Nowcasting greenhouse gases emissions using observational in-situ and satellite information

Scoping paper

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1. Introduction: why is GHG nowcasting a relevant question

Unlike normal forecasts, nowcasts aim at providing precise information about what is happening over a region of the atmosphere right now, or at most, what can be expected over the next several minutes or hours. Actually the definition of nowcasting can vary according to the applications. This concept is widely used in meteorological sciences to provide very short term information about atmospheric conditions. The most important application of Nowcasting is warning for severe weather (tornadoes, severe thunderstorms, hail, severe winds, avalanches and flash flooding...) to minimise the loss of life and property, taking advantage of awareness:
"**Nowcasting & Very Short Range Forecasting**" (VSRF) is defined in a very broad sense as" *user-driven services using appropriate meteorological and related science to provide information on expected conditions up to 12 hours ahead*".

This definition shows that one can define nowcasting as analysis of observed data in terms of their impact within the shortest delay after their production and process. Nowcasting services can cover at these timescales a wide range of applications among which and air pollution, ocean, hydrology. Therefore, users of "*Nowcasting and Very Short Range Forecasting (VSRF)*" services include also the agriculture, construction, energy, transportation and the public sectors, to keep an eye on **short-lived and rapidly developing phenomena** that cannot be easily predicted by traditional forecasting systems.

Although nowcasting can represent a real technological challenge, requirements for applications that can cover a wider field than weather services exist. They are actually linked to greater sensitivity of public and policy makers to climate change, air pollution, accidental toxic realises... Interest for the nowcasting concept has even developed, rather recently in the field of economical and policy sciences. The European Commission published on the 20th August 2009 a communication [COM(2009] related to indicators likely to measure progress in the world. Beyond the usual GDP (Gross Domestic Product) environmental and social indicators should be evaluated according to this recommendation. Climate change, energy use, and air pollution should be included in an integrated environmental indicator together with biodiversity, water quality and waste management. The Communication highlights the need to assess this indicator in a long term perspective and to increase the timeliness of environmental and social data to better inform policy-makers all across the EU. This objective addresses some issues of the Europe 2020 strategy (http://ec.europa.eu/europe2020/index_en.htm) .

Access to new communication technologies, widespread observation networks likely to provide monitoring data with high temporal frequency, operational earth-observation systems allows envisaging new applications for nowcasting, especially in the field of environmental monitoring: getting indicators on the state of the environment in near real time is now possible and expected by decision makers. They can be aware of unusual, accidental or non regulatory releases of pollutants in the environment; follow air or water pollution patterns induced by such emissions and take appropriate decisions for control.

COM(2009) comments : (...) *It has taken major steps to employ these technologies* [automatic stations, satellite and Internet technologies] *with the INSPIRE Directive and GMES. Last year the Commission presented the Shared Environmental Information system (SEIS), a vision of how to link traditional and novel data sources online and make them publicly available as fast as possible. A first example of such "near real-time reporting" is the ozone web of the European Environment Agency (EEA) which provides data on harmful* *ground-level ozone concentrations to support daily decisions such as whether to take the car or public transport, or whether or not to undertake outdoor activities*

So near real time monitoring begins to be considered as a relevant mean for information and for environmental management. Near real time information is necessary to increase awareness of various stakeholders: economical sectors responsible for pollution emissions, decision makers in charge of the implementation of regulatory decisions for a environment and health protection and general public, both daily exposed and potential contributor to environmental pollution.

Therefore, beyond the essential need for management of critic situations involving accidental releases of pollution in the environment, “nowcasting air pollutant and greenhouse gases concentrations” becomes a management tool for chronic situations as well. More precisely it can help in dealing with various challenges:

- ***Science***: understanding the development of some air or water pollution patterns characterized by pollutant concentrations higher than regulatory or health and environment protecting values; better understanding of some chemical cycles especially the carbon cycle which can involve short-term reactions;
- ***Management***: assessing the responsibility of various emitting sectors implies accounting for the temporal variability of emission releases. Significant changes can occur depending on the time of the day and the period in the year. It discloses sensitivity of the emissions to economical activity or to meteorological conditions;
- ***Policy***: Verifying whether commitments agreed between European, national and local authorities and economical sectors in terms of pollutant emissions are respected and understanding the reasons why it cannot be the case. This becomes a particularly important with the implementation of trading schemes.
- ***Communication***: Informing the general public about the situation in terms of environment quality, demonstrating the potential efficiency of local control measures,, building up awareness.

The case of Greenhouse gases (GHG) Emissions is particularly instructive and is developed in this note. COM(2009) suggests that “ *(...)* ***More timely data can also be produced by "now-casting", which uses statistical techniques similar to those used in forecasting to make reliable estimates. For instance, the EEA intends to produce short-term estimates of greenhouse gas emissions based on existing short-term energy statistics. Eurostat intends to extend its use of now-casting to environmental accounts****.*”

More precisely, development of high spatial and temporal resolutions emission inventories of CO2 and other GHG appears to be justified by a number of issues discussed for instance in (NRC, 2010), and (Gurney et al, 2009) as well:

- Getting a description of sources and sinks more consistent with the actual spatio-temporal scales of the dynamic of the atmosphere should make the reporting mechanism more accurate. As an example, Figure 1 illustrates the variability of CO2 atmospheric concentrations against reported emissions. Inter-annual variability of CO2 concentration is due to such complex processes which have to be correctly understood to assess correctly the potential effect of emission reduction strategies ;
- Facilitating the verification process against independent atmospheric measurements (in-situ and satellite for instance) which becomes a very sensitive point for some powerful contributors to global GHG emissions (e.g. the US);.
- Feeding public and local authorities’ interest for NRT information on greenhouse gases emissions, especially where neutral carbon cities initiatives have developed. The Finnish experiment organised over main cities provided successful results with NRT CO2 emissions maps are now available on the Internet (www.environment.fi/canemu).

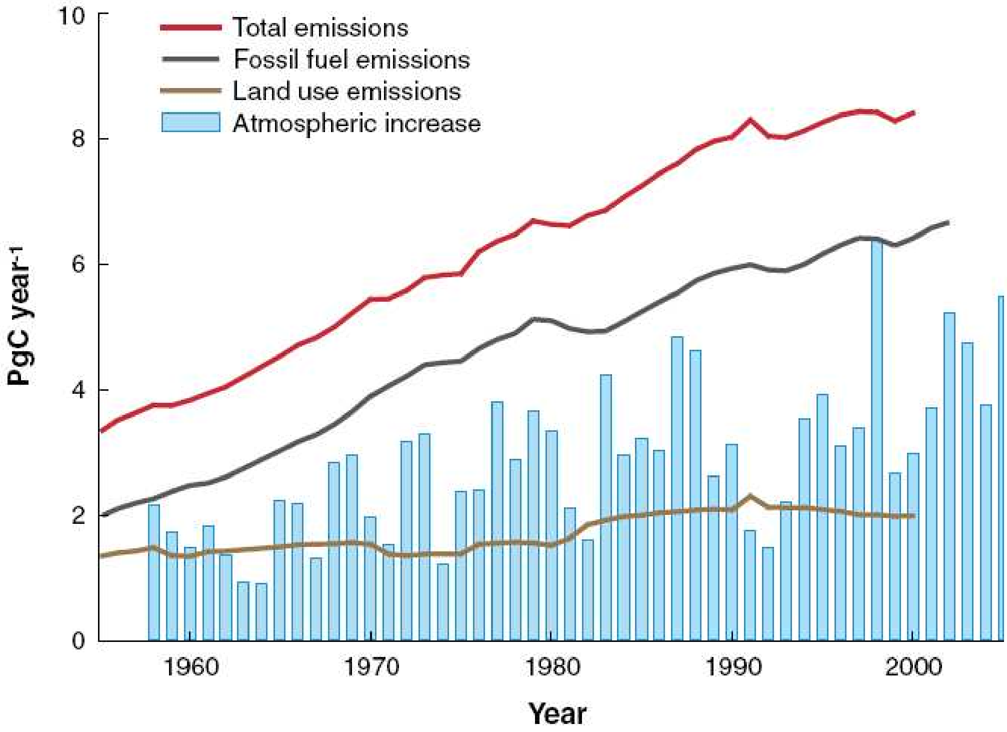

Figure 1. Annual variation in atmospheric CO_2 levels from 1958 until 2005, compared to emissions . SOURCE: Houghton 2007

Although it had never become a law, it is interesting to note that the US Congress proposed in 2009 a bill to authorize the National Oceanic and Atmospheric Administration (NOAA) to establish a comprehensive greenhouse gas observation and analysis system (Rockefeller, 2009). The US administration launched a number of other initiatives devoted to assess the available means to improve and verify CO2 emission declarations. The JASON project (http://www.gotgeoint.com/archives/tag/the-jason-project/ and http://www.fas.org/irp/agency/dod/jason/) has been achieved with a clear political objective of reviewing the actual and future means to assess CO2 emissions from individual countries (JASON, 2011) in support of monitoring international agreements. This project also investigated how more detailed information related to energy infrastructure could be compiled. The VULCAN project (http://vulcan.project.asu.edu/) is funded by the Department of Energy (DoE) and the NASA and is clearly focused on high resolution CO2 emission inventories across the US, with special care accorded to some activity sectors like fossil fuels consumption.

Therefore, there is no doubt that nowcasting science will develop in the future, but nowcasting GHG emissions is not an achieved issue. A lot remains to be done both for getting relevant information and for using it appropriately. The scope of this note is to review use and interest of GHG emissions nowcasts and to assess the state of the art in term of monitoring and modelling to produce such data. It should support the European Environment Agency to consider possible methodologies that could fill in the information gap caused by a time-lag of the formal and calculated proxy GHG emission inventories.

2. Greenhouse gases emissions reporting

2.1. Short reminder about the international regulatory framework

International protocols and legislations define stringent objectives in terms of GHG emissions reductions for the next decades. Those initiatives are framed by the United Nations Framework Convention on Climate Change (UNFCCC) which aims at achieving the stabilisation of greenhouse gases concentrations in the atmosphere at "*a level which prevents dangerous anthropogenic interference with the climate system*". The Framework Convention entered into force on 21 March 1994. The Kyoto Protocol[1] being one of the main instruments of the UNFCCC for tackling climate change, .entered into force in 2005 and set GHG emission reductions by countries. The first commitment period of the Kyoto protocol will end in 2012.

The greenhouse gases covered by the UNFCCC include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs).

In Europe, the decision n°406/2009/EC of 23 April 2009 on "*the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020*" holds. This Decision contributes to meeting the commitment made by the European Union to reduce its greenhouse gas emissions by 20% by 2020 in relation to 1990 levels. It sets objectives for reducing emissions for each of the Member States for the period 2013-2020 (an objective of at least 5% below the 1990 levels was set in the Protocol for developed countries for the period 2008-2012) and defines the means for checking whether they have been met. These objectives can be increased to speed up compliance with international agreements.

Implementation of emission reduction strategies requires relevant and reliable tools for monitoring and reporting national data to check compliance with target objectives.

To deal with the need for thorough monitoring and regular assessment at the EU level, GHG emissions are yearly reported by the member States and they must be assessed in an accurate way, to quantify whether the emission reduction effort complies with the Kyoto objectives. Current emission reporting legislation is based on accounting methods that are prescribed under the UNFCCC for calculating inventories of emissions of industrial and biogenic GHGs at their sources, the so-called 'bottom-up' emissions reporting.

Detailed guidelines for emissions reporting are proposed by the Intergovernmental Panel on Climate Change (IPCC http://www.ipcc.ch/index.htm), the leading scientific body established by the United Nation Program for the Environment (UNEP) and the World Meteorological Organisation (WMO) for the assessment of climate change. These prescribed procedures are based on activity metrics such as economic and land-use databases, emission factors relating these activities to GHG emissions, and time delays between GHG production and release.

On 23 November 2011, the European Commission proposed a new legislation[2] to significantly enhance monitoring and reporting of GHG emissions, in particular to meet new requirements arising from the package of EU climate and energy laws for the period 2013-2020. It should replace and enhance the 280/2004/EC Decision. Amongst other objective,

[1] The European Community signed the Protocol on 29 April 1999 and ratified it on 31 May 2002
[2] http://ec.europa.eu/clima/policies/g-gas/docs/regulation_20111123_en.pdf

this new regulation, if adopted, should help in the implementation of the climate and energy package which called for "*faster, efficient, transparent and cost-effective monitoring, reporting and verification of greenhouse gas emissions*". It should:

- Facilitate further development of the innovative EU climate policy mix by addressing emissions from land use, land use change and forestry (LULUCF), aviation and maritime transport, among other sectors, and by supporting adaptation to climate change;
- Improve quality assurance and help the EU and Member States keep track of progress towards meeting their emission targets for 2013-2020,
- Take into consideration the lessons learnt after 6 years of implementation of the previous decision. Lack of accuracy, transparency, consistency and efficiency of the former monitoring and reporting system is identified

One can note that the proposed text introduces the concept of "approximated greenhouse gas emission inventory" proposed each year X for the year X-1, addresses emissions from land use, land use change and forestry (LULUCF), aviation and maritime transport, among other sectors, and strengthens the role of the European Environment Agency.

Indeed, for any international agreement to limit greenhouse gas emissions, monitoring and verification of emissions is essential to assess the effectiveness of emissions reductions and overall compliance with the terms of the treaty and to give nations confidence that their neighbours are also living up to their commitments. Independent verification of emissions thanks to ambient monitoring can help in building up confidence. And Although GHG monitoring of ambient concentrations is not an obligation for the countries, networks developed all around the world, both for scientific purposes (carbon-cycle analysis over continents and oceans) and communication issues (to make policy makers and citizens more sensitive to carbon fluxes). Some of these networks run for a long time and allow the provision of medium term series of fluxes and concentrations. How those networks can be used for other objectives as emission verification and for feeding Greenhouse Gases Information Systems (GHGIS) is reviewed below.

2.2. Bottom-up versus top-down approaches

The uncertainty of bottom-up approaches classically used for reporting according to the legislation, is supposed to be assessed in regulatory reports to UNFCCC but it can vary significantly with the considered pollutant and sources.

For instance, it is well-known that the vast majority of CO_2 emissions come from fossil fuel combustion (coal, natural gas, and petroleum), with small amounts from the nonfuel use of energy inputs, and emissions from electricity generation using non-biogenic municipal solid waste and geothermal energy. Other sources include emissions from industrial processes, such as cement and limestone production. Quantification of those emissions is well-framed by the available guidebooks and precursor data (statistical data, activity data, emission factors...). Although the large variability of these emissions in time and space has been demonstrated through several experiments (Gurney et al, 2005), (Xueref-Remy et al, 2011), those estimations are generally considered as relevant enough if used on an annual basis and at the global scale.

However difficulties arise when considering emissions of the biogenic components of some of the most important anthropogenic GHGs such as CO_2, CH_4 and N_2O—emissions associated with land-use changes, agriculture and waste processing. And high uncertainties could also be found when emissions of non-CO2 gases with high Global Warning Potentials (GWPs) are reported. Nature published in 2010 (Nature, 2010) a short article synthesizing questions about the potential underestimation of the GHG emission estimates reported by the countries when they are compared with observations is available. Dramatic discrepancies between bottom-up emission inventories (officially reported or not) and emission estimates issued from observation networks analysis were demonstrated for SF6 in (Levin et al, 2010) (Figure 2). Same conclusions were reported in (Weiss et al, 2011) with the following analysis:

"*Statistical uncertainties in emission factors used in bottom-up protocols are always possible, but such errors ought to be mostly random, and thus do not explain the tendency for the actual emissions to exceed the reported ones, more often than not. When emissions from industrial processes are measured at their sources to establish emission factors, the equipment may be adjusted to minimize emissions, so that the measured values may be lower than they are under typical day-to-day operating conditions, and this would lead to under-reporting. Furthermore, the possible existence of unaccounted or unidentified sources, such as fugitive emissions during industrial production or transportation, would also lead to under-reporting. In addition, the negative impact of GHG emissions on climate, and the financial value of emissions reductions in carbon-equivalent trading markets, both create incentives to under-report actual emissions, whether consciously or subconsciously*."

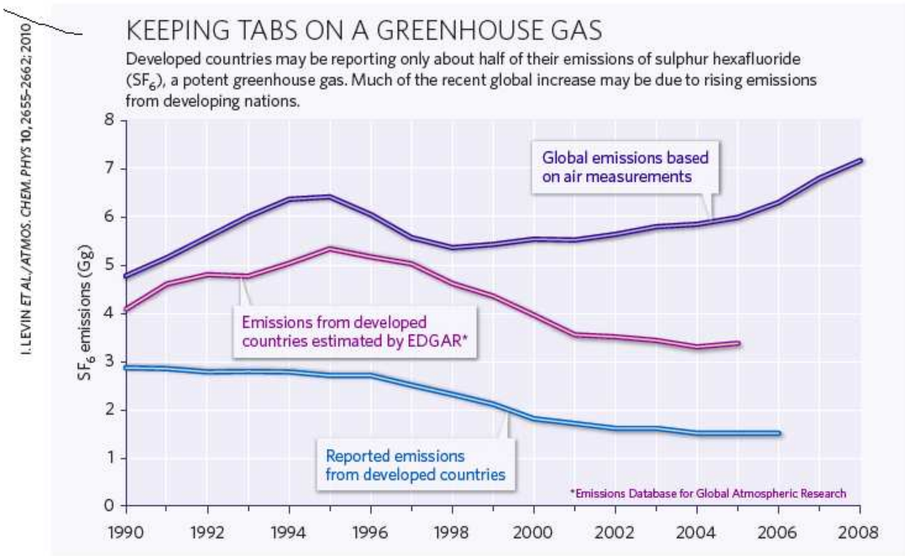

Figure 2. Differences between SF6 global reported emission and emissions based on measurements (source: Nature, 2010)

Availability of in-situ or spaceborne observation data and high maturity of modelling systems fitted to simulate atmospheric composition bring new insights for emission quantification. Indeed inversion modelling techniques using atmospheric observations to constrain chemistry-transport models and to come back to emission estimations provide a completely independent method for verifying "bottom-up" inventory estimates as they use totally different input information. The inversion problem involves minimizing the differences in concentration between the modelled and observed time series. Emission estimates based on inverse modelling are often referred to as "**top-down**" estimates. Figure 3 summarizes how inverse modelling concepts bear top-down approaches for deriving emission inventories and (Manning, 2011) provides a detailed description of the inverse modelling concept applied to the specific topic of the delivery of GHG emission inventories.

For emissions control legislation to be effective, and considering that enforcement is likely to be practical only by bottom-up methods, it is essential that significant discrepancies between bottom-up emissions estimates and "top-down" emissions estimates based on atmospheric measurements be resolved or at least explained. But because emissions control legislation is national or regional in nature, not global, it is also essential that top-down emission estimates be determined at these same geographic scales. Atmospheric GHG measurements and inverse modelling, when proceeding in tandem, allow observations to be used to answer important scientific, as well as regional, emission questions. A comprehensive overview of such issues is given in (Bergamaschi et al, 2007), which details the main conclusions of a EU workshop organised to state the potential benefits of confronting “traditional” bottom-up and top-down methodologies for deriving better GHG emission estimates.

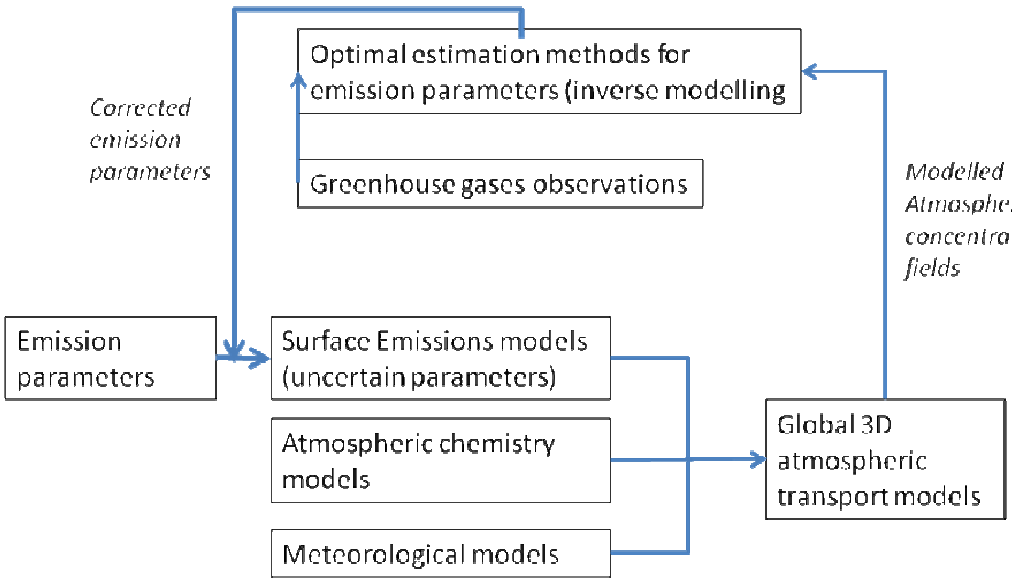

Figure 3. Simplified presentation of the inverse modelling concept for emission estimation or verification.

Inverse modelling approaches are based on some assumptions regarding the spatial resolution and the temporal variability of emissions sources. Usually fossil fuel emissions are considered as rather well-framed (and so rather uncertain) with a small intra-annual variability. But (Peylin et al, 2001) showed that large variability of modelled CO2 emission fluxes could be observed both on an hourly basis and on annual country totals (10% up to 40% variation) according to the spatio-temporal resolution of the emission data inventory. Therefore uncertainty in top-down emission inventories could be significantly improved with high spatially and temporally resolved observation fields.

GHG emissions nowcasting focused on high resolved spatio-temporal information can precisely help in the direction of independent GHG emission verification. Actually, nowcasting can be defined as a kind of “near real time” (compared to usual time scales that are about two years) top-down assessment of emissions.

2.3. A field for improving GHG regulatory reporting?

GHG ambient concentrations monitoring and emission nowcasting can offer the opportunity to **quickly** (within a period of 6 months to 1 year) assess the trends and the impact of the efforts of a given country or region in reducing GHG emissions, with controlled uncertainties.

An interesting and precursor experiment was conducted few years ago by Levin and Rödenbeck (Levin et al, 2008). They tried to assess the potential interest of accurate and long term $^{14}CO_2$ in-situ observations for monitoring the impact of fossil fuel CO2 emissions in South-Western Germany. Although no significant trend in the regional fossil fuel CO2 component. was observed, strong inter-annual variations were highlighted. Dedicated transport model simulations of fossil fuel CO2 showed that they could be largely imprinted by changes of atmospheric transport. Finally, in this paper, depending on the remoteness of the site, changes of about 7–26% in fossil fuel emissions in respective catchment areas of the measurement sites could be detected with confidence by high-precision atmospheric $^{14}CO_2$ measurements when comparing 5-year averages to long term trends. This study proved two things:

1- The relevance of using long term high resolved and accurate observation networks for short term monitoring emission changes (provided that the density and the accuracy of the measurement network is sufficient and that data could be inversed through a reliable transport model).
2- The spatio-temporal variability of CO_2 emission and concentration patterns can be high and should be correctly taken into account when emission inventories are built up.

Currently, yearly official reports on national emission inventories of greenhouse gases are delivered with a two years delay. It corresponds to the time frame considered as relevant and necessary for establishing bottom up emission inventory with validated data on economical activity, social statistics, landuse etc... Therefore it is inherent to the bottom-up approach. This time frame is rather long if we consider that policy makers need to be informed in short time about the effects of the implemented strategies on GHG trends (which management strategies work and which ones do not) or about the impact of unexpected events (like the 2008-2009 economical crisis for instance). Such information delivered with appropriate timeliness should help to strengthen or adapt decision making and to go more or less straightforward through the objectives of the EU regulation and international protocols. Moreover getting some feedback, thanks to measurements, on the occurrence of accidental releases should be rigorously taken into account in the emission budgets although they are not notified in the standard economical statistics.

By combining atmospheric measurements of GHG with inverse methods and atmospheric transport and chemistry models, it should be possible to map and quantify regional emissions, in a short delay (monthly scale). Because emissions are regulated nationally or regionally, not globally, top-down estimates must also be determined at these scales. High-frequency atmospheric GHG measurements at well-chosen station locations can record 'pollution events' above the background values that result from regional emissions (extension of the Levin's experiment). Even with the sparse current network of measurement stations and current inverse-modelling techniques, it is possible to rival the accuracies of regional 'bottom-up' emission estimates for some GHGs (see the ICOS European infrastructure - http://www.icos-infrastructure.eu/index.php?p=hom and the IGCO international network). Moreover, strategic analyses (GEO, 2010) highlight the need for improving density of the GHG in-situ networks so that individual countries could have a chance to benefit from relevant observation data, tools and methodologies adapted to national monitoring, reporting and verification systems, according to the UNFCCC requirements. The Global Earth Observation initiative committed to play an important role in coordinating global observation and facilitating unencumbered access to data by all countries.

Therefore, for reporting applications one can expect to get complementary and useful information on GHG emissions thanks to an appropriate interpretation of atmospheric concentration observations that should develop within organised international networks. Even if the "near real time" or "nowcasting" concepts refer to temporal scales of about few months, it helps in reducing significantly the time when emissions can be assessed and checked for policy purposes.

3. Nowcasting greenhouse gases emissions

The fact that nowcasting objectives require dense observation networks running with high temporal resolution to allow the delivery of diagnostics in short time. Both in-situ and earth observation systems could provide relevant information, and are already used in some applications, but generally not yet devoted to nowcasting analysis. Those networks and systems are reviewed below to illustrate their maturity, short term emission evaluation issues being considered in each section. A table referring current in-situ networks and data portals where data on GHG likely to be used for GHG nowcasting and analysis purposes can be download is given in annex.

3.1. In-situ networks and systems

The North American Carbon Program – NACP (http://www.nacarbon.org/nacp/)

As an element of the US Global Change Research Program, it aims at federating skills and evaluation tools for measuring and understanding the sources and sinks of Carbon Dioxide (CO_2), Methane (CH_4), and Carbon Monoxide (CO) in North America and in adjacent ocean regions. This is a multidisciplinary research program to obtain understanding of sources and sinks of CO2 in North America and adjacent areas. NACP relies upon diverse existing observational networks, monitoring sites, and experimental field studies in North America. Integrating these different program activities and maximizing synergy amongst them required organisation in terms of QA/QC, data sharing and data policy tackled the development of an appropriate framework for dealing with the US strategy for carbon management (Michalak et al, 2011).

Carbon Tracker (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/)

A new system that monitors the amount of carbon dioxide (CO_2) in the atmosphere worldwide is now operational. Utilizing data from more than 60 monitoring stations, CarbonTracker provides an accurate evaluation of changing levels of atmospheric CO_2, and is able to distinguish between natural and anthropogenic influences on those fluctuations. The system utilizes a numerical model that determines carbon release or uptake by oceans, wildfires, fossil fuel combustion, and the biosphere. It then transfers that data onto a color-coded map of sources and storage sinks.

CarbonTracker was created by scientists at NOAA's Earth System Research Laboratory with a primary intention that it be used to evaluate the performance of carbon-emission reduction and storage techniques. It will also provide verification for computer models that project future climate change. There are CarbonTracker projects in both the US and Europe Figure 5), with the European effort carried out in collaboration with Wagenigen University (http://www.carbontracker.eu/) .

CarbonTracker US is fed by observations available from the NOAA’s network (surface data, towers and aircraft monitoring Figure 4) available from the Global monitoring division of the Earth System Research Laboratory (ERLS http://www.esrl.noaa.gov/gmd/ccgg/index.html). The list of the sites is available on http://www.esrl.noaa.gov/gmd/dv/site/site_table2.php ..

Note that most updated Carbon Tracker’s delivered data is related to the situation in 2009 (CT2010). Therefore, high spatially and temporally resolved fields of CO2 fluxes are made available in delayed mode which is not completely compatible with nowcasting objectives (Figure 6).

Figure 4. Measurement sites used in the CarbonTracker system (source: http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/network_map3.html)

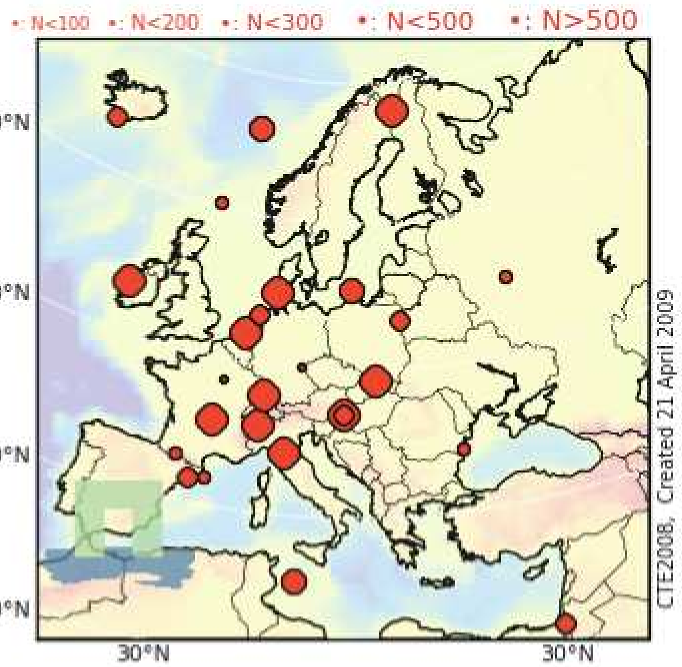

Figure 5. In situ sampling network used by CarbonTracker Europe. SOURCE: CarbonTracker Europe

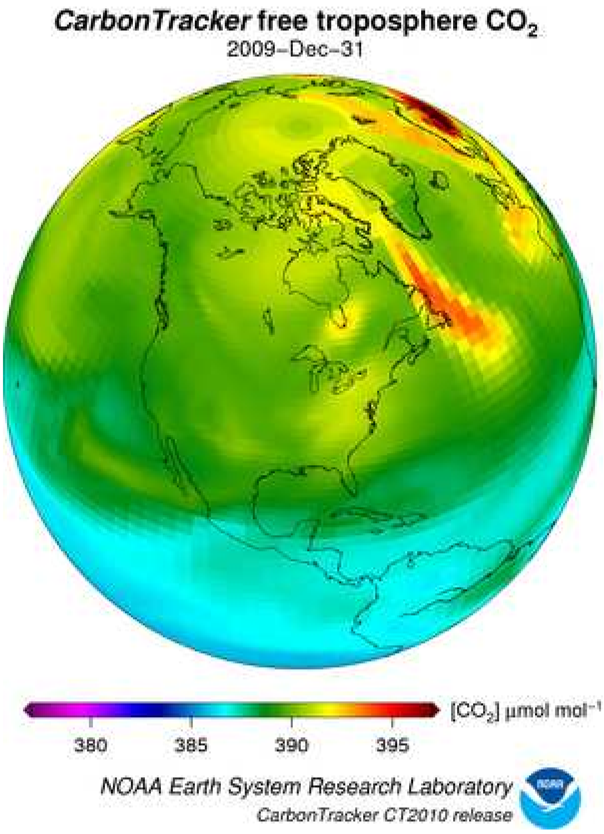

Figure 6. **CO2 concentrations in the free troposphere on the 31th December 2009**

The NOAA/ESRL network (http://www.esrl.noaa.gov/gmd/ccgg/)

Carbon Tracker is an information system which integrates observations influxes and concentrations but raw data is available on the NOAA/ESRL/Global monitoring Division website. Thanks to active international cooperation, the Carbon Cycle Greenhouse Gases group makes ongoing discrete measurements from land and sea surface sites and aircraft, and continuous measurements from baseline observatories and tall towers (Figure 7). These measurements are supposed "*to document the spatial and temporal distributions of carbon-cycle gases and provide essential constraints to our understanding of the global carbon cycle".* All available data can be downloaded on the website: near real time delivery at the NOAA/ERLS measurement stations are made available on the website (http://www.esrl.noaa.gov/gmd/dv/iadv/) and can be used for nowcasting objectives (Figure 8).

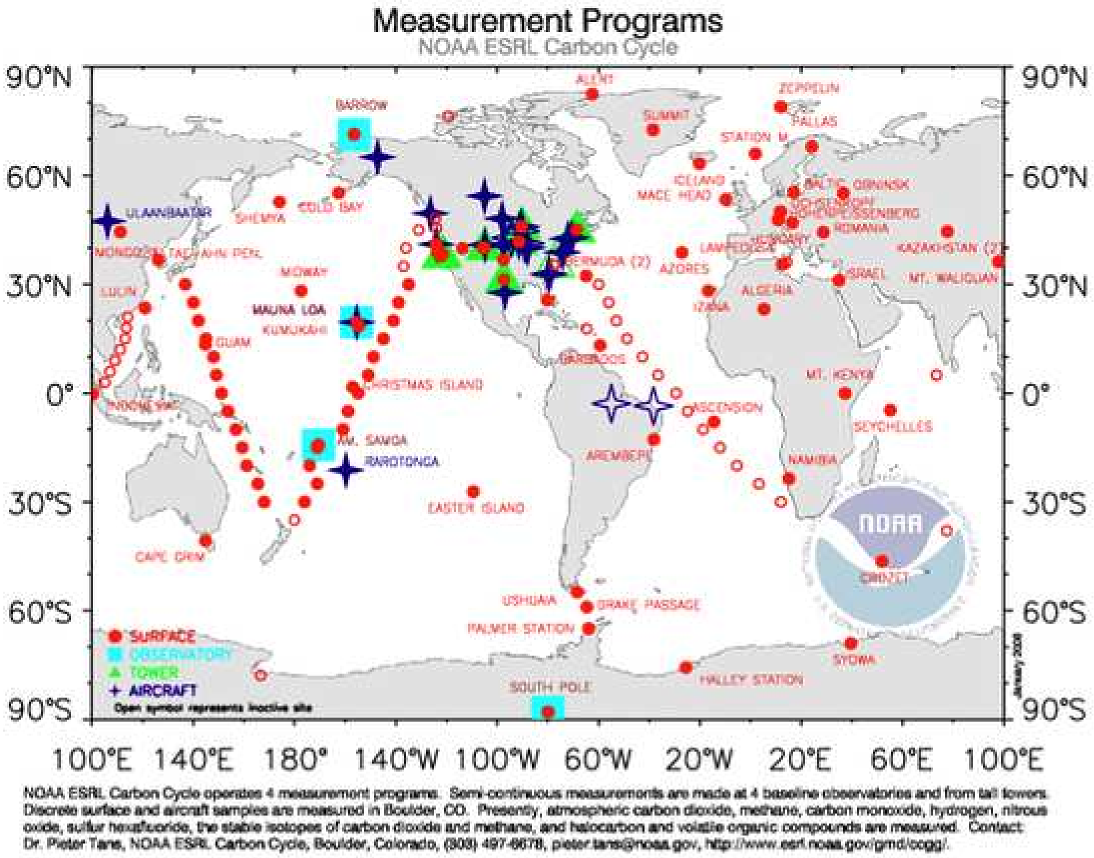

Figure 7. NOAA carbon measurement program: Red dots indicate surface measurements, cyan squares are observatories, green triangles are towers and blue crosses are aircraft. Source:http://esrl.noaa.gov/gmd/Photo_Gallery/GMD_Figures/ccgg_figures/tn/ccggmap.png.html

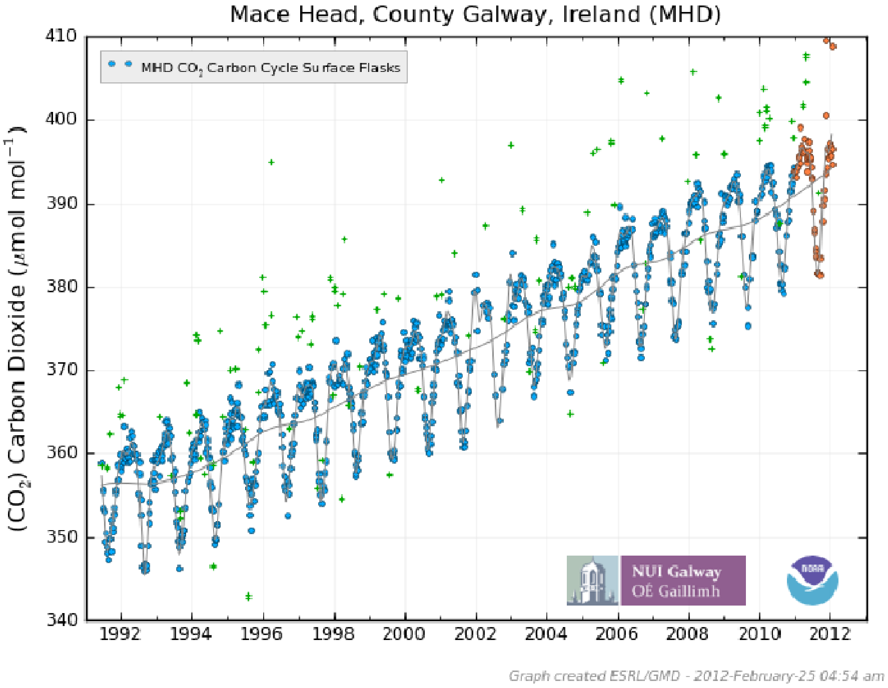

Figure 8. Historical and NRT data for CO2 concentrations measured at the Mace head site. Orange dots correspond to "preliminary" observation data. Source : http://www.esrl.noaa.gov/gmd/dv/iadv/

ICOS (Integrated Carbon Observation System http://www.icos-infrastructure.eu/)

(ICOS, 2010) states that "*The mission of ICOS is to run a long-term monitoring network that produces harmonized sets of high precision and accuracy observational data. These data should be of a density and quality to allow for regular assessment of regional carbon fluxes from atmospheric observations using inversion models that aim at mapping the regional distribution of greenhouse gas fluxes with a grid size as low as 10 km. Thus, ICOS data might gauge the success of mitigation strategies in reducing greenhouse gas emissions, not just with inventories but with measured data*."

ICOS is a new research infrastructure gathering contributions and know-how of about 16 European countries in terms of CO2 fluxes monitoring. It is based on an extensive monitoring network including atmospheric concentrations sites, ecosystem monitoring sites and aircraft measurements (Figure 9). These data will allow a unique regional top-down assessment of fluxes from atmospheric data, and a bottom-up assessment from ecosystem measurements and fossil fuel inventories. A common data center, the Carbon Portal put into place by ICOS, will provide free access to ICOS data services, as well as to links with inventory data, and outreach material. This portal will allow the production web based tools for the survey of sources and sinks in near real time. ICOS will deliver the information in near real time with a quantification of the uncertainty associated with the results due to the use of several different models using different methodologies.

Target is a daily mapping of sources and sinks at scales down to about 10 km, as a basis for understanding the exchange processes between the atmosphere, the terrestrial surface and the ocean. ICOS will enable Europe to be a key global player for in situ observations of greenhouse gases, data processing and user-friendly access to data products for validation of remote sensing products, scientific assessments, modeling and data assimilation.

The ambition of ICOS is to become a European GreenHouse gases Information System (GHGGIS) acting as support to decision making, monitoring emissions. Actually**, it can certainly be considered as the first experiment dedicated to CO2 emissions nowcasting.**

At this stage ICOS gathers skills, competences and data developed in previous years through research programs (e.g. CarboEurope http://www.carboeurope.org/) . It is still in a preparatory phase to set-up the network and to secure funding. **The first operational phase will start in 2014**.

Until then few data and time series of CO2 concentrations are punctually available in a short term delay (15 days) at various stations considered to be included in the ICOS network. Four observatories deliver on a daily basis CO2 and CH4 concentrations used for modelling and mapping experiments (https://icos-atc-demo.lsce.ipsl.fr/node/20#).

Figure 9. ICOS terrestrial implementation. SOURCE : (ICOS, 2010)

AGAGE network (Advanced Global Atmospheric Gases Experiment http://agage.eas.gatech.edu)

AGAGE, sponsored by the NASA (Figure 10) and its predecessors (the Atmospheric Life Experiment, ALE, and the Global Atmospheric Gases Experiment, GAGE) have been measuring the composition of the global atmosphere continuously since 1978. The AGAGE is distinguished by its capability to measure over the globe at high frequency almost all of the important gases species in the Montreal Protocol (e.g. CFCs and HCFCs) to protect the ozone layer and almost all of the significant non-CO_2 gases in the Kyoto Protocol (e.g. HFCs, methane, and nitrous oxide) to mitigate climate change.

All data since 1978 are available on the AGAGE website and on the Carbon Dioxide Information and Analysis Center (CDIAC) at the U.S. Department of Energy. Montnhly averages of 33 chemical compounds are available (Figure 11). Those data have been extensively used to demonstrate thanks to inverse modelling approaches a significant underestimation of most of the non-CO_2 greenhouse gases emissions reported to the UNFCCC (Weiss et al, 2011).

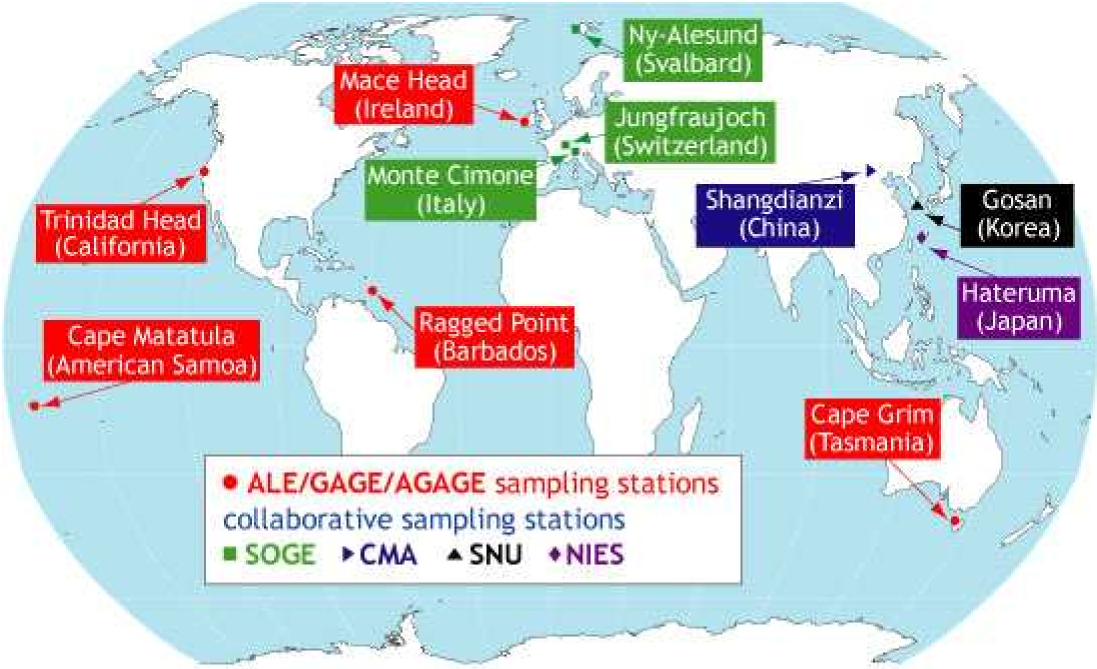

Figure 10. AGAGE network

Figure 11. Example of AGAGE data : monthly averages of N_2O concentrations and standard deviation at the AGAGE stations

The WMO/GAW (Global Atmospheric Watch program) contribution: the world data center for GreenHouse gases (http://ds.data.jma.go.jp/gmd/wdcgg/)

The WDCGHG is one of the WDCs under the GAW programme. It serves to gather, archive and provide data on greenhouse gases (CO_2, CH_4, CFCs, N_2O, surface ozone, etc.) and related gases (CO, NOx, SO_2, VOC, etc.) in the atmosphere and ocean. It was established at the Japan Meteorological Agency (JMA) in October 1990. It gathers daily, monthly or annually data from more than 250 stations (half of them from the NOAA/Earth System Research Laboratory network) from 57 countries Figure 12. This initiative allows getting a unique collection of **measurement data available following a near real time process which could in final be used in nowcasting integrated systems**. Note that most of the data available for the previously described programs can be found in the WDCGHG databases.

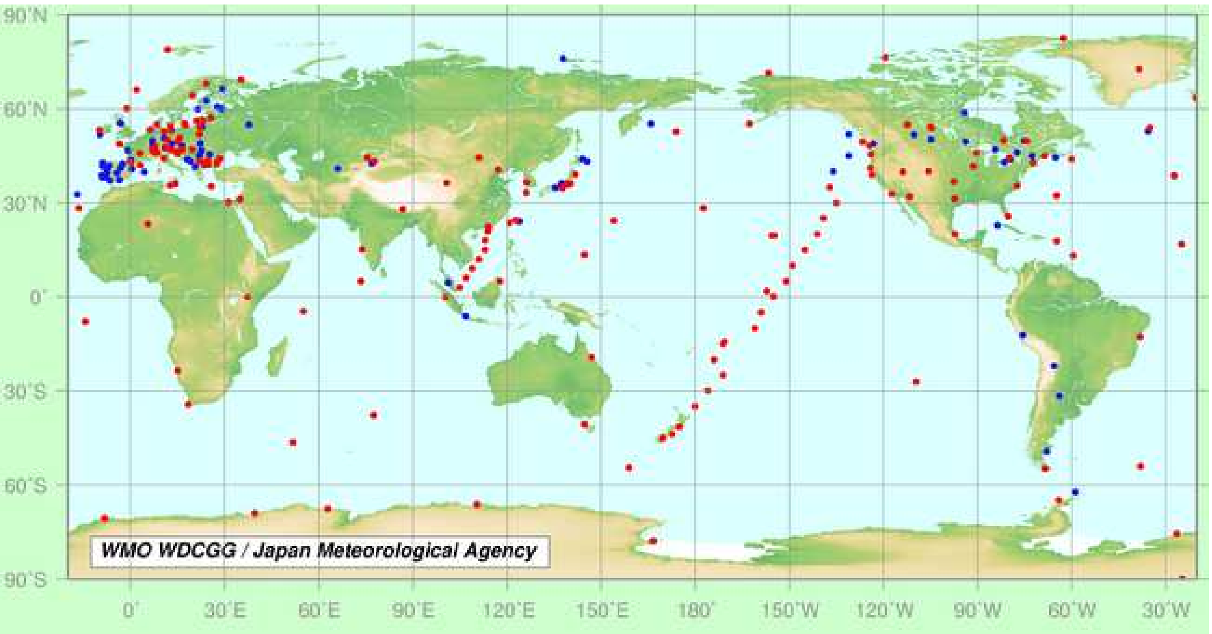

Figure 12. Stations reporting GHG observation data to the GAW/WDCGHG

3.2. Earth observations

Space-based instruments are a new means of contributing to careful monitoring of carbon dioxide and methane in view of checking the emission targets are met. Space borne platforms are extending the atmospheric GHG records by providing high quality measurements with high coverage and density in space and time, augmenting local and regional measurements from ground and airborne sensors to provide a global context for existing measurements, and cover regions not readily accessible or instrumented by other means. The AIRS-TES-OCO series of NASA satellite CO2 observations as well as observations from the SCIAMACHY (ESA) and GOSAT (JAXA-MOE-NIES) sensors contribute to these objectives.
An extensive review of satellite based remote sensing for climate has been recently established by (Thies and Bendix, 2011). An accurate description of technical progress in that science is provided. A short review of the current earth observation missions is given below:

- The Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (**SCIAMACHY**) instrument was the first space sensor capable of measuring greenhouse gases with high sensitivity down to Earth's surface (Buchwitz et al, 2005). It was launched in 2002 aboard ESA's ENVISAT spacecraft. Based on three years of observations from the SCIAMACHY instrument aboard ESA's Envisat, scientists have produced the first movies showing the global distribution of carbon dioxide and methane (http://envisat.esa.int/instruments/sciamachy/). The spatial resolution is about 30 km which is rather law
- The Atmospheric Infrared Sounder (**AIRS**) is one of six instruments on board the Aqua spacecraft as part of the Earth Observing System's Afternoon Constellation launched in 2002 (Figure 13). Although originally designed to measure atmospheric water vapor and temperature profiles for weather forecasting, data from the Atmospheric Infrared Sounder (AIRS) instrument on NASA's Aqua spacecraft are now also being used by scientists to observe atmospheric carbon dioxide.. AIRS can also measure trace greenhouse gases such as ozone, and methane. Data from AIRS have been used to produce global maps of CO_2 concentrations in the mid-troposphere for the first time (Figure 14 and Chevallier et al, 2005). These data

provide important new constraints on the global distribution and transport of CO_2 with a Global Sample Distance (GSD) of about 13 km.

- The Tropospheric Emission Spectrometer (**TES**) is a high resolution Fourier Transform Spectrometer aboard the Aura satellite, also in the A-train constellation, launched in 2004. TES sensitivity peaks in the mid-troposphere. Retrieved species (CH_4, CO, CO_2, H_2O, HDO, HNO_3, NH_3, O_3) volume mixing ratio or temperature data interpolated onto a uniform global latitude/longitude grid at selected pressure levels are available on a daily basis (http://eosweb.larc.nasa.gov/PRODOCS/tes/table_tes.html). Initial comparisons have been made with AIRS retrievals and aircraft flask CO2 data. Near term activities include assimilation and inverse modelling of TES CO2 measurements, using the chemical transport model GEOS-Chem. Retrievals resolution is about 50 km. TES Special Observations are research measurements of targeted locations or regional transects which are used to observe specific phenomena or to support local or aircraft validation campaigns.
- The Infrared Atmospheric Sounding Interferometer (IASI) is a key payload element of the METOP series of European meteorological polar-orbit satellites. It is developed by CNES in the framework of a co-operation agreement with EUMETSAT.The first flight model was launched in 2006 onboard the first European meteorological polar-orbiting satellites, METOP-A (http://smsc.cnes.fr/IASI/index.htm) . It is designed for measuring meteorological parameters with a very high resolution and accuracy, and for atmospheric chemistry as well, aiming at estimating and monitoring trace gases like ozone, methane or carbon monoxide on a global scale. The total amount of ozone under cloud-free conditions is measured with a horizontal resolution of 25 km and an accuracy of 5%, and total column-integrated content of CO, CH_4 and N_2O with an accuracy of 10% and a horizontal resolution of 100 km.
- The Greenhouse Gases Observing Satellite "IBUKI" (**GOSAT**) is a collaborative project by JAXA, the National Institute for Environmental Studies (NIES,) and the Ministry of the Environment (MOE) to provide the world's first satellite dedicated to observe global greenhouse gasses from space. Its resolution is about 10 km. It was launched in 2009 and provides since then operational data related to monthly CO2 concentration averages. A very recent study demonstrated that with the addition of the GOSAT observational data to the global ground-based monitoring data, significant uncertainty reduction was achieved in the monthly regional CO_2 flux estimates especially in some regions of the world (South America, Africa, Asia). Monthly fluxes calculated from the GOSAT data and the ground-based monitoring data in some regions show differences to those calculated from only the ground-based monitoring data. It is expected that continuous monitoring by GOSAT and further research undertakings will yield further understanding of the CO_2 flux behaviour (http://www.gosat.nies.go.jp/eng/related/2011/201111.htm).
- The Orbiting Carbon Observatory -2 (**OCO-2**) is based on the original **OCO** mission that was developed under the NASA Earth System Science Pathfinder (ESSP) Program Office and launched February 2009. Before spacecraft separation, a launch vehicle anomaly occurred that prevented the OCO spacecraft from reaching injection orbit. The spacecraft was destroyed during re-entry. The Orbiting Carbon Observatory-2 (OCO-2) mission was authorized to enter a tailored formulation phase on March 2010. The OCO-2 Project is directed to make every effort “to duplicate the original OCO design using identical hardware, drawings, documents, procedures, and software wherever possible and practical” to minimize cost risk, schedule risk, and performance risk. OCO-2 should be launched in February 2013 and its foreseen ground sample distance is about 1,5 km (http://oco.jpl.nasa.gov/) .

For performing nowcasting and emission monitoring the JASON[3] project considered carefully the fact that all these Earth Observation systems are based on LEO (Low Earth Orbits). Indeed, the repeat interval at which nadir-looking LEO instruments return to the same patch of ground is of order 15-20 days, depending on orbit details (even assuming cooperative clouds). That actually can be a strong limitation and this is the reason why GEO (geostationary) satellites are carefully considered for future missions. JASON report (Jason project, 2011) highlights a number of strong advantages in developing such an EO strategy for GHG emission monitoring and nowcasting :

- "*GEO offers the option, unavailable at LEO, of revisiting important locations frequently on time scales of hours or days, and looking at them longer. This option would be key to monitoring power plants and other sites with anthropogenic sources of CO2"*.
- "*Since a number of LEO instruments exist already, with plans to be augmented soon by OCO-2, the GEO instrument would provide a nicely complementary spatio-temporal sampling function*".
- It could allow measurement of simultaneous data (CO2 and another GHG compounds for instance)

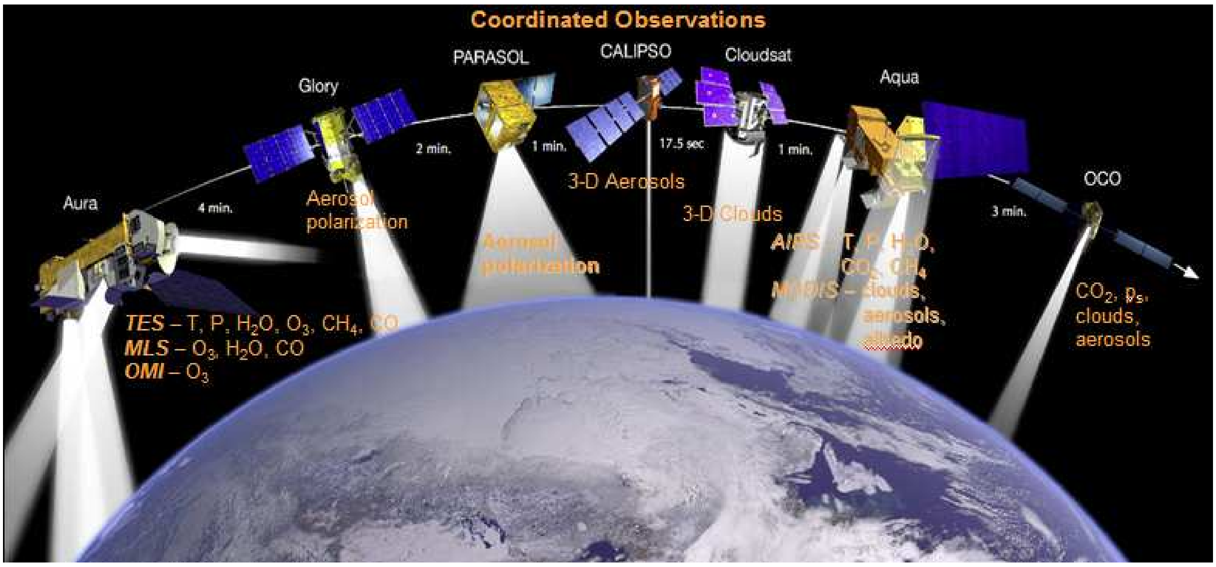

Figure 13. The Earth Observing System Afternoon Constellation ("A-train"). Source: NASA

[3] JASON is an independent scientific advisory group that provides consulting services to the U.S. government on matters of defense science and technology (http://www.fas.org/irp/agency/dod/jason/)

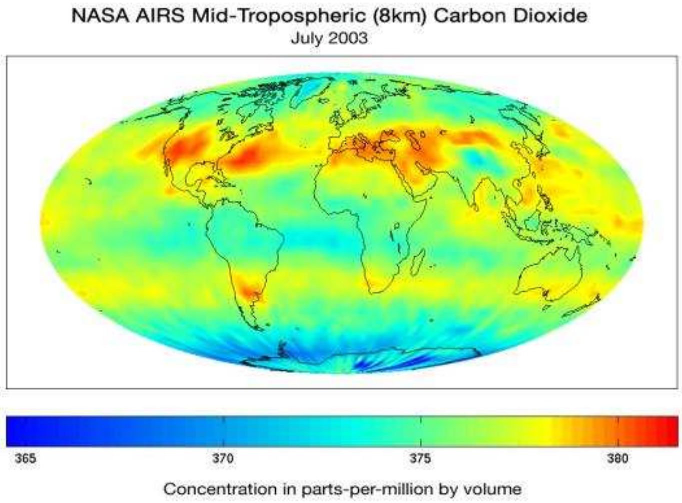

Figure 14. AIRS Global Map of Carbon Dioxide from Space.
SOURCE : AIRS Global Map of Carbon Dioxide from Space

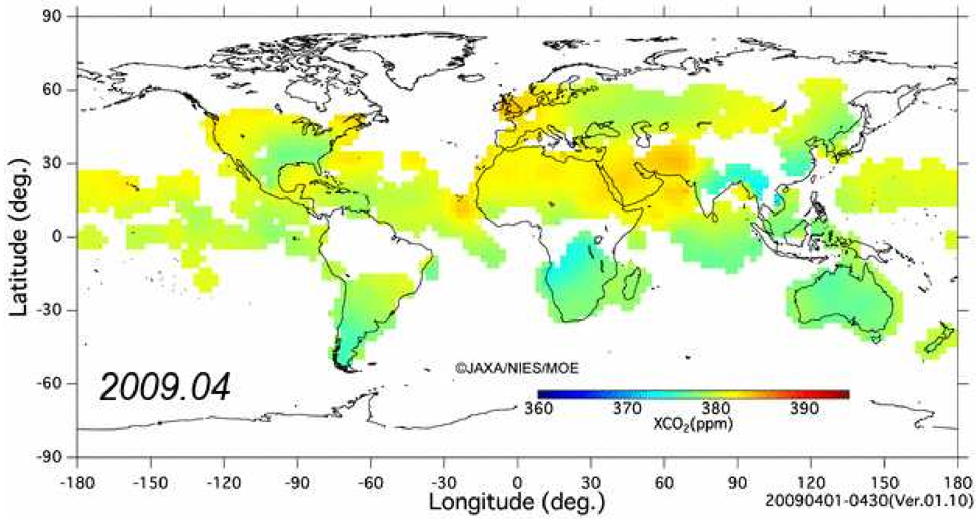

Figure 15. GOSAT Global map of CO2 monthly means (April 2009)
SOURCE : https://data.gosat.nies.go.jp/GosatBrowseImage/browseImage/XCO2_L3.gif

The new NASA initiative for defining the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (**ASCENDS**) mission should be mentioned (http://cce.nasa.gov/ascends/index.htm) . Scientists and experts groups recommended its implementation for mid-term (Launch Readiness 2013-2016). This mission is dedicated to enhance understanding of the role of CO2 in the global carbon cycle with the following objectives:

- Quantify accurately spatial distribution on scale of weather models
- Quantify global spatial distribution of CO2 terrestrial and oceanic sources and sinks on a 1°resolution grid at a weekly resolution
- Provide scientific basis for future projections of CO2 sources and sinks.

Therefore, ASCENDS mission should help in filling in the remaining significant gaps in our understanding, particularly related to the distribution and variability of terrestrial and oceanic sinks and the processes controlling this variability. In particular, it should help in improving understanding of the time varying behaviour, and underlying processes of natural sources and sinks, including processes that occur over short (e.g. diurnal) time scales, medium (seasonal/annual) time scales, and extended (climatological) time scales, including processes resulting from ecosystem/biosphere disturbances. Therefore, reducing uncertainties on the natural sources it is expected that ASCENDS will enable continued investigations of anthropogenic emissions (from fossil fuel use or land use changes) using a top-down approach, constraining the emissions determined by the current bottom-up inventory approach. These considerations are detailed in a report issued from a workshop organised by the NASA in 2008 (ASCENDS, 2008).

The CEOS (Committee on Earth Observation Satellites) coordinates space borne Earth observation initiatives. 50 space agencies participate to this Committee (http://www.ceos.org/) It provides information on current and future priorities for Earth observation missions and several portals offer access to maps and data (see for instance the Atmospheric Composition Portal http://wdc.dlr.de/acp/). The CEOS has been engaged by the Global earth Observation (GEO) experts to consider an appropriate strategy for improving monitoring of the carbon cycle (see below). CEOS decided to create the Carbon task Force (CTF) under the leadership of JAXA and NASA (http://www.ceos.org/index.php?option=com_content&view=article&id=287:carbontaskforceintrotext&catid=159:carbontaskforce&Itemid=204) . The work of the Task Force will take into account the information requirements of both the UNFCCC and IPCC and consider how future satellite missions will be able to support them. It should also take account of, and be consistent with, the GCOS (Global Carbon Observing System) Implementation Plan requirements (GCOS, 2010 http://www.ceos.org/images/ctf/gcos-138.pdf).
The Carbon task Force established the following table to illustrate from 2009 to 2025 the missions dedicated to climate and GHG monitoring. The Carbon Task Force aims to provide a final and comprehensive report – The CEOS Strategy for Carbon Observations from Space will be published by late 2012.

Mission	Instrument	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Nadir Absorption, weighted to the Lower Troposphere																		
ENVISAT	SCIAMACHY																	
GOSAT	TANSO-FTS																	
OCO-2	OCO Spectrometer																	
Minicarb	FTS																	
GOSAT-2	FTS																	
CarbonSat	Spectrometer																	
ASCENDS	Laser Spectrometer																	
GOSAT-3	Laser Spectrometer																	
Nadir Emission, weighted to the Mid-Troposphere and Upper-Troposphere																		
EOS-AQUA	AIRS / AMSU																	
EOS-AURA	TES																	
METOP and NOAA	HIRS	5	5	5	5	4	4	3	3	2								
Metop (A,B,C)	IASI																	
FY-3 (C,D,E,F,G)	IRAS						2	2	3	2	3	2	3	2	2			
NPOESS (1,3,4)	CrIS										2	2	3	2	2	2	2	2

Lower Troposphere missions beyond OCO-2 (2016) are uncertain. All of the missions are in concept development and may not be flown, as shown with the grey color. A timeline gap may exist.
Indeed, it is unlikely that ENVISAT and GOSAT will last beyond 2015 due to mission fuel constraints. OCO-2 has fuel for 8-years (until 2020).

OCO-2 could be the only CO_2 mission measuring the lower troposphere beyond 2015 with limited repeat cycle (16 days) and spatial coverage (swath width 10-km). The CEOS recommended that more wide-swath CO_2 missions should be implemented.

3.3. Integrated inverse modeling systems and nowcasting

Examples where use of available in-situ and satellite information was used to derive GHG fluxes and to improve emission inventories exist and have been recently updated. (Corrazza et al, 2011) assessed such capacities for deriving N_2O emissions from various in situ observation networks and satellite observations. (Xueref-Remy et al, 2010) and (Xueref-Remy et al, 2011) focused their study on the variability of the budget of CO2 in Europe using data collected during the CAATER airborne field campaigns which held in 2001 and 2002.

But most of these studies derived a posteriori evaluation, potentially with high spatio-temporal resolution but in delayed mode. This corresponds to the state of the art, even if most of scientists and decision makers realize how nowcasting could be worthwhile in the GHG emission verification process and to improve knowledge of the variability of carbon sinks and sources.

One of the most achieved and promising initiative runs currently with the GMES (Global Monitoring for Environment and Security) initiative. The FP7 MACC project (Monitoring Atmospheric Chemistry and Climate) develops a set of operational services devoted to the atmospheric environment monitoring. One of them is precisely focused on GHG emissions fluxes (http://www.gmes-atmosphere.eu/services/gac/ghg_delayed/). MACC monitors greenhouse gas concentrations and their surface fluxes by assimilating satellite and in-situ observations. The assimilation runs about 6 months behind real-time to make maximum use of available observations. It was started in December 2009 for the 1st of June 2009 and plot and data products can be accessed through the Internet.

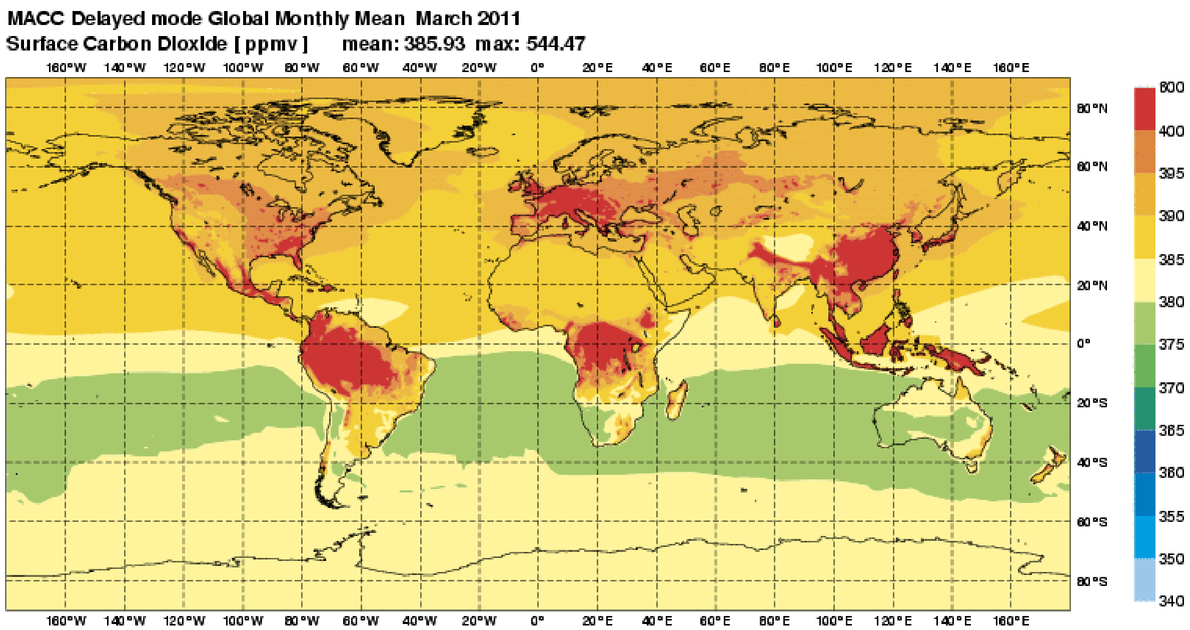

Figure 16. MACC delayed analysis of global CO2 fluxes: March 2011.
SOURCE : http://www.gmes-atmosphere.eu/d/services/gac/delayed/

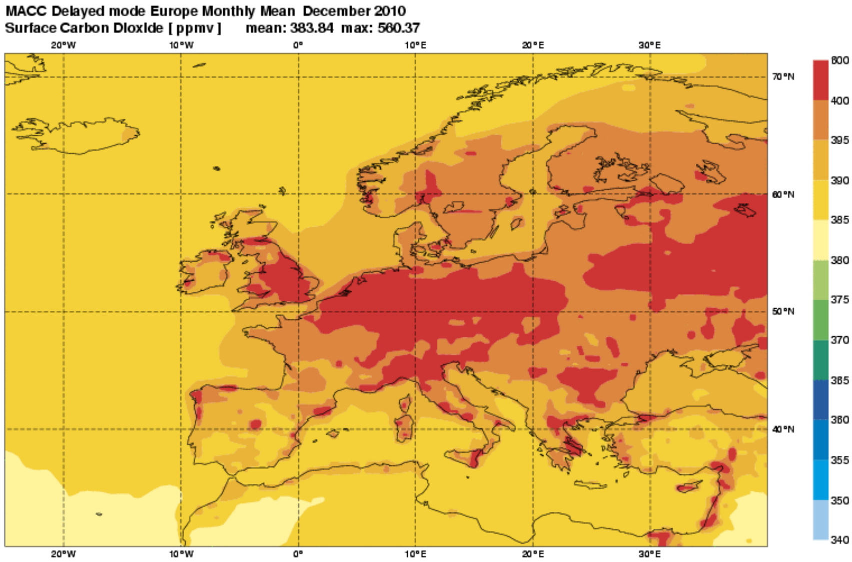

Figure 17. MACC delayed analysis of European CO2 fluxes: March 2011.
SOURCE : http://www.gmes-atmosphere.eu/d/services/gac/delayed/

The availability of observation is one of the limits which justify the delayed mode. Other technical issues related to the computing cost or necessary time for a relevant analysis of the results can slow the development of near-real time systems providing nowcasting emissions. However this is the future step of GHG emission sciences carried away by the need for verification, regional monitoring, information and science improvement. New scientific material will be available for the post-Kyoto next round of Climate negotiations, with more organised and sustainable in-situ networks, ambitious GHG earth observation policies and more reliable models. Integrated operational systems that allow the reduction of time scales to release GHG assessments will frame the new generation of supporting decision tools and can, be considered as a realistic issue.

Finally one should mention the Global Earth Observation (GEO) work which aims at organising delivery and use of space borne observation data to monitor greenhouse gases and climate change. The GEO through its Members and Participating Organizations, has begun work to implement a global carbon observation and analysis system addressing the three components of the carbon cycle (atmosphere, land and ocean) to provide high quality information on carbon dioxide (CO_2) and methane (CH_4) concentrations, and emission variations. By combining observations, reanalysis and product development development of tools for carbon tracking and carbon storage evaluation, including improved global networks of atmospheric CO2 observations, air surface exchange flux networks, as well as surface ocean CO2 and related marine biochemistry observations will be encouraged. One other major activity is to foster the use of space-based greenhouse gas (GHG) observations and consolidate data requirements for the next-generation GHG monitoring missions. In (Ciais et al, 2010) the ideal infrastructure to settle an operational and integrated system dedicated to Carbon tracking and budgeting is presented together with the necessary effort in term of observation network. Figure 18 extracted from this report gives an overview of the final objective.

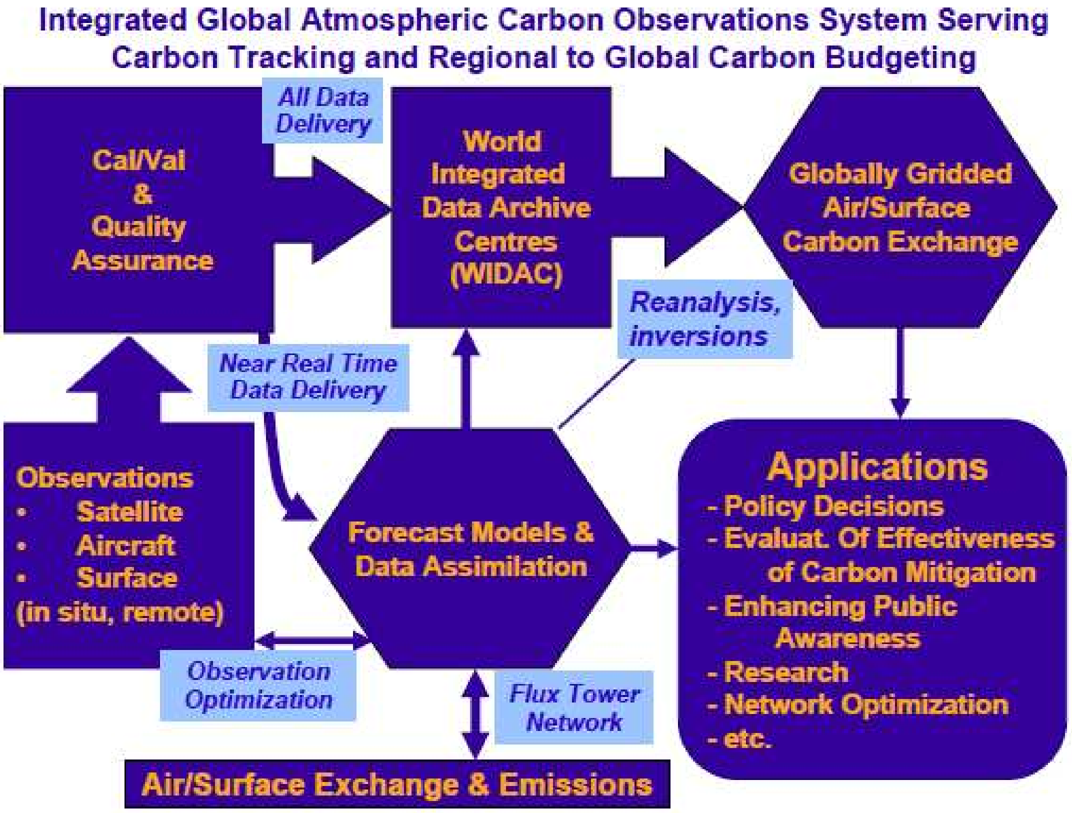

Figure 18. Overview of the infrastructure to be implemented for carbon tracking and budgeting. Source (Ciais, et al, 2010)

4. Synthesis and Conclusion

Up to now, efforts to monitor and report CO_2 and other GHG emissions have been based mostly on limited land-use observations, self-reported data on energy use, and extrapolated point source emission measurements. Such data are known to have many uncertainties that limit their ability to support GHG management strategies. Selecting the appropriate mitigation options depends upon how current and potential impacts of the anthropogenic perturbations on the carbon cycle, both globally and regionally, are understood.It is also obvious that the ability of nations to implement policies that limit atmospheric CO_2 and other greenhouse gas (GHG) concentrations will depend on their ability to monitor emissions and progress in their reduction and to determine what is, and what is not working.

This presents a challenge to implementing the range of GHG policies that are being discussed in many countries. These policies include supporting treaty negotiations, verifying treaty obligations, certifying tradable permits, offsetting GHG emissions, and providing more accurate inventories of emissions and offsets. Consequently, there is an urgent need for a globally integrated observation and analysis system to track changes in atmospheric GHGs and provide routine estimates (with confidence limits) of net atmosphere-surface exchange at regional or sub-regional scales.

Various promising new approaches arise for verification of anthropogenic CO2 and other GHG emissions and are presented in this report. Extensive use of in-situ measurements at observation sites that develop with the aim of supporting decision makers should increase in the coming years together with inverse modelling systems. The use of dedicated GHG satellites with high accuracy and high spatial resolution should increase as well. Therefore, for reporting applications and verification one can expect to get complementary and useful information on GHG emissions thanks to an appropriate interpretation of atmospheric concentration observations that should develop within organised international networks. Several studies showed how it is important to be able to assess emission variations at the regional scales and with a high temporal resolution. This approach suits to the scales characterizing the studied phenomena and should help in the improvement of the regulatory reporting process according to the international protocols and the EU Directives. However, time needed to analyse, retrieve, process and qualify observations increase the delay after observations are made when the emissions and GHG fluxes could be estimated.

Consequently, the “near real time” or “nowcasting” concepts refer to temporal scales of about few months. However compared to the current delay (of two years) the member States need to comply with their official reporting obligations, the situation should improve significantly for emissions assessment and policy purposes checking. The analysis demonstrates that many international initiatives to structure in-situ networks dedicated to an integrated assessment of GHG emissions and fluxes, are on-going. The GAW program supporting regional integrated observation systems such as ICOS in Europe can offer an established international mechanism to fill these gaps. The satellite community plans to strengthen provision of high spatial-resolution CO_2 and CH_4 in the coming years to participate to a better qualification of climate forcers monitoring.

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ANNEX : summary of in-situ GHG networks and databases likely to provide historical or up-to-date preliminary data

Source	Description	Availability
NOAA carbon measurement program **http://www.esrl.noaa.gov/gmd/**	Discrete measurements (68 active sites with flasks http://www.esrl.noaa.gov/gmd/ccgg/tables/) Aircraft measurements (http://www.esrl.noaa.gov/gmd/ccgg/aircraft/) Observatories (4 sites http://www.esrl.noaa.gov/gmd/ccgg/insitu.html) Towers (10 sites http://www.esrl.noaa.gov/gmd/ccgg/towers/)	Up-to-data preliminary data available in a few weeks Programme started in 1992, discontinuous measurements, Up-to-data preliminary data available in a few weeks From 1973 until now; up-to-data preliminary data available in a few days From 1990 until now, up-to-data preliminary data available in a few days
ICOS network **http://www.icos-infrastructure.eu/**	European network set to secure long term in-situ CO2 observation sites Preparatory phase until 2013 Operational phase to be started in 2014 4 European observatories associated to ICOS: Cabaw NL (https://icos-atc-demo.lsce.ipsl.fr/cabauw-observatory) Mace Head UK (https://icos-atc-demo.lsce.ipsl.fr/mace-head-data) OPE-ANDRA F (https://icos-atc-demo.lsce.ipsl.fr/ope-andra-observatory) Puijo FI (https://icos-atc-demo.lsce.ipsl.fr/puijo-observatory)	Not operational. Few data available in a short term delay (15 days) on http://www.icos-infrastructure.eu/?q=nrt_15d Daily CO2 and CH4 concentrations and time series available for each observatory.
AGAGE network **http://agage.eas.gatech.edu**	Global measurements at high frequency of almost all of the important gases species in the Montreal Protocol (e.g. CFCs and HCFCs) to protect the ozone layer and almost all of the significant non-CO_2 gases in the Kyoto Protocol (e.g. HFCs, methane, and nitrous oxide)	Availability of all measured data until march 2011 (http://agage.eas.gatech.edu/data_archive/)
WMO/GAW network and its contribution to the World data center on GHG **http://ds.data.jma.go.jp/gmd/wdcgg/**	Unique and easy access to a large number of data associated to various observation systems and projects http://ds.data.jma.go.jp/gmd/wdcgg/cgi-bin/wdcgg/catalogue.cgi	Only historical datasets available