

At the sector scale building upon the successful characterization of methane emissions from the USA oil and gas system the Climate and Clean Air Coalition (CCAC), the Oil and Gas Climate Initiative (OGCI) and Environmental Defense Fund are working together to initiate a series of scientific studies to measure emissions across the global oil and gas sector. These studies will build on recent advances in methodologies on how to effectively measure methane emissions from the oil and gas supply chain.

In order to develop an effective research plan for what measurements should be undertaken to allow global oil and gas methane emissions to be accurately estimated, a clear understanding of what data exists and where the knowledge gaps are is required. The early work of the international project described above was structured to gain a clearer understanding of the data currently available about infrastructure and emissions and how they vary across the globe. This initial work is informing the design and location of the emission measurement studies being undertaken. It is anticipated they will consist of a series of field studies using multiple measurement methods (both top-down and bottom-up) focused on geographies/sectors where there are clear data gaps (for example, LNG, offshore).

Measurement needs and challenges

As demonstrated above, the main support from the IG3IS community towards the goal of reducing methane emissions has been through data provided through intensive science driven studies. These have included, for example, large-scale monitoring campaigns and detailed analysis of satellite data. A key driver for future measurement support will be to provide routine, cost effective monitoring information that can be used by industry and other stakeholders to effectively reduce emissions (such as, monitoring the efficacy of mitigation). This extension from science driven campaign-based studies to stakeholder driven information provision will be a key area of capacity building in the future. In some cases, this will mean the development and deployment of lower cost sensing systems, combined with suitable means for data processing, visualization and quality control, in other cases it will be the development of more routinely accessible data products providing wider access to existing high cost data sources (such as, satellite platforms or complex models).

5. OBJECTIVE 4: IG3IS IN SUPPORT OF THE GLOBAL STOCKTAKE

5.1 Overview

The policy communities are challenged to provide the needed framework making use of the Measuring, Reporting, Verification (MRV) process to monitor the effectiveness of GHG emission reductions under the Paris Agreement in a transparent way. The UNFCCC reporting guidelines on national inventories for their Annex I Parties (industrialized countries), established under the principles of Transparency, Accuracy, Completeness, Comparability, Consistency, need extension. A key priority is to support the global stocktake process of the UNFCCC (Figure 6), which creates a space for a continuous political momentum for enhancing the implementation of the Paris Agreement and strengthening the global response to climate change. The purpose of the global stocktake is to assess the collective progress towards achieving the near- and long-term objectives of the Agreement, considering mitigation, adaptation and the means of implementation.

The first global stocktake that will be effective in 2023 shall be based on the best available science assessed through the IPCC, providing a common scientific platform. This requires new research to account for cost-efficient observation-based approaches to monitor GHG fluxes and their trends with high accuracy and precision. More reliable and precise quantification of GHG emissions and sinks from in situ data and satellite Earth observation are necessary in order to identify areas with fast changes, monitor the response of ecosystems to land use and land management drivers, the GHG impacts of shifts in energy use and to bring improved descriptions of key processes and feedbacks.

Currently, the detailed GHG emission data compilation at national scale and its regular updating is the mandate of national inventory agencies. This scheme follows the IPCC Guidelines (different Tiers) and has quality control and verification procedures based on audits, mainly focusing on the compliance to IPCC and UNFCCC methodologies, and it will represent the backbone of the transparency framework under the Paris Agreement. Current UNFCCC procedures do not incorporate independent large-scale observation-derived GHG budgets, but few countries (for example, Switzerland and UK) are already using atmospheric GHG measurements as an additional consistency check of their national declarations.

A key feature after the transparency framework of the Paris Agreement is that non-Annex 1 (mainly developing) countries are engaged to provide regular updates of their declarations to

UNFCCC. Many of these countries are facing challenges to improve inventories and reduce uncertainties of their GHG statistical accounting systems, which calls for robust and transparent approaches that can be applied to different situations.

First, it is crucial to maximize the impact of atmospheric information delivered through IG_3IS for the global stocktake process of the Paris Agreement by ensuring the effective use of its results by national inventory agencies, the prime organizations providing the emission inventory time-series, which have to be reported on an annual basis to the UNFCCC.

IG_3IS proposes to contribute to the stocktake process through the revision of IPCC Guidelines for emission inventories that will see a major update in 2019 by establishing the draft of a guidance document that will describe what are inversions, and how their results should be used and interpreted to support national inventories. The proposed process is in 4 phases.

Phase 1. 2017-2023. Build on the example of "early movers" countries like UK and Switzerland who are currently using atmospheric inversions for non-CO_2 gases as additional information to corroborate their inventories. This approach can be extended to other countries where for example, regional inversions and continuous measurement networks are already in place or planned in the near future (such as, New Zealand) by fostering a constructive dialogue between national science communities and national inventory agencies so that agencies will include atmospheric information as supplementary material to their national communications. Engaging developing countries through IG_3IS is important in making this step happen so that inversions are not considered as a "technology for developed countries".

Phase 2. 2018-2030. Consider the feasibility of making available GHG inversion results for GHG budgets and their uncertainties at national scale made available from existing global inversions and for CH_4, N_2O and CO_2. These estimates will be traceable to peer reviewed scientific literature and regularly (annually) updated along with documented changes in inversions settings and versions (for example, number of stations, prior fluxes). It is foreseen that in a first step, global inversion results will rely on in situ networks and that satellite data will be used by $\approx$2025. Scientific synthesis and possible reconciliation between satellite based and in situ based inversions will have to be planned in advance to avoid discontinuities or inconsistencies between estimates from both approaches.

This information could be made available on an interactive web data visualization platform like the Global Carbon Atlas (http://www.globalcarbonatlas.org) presently does for annual updates of fossil fuel and cement CO_2 emissions from CDIAC and UNFCCC provided through the Global Carbon Project (GCP) global carbon budget activity. The uptake of this information by national inventory agencies should be non-prescriptive but policy relevant. This step could be supplemented by a policy relevant tool displaying time series of national GHG budgets together with regularly updated NDC targets, interpreted in terms of emission targets. The requirements, design, prototyping and production of this tool should be co-constructed by IG_3IS and UNFCCC SBSTA, in close linkage with the demand expressed by national inventory agencies.

Phase 3. 2023-2030. In parallel to phase 2, results from regional inversions foreseen for "early movers" in phase 1 can be made available and displayed on the policy relevant web based tool described above, with full documentation and regular updates

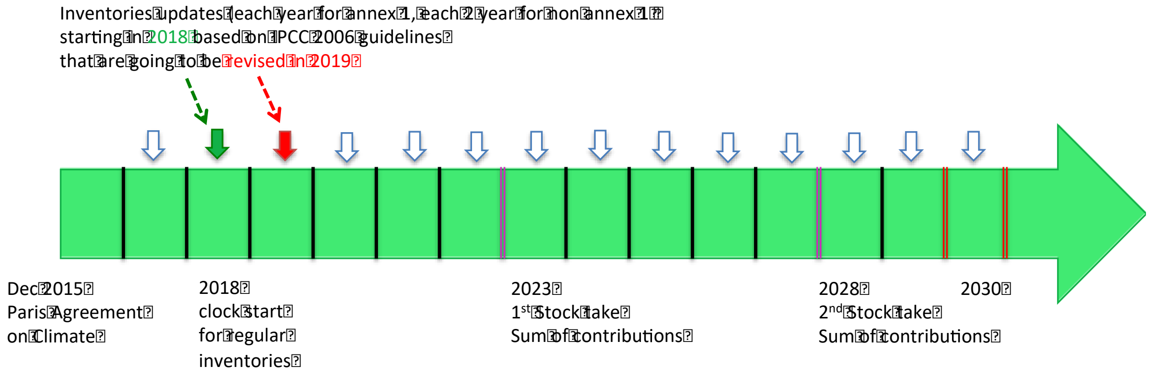

Figure 6. Different stages of the global stocktake process

Source: WMO

6. IG3IS INVERSE MODELLING CROSS-CUTTING ACTIVITY

6.1 Overview

All of the IG3IS objectives outlined above make use of inverse modelling techniques at scales ranging from sub-continental (for example, North America, Western Europe) to local (that is, city scale), making use of different types of measurements. While these techniques have been developed for more than three decades at the global scale, progress toward achieving inverse modelling capability at a regional-scale and smaller, needed for many policy relevant applications, has emerged more recently and remains an active field of research. To achieve a level of performance consistently relevant to the broadest range of policy needs is a grand challenge for IG3IS. In support of this process, the progress that is made by researchers worldwide needs to be actively tracked and integrated in IG3IS. For example, important progress has been made in recent years to increase the resolution of inversion systems and develop new inverse methodologies to assimilate dense and varied types of measurements. To meet the challenge of being able to bring valuable information to stakeholders engaged in GHG emissions reductions, the robustness and accuracy of inversion systems need to be unequivocally demonstrated. The urgent need for greenhouse gas emission reduction, and the current momentum of the Paris Agreement to accelerate these actions, poses both a great opportunity and challenge for the inverse modelling community to help inform and guide these efforts.

The main objective of the IG3IS cross-cutting activity is to support the international coordination of scientific efforts to bring inversion modelling methods to the level needed: 1) to help assess emission reduction actions; 2) for reliable climate change prediction, as limited currently by gaps in our understanding of the feedbacks of the natural carbon cycle to climate change. Such a coordinated effort is currently missing. However, as explained below, it is needed for the exchange of expert knowledge, the education and motivation of young scientists, the assessment of progress and the identification and prioritization of hurdles that remain to be taken. International coordination will be needed to accelerate progress, and to improve the interface between the inverse modelling community and other components of the climate observing system. It will be vital for building confidence in our progress towards emission reduction targets and in support of the climate prediction needed in the coming decades.

6.2 Role of IG_3IS

The IG_3IS inverse modelling cross-cutting activity will address two critical needs of the atmospheric GHG information systems: demonstrate the skill (certainty) and robustness (consistency) of inversion systems in order to inform decision- and policymaking stakeholders, and support future technical developments of inversion systems. IG_3IS cross-cutting activity will also play a critical role of organizing the international inverse modelling community to provide expert guidance. The envisioned format is similar to the way in which WMO/GAW supports the GGMT measurement community, including bi-annual meetings, a secretariat at WMO, a scientific steering committee, and linkage to the World Data Centre for Greenhouse Gases (WDCGG) for the archiving of data. To strengthen the interaction between experimentalists and modellers, IG_3IS cross-cutting activity workshops and GGMT meetings will hold periodic joint sessions. In an effort to gather knowledge from international experts and make progress across nationally- or locally-funded efforts, IG_3IS will support international projects at the comparing existing methodologies and new developments through joint exercises and will work to define the state of the art and good-practice standards for atmospheric inverse modelling techniques.

6.3 Development of inverse modelling techniques

In the 1980's (Tans et al., 1989), when inverse modelling was first applied to the estimation of global sources and sinks of CO_2, the inverse problem methodology, where measured effects are used to calculate the causes, was generally known to be mathematically ill-posed (Tarantola, 2004). Inverse estimates provided information at coarse resolution by assimilating a limited number of measurements. In the last two decades, the variety in inverse modelling applications has evolved into multiple applications, exploring, for example, the use of different measurement techniques, the assimilation of new observable parameters, and solving at higher spatial and temporal scales in order to describe more accurately the observed variability over continents. The strength of the inversion approach lies in its capacity to integrate the variability from highly heterogeneous spatio-temporal patterns of fluxes from a limited number of atmospheric measurements. Compared to direct approaches, atmospheric inversions are a powerful means to constrain carbon fluxes by applying the mass conservation principle to the atmospheric reservoir.

Uncertainty calculation

The Bayes theorem provides a rigorous mathematical framework to quantify uncertainties. However, to obtain reliable inversion-optimized emissions and corresponding uncertainties using Bayes requires a reliable characterization of the uncertainty of the a priori fluxes and the observations that are used. In the IG_3IS inversion framework, the characterization of uncertainties represents one of the most fundamental steps to produce reliable inverse solutions and to quantify rigorously the uncertainties of the inverse fluxes. At most spatial scales, that is, continental to urban, direct evaluation of the performance of inversions is in practice impossible due to the absence of independent estimates of the fluxes at those scales. This explains why the inverse modelling community has been relying on intercomparison exercises to assess the robustness of flux estimates. Other approaches have involved the comparison of the optimized model with independent atmospheric measurements or to evaluate the sensitivity to specific components of inversion systems such as transport models and a priori information.

Unfortunately, the variability across inverse models only represents an approximation of the actual uncertainty. While intercomparison experiments were an indispensable step in the development of inverse modelling methods, a next step must begin, by establishing statistical metrics and testbed experiments to quantify more rigorously the uncertainties in inversion systems. We describe hereafter a framework to implement the IG3IS cross-cutting activity focusing on the systematic quantification of uncertainties to provide robust and accurate estimates of surface fluxes at the different scales.

6.4 Benchmarking and intercomparison activities

As the range of inversion methodologies and IG3IS applications is expanding, so is the need for independent performance evaluation and benchmarking. The inverse modelling approach includes various sources of uncertainties that need to be systematically quantified and reduced to provide reliable information to policy- and decision-making stakeholders. The benchmarking activities will provide testbeds (that is, IG3IS projects) to evaluate inversion systems over documented study cases, and a comprehensive guideline defining the most valuable statistical metrics in order to assess the inversion's performance. The evaluation of the inversion systems will cover a wide range of inverse methodologies and approaches, including the evaluation of atmospheric transport models via tracer release experiments, meteorological measurements, and model intercomparison exercises. A set of statistical metrics and scores will be defined to provide a generic framework for model evaluation, not specific to any particular system. The cross-cutting activity will be adapted to the use of existing and new models in a rapidly changing field of research. IG3IS cross-cutting activity will provide tier-level requirements for various stakeholder objectives, from actual quantitative metrics to statistical inversion diagnostics to demonstrate the robustness of any inversion system, from urban to national scales.

6.5 First urban-scale experiments: demonstration of the approach

During the last decade, several research groups around the globe have initiated testbed experiments in large metropolitan areas (Whetstone, 2018). These urban experiments combine multiple types of atmospheric measurements and high-resolution emission products in order to achieve various objectives, from the detection of whole-city emission trends (such as, London) to high-resolution mapping of anthropogenic and biogenic emissions (for example, Indianapolis). The commonality of these experiments was the use of atmospheric observations, in support of bottom-up emission products, to inform policymakers wanting to improve their current understanding of urban fossil fuel emissions. At first glance, these experiments offer an unprecedented collection of atmospheric measurement-based emission estimates, the precision and accuracy of these atmospheric systems remain difficult to assess. Two critical steps in the system design have to be considered as part of an effort to reach a consensus on methodological validity amongst the broadest range of scientific experts: the observational constraint from measurements collected, and the fidelity of the inversion systems in generating robust information on anthropogenic and biogenic emissions. While atmospheric measurements have been subject to systematic evaluation (for example, GAW), the placement of the observing networks has to be based on technical requirements directly dependent on the policy objectives. Similarly, inversion systems have been designed for specific objectives over particular metropolitan areas, prone to significant differences in their design. Hence, the generalization of these systems will require a task force to support the deployment of inversion systems in any context, across cities in various geophysical environments and with a variety of socioeconomic characteristics (urban metabolisms), which are addressing a range of short- to long-term goals.

Independent evaluation of the inversion systems will be a core element of the IG_3IS cross-cutting activity. Other approaches relying on atmospheric measurements such as aircraft mass-balance approaches or direct eddy-covariance flux measurements have been proven highly valuable to the evaluation of inversion systems. Beyond the evaluation of sub-components, the independent evaluation of inverse fluxes provides an additional level of confidence in inversion systems.

The IG_3IS community will be actively pursuing intercomparison activities to better understand uncertainties across methods and modelling systems, similar to the international efforts of TransCom (Denning et al., 1999) to intercompare atmospheric transport inverse models. Initially related to support global carbon cycle science, the transport model comparison project TransCom was initiated at the 4_{th} International Carbon Dioxide Conference (ICDC-4) in Carqueiranne in 1993. TransCom experiments were organized by different research groups, and some of these experiments are ongoing today. Meetings have been organized on an annual basis, reporting on the status of ongoing experiments, and allowing in-depth discussions on various topics relevant to the community. The TransCom intercomparison exercise differs from those organized, for example, by the Regional Carbon Cycle Assessment and Processes (RECCAP) and GCP-CH_4 activities, which are meant primarily to support the annual GCP assessments of global CO_2 and CH_4 budgets (https://www.globalcarbonproject.org). TransCom experiments target specific aspects of transport models or inversions, which are important for identifying priorities for further development, and directions for improvement. We propose here to continue similar activities to provide sensitivity experiments and uncertainty assessment across inversion methods. While we acknowledge that intercomparison exercises offer less information related to the robustness of inversion systems, the value of comparing multiple realizations has been demonstrated in the inversion modelling community by providing indirect evidences of weaknesses in inversion systems. Discrepancies among inversion systems has highlighted issues and led to important technical improvements in inversion systems. This activity will be supported in parallel to benchmarking activities.

6.6 Testbeds at national and urban scales

First national-scale inverse model cross-cut experiments

To assess and reduce uncertainties associated with the application of inverse modelling to emission estimates on the national scale is quite challenging, but also quite relevant from the policy perspective. At this time, the United Kingdom, Switzerland and Australia are the only countries, who make use of atmospheric measurements and inverse model analysis as part of their National Inventory Report to the UN Framework Convention on Climate Change, and their efforts serve to inform the planning and implementation of the inverse modelling cross-cut national-scale experiments. While looking at the assessment and advances of inverse modelling methods at national scale, it is recognized that national borders will never be exactly resolved by inverse modelling, except in special cases such as islands. Besides this issue, the national scale itself is ill defined given the wide range in the size of countries. For practical reasons, in this document the national scale is defined as a technical term that geographically corresponds to the scale of medium size countries such as France.

To address emissions from countries using inverse modelling methods requires a dense regional network of measurement sites. Currently, this limits national-scale applications to regions where such a reasonably dense measurement networks exist, such as the Integrated Carbon Observation System (ICOS) network in Europe and the North American Carbon Program (NACP) in the United States. In the future, the measurement capabilities will be strengthened further by satellite measurements (such as NASA OCO-3 and GeoCarb, and

EU/ESA CO2M), which are being investigated in studies supporting the development of new missions such as the H2020 CHE Project (https://www.che-project.eu).

To develop benchmarking capabilities on the national scale, the most promising testbeds are Western Europe and the United States. Assessments of the capabilities of existing inverse modelling systems have been conducted as part of the EU FP7 project InGOS for CH_4 (Bergamaschi et al., 2018) and the ongoing French – Swedish project EUROCOM for CO_2 (https://eurocom.icos-cp.eu). Within the EU funded H2020 project VERIFY inverse modelling tools are being developed for the preoperational monitoring of national emissions of CH_4, CO_2 and N_2O, focusing on Europe (http://verify.lsce.ipsl.fr). The European Union has set ambitious targets for greenhouse gas emission reduction in the framework of the Paris Agreement. For example, the Netherlands is preparing for CO_2 emission reductions of 50% by 2030, and 85-95% by 2050 relative to 1990. These ambitious climate policies in combination with a dense network of measurements make Western Europe a very suitable testbed for the monitoring of national emission trends.

The first IG_3IS national-scale experiment will build on the work of Bergamaschi et al. (2018) on CH_4 making use of extended measurement time series currently available from the ICOS network. This experiment will benefit from input datasets on European emissions which are currently compiled within the H2020 VERIFY project. The IG_3IS national-scale experiment aims at engaging the international inverse modelling community to take optimal advantage of these existing activities and join forces to increase the number of inverse modelling estimates available for assessing the long-term trend in national CH_4 emissions over Western Europe, and the development of benchmarking procedures.

National-scale benchmarking will support not only the development of inverse modelling methodology, but will also support strategies to make optimal use of the information provided by inversions in the national context. To achieve this, the information transfer from inversions back to inventories needs to be facilitated. Currently, the capability to do this is limited by the disaggregation methods used in inventories that make use of proxies (such as, population density) rather than actual information on the location of sources. Efforts to improve the spatial temporal representation of emissions in inventories (for example, Maasakkers et al., 2016) improve the comparison, and thereby the information exchange, between inventories and inversions at the scales that are resolved by the inversion. The spatial-temporal representation of inventory emissions can subsequently be used to translate back to national totals.

With the development of permanent measurement stations across North America, a series of atmospheric inversion studies was published taking advantage of the growing interest from biogeochemists and ecologists to better understand the role of the vegetation in the global carbon cycle (such as, Peters et al., 2007). The role of the natural ecosystems in the carbon cycle is critical to understand and predict the atmospheric growth rate of greenhouse gases, directly impacting the radiative budget of Earth’s atmosphere. The role of agricultural activities across the United States (Schuh et al., 2013) and the impact of major droughts in the western and southern regions (for example, Schwalm et al., 2012) was quantified and confirmed by inversions thanks to the expanding network of observations. While major findings have been made related to climate-carbon interactions over the North American continent, several studies highlighted the lack of convergence in the inverse estimates at seasonal and regional scales (Peylin et al., 2013). Both the lack of measurements across the continent and unaccounted uncertainties still impair the ability of atmospheric approaches to resolve regional-scale differences. As the first limitation is being addressed by the expansion of observing systems,

the later issue will benefit from an organized and structured approach as initiated in the IG3IS cross-cutting activity.

First urban-scale inverse model cross-cut experiments

The Indianapolis Flux Experiment (INFLUX) funded by the U.S. National Institute for Standards and Technology (NIST) Greenhouse Gas Measurement Program (https://www.nist.gov/topics/greenhouse-gas-measurements) involved ten academic and research institutions from the United States of America, deploying 13 continuous analysers measuring carbon dioxide, methane, and carbon monoxide, complemented by aircraft flights, meteorological instruments, discrete flask sampling, and eddy-flux covariance towers. The high-density network of observations was designed to quantify the anthropogenic and biogenic components of the greenhouse gas budget, producing 1-km resolution maps, weekly, over the 12th metropolitan area of the country (Davis et al., 2017). The inversion system, supported by a high-resolution product of CO_2 emissions (Hestia; Gurney et al., 2012), produced 5-day 1-km resolution maps of CO_2 emissions with a 20% uncertainty over 6 months (Lauvaux et al., 2016). Now applied to the long-term record of surface tower measurements, the inversion entered a second phase of development using CO_2 and CO mixing ratios to address sector-level changes in the emissions. Recent progress has been extensively documented with a Special Issue in Elementa (14 papers published - https://collections.elementascience.org/quantification-of-urban-greenhouse-gas-emissions) and more than 10 peer-reviewed publications in other highly-ranked journals.

The first intercomparison exercise will focus on estimating city-wide CO_2 emissions in the year 2016 during which the largest CO_2 emitter, a power plant located within the city limits (Harding Street Power Plant), switched from using coal to natural gas to generate electricity. The change in emissions due to the switch in fuel type has been documented and quantified using hourly electricity generation statistics by two independent approaches, both following USA standards for greenhouse gas emission reporting, one from the U.S. Energy Information Administration (EIA) and a second from the Clean Air Markets Division (CAMD) within the U.S. Environmental Protection Agency (EPA). Uncertainties in reported emissions are inferred by the difference between these two estimates, and will be used as a reference for evaluating urban inversions from various research groups across the world. This first-of-its-kind intercomparison exercise will serve as a benchmark for developing new techniques.

Evaluation of inversion system robustness

The IG3IS cross-cutting activity will support the development and validation of inversion systems from the scientific community by creating an active environment across research groups, government policymakers and decision-making stakeholders more broadly. The activity will establish the requirements in terms of atmospheric measurements and inverse models to achieve the information needs and objectives of a range of applications as skill becomes commensurate with decision-making needs. With clearly identified goals in each IG3IS project, (for example, whole-city emissions, sectoral contributions, long-term reduction trends) accompanied by an expected level of precision and accuracy (such as, relative uncertainty, detection limit), the IG3IS cross-cutting activity will provide guidance to the IG3IS project team, with pre-defined technical requirements and good-practice standards according to state-of-the-art techniques. These recommendations are expected to evolve over time, as research continues to advance our skill in applying inversion techniques led by technical experts. A tier-level approach corresponding to the desired outcomes will define the observational needs and evaluation process to provide the confidence in the scientific results as the bedrock of future emission reduction plans.

6.7 Transfer model

The IG3IS cross-cutting activity has a vision and long-term goal to provide a state-of-the-art inversion system to allow for the rapid implementation of atmospheric systems and the evaluation of newly developed systems. This vision will be realized through the implementation of the IG3IS Transfer Model (IG3IS-TM). The IG3IS-TM will be realized in partnership with the VERIFY project and consist of a platform to perform inversions at national and urban scales with a reference system to be adapted to the specificity of the geographic locations. Based on globally available products, the IG3IS-TM will provide a flexible and documented system to avoid the systematic intervention of experts and allow international, national, or local governments to implement their own atmospheric inversion systems. IG3IS-TM will help homogenize the development of inversion systems by providing the latest developments in a stand-alone state-of-the-art system. The specificity of the system will be agreed by a consortium of experts and distributed to interested parties to promote and support the use of atmospheric inversion systems in the implementation of emission reduction policies and actions.

Supporting the development of inversion systems

New types of measurements, atmospheric models, and optimization methods are rapidly becoming available. The cross-cutting activities will also pay specific attention to new approaches moving beyond the conventional estimation of fluxes, towards the optimization of the underlying processes or economic sector of activities. Examples are data assimilation methods that allow combining multiple data streams, as in Carbon Cycle Data Assimilation System (CCDAS) and Fossil Fuel Data Assimilation System (FFDAS). To guide the development of inversion systems, IG3IS cross-cut activity will work to identify among these inversion systems the technical strengths and weaknesses to provide essential information to both practitioners and stakeholders. The activity will promote key research efforts among the community by connecting experts from the various research groups working on these issues to stakeholders. This activity will closely follow technical developments of inversion methods, novel instruments, and progress in inversion systems, and support development directly relevant to improving national and urban scale reported GHG flux estimates. The IG3IS cross-cutting activity will also define development needs by proposing new areas of research, including new greenhouse gases or providing guidelines for future development to the entire community.

A schematic representation of the main elements of the extended inversion evaluation that is foreseen as part of this activity is presented in Figure 7.

The design, implementation, submission, and analysis of intercomparison experiments will continue to require in kind contributions of participating scientists on a voluntarily basis. Requests for specific experiments can be made (from within or outside IG3IS), in which case financial support may be requested for coordination. The role of the IG3IS cross-cutting activities are primarily scientific, in the sense that their aim is to support the scientific development of techniques and the evaluation of progress towards that goal. The operational application is outside its scope, although support will be given to such activities, for example, by developing good-practice guidelines for the use of inverse modelling for improved emission estimates. This also includes methods for testing the statistical consistency of inverse modelling-derived estimates and their quantified uncertainties, and evaluation of these estimates using independent data.

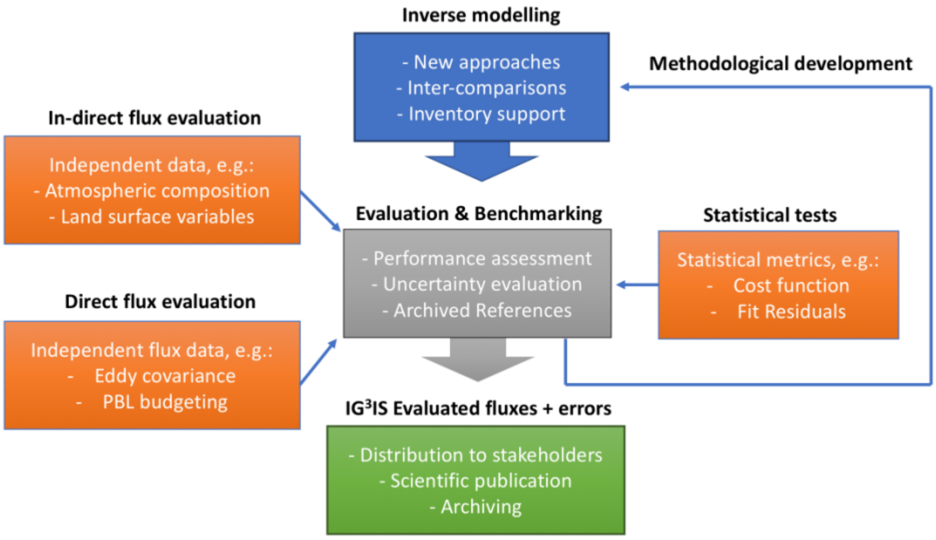

Figure 7. IG3IS inverse model evaluation strategy, combining results of intercomparison experiments, with extended benchmarking and error assessment.

Source: WMO

6.8 Interface with other activities

The interface of the IG3IS inverse modelling cross-cutting activity with other activities is represented schematically in Figure 8. It highlights the close connection with input data providers, who provide the various boundary conditions that are used in inversions. On the side of the observational data, this includes the GGMT community mentioned earlier, but also the TCCON and satellite community, and other programmes providing atmospheric data. "Inventory data" refers to external information about surface fluxes as provided by emissions inventories, or results from ocean and land surface modelling.

The data that are generated by the cross-cutting activity are archived for analysis by the participants, the monitoring of progress, and periodic assessments of greenhouse gas budgets. The first requires a data storage facility that is open only to participating scientists during the first phase of intercomparison experiments when results are being analysed and prepared for publication. The latter is open to the public requiring a dedicated web interface. However, the intention is not to duplicate work that is currently done within RECCAP or GCP-CH_4. The interface with GCP should mesh the activities with one another, which will be facilitated by the significant overlap between the scientific communities of the GCP and the IG3IS cross-cutting activities.

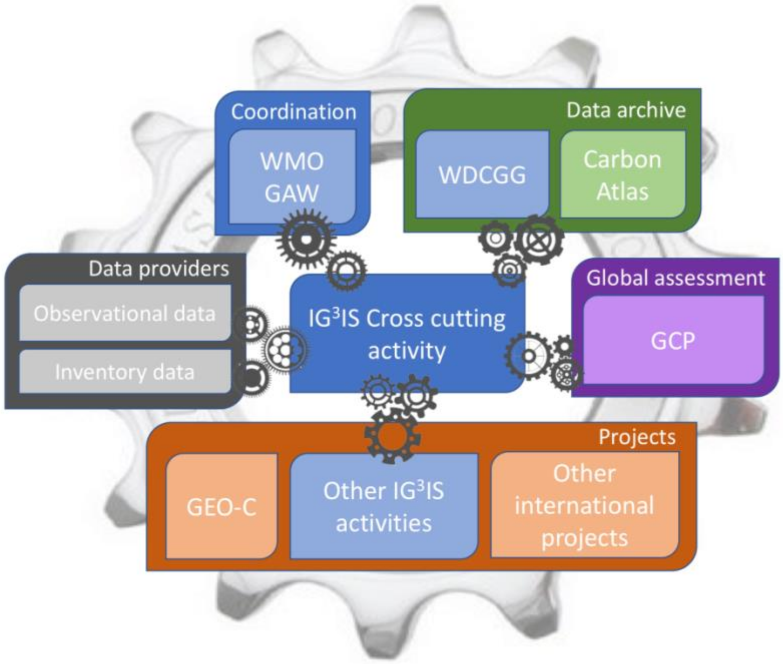

Figure 8. Interface of the IG3IS inverse modelling cross-cutting activity with other activities

Source: WMO

7. NEXT STEPS: IMPLEMENTATION

The success of IG3IS will depend on the international coordination of WMO Members and collaborations with a number of WMO partners such as the United Nations Environment Programme, the International Bureau of Weights and Measures, the Group on Earth Observations, the IPCC and many others. IG3IS will establish and propagate standards and guidelines for methods that produce consistent and intercomparable information, such as those that GAW already produces, for concentration measurement standards. Over time, the IG3IS framework must be capable of promoting and accepting advancing technical capabilities (for example, new satellite observations and sensors), continually improving the reach and quality of the information and increasing user confidence.

The information tools provided by IG3IS must be as rapidly scalable as the mitigation solutions that they seek to inform. In order to facilitate the development of IG3IS tools and the accessibility of IG3IS capabilities to stakeholders, IG3IS seeks to define an ecosystem to support such success. One element of this ecosystem is the Steering Group that was established in 2017 to ensure integration and mutual benefits within the other GAW elements and ensure ownership of IG3IS by WMO Members. It will also guide the strategic development of IG3IS and the projects within it. To be inclusive across the scientific community and to leverage the expertise of the community IG3IS will maintain its science team (established 2015) to serve as the key technical and implementation body of IG3IS that develops science-based methodologies and fosters pilot and demonstration projects. It also strongly interacts with the researcher and implementers that conduct demonstration projects, contribute to standards and perform fundamental research relevant to IG3IS. It is important to highlight the other implementers beyond the traditional research community (NGOs, private companies, and so forth) will also play a key role in the delivery of these services and are necessary to ensure that solutions developed in IG3IS are also scalable according to demand. A key role in this ecosystem also falls to the international programme office, which will among other tasks,

coordinate the day-to day activities of the IG3IS initiative and its projects, support proposal preparation processes and interact with the stakeholder community. To increase the reach of IG3IS a high-level leadership group will be established which will help to create high-level political support of IG3IS for the inclusion of IG3IS in the strategic plans of the relevant organizations that allow to scale solutions to provide them to a large group of stakeholders and promote to include IG3IS activities in the plans of funding agencies.

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