

An Integrated Global Greenhouse Gas Information System (IG³IS) Implementation Plan

1.0 Motivation, Principles and Objectives

1.1 Motivation for an IG³IS

Accurate and precise atmospheric measurements of greenhouse gas concentrations have revealed the rapid and unceasing rise of global GHG concentrations due to human socioeconomic activity. Accurate and precise long-term observations also show a resulting rise in global temperatures and evidence of negative impacts on society. In response to this mounting evidence, nations, sub-national governments, private enterprises and individuals are establishing and accelerating efforts to reduce GHG emissions while meeting the needs for global development and increasing energy access.

Now, with appropriate investments, the same evidence-based scientific approach that rang the climate change alarm bell stands ready to guide us along solution pathways and provide metrics for the success of the solutions. With this motivation, WMO and its partners have called for an Integrated Global GHG Information System¹ (IG³IS). The IG³IS will serve as an international coordinating mechanism to establish and propagate consistent methods and standards to help assess emission-reduction actions. For the IG³IS initiative to succeed the end-users must understand, trust, and recognize the value of the information they will receive, and act more effectively in response. Over time, the IG³IS framework will be capable of promoting and accepting advancing technical capabilities (e.g., new satellite observations) continually improving the quality of and confidence in such information.

Leading up to COP15 in Copenhagen December 2009, the climate change community developed a number of reports [e.g., 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)] that reported on the state of carbon cycle and GHG research, and on the readiness of atmospheric GHG concentration measurements, combined with other forms of data and model analyses to independently evaluate and improve the accuracy of the traditional "bottom-up" GHG emission inventories. In 2010, these studies concluded that with key research investments, increased density of well-calibrated atmospheric GHG measurements, and improvements in atmospheric transport modelling and data

¹ The IG³IS resolution approved by the 17th World Meteorological Congress in June 2015 refers to an "Integrated Global Greenhouse Gas Information System." The IG³IS Planning Team suggests substituting the word "Services" in place of the word "System" as a better representation of the IG³IS initiative's mission.

assimilation capabilities, a GHG information service framework could be achieved that would fill information gaps and serve the evolving needs of policies and actions to reduce GHG emissions.

Out of COP17 in Durban came a UN mandate to negotiate a new global agreement to reduce global GHG emissions recognizing that the unique needs and conditions of the member-states should drive definition of their pledges and goals. This was the rationale behind the Nationally Determined Contribution (NDC) approach approved at the COP20 in Lima and that contributed to the success at the COP21 in Paris.

The IG³IS Planning Team is applying these lessons learned from the UNFCCC process. The IG³IS plan will not be solely focused on the long-term vision for a comprehensive, totally independent integrated GHG information system. Instead, the IG³IS plan begins with practical and focused near-term objectives. The IG³IS Planning team defined a set of questions that must be answered with criteria for selecting these confidence-building, near-term objectives:

- What are the main improvements needed to strengthen the existing national inventory reporting system, and how can IG³IS contribute to these improvements?
- Are there research capabilities with demonstrated skill to meet these information needs in a quantitative and timely way?
- What valuable and additional outcomes will result?
- Will stakeholders see this value and be early and active partners in this effort?

For the near-term objectives, both the policy applications and the technical skill are at hand and are well matched. The mid-term goals 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 current sum total of the emission reduction pledges from current NDCs does not put us on a least-cost pathway to achieve this goal. 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

1.2 IG³IS Principles

Implementation of an IG³IS requires that all elements of the system provide accurate, consistent and timely information useful for a broad range of policy uses, accommodate future policy changes, and take advantage of advances in emission

inventory methods and information.

These are the principles by which IG³IS will achieve its objectives:

- IG³IS will serve as an international coordinating mechanism and establish and propagate consistent methods and standards for the use of atmospheric measurements and models in support of improving GHG emission inventory,
- The IG³IS credibility rests upon the undisputed and high-quality atmospheric concentration measurement standards disseminated by the WMO GAW with very active participation by the international metrology community, and the relevance of these measurements toward assessing anthropogenic GHG emissions.
- IG³IS will provide a common framework for development of the good practices utilizing diverse measurement and analysis approaches inside a framework of standards.
- Stakeholders are significantly involved in planning and implementation from the beginning to ensure that information products meet user priorities and deliver the foreseen value.
- The system must be practical and focused on where the scientific and technical skill is proven, the use-case exists and the decision-maker recognizes value.
- Success-criteria are that the information provided guides additional and valuable emission-reduction actions.
- IG³IS must mature in concert with the evolution of user-needs, policy and technical skill.

1.3 IG³IS Objectives

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 modeling since 2010. A planning team comprised of scientists and stakeholders from developed and developing countries in 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.

However, 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 (concentration/time). The IG³IS analysis system must have in addition 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 fulfill the IG³IS mission.

IG³IS will focus on existing-use cases for which the scientific and technical skill is proven and on where IG³IS information can meet the expressed (or previously unrecognized) needs of decision-makers who will value the information. The ultimate success criteria are that the IG³IS information is “used” and guides valuable and additional emission reduction actions, building confidence in the role of atmospheric composition measurements as an essential part of the climate change mitigation tool kit.

The success of IG³IS will depend on 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 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.

IG³IS implementation is now underway following the endorsement of the Concept Paper by the WMO Executive Council in June 2016. The IG³IS team defined four implementation objectives, the first three being:

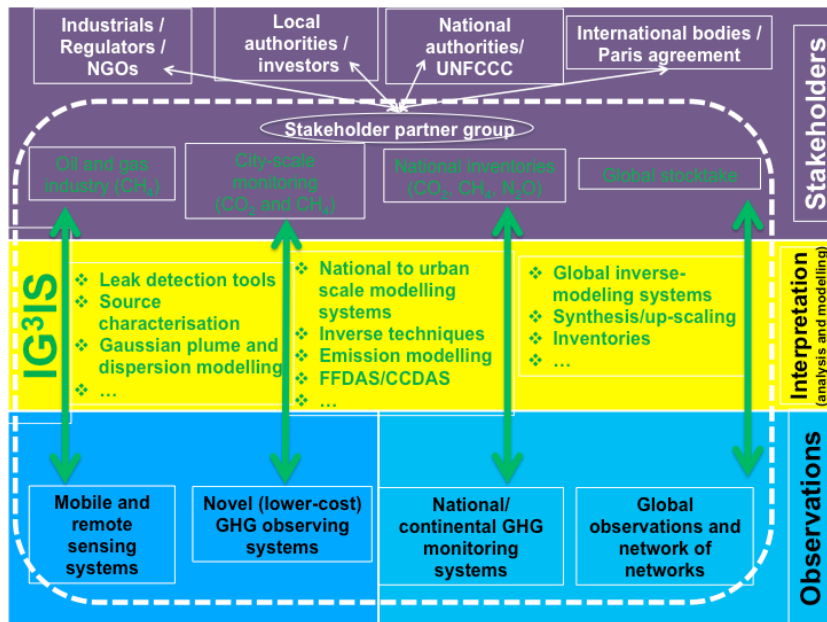
- 1) reduce uncertainty of national emission inventory reporting to UNFCCC;
- 2) locate and quantify previously unknown emission reduction opportunities such as fugitive methane emissions from industrial sources; and,
- 3) provide subnational entities such as large urban source regions (megacities) with timely and quantified information on the amounts, trends and attribution by sector of their GHG emissions to evaluate and guide progress towards emission reduction goals.

The fourth IG³IS objective is similar in nature and scope to objective 3), but is focused on support for the Paris Agreement’s global stock take. It will by necessity be implemented at national and global scales, but it is less mature than the other three objectives at this time. One reason is that although IG³IS has a vision for how to support stocktaking, the Paris Agreement does not specify how the global stocktake will be conducted. Another reason is that accounting for fossil fuel CO₂ via

top-down methods lack the maturity to match the accuracy of IPCC TFI Tier 3 protocols for estimating fossil fuel CO₂ emission inventories at the national scale. This is because atmospheric measurements of CO₂ contain a significant biospheric signal and are therefore necessary, but not sufficient, to infer fossil fuel CO₂ emissions.⁶ However, it has been demonstrated that fossil fuel CO₂ emissions can be inferred by inverse model analyses of a combination of atmospheric CO₂, radiocarbon (¹⁴CO₂) measurements, together with measurements of other co-varying atmospheric species.⁶

IG³IS implementation is proceeding along two lines of activity:

- The preparation of methodological guidelines that describe “good practice” use of atmospheric measurements for implementation under each objective area, and
- The initiation of new projects and demonstrations that propagate and advance these good practice capabilities and build confidence in the value of IG³IS information with stakeholders.



2.0 Objective 1: IG³IS in Support of 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. Data 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.

Atmospheric inverse modeling that incorporates information from measurements of atmospheric greenhouse gas concentrations can support this process by providing an independent “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 can not forget or double count any sources.

The United Kingdom, Switzerland and Australia already successfully include “top-down” analyses to guide improvements to their reporting. Other Annex 1 countries have comparable measurement and modelling capacities and could follow these examples. Developing countries are often lacking the infrastructure to collect all statistical data that is necessary for developing accurate emission inventories, but through the Paris agreement they are now tasked to report their emissions on a regular basis. These countries could benefit from independent “top-down” estimates to guide this development, but may require setting up additional measurement infrastructure.

An IG³IS 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 IG³IS initiative has already made progress on this objective through participation in a recent IPCC TFI Expert Meeting. This near-term IG³IS objective was presented to the IPCC TFI members who recommended that more information on top-down approaches such as IG³IS be incorporated as part of targeted updates to the 2019 Refinements to the methodology report updating the IPCC 2006 Inventory Guidelines.

2.2 Customer-based Information Requirements, Current Capabilities and Gaps

Determine the main improvements needed to strengthen the existing national inventory reporting system, and how atmospheric measurements and model analyses contribute to these improvements.

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

Although in most countries the emissions of CO₂ are the dominant contribution to the national GHG budget, they are not necessarily the largest source of uncertainty. CO₂ 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 CH₄ and N₂O occur from mostly diffuse, complex and time-varying sources and are, in relative terms, much more uncertain than those of fossil fuel CO₂ 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 CO₂ inversions are likely the most robust method for determining net CO₂ 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. For non-CO₂ greenhouse gases, atmospheric inversions have a great potential to provide additional insights, to identify shortcomings, and to build confidence in the national reporting, as demonstrated by the examples from UK, Switzerland and Australia.

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 modeling capabilities.

2.3 *Measurement Network Design*

Identify most suitable sites (e.g., towers, buildings, hilltops) in country and potential gaps in coverage.

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 CO₂ 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 setup 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 based these sensitivities, 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. 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 (e.g., EDGAR) and natural biospheric fluxes of CO₂ and CH₄ from terrestrial ecosystem models (e.g., 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, e.g. by analyzing the dominant wind sectors and identifying potential disturbances such as nearby sources in those sectors.

2.3.1 *Measurement Network Development*

Selection of appropriate instrumentation for greenhouse gases, for co-emitted species, and for key local meteorological parameters such as planetary boundary

layer height.

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 NO_x, 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 setup:

- selection of adequate greenhouse gas analyzers with necessary precision and accuracy and with stable performance and low needs for intervention
- selection of peripheral equipment (data acquisition, valves, pumps, flow control, water removal, calibration units etc.)
- selection of instrumentation for auxiliary measurements, e.g. for co-emitted air pollutants like NO_x, 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 setup, i.e. installation of all equipment on site, mounting of inlets and sampling lines, air conditioning, etc.
- definition of standard operation procedures, i.e. responsible personnel, frequency of station visits, interventions and maintenance, etc.
- development of a quality assurance / quality control framework (e.g. calibration strategy, selection of reference gases, reference scales, traceability to WMO, network intercomparability, 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)

Mention recommendations and requirements by WMO, ICOS, etc.?

2.4 *Model development*

A large number of atmospheric inversion systems have been developed in the past based on different flavors of the Bayesian principles (analytical, variational and ensemble formulations). These 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 IG3IS.

In order to orientate these system 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-source. 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 policy makers.

The setup 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.

2.5 *Communications and Technical Support for Inventory Builders*

Determine the information format, meta-data, as well as procedures for interfacing with the inventory building team in country.

As inventory builders work with emission factors and activity data, the outcome of inverse modeling/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.

2.6 *Capacity Building and Outreach*

Good-practice greenhouse gas observations, associated data processing and management, as well as meteorological and inverse modeling 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.

National Reporting Project Examples and Description

South Africa, Morocco, Japan, Korea, France, Germany, and Finland, New Zealand

Writing Team Roles, Responsibilities, Schedule for Document Preparation

Working meetings/teleconferences/activities /dates

3.0 Objective 2: Detect and Quantify of Anthropogenic Methane Emissions

3.1 *Overview*

While carbon dioxide is 200 times more abundant than methane in the atmosphere, methane has a 120 times higher global warming potential relative to CO₂ (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 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.

[Include matrix summarizing major sources – in preparation-]

Regardless of which specific sources dominate historic increases in atmospheric methane concentrations all anthropogenic sources have played a role. Initial emission reduction efforts should focus on those sources where cost-effective, readily available control technologies already exist. Of particular interest are methane emissions from the oil and gas supply chain, a system that in comparison with other anthropogenic sources e.g. agriculture is more physically concentrated and the number of actors is also relatively limited, facilitating the implementation of mitigation strategies. In addition, recent estimates from Schwietzke et al., suggest that global fossil methane emissions (natural gas, oil, and coal production and use) could be 20-60% higher than current estimates; highlighting the importance of mitigation of methane emissions from the oil and gas industry.

As the US was embracing the shale gas revolution, there was a growing recognition of the uncertainty in our 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.). To address this uncertainty, a large scientific effort was undertaken starting in 2012 and focused on characterizing the magnitude of methane emissions from the natural gas supply chain in the US.

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. Attribution has greatly improved over the past few years through a combination of isotope and/or hydrocarbon ratios, inverse modeling, or by creating an inventory of biogenic sources and subtracting from the total top-down methane estimate.

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 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. synthesized the results of a coordinated measurement campaign that involved a dozen research teams in the Barnett Shale production region (Texas, US), the oldest, where multiple multiscale methodologies were deployed resulting in convergent top-down and bottom-up emissions estimates. This measurement strategy provides a roadmap through which it should be possible to constrain estimates of global oil and gas associated methane emissions.

Furthermore, over the course of the past five years an extensive body of research has been created that characterizes methane emissions from the different stages of the natural gas supply chain in the US, which in turn is now reflected in improvements to the US National GHG inventory, making it more accurate and precise.

An important feature of the observed patterns of methane emissions found across the US 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 possess the challenge of designing sampling strategies that can effectively observe low-

probability, high-emitting sources.

This IG³IS objective intends to extend the significant successes in estimating and characterizing methane emissions from the oil and gas supply chain in the US to the world. This effort has excellent potential to provide oil and gas operators with improved data that should allow them to increase methane mitigation cost effectively. 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 LNG sector, can potentially provide further reductions. IG³IS also intends to extend these approaches to other methane emitting sectors as a subsequent initiative (e.g., rice production, waste and wastewater) and develop sector-appropriate methodologies. Some of these sectors have close links with urban methane emissions as they are often located in or close to cities, more so than oil and gas production sites.

3.1 Customer-based Information Requirements, Current Capabilities and Gaps

Determine the main improvements required to increase the accuracy and precision of existing national inventory methane emissions reporting systems, and how atmospheric measurements and model analyses can contribute to these improvements.

Inventory method is based on:

- detailed source categories for specific sectors and specific regions,
- activity data (accurate counts of facilities/equipment),
- representative emission factors or emission models for specific processes

Accurate inventories depend on:

- completeness: facility/equipment counts, types
- up to date / current activity data and emission factors or models
- characterization and quantification of super-emitters, episodic emissions
- capacity to quantify trends in emissions reflecting shifts in practices
- ability to have independent evaluation

What is current best practices for inventory building according to IPCC guidelines?
How is US (EPA, industry, or stakeholders) sharing recent findings and improvements to inventory for this sector with the UNFCCC?

3.3 Measurement Network Design and Modeling Framework

Building upon the successful characterization of methane emissions from the US 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 produce a series of scientific studies to measure emissions across the global oil and gas

sector. These studies will build on the methodologies and tools developed during the recent US studies of 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 gaps are is required. Phase 1 of the international project described above is structured to gain a clear understanding of the data currently available about infrastructure and emissions and how they vary across the globe. This first phase will inform the design and location of future emission measurement studies which are anticipated will consist of a series of field studies using multiple measurement methods (both top-down and bottom-up) focused on regions/sectors where there are clear data gaps.

A global inverse modeling system has been developed for estimating methane emissions from 53 land regions for their period 2002–2012 using measurements taken at 39 sites and ACTM simulations. An ensemble of 7 inversions is performed by varying a priori emissions. Global net methane emissions varied between 505–509 and 524–545 Tg yr⁻¹ during 2002–2004 and 2010–2012, respectively (ranges based on 6 inversion cases), with a step like increase in 2007 in agreement with atmospheric measurements. The inversion system did not account for interannual variations in OH radicals reacting with methane in the atmosphere. Our results suggest that the recent update of the EDGAR inventory (version 4.2FT2010) overestimated global total emissions by at least 25 Tg yr⁻¹ in 2010. The increase in methane emission since 2004 originated in the tropical and southern hemisphere regions, coinciding with an increase of non-dairy cattle stocks by ~10% from 2002 (with 1056 million heads) to 2012, leading to ~10 Tg yr⁻¹ increase in emissions from enteric fermentation. Forward simulation results using both the a priori and a posteriori emissions are compared with independent aircraft measurements for validation. Based on the results of the comparison, we reject the upper limit (545 Tg yr⁻¹) of global total emissions as 14 Tg yr⁻¹ too high during 2008–2012, which allows us to further conclude that the increase in methane emissions over the East Asia (China mainly) region was 7–8 Tg yr⁻¹ between the 2002–2006 and 2008–2012 periods, contrary to 1–17 Tg yr⁻¹ in the a priori emissions.

More details in Patra et al., *J. Meteorol. Soc. Jpn.*, 94, 91-113, 2016; http://ebcrpa.jamstec.go.jp/~prabir/papers/jmsj-2016_085_107.pdf

Other Research Question: coupling/decoupling between methane and ethane in NH and globally

Identify stakeholders needs more clearly

Measurements require expensive campaigns or long-term programs

Mitigation:

As shown in the US, there are a number of cost-effective mitigation options that can

significantly reduce emissions at multiple points along the natural gas supply chain. As the international studies are able to details methane sources and hwo they vary geographically, it will be possible to assess which existing mitigation options are applicable in other regions. Some examples might include: green completions, comprehensive and frequent leak detection and repair programs (LDAR), continuous monitoring, venting minimization.

3.4 *Communications and Technical Support for Inventory Builders*

Determine the information format, meta-data, as well as procedures for interfacing with the inventory building team in each country.

3.5 *Capacity Building and Outreach*

Good-practice greenhouse gas observations, associated data processing and management, as well as meteorological and inverse modeling 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.

3.6

4.0 Objective 3: IG³IS in Support of City-Scale Mitigation Efforts

4.1 Overview

The Lima–Paris Action Agenda of the Paris Agreement has formalized a role for sub-national entities such as cities (large urban source regions) as leaders in greenhouse gas mitigation and climate adaptation. Cities account for roughly two-thirds of energy-related greenhouse gas emissions due to their concentration of population and economic intensity. In order to provide a diagnosis of urban emissions at scales relevant to urban decision making and enable identification of low-carbon or carbon mitigation opportunities, cities need to understand their emitting landscape due to both natural and human activities. Given the widely varying existing knowledge and needs of city stakeholders IG³IS provides 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 time scales relevant to urban decision making, and include if possible attributes such as economic (sub-)sector and fuel types.

A number of research projects around the world, such as the Indianapolis INFLUX study depicted in Figure 5, and the Los Angeles and Paris test-bed systems, 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. IG³IS will describe the principles and components available to provide information at various tiers of detail, particularly for the low- and middle-income countries where GHG information needs are greatest and capacity is limited.

IG³IS goals include having short feedback loops to help cities demonstrate the positive impact of mitigation activities quickly (faster than the current 1-2 year delay 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 time scales to highlight potential co-benefits and trade-offs such as air quality reductions, traffic management, and environmental justice.

4.2 Customer-based Information Requirements, Current Capabilities and Gaps

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 like C40, ICLEI and the Global Covenant of Mayors as well as partnerships with other stakeholders such as climate-KIC, the Carbon Disclosure Project (CDP) and the World Resources Institute (WRI) that have previously performed demand assessment studies. Direct connection with authorities at the city of interest will provide the best benefit, as each city will have its own priorities and these may change rapidly.

Match existing experimental and pre-operational urban scale monitoring and modeling systems to the information needs of stakeholders e.g. whole city emissions, trend analysis, emission quantification, sector specific analysis of emissions, co-benefits for better understanding air quality inventories, role of the urban land carbon sink. Identify where current knowledge and techniques are insufficient to meet stakeholder needs and outline a pathway to resolve them.

4.2.1 Urban typology

Cities vary widely in such things as their geographic location, topography, water availability, urban density, and emission sources. The creation of an 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 the previous work within WMO-GURME will help accelerate our progress.

4.2.2 High spatial and temporal resolution bottom-up inventories

Data requirements for bottom-up data products (traffic data, building data, tax assessor data, local pollution reporting, vehicle fleet information, etc.

4.3 *Measurement Network 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, 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. Our skills should be critically assessed to see where we meet the demands/challenge from the stakeholders and where future developments needs to be directed towards to

Measurement networks

Several different types of CO₂ sensor are available, including high precision (<0.1 ppm uncertainty) that may be deployed at fixed sites or on mobile platforms, lower-cost sensors, total column and open-path sensors. Urban areas typically have large signals so that instrumental precision may be less critical than for national or global-scale studies.

The choice of sensor location will determine the its 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. Low-density networks (often with high precision instruments) will require high altitude locations to cover an urban area, whereas lower altitude sites may be sufficient for high-density networks, e.g. with lower-cost medium precision sensors (ca. 1ppm long-term repeatability).

CO₂ measurements alone may be insufficient to quantify urban CO₂ emissions, particularly when sectoral information (anthropogenic vs natural, fossil vs biogenic, traffic, electricity generation, residential, etc.) is needed. Isotopes (primarily ¹⁴CO₂) and co-emitted/co-located trace gases (carbon monoxide, air quality gases, particulates, hydrocarbons and halocarbons) are essential to addressing these needs. Sensor types vary for each species, and in many cases, it may be necessary to collect air for offsite analysis (e.g. ¹⁴CO₂). In the highly variable urban environment, time-integrated sampling is beneficial to avoid sampling short-term variability that is difficult to interpret. Meteorological information including wind speed and direction and boundary layer height will be needed in most cases. When the objective is to constrain urban emissions, the up-wind or background CO₂ (and tracer) concentration must be appropriately quantified to isolate the signal of the urban region. These critical observations may need a significant investment. The objective of these reference measurements is to determine what the signal would have been in the absence of the urban emissions, but in practice is typically determined from observations upwind or on the edges of the urban area, sometimes in combination with sophisticated regional atmospheric transport modelling. 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.

4.4 *Modeling Framework*

Data analysis and modeling variety of analysis techniques can be applied to interpret the observational and model data in terms of emission fluxes.

A large amount of information at the whole city scale can be obtained from direct comparison 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 those two tracers is independent of atmospheric transport, as long as the 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, e.g. using Rn222 and CO₂ measurements together. The relative partitioning of CO₂ into source sectors can also be achieved through the ratio technique, e.g. splitting the total CO₂ flux into fossil and biogenic components using ¹⁴CO₂ observations.

Mass balance techniques can determine whole city fluxes using aircraft measurements, combining CO₂ observations and meteorological data with some assumptions about atmospheric mixing processes. Mass balance can be quite effective in “plume” urban typologies (e.g. Indianapolis).

Forward and backward atmospheric transport modelling are used to describe the movement of the air and relate observed atmospheric concentrations to the emission flux. Meso-scale 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.

Atmospheric inversions provide the most 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”, and use an atmospheric transport model to predict the concentrations at observing sites. 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 and the atmospheric “truth” that integrates across all sources.

4.4.1 *Data processing and management routines*

Archiving observations, metadata, model code, model outputs, Observation data 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 (e.g. different wind directions), and/or additional calculations such as enhancements over background or additional information (e.g. fossil CO₂) calculated from initial observations. Definition of operating procedures, QA/QC framework, Scales/calibration, Data management, visualization, dissemination of data and findings.

4.5 *Demonstration experiments*

Selected demonstration experiments should be conducted to highlight the usefulness of IG3IS solutions/systems. Phase one will use existing bottom-up inventory efforts and existing integration/reconciliation with atmospheric monitoring-based approaches. Phase two will extend to demonstrate the ability of novel tools (bottom-up data products, observations and modelling), ideally at cities that were previously investigated.

Current existing urban GHG monitoring project examples:

NIST pilot experiments: Indianapolis, Northeast Corridor, Los Angeles, Boston

LSCE pilot experiments: Paris, Recife, Mexico City

4.6 *R&D for novel/other observing and modelling systems to pre-operational status*

New and novel techniques for GHG observing systems are evolving rapidly, and should be investigated, including, but not limited to:

- Dense low-cost in-situ sensor networks
- Open-path measurements
- Satellite observations - algorithms to transform existing remote-sensing data products to flux-related information
- Novel tracers and isotopes
- air quality tracers

In many cases, OSSE will be a useful tool in evaluating the utility of these techniques. Meso-scale modelling, particularly in the highly heterogeneous urban emissions landscape, can still benefit from refinement and further understanding of the biases and uncertainties in the systems. This work will be depending on the strong exchange with the cross-cutting (inverse) modelling component.

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 parameterization.
- The robustness of different data assimilation approaches for atmospheric inversions (analytical Bayesian, variational Bayesian, Kalman filter, etc.).
- Novel data streams used to create prior emission inventories (e.g. cell phone data, high-res. satellite imagery, biogenic flux models).
- Novel inversion systems such as those without spatially explicit prior

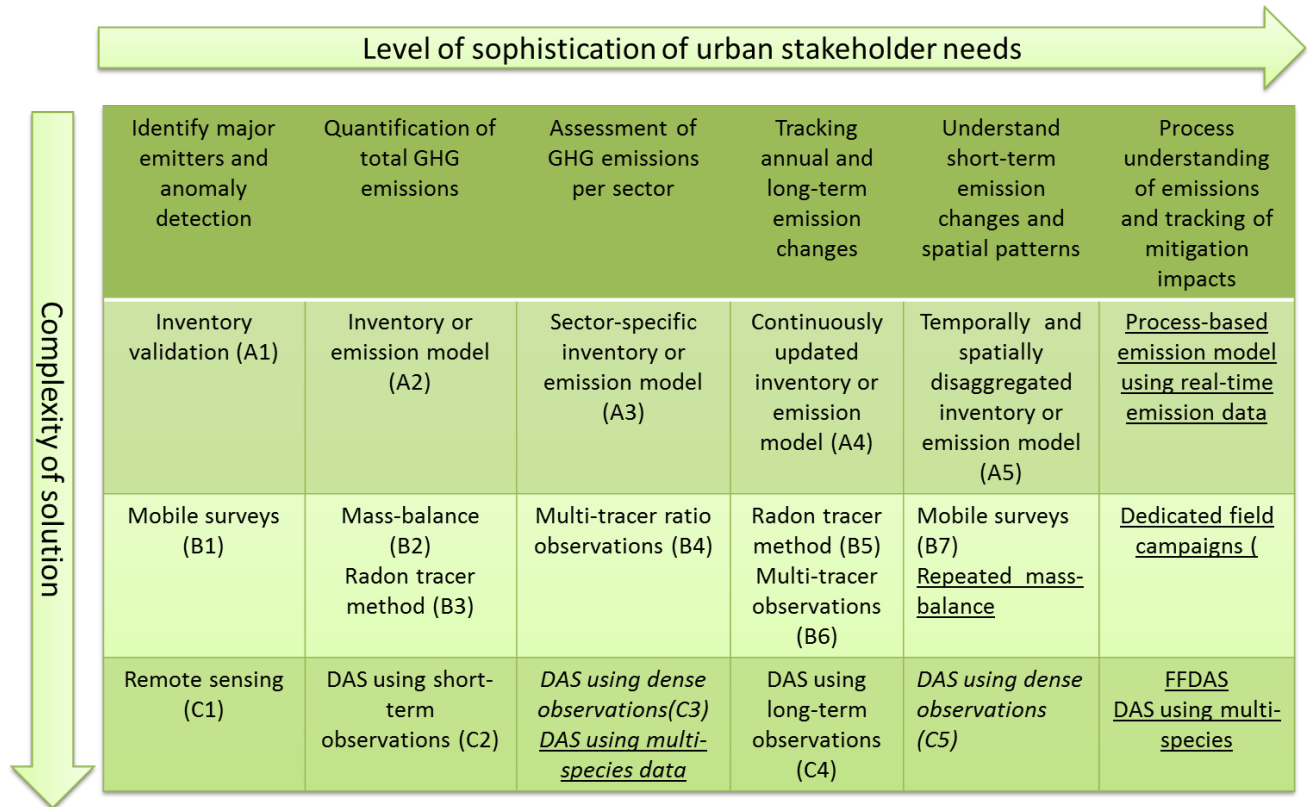
(bottom-up) flux information, fossil fuel data assimilation systems (FFDAS), and multi-species inversions.

4.7 *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. IG³IS therefore supports the building of local capacity through knowledge transfer and training, and links to existing international standardization organizations such as the WMO Greenhouse Gas Measurement Techniques (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 IG³IS findings.

Identified needs and examples of relevant tiers of information:

For each need, information can be provided, 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 given in Table 4.1 below.



Demonstrated skills
Theoretically tested skills
Future potential skills

DAS = data assimilation system

References:

- A1, ...
- B1, ...
- C1, ...

5.0 Objective 4: IG³IS in Support of the Global Stock Take

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 after 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 stock take process of the UNFCCC, 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 stock take 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 stock take 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 (e.g. 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 IG3IS for the global stock take 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.

IG3IS proposes to contribute to the stock take 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.

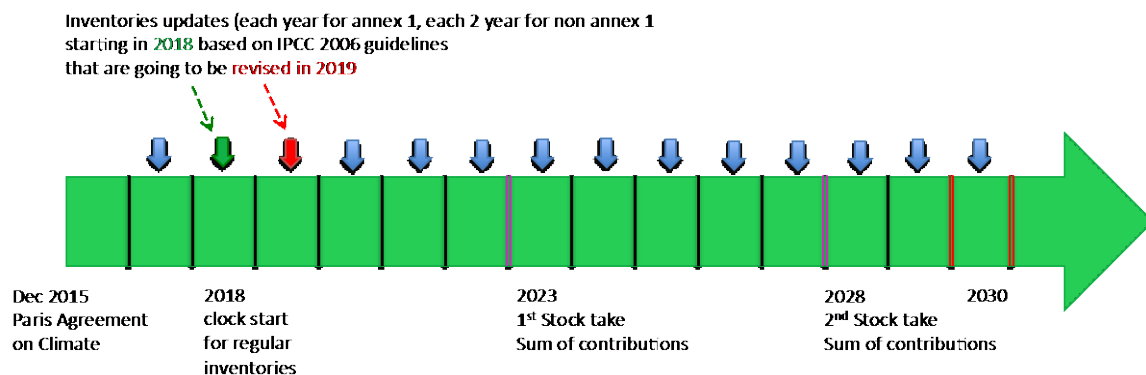
Phase 1. 2017-2023. Build on the example of "early movers » countries like UK and Switzerland who are currently using atmospheric inversions for non CO2 gases as additional information to corroborate their inventories. This approach can be extended to other countries where e.g. regional inversions and continuous measurement networks are already in place or planned in the near future (e.g. 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 IG3IS 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 CH₄, N₂O and CO₂. These estimates will be traceable to peer reviewed scientific literature and regularly (annually) updated along with documented changes in inversions settings and versions (e.g. 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 ≈ 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 CO₂ emissions from CDIAC and UNFCCC provided through the 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 IG3IS 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



6.0 IG³IS Inverse Modeling Cross Cutting Activities

6.1 *Overview*

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) was created to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in simulated atmospheric transport. TransCom was conceived at the Fourth International CO₂ Conference in Carqueiranne in 1993.

IG³IS recognizes a need to organize a TransCom like activity focused on defining standards or skill criteria for inverse modeling activities that must meet requirements for information needs at the “decision-scale” of nations, states, cities and facilities. This activity will not set out to homogenize the diversity of mathematical inverse modeling approaches into one single approach, but will work toward defining the state of current good practices and the currently available skill that is ready to meet currently existing user requirements

7.0 IG³IS Research and Development Activities

8.0 IG³IS Governance, Management and Support

This section will describe governance, management and support structures that will be responsible for the ongoing IG³IS program definition and execution. The WMO Commission for Atmospheric Sciences has established an IG³IS Steering Committee and Science Advisory Board. Progress is being made toward the creation of a Program Office or Secretariat.

9.0 IG³IS Partner, Stakeholder and Sponsor Coordination

9.0 Summary/Conclusion