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Earth observation satellites: Monitoring greenhouse gas emissions under the Paris Agreement

A case study on scientific expertise and public policy

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Abstract

As anthropogenic greenhouse gas emissions are rising; climate change mitigation is becoming a top global priority. Under the Paris Agreement, Parties agreed on the ambitious goal of holding in the global average temperature below 2°C. However, capacity to monitor state GHG emissions mitigation performance remains unavailable globally. Through its Earth Observation programme, Copernicus, the European Commission aspires to contribute to close this gap and set a global monitoring verification capacity. Satellite measurements to track progress towards the Paris agreement raise issues on their feasibility and on the impact on global governance. This research, through a qualitative methodology, discusses these questions as a case study on how scientific expertise incorporates in public policies. Its outputs show that, in the future, satellite will provide valuable data to support a global monitoring capacity even if this technology should not be overestimated. On global governance, space-based observations may constitute a lever of transparency and cooperation but also raise concerns on sovereignty. Finally, to give a broader understanding of public policies, the case study results have been confronted to a theoretical framework on the diptych expertise-responsibility, suggesting insights on the articulation between science expertise and the decision-making process.

Key words
Paris Agreement, Climate change, Earth Observation data, Satellites

WHY SHOULD I READ THIS RESEARCH?

"Climate change is the defining challenge of our age." (Ban Ki-moon, CMP 3, Bali, Indonesia).

Caused by human activities, the rise in greenhouse gases emissions is significantly changing Earth's ability to welcome life. Altering the fragile equilibrium of the atmosphere, carbon dioxide and methane, are at the centre of attention. Two goals stand out: mitigate emissions and increase society resilience to climate change consequences. Food security, natural catastrophes, biodiversity extinction are threatening humanity as the global temperature is rising. Facing this emergency, states have expended and reinforced their cooperation into a global governance of environment. Under the United Nation mandate, the Conference of Parties is a unique instance of international unity. In 2016, the Paris Agreement united 195 parties towards an ambitious, yet indispensable objective: holding the temperature increase below 1,5-2°C above pre-industrial levels.

The first reaction of a doctor to cure fever is to measure it. However, today, there is no global system to measure GHG emissions. Despite the importance of climate change, its thermometer is missing. Global challenges require global data.

This research is exploring this paradox through a case study on space-based data. Satellites, in orbit around Earth, are offering a unique point of view on the planet. Earth Observations are already changing how environmental issues are monitored; however, measurements of anthropogenic GHG are still an on-going research. The potential of a such technology on setting a global monitoring capacity could be decisive in reaching Paris Agreement goals. The idea of satellites being guardians of the climate might feel as though it is coming from a science fiction novel but is already starting to be tangible through the ambitions of the Copernicus programme, the Earth Observation programme of the European Commission. This is why, this case study aims to understand: (i) if the realization of a such aspiration would strengthen GHG emissions measurements; (ii) how a space-based global monitoring capacity would fit in global governance.

Analysed and discussed from a multi-disciplinary approach, this research mobilizes technical, sociologic, and international-relationships knowledge. Exploring the case study and interviewing experts led to question how scientific expertise interacts with the policy-making process. To give a broader output on public policies, the case study is confronted to a theoretical framework on the diptych expertise-responsibility. Therefore, the following analysis displays a singular highlight on the topic contributing, modestly, to build bridges between science, policy and society.

How to read this research? Beside the analytic development, the structure and redaction have been thought to synthesize complex topics (climate change, satellite remote sensing) and institutional functioning (UNFCCC, Copernicus programme). Thus, each section can be apprehended independently to give insight on its specific theme.

Who would benefit from reading this research? Readers looking to discover Earth Observation and the Paris Agreement ambition mechanism would particularly benefit from reading this research. For more advanced readers, this research may be of interest as it is putting in perspective various sources of knowledge and attempting to set the first stones of a broader theoretical framework on public policy and science.

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INTRODUCTION

"What they should have sent was poets because I don't think we captured in its entirety the grandeur of what we had seen" Frank Borman, Apollo 8 astronaut.

In 1968, for the first time, the World discovers the Earth. The Mission Apollo 8 captured the first picture of the Blue planet from space. *Earthrise* becomes one of the 100 photo that shaped the human experienced (National Geographic, 2018). The Marble planet was *our* planet, as unique as fragile. This picture coincides, in the seventies, with rising concerns on how human activities were impacting environment, highlighting the finitude of Earth and its resources.

In 1972, with the Dubos report, the Meadows report and the first United Nations conference on the Human Environment (Stockholm), a global answer to humans' impact on the environment started to emerge. The creation of the Intergovernmental Panel on Climate Change (1988) and its reports were turning point, setting the rise of global temperature, *climate change,* as a global priority. Following the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), the successive Conferences of Parties became milestones of global climate change governance. Under the United Nations (UN) mandate, goals, means to reach them and international unity were agreed on, setting a *global governance* on climate change mitigation. Cooperation was translated into historic treaties such as the Kyoto Protocol (1997) and the Paris Agreement (2015[1]), which went beyond setting goals to reduce greenhouse gases emissions, but determined how the Parties should report their progresses and contributions. There is no governance without levers to monitor objectives, GHG emissions, and reciprocity in treaty compliance. However, access to national environment data on emissions is, currently, limited as only industrialized countries (Kyoto Annex-1 parties) are annually communicating their national GHG emissions record, the GHG inventory. The Paris Agreement answers this gap by setting a new "ambition mechanism" where each of the 195 parties must summit their national determined contribution (NDCs) as well as their biennial emissions report. Then, every five years (Global Stocktake, GST), parties will reunite to evaluate the progress and help each other to reinforce the global strategy towards their mutual goals. This virtuous circle has started in 2020 but is still surrounded by uncertainties.

Remaining uncertainties occur at two levels. First, GHG inventories are not measurements and rely on estimations. Their accuracy is depending on the will, or possibility, of states to invest in costly inventory methods and to cooperate. In a word, there is no capacity verify if policies are effective. Secondly, existing measurements methods of GHG emissions are mainly based on in-situ (stations on the surface) networks. Current coverage remains insufficient to provide a global GHG emissions monitoring capacity.

[1] Adopted in 2015, Effective since 2016.

To find new data, ensuring global coverage and independency, another perspective might stand as relevant: the outer space. Satellites, in orbit around Earth, if they provide relevant data, could contribute to a global GHG monitoring capacity, reduce uncertainties and facilitate the Paris Agreement governance. Such instruments are still an ongoing research, one of the leading initiatives being carried by the European Commission Earth Observation programme, Copernicus. At the horizon 2025, two satellites are to be launched, becoming the first space mission to target directly anthropogenic CO2 emissions. Nonetheless, this ambition is not without ambiguity, notably on technical feasibility and on its impact on the global governance of GHG monitoring. Indeed, global monitoring from outer-space data rise issues on sovereignty, on the strategic aspect to supply the capacity and on how other states would appropriate these data to defend their interests.

The issue of the contribution of space-based data to the global governance of the Paris Agreement, is the case study of this research. Furthermore, this case study questions the role of scientific *expertise* as a space GHG monitoring capacity is led by scientists. Their expertise is confronted to other actors such as policymakers and citizens. Thus, the synergy between these actors leads to define their *responsibilit*y in the decision-making process. Therefore, this research sets a theoretical framework on the diptych expertise-responsibility to highlight insights on the scientific expertise within the case study and more broadly, in public policies.

To summarise, this research aims to provide avenues on three main questions:

(i) Are space-based data a lever to address uncertainties on GHG emission monitoring?
(ii) What would be the impact of a satellite monitoring capacity on global governance?
(iii) How could this case study contribute to the understanding of scientific expertise and responsibility in public policies?

To answer them, this research sets six hypotheses on these questions, which are then tested through the qualitative methodology. The latter combines two sources of data, expert interviews, and data from multiple fields. The research presents an interdisciplinary state of knowledge (1.), highlighting all the knowledge necessary to understand the analysis. Then, the following section (2.) details the hypotheses and the methodology. The last part (3.) analyses the three questions, discussing views and limits.

1. INTERDISCIPLINARY STATE OF KNOWLEDGE

In this first part, an inter-disciplinary state of knowledge is provided to address key concepts, which will shape the hypotheses and the ensuing analysis. The following reflection follows a bottleneck approach from the most general consideration to the most specific. In the first section, the link between climate change, global governance through the Paris agreement and data collection is laid out. Then, the second section aims at describing the technical aspect space-based Earth Observation and focuses on the Copernicus programme. Finally, the third section, taking stock of all aspects mentioned above, sets a theoretical framework on the link between environmental policies and scientific expertise.

1.1. Climate change: a global challenge

"Climate change is one of the biggest challenges of our times", the European Environment Agency stated (EEA, 2021). The notion of *climate change* covers a complex dynamic which deserves to be specified in this research.

Climate change is here understood as one of the planetary boundaries. In 2009 (Rockström J. et al., 2009), nine variables of the Earth system were identified as essential for human survival: climate change, ocean acidification, chemical pollution, particle pollution of atmosphere, biodiversity integrity, deforestation and other land use changes, freshwater use, biochemical flows, ozone depletion[2]. Therefore, their degradation above a set threshold could durably damage the Earth ability to welcome life. The framework has been updated in 2015 (Steffen, W. et al., 2015), under which two boundaries have been assigned to a "high risk zone", biodiversity integrity and biochemical flows, and two are in a "zone of uncertainty", climate change and land-system change.

A typology is proposed with two criteria "boundary character" (processes with global scale threshold / slow processes without known global scale threshold) and "scale of process" (systemic processes at planetary scale / aggregated processes from local and-or regional scale)[3]. Two of the nine boundaries are fully global (impact is at the planetary scale), "climate change" and "ocean acidification". Climate change and biodiversity integrity are considered as "core" (ibid), meaning they are capable to drive the Earth system into a new state by their own. At the intersection of "global" and "core" boundaries, climate change holds a unique position in environmental policy.

As a closed system, Earth is sensible to small changes in its balance. The atmosphere is balanced between different greenhouse gases (GHG) which trap part of reflected Sun radiation, thus heating the Earth (McNall, 2011). The budget between the received and emitted energy is the Earth's energy. In a natural state, there is a balance between GHG

[2] In 2015, the framework has been refined including "novel entities", an undefined form of pollution such as micro-plastic with uncertain impact on the Earth System.
[3] Figure 1, Annex

emission and GHG absorption by natural sinks such as forests and oceans. The atmosphere is made up of constant gases and variable gases, whose presence depends on natural variation but also human activities. Even if carbon dioxide (CO2) or methane (CH4) are but a marginal percentage of dry air, about 0.035% for CO2 (MeteoFrance, n.d.), the balance of gases has been disturbed by human emission in the industrial era. CO2 and CH4 are "heat-trapping gas" (McNall, 2011), whose rising concentrations lead to a warming in Earth's temperature. Since preindustrial times (before 1750), GHG atmospheric concentrations increased significantly: 46% for CO2, 275% for CH4 and 122% for N2O (Petrescu, A., 2020). Moreover, CO2 remains in the atmosphere for 100 to 500 years (ibid) implying an acceleration of global warming when emissions are rising over a short period. The foreseeable consequences of such a warming is a global degradation of the Earth system, which would entail many adverse effects on our environment such as an increase in the frequency of natural catastrophes or stress on food and water security (Magny, M., 2021).

This is why, climate change is a global issue which calls for a global governance.

1.1.1. The UNFCCC and global governance

1.1.1.1. Before the Paris Agreement

In the wake of emerging global environmental concerns, such as those illustrated by the Meadows reports "The limits to Growth" (1972), the United Nations (UN) General Assembly determined "that necessary and timely action should be taken within a global framework" in its 43/53 resolution in 1988. As regards GHG emissions, the United Nation Framework Convention on Climate Change (UNFCCC) set a first legal multilateral agreement. The Convention, signed in 1992, acknowledged the effects of climate change article 1), reaffirmed the sovereignty of States to exploit their resources while highlighting the need for cooperation. It also established the annual Conference of the Parties (COP, article 2). The COP aims to stabilize GHG atmospheric concentration: it is the main decision-body under the UNFCCC. The first legally binding application of the UNFCCC is the Kyoto Protocol signed in 1997 (COP3), whose targets added up to 5% emission reduction compared to 1990 levels over the period for 37 countries (mainly industrialized) and the EU (UNFCCC, n.d.). The Protocol has two main characteristics. First, it distinguishes between developed countries, known as the "Annex I Parties", and emerging countries (Non-Annex I Parties). Second, it provides for the establishment of emission monitoring through GHG national reporting. These two components were reaffirmed for a second period by the Doha agreement adopted in 2012 (2012-2020).

In 2011, the COP17, meeting in Durban, highlighted that, chances of containing the increase in global average below 2 degrees census were reducing. To tackle this challenge, the COP established the Ad Hoc Working Group on the Durban Platform of Enhanced Action (CP.17, 2011), which was tasked with developing new legal instruments under the Convention.

This dynamic shows two principles of global governance under the UN Framework:

(i) The principle of "common but differentiated responsibilities" (Moring, J-F, 2020) between Parties remains. Economic growth and social development are transversal preoccupations under the UNFCCC convention; consequently, differentiation between developing and developed countries remains necessary. Ultimately, this division of responsibilities may be extended to all the actors of environmental policies such as citizens, private sector or scientists.

(ii) Global governance through international agreement relies on the principle of consensus between actors. Thus, consensus is obtained under the condition of reciprocity (Morrow, 2007). Cooperation is obtained through transparency of data at a global scale. Then effectiveness and control on agreement application need to be ensured.

1.1.1.2. The Paris Agreement: a turning point

In 2015, 195 countries adopted the Paris Agreement (also referred here as "The Agreement") under the UNFCCC framework, following up the Durban Platform for Enhanced Action's work. The 2nd article states the objective of the Parties to hold the increase in the global average temperature to well below 2°C above pre-industrial levels, nay 1.5°C above, "recognizing that this would significantly reduce the risks and impacts of climate change" (article 2). The Agreement, also reaffirmed the two components of global environmental governance:

(i) equity through differentiation between diverse national circumstances (Article 2),

(ii) provision of necessary information to track progress (Article 13).

The legal structure of the Paris Agreement is a legally binding international treaty, which excludes reservations (as to be "ratified as a whole and "as is"" (Bodle, R., 2017)). However, under the Agreement, mandatory plans, the so-called *nationally determined contributions* (NDCs), are discretionary even if they shall be transparent (ibid). Unlike the Kyoto Protocol which includes an observance mechanism (article 18), the Agreement approach was to favour a universal treaty over a highly constraining convention. Indeed, enforcement mechanisms may either be inefficient or a factor of international divisions. For example, the inefficiency of the provisions on shared values in the European Union, such as that enshrined in article 7 of the Treaty on European Union, is mentioned as a weakness of Rule of law endorsement (Joannin, P., 2015). Symmetrically, it may be inefficient to rely on an observance mechanism to enforce an international environmental treaty. Moreover, as regards international divisions, the Kyoto protocol itself does not set any control mechanism, as no compromise could be found (Maljean-Dubois, S., 2007). Therefore, the mechanism set in place under the Kyoto protocol is considered as a "flexible" regime leaning towards prevention. The *softer enforcement* (Yoshida, O., 1999) path of international environmental treaties including the Paris Agreement is a key component of global governance to progressively reach a cooperative framework.

Succinctly, in term of global governance, the Paris Agreement is a "turning point" as it finds a balance between differentiation and strengthening the transparency (Dagnet, Y. et al., 2017). Moreover, considering that the UNFCCC's "consensus-based structure and one-member-one-vote rule", the Agreement is a global success (Stephenson, S., 2019).

1.1.1.3. Global environmental governance and data collection

Even before the UNFCCC, the United Nations, through the Intergovernmental Panel on Climate Change (IPCC), initiated international cooperation on climate change. The General Assembly's resolution 43/53 (1988, see above) endorsed the World Meteorological Organization's (WMO) and the United Nations Environment Programme's (UN Environment) action to establish the IPCC. The latter aims to provide knowledge on sources and impacts of climate change including different scales (especially regional and global), diverse fields (notably Earth system sciences and socio-economic analysis) and potential response strategies. The IPCC has a specific organization as its form is inter-governmental. Thus, its work programme is decided by a Panel of 195 governments representatives, including the scope and outline of its report and the mandate of the IPCC Working Groups and task force. The Bureau is elected by the Panel to provide guidance to the Panel on scientific and technical aspects. Beside governance bodies, the IPCC is composed by three working groups (WGI, WGII, WGIII) working to gather knowledge on a specific thematic such as mitigation of climate change (WGIII), and one Task force on National GHG inventories (TFI).

The IPCC reports are made to influence nay be implemented in environmental policies. One of its first recommendations in 1990 (IPCC, 1990) was to improve predictive capabilities, focusing on gathering data from Earth observation: "to improve the systemic observation of climate-related variables on a global basis", "to develop improved models of the Earth's climate system" and "to facilitate international exchange of climate data". This is why, article 4 and 5 of the UNFCCC provide that Parties agree to strengthen cooperation and to develop levers for the collection and sharing of climate data.

The Paris Agreement contributed to increase the need for more specific data on emissions and their reduction and to realign climate data not only towards scientific research but towards users' needs and public awareness (GCOS, 2016). More specifically, the Agreement reinforced the role of the Global Climate Observing System (GCOS), a programme that is co-sponsored by several bodies of the UN system. The GCOS is composed by three "expert panels" (GNOS, 2015) which do not produce data on climate change per se but ensure that contributing systems are improving knowledge on climate change and providing information required to set policies. The framework set by the GCOS uses the concept of Essential Climate Variables (ECVs). For each ECV such as CO2, CH4 and other GHG, a "Data sources" is compiling origins of data used by the GCOS. Reports published by the GCOS are then a driver of policy through the Subsidiary Body for Scientific and Technological Advice (SBSTA) which is one of the two subsidiary bodies to the COP. The SBSTA links scientific information and the policy perspectives.

Global governance on climate change is then *shaped* by environmental data but is also *shaping* them. Besides, the Agreement is setting a transparency framework which put environmental data at the heart of global governance.

1.1.2. The Paris agreement: objectives and current trajectory

1.1.2.1. Objectives

The Paris Agreement is known for its objectives listed in Article 2 such as temperature mitigation and increase resilience capacities. To achieve these goals, the Agreement relies on a stronger transparency framework.

As already mentioned, this is an essential, nay the most important, component of global governance. Transparency in international relations is imbued with ambiguity (McCarthy et al., 2017). However, there is a wide consensus on how transparency mechanisms are a mean to overcome conflicts and democratize global governance structures. In the case of environment, due to the diffuse aspect of sources of pollution, reaching transparency is a precondition to a successful governance. Therefore, the Agreement is establishing a transparency framework (article 13). Dagnet Y. and Levin, K. (2017), in their analysis of this framework, distinguished two principles: "(a) enhancing the way countries share information on progress made to mitigate, adapt, provide or receive finance, advance technology development and transfer, and strengthen capacity-building; and (b) the process for the subsequent review and consideration of such information". The modalities were agreed during the COP 24 in 2018 by decision 18/CMA.1, 19/CMA.1 and Annexes:

(i) The SBSTA must undertake the first global review no later than 2028;
(ii) All Parties must submit their first biennial transparency report and national inventory report (as a stand-alone report even for the Non-Annex I Parties) no later than 2024;
(iii) A technical expert review of the information submitted by the Party, once every five years shall be conducted.
(iv) As a whole exchange of information under the framework concerns: national inventory report of anthropogenic emissions by sources and removals by sinks of GHG, relevant tracking information on NDC implementations and information on financial, technology development and transfer provided to developing countries.

Moreover, as referred in the Article 14, the Global Stocktake (GST) assesses progress, especially implementation of the NDCs. The GST will address the progress but "in the light of equity and the best available science" (article 14). All these components are forming an "ambition mechanism"[4] which will provide evaluation elements every five years (started in December 2020 with the Climate Ambition Summit).

This is why, the GCOS assessed that "The Paris Agreement will drive climate policy for many years to come" and that, for it to succeed, "observations are vital" (GNOS, 2018).

1.1.2.2. Current trajectory

At the time of this research, 2020-2021, five years have flown by. Even if assessing progress is not at the core of the development, the current trajectory towards the Agreement is relevant to understand the context of this analysis.

Firstly, the effectiveness of the ambition mechanism cannot be assessed as it took effect this year. Since 2016, 191 Parties have submitted their first NDCs, some parties have updated their first contribution but only 8 their second NDCs (NDC registry). NDCs, if they are completely implemented, would reduce by a third the gap left by the implementation of current policies (evaluated gap of 22.4 to 28.2 GtCO2eq by 2030 compared to the optimal pathways which would lead to rises in global temperature well below 2 °C and 1.5 °C) (Roelfsema, M. et al, 2020).

According to the IPCC (UN, n.d.), following the current GHG emission trends, temperature could increase by 3 degrees to 5 degrees. The report still sees the 1.5 °C goal as possible whereas other observers refute this scenario. Magny, M. (2021) evaluated that a 3.2° C increase could take place by 2100 based on current national contributions. He also stated that a +4-degree hypothesis cannot be totally excluded. The Copernicus Climate Change Service has developed "The Global temperature trend monitor", using the IPCC framework, to evaluate how soon temperature could reach the 1.5°C target. In March global warming reached 1.19°C, meaning the 1.5°C mark would be attained in February 2034.

Moreover, even if the Paris Agreement admits a subsidiary objective of keeping global warming well below 2°C, immediate benefice of limiting to 1.5°C have been identified. 420 million fewer individuals would be exposed to extreme heat waves and about 65 million fewer people laying open to exceptional heatwaves, assuming constant vulnerability (UN, n.d.). In addition, despite uncertainties, significant benefits from lower levels of warming are likely in term of Gross Domestic Product per capita by the end of century (Pretis, F., 2017).

In this context, reaching the Paris Agreement's objectives might be considered as a global top priority. Therefore, implementing policies to mitigate climate change is perceived as an "emergency".

[4] Figure 2, Annex

1.1.3. National greenhouse gas Inventories

The overview of climate change governance leads to detail GHG national inventories under the UNFCCC framework. The IPCC has a central role in gathering data and provides guidelines for national GHG inventories. Under the UNFCCC framework (article 4 and 12), the TFI objectives are to develop and refine an internationally agreed methodology for the calculation and reporting of national GHG and encourage the widespread use of this set methodology. At an international scale, national inventories are the main source of data on national anthropogenic emissions. First guidelines have been published in 1994, replaced in 1996 by revised ones, completed in 2006. The 2006 (volume 1) guidelines define main concepts such as which GHG are covered, geographic and temporal perimeter, sectors of GHG emission or removal (sources / sink). The methodology of national emission is based on socio-economic data reflecting human activity on the national territory (called *activity data,* AD) with a coefficient which quantifies emissions or removal per unit activity (called *emission factors*, EF). The equation is then:

Emission = AD * EF

EF factors are gathered in the emission factor database which is a supporting tool set by the IPCC. It adopts a participative policy, whereby users are encouraged to summit data proposal. Two types of data coexist:

- (i) Default data from IPCC reports and publications;
- (ii) Data from peer-reviewed journals and other publications including National Inventory Reports (NIRs).

Each EF is referenced by an EF ID and the following information (when available): GHG (mainly CO2, CH4, N2O) / absorbed; description; technologies / practice; parameters / conditions; region / regional conditions; control technologies; value; unit; data provider and source of data. This approach aims at accumulating various data to adapt the EF to different conditions. On the other side, AD are produced by the country, and details should be mentioned in the reporting table. Each party is encouraged to produce and adapt EF and AD to their specific environment (CMA/2018/3/Add.2)[5]. Moreover, all the methodology has been refined in 2019 to acknowledge scientific improvements and ensure inventory quality.

Finally, as mentioned on global governance, efforts are meant to be proportional to the mean of the country. Therefore, currently, Annex I parties are required to provide an annual stand-alone inventory whereas Non-Annex I are only expected to communicate biennial information.

[5] In the IPCC methodology, nations apply “Tiers” methodology, the Tier 1 is based on default data. Whereas Tier 2 and 3 methodologies are producing estimations with “high degree of spatial and contextual resolution” (Bradford et al, 2020).

1.2. Space-based data and climate change

Global governance then requires global data. Besides GHG national inventories, emissions measurements are obtained by *in-situ*[6] stations or *remote-sensing* (Onoda, M. 2017)[7]. Structurally, in-situ measurements are local whereas remote sensing methods have a wider coverage. Remote-sensing measurements are collected mainly by aircrafts and satellites, the latter offers a global coverage of the Earth. Hence, space-based data collection is *a priori* relevant. This section is setting the main technical considerations that are necessary to understand the discussion and analysis.

Earth observation (EO) is at the core of space exploration since the launch of Sputnik I, the first satellite, in 1957 (National Research Council, 2008). Artificial devises intentionally placed into orbit[8] (here the Earth's orbit) are referred as satellites. When they are carrying dedicated remote sensing captors, they are part of the global EO system[9]. According to the World Meteorological Organization (2018), the concept of Global Observing System (GOS) "was totally revised" with the rise of satellites technologies offering "the unique opportunity of uninterrupted global coverage and frequent observing cycles". Beside completing *in-situ* data, space-based data offers a better understanding of remote area or less accessible environments such as oceans.

EO imagery[10] is mainly performed by exploiting electromagnetic radiation of the electromagnetic field including radio waves, microwaves, infrared, (visible) light, ultraviolet, X-rays and gamma rays. Two types of instruments coexist (Beven et al., 2018):

(i) Passive instruments which receive the radiation leaving the earth-atmosphere system and measure solar radiation reflected, emitted infrared radiation or radiation resulting from emission.
(ii) Active instruments which send pulses of radiation and measure the returned radiation.

Moreover, different parameters of EO data are taken in account:

(i) Spatial resolution (the level of details);
(ii) Scene size;
(iii) Revisit time (when and at which frequency data are collected);
(iv) Other quality-related parameters such as, for example, cloud cover.

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[6] In-situ referred to "on Earth", meaning in the environment.
[7] Acquisition of information about an object without physical contact.
[8] Different orbits coexist depending on the satellite missions. Mainly:
1. Geostationary orbit (GEO): circle above the equator, often used for telecommunication satellite
2. Low Earth orbit (LEO): altitude of less than 1000km, often used for high resolution imagery satellite
3. Medium Earth orbit (MEO): between GEO and LEA, often used for navigation satellites such as the Galileo programme
4. Polar orbit and Sun-synchronous orbit: type of LEO, offers a daily coverage of Earth

[9] In this research, EO system refers to all space programmes aiming to gather information on the Earth via remote sensing technologies. Not to be confused with the Earth Observing System which is a specific programme by NASA.
[10] Figure 3, Annex.

Considering those parameters, remote-sensing data are contributing to models to monitor ECVs.

1.2.1. Earth Observation: to take the Earth's pulse

1.2.1.1. Development of global Earth Observation system

As human activities increasingly impact the Earth system equilibrium, addressing environmental issues has been concomitant with the development of new sources of data. As noted by Onoda M. (2017), "there is simply no alternative for constantly tracking changes in environmental conditions at a global scale" than satellite EO. Satellite EO offers a unique perspective, helping to detect new problems and are the only option for measuring Earth's energy balance without interference from the atmosphere (ibid). Furthermore, variables altering this balance (ECVs) can mostly be monitored from space.

Thus, remote-sensing data are recognized as key to understand and monitor climate change variables. To strengthen knowledge and ensure international cooperation, EO are shared through the Group on Earth Observations[11] (GEO) aiming to develop a "coordinated, and sustained Earth observation system of systems" (GEO, 2015), the Global Earth Observation System of Systems (GEOSS), as a "basis for sound decision-making" (ibid). On climate change, the 2020-2022 GEO work programme approved "climate change, with specific emphasis on the Paris Agreement" as one of three key policy priorities.

In conclusion of this section, the link between EO development, space-based data and global governance of climate change is clearly established. Even more, under the Paris agreement framework, space-based data are part of the global governance.

1.2.1.2. The European context

1.2.1.2.1. General consideration on European space programmes

If governance or policy on environmental data could be set at a global scale, collection of data depends on national or regional initiatives. In this research, the four geographic groups set by Borowitz M. (2017) are retained: the United States, Europe, Japan, and the BRIC's (Brazil, Russia, India, China, South Africa). The perimeter of the research is limited due to information availability: Europe will be the main area studied. In the European context, two types of agencies coexist: national agencies and the European space agency (ESA). National agencies in Europe are mainly driven by the French Agency, The

[11] Established in 2005, Intergovernmental organization, 100 members including the EU and Participating organizations (e.g., IPCC).

Centre National d'Etudes Spatiales[12] (CNES), and the German Agency, Deutsches Zentrum für Luft- und Raumfahrt[13] (DLR).

The ESA was established in 1975 (Convention for the Establishment of a European Space Agency), considering the relevance of mutualizing resources withing European states[14]. ESA is mostly a cooperative institution (EUMETSAT, n.d.), other bodies are involved to implement its programmes. For instance, the European Organization for the Exploitation of Meteorological Satellites (EUMESTAT) supervise European system meteorological satellites (article 1, EUMESTAT Convention).

This framework is the complexes interaction of different, national, inter-governmental and supranational (through the EU) scales. All the pre-cited bodies are part of the Copernicus programme.

1.2.1.2.2. The Copernicus programme

Copernicus, "Europe's eyes on Earth" is the EU's Earth Observation programme. Under the European Parliament impulse (EPRS, 2017) and the Commission report "Crossroads in Space" (1991), a global strategy on EO is defined as a strategic objective. The European Commission, ESA, EUMETSAT and the national agencies adopted the Baveno Manifesto establishing the Global Monitoring for Environment and Security (GMES). On the GMES basis (COM/2004/0065), the regulation 377 in 2014 formally established the Copernicus programme, clarifying its objectives such as provide "accurate and reliable information in the field of the environment" and set the programme contribution to the GEOSS.

Furthermore, key features of Copernicus must be highlighted. Firstly, the Copernicus is a user-driven[15] service, designed to evolve depending on public and private interests. As Copernicus aims to serve users' need, one of its components (article 5) is to provide services on: atmosphere, marine environment, land use and its implications, climate change. Those services are based on data collected and gathered under the Copernicus programme, from open-dataset or Member states contributions. Two components are serving this objective of gathering and collection data: the space (article 6) and the *in-situ* component. *In situ* data is provided "mainly by the Member States", while the Copernicus programme primarily aims to ensure autonomous Union capacity for spaceborne observations through its own missions ("dedicated missions") or the states led missions ("contributing missions"). Thus, satellites were developed for the need of the Copernicus programme: the Sentinels fleet.

From these observations, three main features are shaping the relevance of Copernicus framework of this research:

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[12] National Center for Space Studies
[13] Literally: German Center for Air- and Space-Flight
[14] Table 2, Annex
[15] Users are distinguished in two categories: "core users", which refers to European and national institutions and public authorities, and "civilian users", ranging from researchers to commercials users or charities. International organizations are also directly mentioned in the 2014 regulation.

(i) Copernicus is nesting under three governance scales (national, regional and global) and four operational scales (local, national, regional and global).
(ii) Copernicus data are considered as operational data which are not serving the unique purpose of understanding the Earth System but are also meant to provide tools to create private and public value.
(iii) Copernicus is at the junction of three spheres involved in environmental policies: scientific expertise, citizens implications and policy-making decisions.

1.2.2. Copernicus data and essential climate variables

As mentioned above, the GNOS identified a set of 54 ECVs which can be divided in three categories, atmosphere, oceans and land, corresponding to Copernicus services. Up to 60% of these variables can be addressed by satellite data (ESA, n.d.). Moreover, the programme has a service dedicated to climate change (C3S).

1.2.2.1. Copernicus services and essential climate variables

Oceans, lands and atmosphere are three areas of Copernicus services, all of them provide valuable information to monitor GHG emissions and absorption. This section highlights an example of the operational use of the atmosphere service and how users are involved[16].

The Copernicus Atmosphere Monitoring Service (CAMS) provides continuous data on atmospheric composition notably focusing on air quality, emissions and surface fluxes, solar radiation and climate forcing. CAMS gather information from more than 40 satellites, *in-situ* measurement[17] and inventories to estimate GHG emissions.

Moreover, CAMS air quality mission constitutes a relevant case study to understand the link between science expertise – citizen and policy making. As science expertise assessed the link between high level of air pollution and damage to most of organs of the body (Schraufnagel, D. E et al, 2019), policy makers have set legally binding concentration limits (e.g., the directive 2008/50/EC). This is why, in the report on the implementation of the Ambient Air Quality directives (March 2021) the European Parliament encouraged the Commission and Member States to strengthen "the further use and integration of satellite data from the Copernicus Atmosphere Monitoring Service". At the citizen scale on a daily life basis, CAMS provides help and data to develop products allowing easy access to air quality information to protect health and ensure awareness. For example, "DiscovAir" provides location-specific, personalized alerts and advice answering question such as "Is it likely that I will have breathing difficulties in the place I wish to visit?".

[16] On ocean and land, see Box 1, Annex.
[17] In situ measurements in atmosphere are for example provide by commercial aircrafts or balloon sondes.

This articulation shows how Copernicus services are fit in the ECV monitoring and how space-based data contribute to environment policy, this virtuous synergy is at the core of the will to monitor GHG emissions with Copernicus.

1.2.2.2. Copernicus Climate change service: a co-constructive approach

More specifically on climate change, the Copernicus Climate Change Service[18] (C3S) provides climate information through the Climate Data Store (CDS). As stated in the 2014 regulation (article 5), the Climate Change Service aims to "provide information to increase the knowledge base to support adaptation and mitigation policies, (…), contribute to the provision of ECVs". Considering this objective, the C3S is a climate service in the sense of the GNOS as it participates to deliver "science-based trustworthy climate data" "to support policy- and other decision-making process" (GNOS, 2018). Therefore, C3S does not only furnish data set but also aims at guiding users in how to use them through toolkits, documentation but also a user learning services. The C3S has an important co-constructive approach. For instance, users are encouraged to submit their own case studies. By comparison, the UK climate service is more consulting-oriented aiming to furnish a climate expertise service (UKMet, n.d.).

The co-construction approach helps to identify users' needs. Vincent K. et al. (2018) identified three characteristics and three principles in co-produced climate services.
Characteristics, or conditions, are understood as features derived from core objectives of climate services:

(i) "Decision driven": climate services are developed to address user needs; co-exploratory processes are vector of decision-making.
(ii) "Process-based": to ensure effectiveness of co-producing process, users and producers are on an equal footing implying trust and knowledge exchange.
(iii) "Time-managed": timing between information availability and key decisions need to be monitored in order to guarantee adequate co-construction.

Whereas principles, or facilitators, are derived from practicing co-produced processes. Three main principles are retained by these authors: "collaborative", "inclusive", "flexible". The co-conception approach, that is assumed to be followed in theory (or at least pursued) by Copernicus[19], reflects a questioning on the "hegemony of science" (Vincent K., 2018) by introducing an active role of other parties besides scientific experts.

1.3. Theoretical Framework: Responsibility, expertise, decision-making

[18] To be noted: CAMS and C3S are implemented by the European Centre for Medium-Range Weather Forecasts (ECMRWF), an independent intergovernmental organization.
[19] This research will not debate if Copernicus fully address all these points but will state as "knowledge".

The Paris Agreement governance relies on a renewed ambition mechanism, requiring continuous, verifiable and reliable data. More than understanding climate, environmental data such as the ones produced by Copernicus are designed to be decisions tools that make it possible to assess progress, to evaluate the impact of policies and to guarantee public information. Hence, space-based data have the specificity to provide a global source of data independent from territorial considerations or state cooperation. This specific type of data may strengthen transparency, nay, drive public policies. Based on this, the decision-making process in global environmental politics involves different *voices* (or actors) corresponding to different types of *expertise* leading to specific *responsibility*.[20]

1.3.1. Expertise and space-based knowledge

1.3.1.1. An expertise framework

Unlike scientific knowledge as objective facts, sciences enter politics as expertise (Jasanoff, 2021). "Being expert" means to master relevant objective or subjective knowledge during circumscribed moment in time and place (Agacinski, 2021). Then, expertise is a position in a relationship involving the whole society.

Society increasingly valorizes sciences. This is why, Stehr N. (2000) identified a transition between an industrial society to a "society of knowledge". Moreover, the "scientific discourse considers in a way that is own knowledge as being self-evident" (ibid) reinforcing the role of scientific knowledge. However, science *for knowledge* is not science *for action*.

Expertise is integrated in the decision-making process through different means. Irène Thery (2005) theorized three ideal types:

(i) "Expertise of service" refers to a form of technical expertise, whereby the expert is mandated by the policymakers and produces information to help the decision. The arbitration between the expert's information and action is supposed to be taken in full by the decision-maker.

(ii) "Expertise of consensus" is mainly expressed through the institutional form of a commission. If part of the process is close to the expertise of service (the decision-maker mandates the commission), it includes a procedural form of confrontation between an heterogenous group of experts. The commission has the ability to define norms. This type of expertise entails a form of opacity.

(iii) "Expertise of engagement", unlike expertise of service, action and knowledge are complementary. Expertise includes an operational thinking on how conclusions will be accepted or not by the civil society. Scientific analysis and its social reception are perceived as on an equal footing and complementary.

Scientific expertise (science for action) interacts with other objectives and subjective narratives (*voices*). In those different process, *science for action* have either a support

[20] The resonance of these concepts is inspired by the ANSES Symposium.

function (expertise of service) or a decisional power (expertise of consensus and engagement).

1.3.1.2. Specificities of space-based knowledge

The outer space has not been a main subject of sociological studies, as Pass J. (2011), the founder of the astro-sociology highlighted: "A void has existed within the social sciences for over fifty years since the launch of the first Sputnik satellite". Yet, as social sciences have recognized specificities of different spaces and their social impacts[21], outer space sociology reflects an extension of this thinking (Peter, 2017). The objective of space sociology is to show that spaces are not neutral. For instance, the social construct of space affects the perception of what have been produced from those spaces. The relationship from a space to another is then fundamental in the understanding of the space that is under study. One of the main characteristics of outer space is to be fully external of the object (the Earthly society) and therefore feed a narrative of universality (Peter, 2017). In this sense, space-based knowledge reinforces the impression of impartial global reality. Sheila Jasanoff (2012) illustrated this dynamic by focusing on the "we" used by astronauts and the World Commission on Environment in the 1987 report *Our Common future*. In this report, the photograph of the Earth from space (and, thus, EO) are presented as a "Copernican Revolution". This expression, explained by Bruno Latour (1985), is used to describe "the transition from obscure knowledges, tuning around things without understanding them, to those exact sciences as they made turn things around them"[22]. Then, space-based science changes drastically our perspective on knowledge and on scientific expertise. Therefore, it can be stated that methods (Latour, 1985) used to collect environmental data have different effects on perception of those data.

Following the expertise framework, the three ideal types interact within institutional bodies implied in global environment governance, for instance:

(i) The IPCC workings groups or the GCOS are contributing to strengthen knowledge and supports other expertise in their understanding of climate change.
→ Both of those structures are using space-based knowledge to support technical expertise.

(ii) The IPCC or the COP are expertise of consensus producing deliverables which have an instating value by itself. Respectively, IPCC reports and their recommend have an authority value, COP decisions may be legally binding or at least provide orientations.
→ Here space-based data could have a function of control within the Paris Agreement ambition mechanism.

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[21] On this topic, see Henri Lefebrve work.

[22] « ce passage des savoirs obscurs, tournant autour des choses sans les comprendre, à ces sciences devenues exactes parce qu'elles font tourner le monde autour d'elles », p. 19

(iii) The Copernicus programme, through its co-constructive approach, epitomizes an expertise of engagement.

→ Here space-based date are a lever to co-construct global environmental governance.

The next question is how space-based data on GHG will be integrated in this expertise framework in regards of the growing stakes around emissions. The value given to this type of data may impact the governance which is the object of this research discussion.

Moreover, Jasanoff S. (2012) exposed the limits of the universal significance of space-based Earth photography. A global environmental consciousness is a gradual product involving social, ethical, and local dynamics. Symmetrically, space-based data and their objectivity are confronted to other actors and their own discourse. As identified in the Copernicus programme section, three categories of *voices* coexist: (i) scientific, (ii) citizens and (iii) policymakers. All of them contribute to the production and use space-based data. Understand their synergy is essential to capture the value of space-based knowledge.

1.3.2. Responsibility and environmental issues

Along with the mobilization of scientific expertise climate mitigation policies bare a particular weight of *responsibility.* Indeed, the concept of responsibility has known a renewal under the weight of environmental issues.

Jonas H. (1979) developed an ethic of responsibility in consequence of the omnipresence of human activities. This dynamic is abolishing the dichotomy between the *nature* and the artificiality of the *human city*. As a result, *responsibility* is an imperative of adequation between action, effect of this action on human survival. The obligation to act (*responsibility*) is not circumscribed in time and place but has a universal significance. As a concept, *responsibility* has two implications (Gros, 2017). First, its symbolic weight overcomes a presupposed neutrality. Secondly, it is impossible to dispose of *responsibility*. As a result, responsibility is "without boundaries" (ibid). Concretely, expectation on global environmental governance is rising and traduces a need for accountability through transparency.

However, the growing influence of scientific expertise and of citizen engagement dilute *responsibility.* Irène Thery (2005) emphasized how the "precaution principle" consisting in giving priority to the most pessimistic scenario gave to scientific expertise a role as a regulator in the decision-making process. It may in turn transfer part of responsibility for action. In the same way, the collective aspect of environmental issues through independencies underlines a *co-responsibility* between *voices* including a "greater emphasis on shifting the social practices of individuals" leading to a new role of the citizen.

The interconnection between forms of expertise and responsibility in global governance may in turn create questions on how specificities of space-based data would be integrated. Different scenarios might occur especially towards scientific expertise. For instance, science expertise may be reinforced as an "arbitrator". These potential evolutions are at the core of this research.

2. METHODOLOGY AND HYPOTHESIZES

2.1. Hypotheses

The master thesis is a maturation of a reasoning that started during my master's degree class dispensed by Hugo Richard and Eloi Petros on the European space policy. One of the interrogations brought to light by this class was to wonder whether satellites might become the "guardians"[23] of the Paris Agreement. Combined with previous considerations on data, this questioning underlined the added value of a more qualitative approach of this possibility, including a theoretical structure. As explained in the methodology part, the research was progressively enriched through data collection. Therefore, the first hypotheses focused on the feasibility and the technical input of space based GHG monitoring and then applied to governance leading to construct the theoretical framework. Consequently, I divide my hypothesizes in two groups: within the case study and confronting the case study to the theoretical framework.

2.1.1. On the case study

My core assumption relating to the case study is that space-based data on GHG emissions could strengthen transparency under the Paris Agreement. Global governances seemed to require global data and satellites could be the most relevant channel to provide them (Hypothesis 1). Also, satellite first appeared to me as an intermediary object of policy and scientific cooperation. From this partnership, I presumed it became a lever of mutual trust encouraging State collaboration under the Paris Agreement (Hypothesis 2). This way, space-based data would impact global governance by two means, increasing data available and bring consensus in global governance. Finally, I supposed that development of space technology would become a way to evaluate national policy on GHG reduction. Policy evaluation more than enhanced transparency is perceived as a leverage for accountability and for rebuilding trust on climate change policies (Hypothesis 3).

2.1.2. Confrontation with the theoretical framework hypotheses

The theoretical framework is a conceptual extension of hypotheses presented on the case study. The conceptual diptych links responsibility and expertise. I am presuming that space-based data on GHG are perceived differently from other types of data and this difference could impact the role of expertise in the decision-making process (Hypothesis 4). More specifically, I presume that satellites data might assume a role of arbitration and transfer more responsibility on scientific expertise under the Paris Agreement transparency GST (Hypothesis 5).

[23] Terms used in the syllabus of the class.

From the confrontation of the case study and the case study, I speculate that a general understanding could emerge especially on the following points (Hypothesis 6):

(i) Mediums of data collection impact the perception of the data itself and have a social value.

(ii) Scientists, citizens and policymakers have different expertise on the environmental field leading to specific responsibilities which are not well defined.

(iii) Technological developments influence the expertise-responsibility distribution.

The analysis and findings section aims at finding first avenues on these hypotheses, underlining potential knowledge gaps and offering policy recommendations.

2.2. Methodology

Our methodology is qualitative: "description, interpretation, verification and evaluation" (Njie et al., 2014). Qualitative research mobilises various sources of information, such as quantitative, legal, social data or lived experiences. More specifically, this research adopts a case-study approach (Elkatawneh, 2016). The phenomenon under study is thus narrowed and bounded in time. Indeed, as the monitoring of GHG from space is an on-going development, the analysis takes place before it has produced measurable consequences. This research aims to explore a prospective situation and should be considered as such. Furthermore, as a case-study, it serves to highlight a theoretical issue. Also, the technical complexity of spatial remote sensing is only grazed, which is a consideration to be held in mind.

2.2.1. A qualitative approach on quantitative data

A starting point of this research is a questioning on data in public policies from the article written by Wendy Espeland and Michael Sauder, "Rankings and Reactivity: How Publics measures recreate social worlds" (2007). The article offers a framework to understand potential consequences of monitoring public policies through data taking the case-study of law school rankings. In this research, data were contextualized as the result of a social and historical demand for accountability, transparency and efficiency. Therefore, the leading interrogation is whether quantitative data increase transparency and, when it does so, if transparency leads to more accountability and efficiency. Thus, the article underlines, through the case-study, a fundamental limit of data as a public policy tool: measuring, evaluating and monitoring through data shape social behaviours so that ultimately, indicators might not be relevant anymore. To understand the *responding effect* of data monitoring, data should be considered as a social object from which knowledge is derived.

From this first consideration and drawing on my personal interest for climate change, I started investigated the issues surrounding environmental data, especially, how they were globally collected. Recognizing the importance of a qualitive examination on data, I wondered how a specific method of data collection, here from the outer space, could impact public policy. To narrow the scope of the research, I choose to align the scale of the data investigated (global space-based data) and the scale of public policy governance (global as the UNFCCC framework). Moreover, the Paris Agreement reflected the rising requirement for transparency. I then based my qualitative analysis on two components, described below: interviews and an interdisciplinary literature review.

2.2.2. Interviews: case-study qualitative approach[24]

As the research is a case-study, the variety of interviews is limited in order to gather experience and data within the context of the case (Njie et al., 2014). All interviews have followed a core methodology according to three principles:

(i) Interviewees have been selected for their relevant knowledge on the case study considering their institutions or professional function. The selection answers the need for a diverse panel of expertise including notably representatives of scientific experts, representatives of public authorities, elected representatives, Copernicus users, United Nation experts, National inventory experts, legal experts.

(ii) A questionary made on Google form was sent prior to interviews to ensure consent to be part of the research and ensure the protection of personal data. In the minority situations when it occurred that the participant had been unable to complete the form, approval has been collected orally.

(iii) Interviews have been conducted following a semi-formal approach. Questions have been prepared considering the expertise of the interlocutor and its anticipated integration in the case study. The structure of the interviews aimed to follow a bottleneck approach from general considerations on the topic, mostly on technical aspects, to questions that were closer to the theoretical framework. The latter took into account the personal experience of interviewees and how they perceive their own expertise. Most of the interviews have been conducted on the platform Zoom on videocall to improve fluidity. In the context of the theoretical framework, an executively strict interview template would have not permit to capture subjective discourse on expertise and ran the risk of accentuating my own biases. The goal behind this semi-informal approach was to ensure mutual trust and understanding.

From this common methodology, I distinguished two types of interviews: *framing interviews,* conducted first, and *in-depth interviews* aiming to sustain the discussion part. First, *framing interviews* focused on drawing the contours of the research and establishing a sufficient understanding of technical issues. Therefore, questions retained a general formulation and were not exploring the theoretical framework in depth. In fact, the

[24] Table 1, Annex.

theoretical framework could be viewed as co-constructed with the *framing* participants as they highlighted concerns on the role of the scientific expertise. Secondly, *in-depth interviews* targeted more specific questions depending on the participant and tried to confront point-of-views. This is why, leaving a time lapse between interviews has been preferred to avoid confirmation biases between two interviews and so as to favour debate.

Interviews hold a significant influence on this research as the dedicated literature on space-based environmental data remains narrow in the social science field. For the input of this thesis, 13 experts have been interviewed, and 1 written questionary have been sent. Written questionaries replaced interviews when requested by the participant.

2.2.3. Interdisciplinary and multi-channel approach

To conduct this case-study qualitative research, interviews have been crossed with an inter-disciplinary literature to set a theoretical framework under which this specific case would be tested. The literature review is framed by an interdisciplinary and *multi-channel* approach.

The topic itself implies, at least, to rely on technical resources, environmental studies and the inputs of political science on governance. However, as the research targets a case-study approach, the analysis has to be incorporated in a broader theoretical structure which combines, in majority, sociology and epistemology. Given the restricted time and resources of a master thesis, the literature reviews do not give a complete overview of all relevant disciplines but focuses on underlying key concepts. Especially, on technical aspects of remote-sensing or on climate change, simplification and accessibility of the explanation have been preferred over exhaustivity. Another factor taken into account for the selection of sources was how recent they were. As the topic is a new development of technologies and the framework considered is under the Paris Agreement, contemporary literature is assumed to be more pertinent. More than interdisciplinary, a diversification in the form of sources was a preoccupation (*multi-channel approach*). Conferences, oral formats, videos provide a notably suitable channel to observe interactions between different types of discourses and gather subjective information. Specifically, on the Copernicus programme, conferences for the attention of users are a privileged channel. Attending or visioning them provides a clearer comprehension on the programme functioning.

3. ANALYSIS AND FINDINGS

This section analyses the case study through the data collected in compliance with the methodology. Main findings are mentioned at the end of each parts and refers to the hypothesizes.

3.1. Space-based measurement: a lever to overcome limits?[25]

Considering the lack of, and the need for, data under the Paris Agreement enhanced transparency framework, there has been a renewal in the will to develop new instruments to monitor GHG emissions, especially CO2 and CH4. As space-based data have already contributed to understand climate change through ECVs, is seems only natural to ask whether CO2 and CH4 monitoring could be possible from the outer space. This section discusses the potential supply of these data notably in the light of its technical feasibility, focusing on the European Union's efforts (Copernicus programme).

3.1.1. Towards the Paris Agreement: greenhouse gas uncertainties

3.1.1.1. Two complementary methodologies

To assess GHG emissions two methodologies are coexisting. First, the bottom-up methods such as in inventories, "obtained by aggregating statistical data from relevant economic sectors at a given terrestrial scale relevant for mitigation policy" (Pinty, B., 2019). To ensure their accuracy, the IPCC promotes a "self-assessment of the quality" through quality assurance and quality control (QA/QC) process (IPCC, 2000). As highlighted by the CITEPA[26] expert, notably within Europe, inventories are reliable. Even more important, they are comparable over time as they are produced following the same guidelines from a year to another. According to this interview, even if uncertainties in GHG emissions estimations need to be addressed, the imperative is to ensure relevant time series to evaluate the evolution of GHG emissions. Moreover, the CITEPA expert underlined the good quality of the dialogue within the inventories network, guarantor of comparability between nations. The OCDE (2016) analysis supports the assessment of a greater transparency and completeness as Parties are shifted over to higher-level IPCC tiers, notably with a greater use of country-specific emissions factors. In complement to national inventories, the European Commission developed a bottom-up estimation at a global scale, the Emission

[25] To be noted: the section mainly mentions EO satellites, however localization technologies are essential (such as that obtained through the Galileo program) to interpret EO data.
[26] CITEPA is the French aggregated association producing the national GHG inventories.

Database for Global Atmospheric Research (EDGAR), calculating global time series of anthropogenic emissions based on energy balance statistics[27].

However, as expressed by the WMO expert, the bottom-up methodology alone is not enough to assess global emissions and absorption. To the expert, despite efforts to reinforce inventories, estimations need to be confronted to actual measurement. The second methodology, called top-down, is an "approach to determine sources and sinks of greenhouse gases from observations of the atmospheric concentration variations of these gases" (Pinty, B. et al, 2019). Measurements can be provided by in-situ network or remote sensing instruments (including from aircraft or satellites). The WMO is conducted two key programmes for a global use of top-down methodologies, the Global Atmosphere Watch (GAW), coordinating surface-based observational network including more than 430 stations (WMO, 2016), and the Integrated Global Greenhouse Gas Information system (IG3IS). The IG3IS initiative aims to expend the observational capacity and seeks to become a "practical tool" (Bergamaschi, P. et al., 2018) by harmonising top-down methods (GAW, 2019) through "good practices". By these programmes, the WMO contributes to reduce uncertainties on GHG emissions and absorption.

Despite the appearing opposition, both experts are emphasising their complementary and the need for more synergy between the two methodologies. In fact, the IG3IS initiative explicitly envisions to provide complementary information to inventory builders and to support the Paris Agreement GST (GAW, 2019). Only few countries (e.g., Switzerland, UK and Australia, Petrescu, A. et al. (2020) are already using top-down methodologies to improve their inventory, but these experimentations provide concrete examples of inventories' amelioration:

(i) The UK inventory's time series on reporting HFC-134a (a hydrofluorocarbon, uses for refrigeration included withing the Kyoto basket of GHG) (Say, D. et al., 2016) had significant mismatch with the top-down approach (emissions were 50% lower than reported in the inventory). The 2016 inventory correction integrates a synthesis between the two emissions estimates (GAW and WMO, 2018).

(ii) In Switzerland the continuous CH4 measurement from four sites on the Swiss Plateau and two other sites combined with inverse modelling (top-down methodologies) confirmed the bottom-up estimation but significantly decreased the uncertainty (from 16% to 9%) (DeCola, P. 2017).

It clearly appears that to reach the goal of transparency in the Paris Agreement, there is a need to explore the full complementarity between the two approaches.

3.1.1.2. Remaining uncertainties

[27] Statistics from: the International Energy Agency, statistics of the UN Food and Agriculture Organisation (FAO), IPCC.

Even if uncertainties in GHG emissions and absorption cannot be completely lifted, the exigence of transparency also relies on assessing and reducing them.

Global uncertainties are mainly drove by less constraining non-Annex-I Parties reporting conditions. This differentiation was justified under the Kyoto protocol as annual stand-alone reporting requires important means and GHG were mainly emitted by Annex-I Parties. However, their share of emission has increased from less than 40% in 1990 to more than 60% in 2012 (Janssens-Maenhout, G., 2019). This is why, one of the main objectives of the Paris Agreement was to reinforce non-Annex-I Parties reporting to increase global transparency. Moreover, Annex-I inventories are not taking in assessing "imported emissions"[28] despite their growing importance. For example, in France, imported emissions are 70% higher than territory-based emissions (Sgambati, E., 2020), Symmetrically, considering a full picture of the UK's carbon footprint (including consumption-based emissions), in 2016, 46% was coming from emissions released overseas (WWF, 2020). On one hand, imported goods are likely to be produced in Non-Annex I countries (Scott et al, 2015) which are not under the same reporting conditions leading to increase global uncertainties. On the other hand, "net emission importers" (ibid) through their national consumption take part in the increase in GHG emissions without being held responsible. This phenomenon artificially improves climate mitigation policies in developed countries, whereas the actual reduction in emissions is due to an increase of importations. Therefore, the non-incorporation of imported emissions increases uncertainties and diminishes Annex-I inventory utility as a support to policy making. Also, the *imported emissions effect* harms mitigation because of the "carbon leakage" effect (McLaren, S., 2020) and of delay in low carbon technologies diffusion (Scott, et al. 2015).

Within submitted inventories uncertainties remains. This is why, the IPCC 2006 guidelines provides methods to estimate potential gaps in inventories (chapter 3). These methods require "important investments" and implies the participation of specialized experts (CITEPA, 2020). Therefore, the robustness of an inventory that fully complies with IPCC recommendations involves considerable human resources, a fact that explains heterogeneity in inventory quality (OCDE, 2018). Inventories may also comport "significant uncertainties, especially for non-CO2 GHG due to large uncertainties in the emission factors" (Bergamaschi, P. et al., 2018). Furthermore, for some countries (especially non-Annex 1, biennale reporting) reporting contributions are impacted by less developed statistical infrastructures. Finally, inventory process is based on *self-assessment* and officially declared national emissions and absorption. Moral hazard is a remaining concern as the political weight of sustainability increases as already shown in the potential overestimation of "negative emission techniques" (Lenzi D., 2018). Overall, according to Oliver *et al.* (2020), for "most countries, the uncertainty in total GHG emissions is also around 10% (…), a few exceptions where this is up to 15%".

Finally, top-down methodologies also have their own limitations. Firstly, as mentioned only three countries are integrated top-down methodology to strengthen their

[28] Refers to emissions related to imported goods (fabrication and transportation).

inventories. Secondly, coverage of *in-situ* stations is not sufficient to fully take advantage of top-down methodologies (Bergamaschi, P. et al., 2018). The measurement network is "is still far from being sufficient for the purpose of country-level emission reporting" (ibid) with the only exception of the United-States concerning HFC-134a over the 2008-2012 periods (Hu, L., 2017). Bergamaschi, P. et al. (2018) also points out the threat of budget cuts and decommission of some measurement sites.

Even if, undeniably, progress have been made in GHG reporting crossing both bottom-up and top-down methodologies, remaining uncertainties and limits have to be addressed considering rising stakes in reaching Paris Agreement goals through the ambition mechanism.

3.1.2. Motivations behind the use of satellite to monitor GHG emissions

The New Delhi Declaration came into effect on 16 May 2016, translating the will of 60 nations to work together to establish an international, independent system for estimating GHG emissions based on accepted data, including space-based observations (CNES, 2016). This declaration stands as the first agreement across the global space community.

The key assumption behind satellite observations is the ability to provide global coverage on a specific variable using the same metric and ensuring regularity in the data collection. Then, space-data aims to complete top-down methodologies and allows for their extensive use. Indeed, helping countries which have less experience in submitting inventory remains a commitment under the UNFCCC framework. This last consideration is even more important considering the generalisation of the reporting under the Paris Agreement. The need for further developments is stated as such: "no existing network of in situ observations, space-borne measurements and emission inventories as they currently stand can provide sufficient information at the appropriate space and time scales" (Pinty, B. et al, 2017). A constellation of satellite would then constitute an operational observation-based CO2 emission monitoring and verification support (MVS) capacity. The MVS capacity would aim to reinforce the distinction between natural carbon circle and anthropogenic emissions to enable the impact, nay effectiveness, of environmental policies. More specifically, the European Commission (ibid) identifies a global MVS as a policy tool to monitor impact of the NDCs and to assess national emission under the GST. Comparable motivations are mentioned in the Matsunaga Guidebook on the use of satellite greenhouse observation (2018). The latter also states that satellites might contribute to "a system (…) necessary to compare and evaluate the inventories by some independent ways". Even if the accuracy of satellite observations is less important than for ground-based measurements, they provide a wider coverage of carbon sink mapping which is a "key stepping-stone" to develop a global MVS capacity (CMAS, 2019). Moreover, satellite observations are available faster than surface measurement (ibid).

The notion of "independency" supposedly provided by space-based observations stands as a crucial feature in their potential integration in the global governance. The use of satellite imagery as an independent lever of verification of a State's compliance with its international obligations is an increasingly important tool. One case study of this trend is the non-proliferation framework. The International Atomic Energy Agency (IAEA) views satellite imagery as a "particularly valuable open source of information" to support the IAEA safeguards[29]. Thus, the IAEA established in 2001 a Satellite Imagery Analysis Unit (SIAU) (Pabian, F., 2015). The constant flows of information and the ability to cover the whole globe are strong assets. For instance, satellite data support the assessment of the nuclear programme of the Democratic People's Republic of Korea (DPRK) as the IAEA is unable to conduct physical verification (Quevenco, R. 2016). This approach explicitly aims to evaluate a State's declarations under a dedicated global governance framework. The Comprehensive Nuclear-Test-Ban Treaty (CNTBT), which has yet not entered into force, explicitly refers to the use of "monitoring technologies such as electromagnetic pulse monitoring or satellite monitoring" in Article 14, paragraph 11. In light of this governance case, the European Space Policy Institute (ESPI) policy brief n. 14 contemplated the use of space observation under the UNFCCC Paris Agreement framework. Nonetheless, such use of EO to monitor compliance is recognised in the ESPI brief as a "politically charged capacity" such as in regard of sovereignty. Furthermore, on more concrete examples under international law, satellite data have been proceeded by the International Court of Justice in the *Territorial and Maritime Dispute between Nicaragua and Honduras* (2007) case as satellite imagery was delivered to support claims over islands.

Finally, EO has a specific visual impact (*overview effect*). Visualization is a growing aspect in the data science field as it synthesizes information in a simple, nay "attractive" way (Unwin, A., 2020). Even if visualization tends to oversimply and may lead to misinterpretations, it remains a relevant channel to present a large amount of data (ibid). More specifically on climate change, global and regional visualizations underline the transboundary effects of environmental issues. A transboundary process on assessing environmental issues is identified as a growing need to complement traditional territorial approaches (Zapfel P., 2020). Those different scales of visualization are likely to be supported by satellite imagery allowing to combine different scales on maps. Moreover, on environmental issues, visualization helps reaching targeted non-scientific audience. This is why, considering the important impact of visualization in climate change communication, the provision of user-friendly visualization without compromising on the scientific rigor is a growing challenge for the IPCC (Jordan, H., 2020). Finally, space agencies are capitalizing on EO visual value. For instance, the ESA website provides "Images" and "Videos" sections featuring an important amount of EO photography and model visualisation.

The motivations behind GHG monitoring through EO are nourishing both a *science for knowledge* and a *science of action*. However, as highlighted during the interviews, its feasibility is still a question mark.

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[29] IAEA safeguards are a "set of technical measures applied by the IAEA on nuclear material and activities, through which the Agency seeks to independently verify that nuclear facilities" (see: IAEA website)

3.1.3. Space-based GHG monitoring: an on-going research

3.1.3.1. General technical considerations

Remote sensing is based on the understanding of radiation that is received and emitted. Radiation spectra collected by the satellite instrument is analysed to yield information on atmospheric composition (Matsunaga T. et al., 2018). Gases such as CO2 and CH4 interact with radiation, absorbing or emitting specific wavelengths, which are displayed on the recorded spectrum as dark "absorption lines" or bright "emissions lines". The input of information, such as wavelength, pressure and temperature, allows one to compute atmospheric composition from the recorded spectrum. The estimated quantity of GHG is retrieved from the spectrum, this is why the estimates of GHG from space-based observations are obtained through remote sensing retrieval algorithms.

At the current state of knowledge, this method has two technical limitations: (i) as it based on sun radiation, this approach can be used only during the day; (ii) measurements have little sensitivity to GHG near the Earth's surface, where most of sources and sinks are located. This technic allows one to evaluate the overall quantities of XCO2 and XCH4 contained in the atmosphere, not necessarily emitted by human activities. Also, as a biogenic gas, the CO2 has a strong seasonal cycle[30], which adds another difficulty to isolate anthropogenic emissions.

Three generations (Matsunaga T. et al., 2018) of instruments are (or were) targeting GHG observations (but non-specifically anthropogenic emissions):

(i) The first generation was the Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY (SCIAMACHY) designed to observe CO2 and CH4, a tripartite national contribution (Germany, Netherland and Belgium) to ESA which operated from 2002 to 2012.

(ii) The second generation corresponds to the GOSAT et OCO-2 satellites. The Greenhouse Gases Observing SATellite (GOSAT) by the Japanese agency was the first mission dedicated to measuring GHG. It was launched in 2009. Data collected have contributed to the understanding of carbon flux estimations, in particular to estimate regional carbon flux. For instance, results Jiang F. et al. (2021) suggest an overestimation of carbon sinks in North America and Europe. The US Orbiting Carbon Observatory (OCO-2) was successfully launched in 2014 (after the OCO failure in 2009). Unlike GOSAT, OCO-2 only assesses CO2. The Hakkarainen J., et al. (2016) work is the first study using OCO-2 data to assess anthropogenic emissions showing satisfactory results on providing information at regional scale (Europe, USA, China) and smaller emitting areas such as cities. Moreover, OCO-2 retrievals result agrees with *in-situ* measurements, showcasing the

[30] CO2 concentrations vary in function of seasons, for instance plants are absorbing more CO2 during spring through photosynthesis. The complexity is also increased considering the reversed seasons in the south atmosphere (and vis-versa).

growing reliability of this method (Crowell, S. et al., 2019). This provides an opportunity to reinforce the accuracy on oceans carbon fluxes.

(iii) The third generation is quite recent and includes private initiatives (Matsunaga T. et al., 2018):

Country[31]	Satellite / instrument and launching year	Gases targeted
Canada (private company)	Claire – 2016	CH_4
China	TanSat – 2016	CO_2
China	GMI – in 2018	CO_2 and CH_4
Japan	GOSAT-2 - 2018	CO_2 and CH_4
US	OCO-3 - deployed in 2019 on board of the ISS[32])	CO_2
EU	TROPOMI Sentinel 5p – 2017 Sentinel-4 – 2021 (initially 2019) Sentinel-5 – 2021	CH_4
France (also contributing to ESA)	MicroCarb – 2021	CO_2[33]
France and Germany (also contributing to ESA)	MERLIN – 2021	CH_4
US	GeoCARB – 2022	CO_2 and CH_4
US – California	Carbon Mapper - 2023	CO_2 and CH_4
EU	Sentinel 7 - 2025	CO_2 and CH_4

It is to be noted that satellite observation allows one to obtain average gas column concentration, considering the whole atmosphere, and not surface concentration (Olsen, S., et al., 2004). This measurement is noted as XCO_2 and XCH_4 (parts per million, ppm). This distinction is not made in the examples to ensure simplicity, but the notion of column is key.

3.1.3.2. Current European initiatives to monitor GHG emissions involving space-based data

In the path to provide a European capacity for monitoring anthropogenic GHG emissions, the EU is driving two main research projects under the Horizon 2020 programme (H2020): the Carbon Dioxide Human Emissions (CHE) and the Verifying Greenhouse Gas Emissions (VERIFY). Both projects will contribute to the creation of a proposed future dedicated Copernicus dioxide emissions monitoring service in complement of C3S. To be noted that C3S already delivers information about CO_2 based on satellite observations as long with CAMS which produces information on carbon fluxes based on global carbon emission and absorption.

[31] Private initiatives are mentioned under brackets
[32] International Space Station (ISS)
[33] Eventually CH_4 (Courtois, M. et al., 2015)

The CHE is a research project aims to contribute to the design of a global MSV capacity including the use of satellite observation. The CHE outputs are identifying how to transform a research system to a fully operational support capacity. As explained by Choulga *et al.* 2020, the backbone for atmospheric inversion is the estimation of global gridded emissions with the spatially and temporally distributed emissions. The issue with observations is how to trace emissions to identify the emission hotspot. As gas are, by nature, moving, the concentration over a country does not indicate if the country is the emitter. This is why, a MVS capacity to monitor the Paris Agreement and national policies implies a strong understanding of the spatiotemporal emissions distribution. Results from Brunner *et al.* 2019 study suggests that CO2 transportation horizontally at the surface and vertically into the atmosphere should be both equally integrated into models. Building on these results and other studies, Janssens-Maenhout et al. 2020 contributed to draw the design of a policy-relevant MVS capacity supporting the Paris Agreement ambition mechanism. They provide two schematic overviews[34] of a potential CO2 system including the use of satellite CO2 data. The target output is a service providing anthropogenic emissions at monthly and country scale with associated uncertainties as well as multi-year trends to assess evolution.

The VERIFY project also aims to strengthen knowledge on GHG budgets towards a global MSV capacity. The key output of the VERIFY project is to offer syntheses on global GHG harmonising available datasets. The output of overviewing and gathering data should not be underestimates as it allows providing independent estimates of GHG emissions. For instance, the Petrescu *et al*. 2020 study on anthropogenic emissions data from agriculture, forestry and other land use (AFOLU) within the EU28 highlights inconsistencies mainly due to different sources of data related human activity and tiers used. Building on this assessment, European inventories may be improved.

Both projects are contributing to the new prototype system toward the MVS capacity: the Copernicus carbon dioxide service (CoCO2) launched in early 2021, which is a follow-up to the CHE project (CAMS, 2020).

3.1.3.3. The Copernicus satellites to monitor anthropogenic emission project: a discussion

In order to provide an operational MVS which could contribute to the Paris Agreement GST, the European Commission is planning to dedicate Copernicus satellites to this task. As Gianpaolo Balsamo, coordinator for the CHE project stated: “Currently data from the Sentinel 5P satellite are used to measure nitrogen dioxide (NO2) as a proxy for human-related CO2 emissions, and some CO2 concentration measurements from other platforms are available too, but coverage and precision will be much better with the new Copernicus satellites” (ECMWF, 2020).

[34] Figure 4 and 5, Annex.

The Copernicus CO2 Monitoring (CO2M) mission (or Sentinel 7) is one of the new high-priority satellite missions. It explicitly aims to target anthropogenic emission from space. According to the mission requirement document (2020), the launch of the mission is planned for 2026 and would be used during the GST 2 (2028). The ambition is to provide a "an essential service" "with the independent information" to the UNFCCC in collaboration other countries such as USA, Japan and China who also will launch several satellites dedicated to measuring CO2. The mission would also imply to reinforce the ground-based measurements to ensure an operational system at the scale of megacities, large industrial sites, regions and countries. The system will imply multiple satellites to meet the mission requirement in terms of spatial coverage and time-regularity. For now, such a mission is still an on-going process as underlined by the CNES experts. Europe does not have any satellite measuring CO2, and targeting anthropogenic emissions is even more ambitious. In the path to reach this goal, the CNES and ministry of research experts highlighted how Microcarb and the Merlin (member state contributing missions) could contribute to reinforcing the understanding of space-based GHG monitoring. Both missions will enable testing their instruments and their technical capacity such as in terms of spatial resolution. According to the French Government counter-expertise, the Microcarb project could improve the carbon flux measurement up to 50% which is promising for the CO2M mission. However, this type of mission is not fully consensual within the scientific community.

On the one hand, prior contributions of space-based data create high expectations on potential improvements as satellite provide wide nay global coverage and regular collection (Matsunaga T. et al., 2018) as shown in multiple examples within the research. Moreover, a global MSV capacity through satellite data would help non-Annexe I to provide a stand-alone emissions reporting and limit uncertainties in their inventories. Indeed, due to the cost of robust inventories, the Tier 1 methodologies may become the default approach in their inventories (Yona, L. et al., 2020) that will lead to poor quantification. Furthermore, the centralisation of the data in few missions bring long-term stability in the way data are collected and allow for international comparison (ESA, 2020). As identified, XCO2 and XCH4 also provide a vertical concentration assessment, a key component to understand GHG transportation. Also, the current in situ network does not focus on anthropogenic emissions (ESA, 2020), the CO2M missions would then provide a relevant output to target anthropogenic emissions. Finally, in the Microcarb counter-expertise, its net value is estimated at of €31.2 millions considering a €142.4 millions cost (as comparison: contract secured for CO2M is worth €445 millions for the first two satellites). The direct value is determined on the following basis:

(i) A careful hypothesis of a 0.01% contribution to the reduction of emission at the 2030 horizon, using the carbon value of the Quinet report, this benefice being evaluated around €100 millions.
(ii) An estimation of industrial economic value and its linked labour.

This evaluation does not include indirect value such as the gain in scientific knowledge or the political gain in contributing to the UNFCCC framework. This evaluation provides a first answer to Onoda M. (2017) question on whether the taxpayers (citizens) would socially and economically benefit from the use of satellites for environmental monitoring.

On the other hand, satellite observations are mired in uncertainties. First, on the technical feasibility, the mission and its capacity to provide an operational MVS capacity remain ambitious: "breakthroughs are needed" (ESA, 2020) to reach this goal on the overall system performance and modelling. The instrument requirements for a such project are "very hard to satisfy" (Courtois, M. et al., 2015) in terms or spectral resolution, spatial resolution and receptivity. Moreover, intensifying the coverage of ground-based measurements would still be necessary to ensure the quality of space-based observations. The Microcarb cost-benefit analysis also displays a few limits that could be extended to CO2M. Considering the in-situ network coverage in France and its future extension, the input of satellite observation to reduce national uncertainties is minor. That suggests a greater extension of in situ provision could be more efficient. Parallelly, Hungershoefer et al. (2010) have shown that a 200M€ extension of the ground-based network has a similar impact that OCO observations on reducing uncertainties, nay slightly higher. As the projected nature of Microcarb is comparable to OCO observations, it hints at a limited added value. However, it is important to underline that this study is dated, and a progress have been in the recent years as suggested by the other studies mentioned in this research. Additionally, some interviewees have suggested that the economic weight of aeronautic firms may actively promote satellite-based measurement. Consequently, economic consideration might overstep scientific considerations.

In conclusion, the MSV capacity supported by the CO2M project would benefit to the global environmental governance. Indeed, the CO2M missions potentially answers the need for reinforcing data collection and the contribution of satellite observation in GHG evaluation has been strengthening, according to recent studies. Nonetheless, counter arguments and debate should be considered, especially as both space and ground-based measurements are complementary. Satellite ambitions should not overstep on in situ measurement. Lastly, supporting non-annex I countries and improving GHG emissions inventory remains a priority to link measurement to emissions sources. To conclude, the MVS capacity will have to integrate data from inventories, in situ network and satellite modelling to become a trustworthy policy tool. Satellite observations cannot stand as the only lever to overcome current uncertainties.

3.2. Impact on global governance: sovereignty and transparency

The geological and political aspect of space-based observations under the Paris Agreement are not the main aspect explored in the understanding of space missions. However, as pressure to reduce emissions is rising, the development of monitoring stands as a strategic tool in global environmental governance. Two aspects will be discussed here, space-based data as a lever for more cooperation and the issue of sovereignty in the use of space observation.

3.2.1. Space observations: transparency and cooperation

3.2.1.1. Space programme: a cooperation-network

Due to the high complexity and the important source of expertise needed, a global operational monitoring and verifications support capacity is necessarily the fruit of international cooperation. During the Monitoring Anthropogenic CO2 emission with Copernicus workshop (June 2020), EU, UNFCCC and GCOS representatives shared their point of view on the European MVS capacity. All participants agreed on how a such monitoring tool was "essential to achieve the mitigation policies". Due to the potential impact of such a capacity in evaluating national contribution on the Politics and Economics of the CO2, "great reasonability" will emanate from the monitoring system, which highlights the need for cautions, accuracy and cooperation. Coordination fulfills two objectives. Firstly, the reinforced mutualization of data leads to reinforce global knowledge for all nations (especially as many countries cannot provide their own instruments). In this sense, international cooperation serves the objective of responsibility while acknowledging countries are contributing depending on their means. Secondly, involving international institutions, principally through the WMO (GAW programme) and the GNOS, and key partners (e.g. Japan) increase the legitimacy of the MVS capacity to be used globally. On this topic, Briggs S. highlighted (2020) the importance of politics in the contribution of Copernicus in addressing the Paris Agreement. The integration of a European system within the UNFCCC framework is not self-evident as the EU does not bare an international mandate and the system itself is nationally funded. The question on how the Copernicus MVS capacity would and will fit is at the core of the 2018 white paper by the Committee on Earth Observation Satellites (CEOS) insisting on the coordination role of the UNFCCC bodies (particularly SBSTBA), the WMO and the GEO. If Copernicus and the so-called "E" institutions (e.g. ESA, EUMETSAT, ECMWF) are already strongly involved in international cooperation, the workshop conclusions highlighted the need to find more efficient communication channels and obtain a clear UN mandate (Copernicus workshop, 2020). Furthermore, bilateral engagements are key. Japan, China, Canada and USA are already involved but a strategy gap remains on how to engage with non-space component countries (Dowell, M., 2020). Also, as highlighted by the two CNES experts, plurality of actors and competition encourage innovation.

Interestingly, on the scientific aspect, space missions are an important lever of cooperation as shown by the institutional network such as in Copernicus. Satellites act like *intermediary objects* in the meaning given by Dominique Vinck (1999, 2009). His writing focusing on 120 scientific networks in the health field highlights how material objects (papers, DNA samples, particle accelerator) influence scientific cooperation through different types of networks. Two types of scientific networks appeared more relevant within this research, one of the "industrial type" (fifth group) and the other oriented towards producing common results (third group). Producing a new satellite, especially considering the technical challenges, require the structuration of industrial scientific network implying informal discussions, arbitration on technical components and cooperation to success in a common goal. Comparing the process described by Vinck in European Community research on nuclear reactor and the one on satellites conception reveal similarities. Three interviews have highlighted the pertinence of the comparison (CNES, Sodern visit and Gifas meeting). Their main contribution was to show how a common object, here a satellite, became the gravity center of cooperation between heterogenous actors (private companies / laboratories / member states). Therefore, space missions produce an important number of objects that are channels of cooperation. Secondly, the realization of the MVS capacity or other data compilation projects (e.g., CHE and VERIFY) focus on the data gathering, the establishment of dedicated protocols, and the polarization of the network between data emitter (scientific communities) and data receptor (policymaker and civil society). This form of cooperation is, theoretically, shaped with a strong differentiation between data emitter / data receptor roles. However, this dichotomy is not as strong in this case study as the user's aspect of climate service and the inter-governmental governance of bodies such as the IPCC suggest a stronger mutual influence between these two roles. This scientific cooperation through intermediary objects finds its equivalent in the global environmental governance with dedicated bodies (e.g., GNOS, IG3IS, SBTSA) supporting climate change international policies.

Moreover, structurally, space-based data have the particularity to reinforce a synergic approach between global, regional, national and local scales. According to Jean-Frédéric Morin et al. (2020), global governance is reinforced when transborder pollutions are documented. For instance, the study by Young O. (1999) has shown how the Convention on Long-Range Transboundary Air Pollution was a strong learning facilitator, making states aware of inter-connectivity of pollution. The transboundary aspect is not a guarantee of success and generalization is disputable, but it at least allows policymakers to reinforce the perception of mutual interest in implementing environmental policies. As a counter-factual, Young compared this situation the Convention to the Barents Sea Fisheries where scientific uncertainty on the mutual utility to regulate led to less cooperation. Space-based observations, unlike GHG inventories (national scale) or ground-based measurement (scale of relevance depends on the network density), provide the wide coverage needed to visualize and assess transboundary pollution. For instance, during the plenary session of the European Parliament in 2018 on the *New space regulation* many examples focused on local issues, such as landslip in Venice. Symmetrically, the Opinion of the Region Committee on the same regulation suggested "more clarity on how the Space Programme proposes to support the initial investment for those local and regional authorities, in introducing the use of satellite data to ensure they fulfil their responsibilities when facing (…) expertise related obstacles". As well, Ministry of the ecological transition experts underlined how crucial it was to include a local understanding in global governance, as locality and regional authorities are implementing environmental policies in the everyday life.

Lastly, space-based observations are contributing to the GST leading to more transparency. Environmental politics have known a "proliferation in instruments that aim to increase transparency" (Morin, J-F, et al., 2020) contributing to the learning and assessment process that helps actors to agree on reciprocal commitments in a contractual set of minds. The root of international institutions is indeed to promote transparency to enhance cooperation. The international relations and economic literature provide many arguments on the link between efficiency, transparency, and compliance (Mitchell, R., 1998). Transparency and information sharing can be viewed as a tool to avoid the prisoner dilemma or the "tragedy of commons" (Morin, J-F, et al., 2020) in environmental international policies. Space-based observations, in particular, promote transparency through the open-data policy (see below). However, transparency within an inappropriate framework of information sharing might lead to tensions, nay failures in implementing international treaties when the transparency is "politized", especially in domestic public debate. Barkin S. (2015) has underlined this pitfall in two case studies including an environmental related one, *the bilateral Treaty concerning Pacific Salmon* (1985). The treaty provides a *focal point* on regulating fishery. The transparency ensures by the treaty created domestic tensions which ultimately jeopardized the cooperation. The risk of "too much transparency" should not be ignored and will be discussed over the notion of sovereignty.

3.2.1.2. Open-data policies: a key for cooperation and transparency

The open-data aspect of environmental satellites is a key feature and is identified as a condition for space policy success. As explained by Borowitz M. (2017), public-funded space programmes tend to adopt more open-data policies even if the sharing of data models is more limited. Indeed, data may be seen as "raw bits" recoding a time and place variable, the value is created by the products made from them (e.g., visualizations, applications, reports). The satellite data sharing policies for EO satellite launched between 1957 and 2016 (excluding classified information) is divided as: 38% open, 27% unknown or unavailable, 25% restricted and 10% commercial. The term "open data" in a policy context was actually mentioned for one of the first times in the space community in the early 1970's by the NASA (ibid). The open-data policy for satellite observations covers numerous countries and organizations, and particularly the U.S., Japan or ESA (in 2012). For instance, Article 23 of Regulation (EU) 377/2014 establishing the Copernicus programme enshrines the open-data and information policy including its limitations (e.g., security interests or third party licensing). An interesting output of Borowitz' research is the common pattern followed by open-data leaders, described as: "from free data provision to more restrictive policies, and then back to free and open sharing". Also, technologies advancement drives the open-data policy. For instance, new technology might make a particular data less competitive and less of an economic concern. Even if multiple considerations are discussed on whether satellite data should be fully openly shared, a consensus appears on how opening data maximizes the users and overall creates more value.

The value itself is difficult to quantify, as agencies are not putting in place mechanisms to quantify economically how the EO data are used, and as indirect qualitative benefits (e.g., transparency and higher participation to politics) are not easy to evaluate. On the open policy of the Landsat programme (American EO programme) Zhe Zhu et al. (2019) studied the number of data downloads since 1972 and 2017 comparing the restricted access period (variable prices) and the open period (since 2009). From 1972 to 2008 less than 3000 images were sold whereas nearly one million images were downloaded in 2009. To access the economic value of this policy change, a survey held in 2015 evaluate that the U.S. Landsat data user have gained 1.8 billion USD from the 2.38 million images downloaded. According to this research, the Landsat open-data policy influenced the adoption of similar policies including for the Copernicus programme. More generally, open-data policies are viewed as a lever for economic growth and improving accountability. For example, the estimated direct market size of open data in the EU is evaluated at €325 billion over the 2016-2020 period (Berends, J. et al., 2020). Moreover, as highlighted by the Bothorel report (2020), access to data is a sine qua non condition to strengthen scientific research and its operational capacity, even if an impact evaluation is needed to fully address the economic, social, and scientific benefits of open-data policies. Interviews conducted for this research all highlighted the necessity of data transparency and the urge to facilitate access. The Copernicus user interviewed supports the openness policy as "the data produced and made available by Copernicus is seen as a public good which should not be monopolized". He also highlighted the value created by "spill-over of knowledge, resource- and expertise-sharing" implied by open-data policies on climate change data services.

However, as highlighted by Ministry of Ecological transition and Ariane Group experts, environmental data and even more GHG measurements, have a strategic value that cannot be ignored. This value of satellite data could be captured by big-tech enterprises such as the so-called GAFAM (Google, Amazon, Facebook, Apple, Microsoft), leading to ambiguous effects. On the one hand, considerations would then emerge on the ethics and the capacity of the market to maximize general interest. As space missions are states funded, taxpayers would be providing free resources to private compagnies in such a situation. The oligopoly situation of GAFAM harms concurrence and thus innovation, decreases variety for consumers' choices and accentuates biases (such as on chosen Google research results) (Nadler, J. et al., 2020). To extend the reasoning, giving the ability to private powerful companies to monitor emissions could constitute a lever for industrial espionage on evaluating other companies' production. On the other hand, considering that GAFAM also contribute to the public good by providing research and free services, for instance Google Map and Google Earth, which are using satellite images (Landsat and Copernicus), the surplus created by using satellite observation is partially shared with citizens. It is to be noted that prices do not appear as a relevant tool for regulation as it would not be efficient to restrict access to wealthy enterprise. Restricting access to some data or products depending on the users could then be discussed considering all these elements.

Finally, quantity and availability of data may have a counter effect on transparency. Noucher M. et al. (2013) emphasized a tension between transparency and confusion because of open-data policies. On the case study of geographical and localized data, authors highlighted the lack of empiric knowledge on democratic transparency led by open data. Their survey (three rounds, addressed to francophone professionals) has not released an opinion consensus and even underlined potential contradictions. 60% of the participants do not think open data is vector of a reinforced democratic control but 70% think that open data tools are leading to more effort from the public authority for transparency. On environmental conflicts, the study shows that availability of the data has not contributed to reducing power asymmetry between actors as the capacity to understand and use data is not shared. This example shows that open data is not sufficient to provide transparency and relevant responsibility tools. Moreover, the proliferation of data leads to a form of governance opacity, even more when public opinion is exposed to scientific debate and contradiction (ANSES, 2021). On a governance aspect, multiple sources of information and data accentuate the *confirmation bias* (Morin, J-F, et al., 2020, strengthening parties and actors in their initial positions, harming cooperation.

By extension, the open data policy in space-based observation is an asset to reinforce the cooperation under the UNFCCC framework. However, limitations should not be ignored and could encourage building a stronger structure for the future GHG monitoring capacity and deriving data products.

3.2.2. Satellite environmental data: discussion on sovereignty

As suggested previously, the impact of transparency and monitoring resonates with the concept of sovereignty. The Paris Agreement, unlike the Kyoto protocol or the Copenhagen approach (COP15, 2009), is based on transparency and mutual self-assessment. According to Stephen Briggs, the Copenhagen approach was "we will validate / verify reporting" whereas the Paris one is "we will help you improve your reporting". Indeed, the GST is thought as a virtuous cercle, assessing emissions is the basis to ameliorate policy and not a lever of sanctions. Article 13 of the Paris Agreement on the enhanced transparency framework states that it should be implemented "in a facilitative, non-intrusive, non-punitive manner, respectful of national sovereignty, and avoid placing undue burden on Parties". This is why, the purpose of the transparency is described as a way to "provide clarity" (article 13.6).

In this context, the term *verification* is ambiguous. In the scientific context, to *verify* refers to a technical verification, the 2006 IPCC guidelines give a definition to avoid confusion: "verification refers specifically to those methods that are external to the inventory and apply independent data". Despite the technical meaning, integration in the context of international cooperation induces a careful use of verification methods. For instance, in the JRC report on GHG emission of all world countries using EDGAR (Janssens-Maenhour, 2017, 2020), which is a verification method in the sense of the IPCC, includes a "disclaimer": "this publication aims at presenting the CO2 and GHG emissions from all countries without any prejudice to the status or sovereignty over any territory". The evolution between the Copenhagen and the Paris Cops shows the evolving paradigm from top-down methodologies that verify bottom-up inventories to a complementary approach of both methods. As a result, in 2009 the objective advocated by the science community was to set a "grand top-down GHG information system", whereas the Paris agreement privileges a federation of focused monitoring systems advocated by a wider range of actors such as WMO, cities, NGOs or industries (WMO and GAW, 2018). In this context, space-based global observations might, on one hand, reinstate a "2009 conception" of verification, and one the other hand, enter in confrontation with the notion of sovereignty. Initiatives such as VERIFY, or CHE, show how research projects advocate for science-led verification. This is why, while acknowledging the relevance and participating to the initiative, the WMO expert expressed her reservations on the choice of the name "VERIFY". Moreover, doubts are emphasised as the system capacity is led by a regional force. European Union is indeed pursuing a leader role, as mentioned by Pinty B., et al. (2017) "this operational capacity [the MVS capacity] will constitute a strong asset to re-assess its leadership in fighting climate change".

This ambiguity is accentuated by the global and extra-territory nature of space-based measurements. Outer space international law is defined by three key principles in the *Outer Space Treaty* (1967). The exploration should be carried on: for the benefit of all people, while encouraging international co-operation for scientific and legal purpose, without the possibility to claim sovereignty. Therefore, states are permitted to perform EO without the permission of the state being observed (article 1). More precisely, on satellite remote-sensing, principles are articulated in the 41/65 UN General Assembly resolution *Principles Relating to Remote Sensing of the Earth from Outer Space* (1986). Even if resolutions are not legally binding, "to the extent that they represent state practice, they have considerable weight" (Aganaba-Jeanty, T., et al., 2019). According to this resolution, the sensed state does not have a veto to prevent remote sensing activity and is not given preferential right of access to the data. However, the sensed state has the right of access to primary and processed data concerning its territory on a non-discriminatory basis (including reasonable costs). Besides this resolution, the GEOSS developed principles in data-sharing for satellite EO. In practice, EO observation data might be restricted over strategic or safety considerations. As a result, "states are likely to have significant concerns about sensitive integrated emissions data" (ibid). The preoccupation over sovereignty is even more important for countries without space programmes as it would constitute a considerable disadvantage (ibid).

The ambiguity over sovereignty and space-based data might have paradoxical consequences. On one hand, being assessed may be an incentive for States and industrial actors leading to more effort to reach the Paris Agreement goals. Some interviews led during this research plead that the simple possibility of GHG remote-sensing verification was already a vector of more efforts to cooperate. Moreover, the national pressure by civil society for transparency and accountability advocate for independent, open and legally binding verification. The "shift of power" towards non-state actors through satellite information has already been observed in their use on nuclear non-proliferation (Pabian, F., 2015). Therefore, the transparency induced by satellite observation and its capacity to evaluate policy could reinforce, firstly, trust in global governance at a national and local scale and, secondly, international cooperation by emphasizing the reciprocity of the mitigation efforts. On the other hand, tensions could rise and jeopardize the cooperation as mentioned on the Kyoto observance mechanism or on the *bilateral Treaty concerning Pacific Salmon* case study. A third path could be a "*quiet-uncooperative"* situation without direct confrontation. Countries would set less ambitious NDCs to ensure they will be able to fulfil them to avoid "name and shame" practices.

As a result of the case study, considering all collected information, three key factors are identified as governance-drivers in the use of satellite observation to monitor GHG emissions within the Paris agreement GST:

(i) Technical feasibility and related trust: More than the technical feasibility *per se* a shared consensus on the monitoring reliability is necessary to ensure the articulation between scientific expertise and the decision-making process. Complementarity of measurements methods (top-down, including satellite observation) and GHG inventories (bottom-up), scientific cooperation as well as open-access to data for research purposes are identified as primary conditions to achieve unity over monitoring services. Secondly, as the debate on the term *verification* has shown, alongside with the analysis on scientific networks, scientific cooperation has to be considered as a political and social interaction supporting mutual understanding. Moreover, integration of scientific expertise is reinforced by a clear positioning on its responsibility within the decision-process, avoiding transforming transparency into confusion. Finally, the ability to adapt the communication to the user (e.g. co-constructions approaches) level the playing field between interested parties. In conclusion, budling trust around the technical feasibility allow satellite GHG observation to become policy tools.

(ii) Capacity to coordinate governance and expertise: Cooperation is led by a fluid synergy in governance. This research underlines a holistic understanding including the traditional institutional form of cooperation (UN, EU and States related institutions) but also the plasticity between geographic scales and between diverse source of expertise. In the Paris Agreement framework and in the Copernicus programme, these institutions remain the principal medium of governance on climate change and on satellite observation. The ability to promote cooperation, to channel concurrence into efficiency and to encourage visibility on their respective roles are key objectives for involved governance bodies. Beside these long-established objectives, global governance will have to integrate a growing interconnectivity between geographical scales and local authorities' implication (such as California). This integration will be an important cooperation driver as localities are becoming stronger political voices. In parallel, global environmental governance faces a need for reinforcing an integrated approach of interdisciplinary expertise. The WMO interviewed expert suggested two main areas, social sciences and psychology, to ensure application and acceptability of mitigation efforts.

(iii) Parties and non-states actors' interest: The development and integration of space-based observation in the GST will also depend on other actors' interest even more, their ability to advocate for them. States parties, especially without space programs, could perceive space-based monitoring as a threat towards their sovereignty, but also as an opportunity. First, space-based services will provide additional resources to facilitate costly and complicated GHG reporting. Second, smaller vulnerable countries to climate change, such as insular Pacific states (Redon M., 2019), will have new diplomatic leverage to assess the behaviour of large emitters states. Non-state actors will also express polarized interests. Some emitting sectors might be concerned by a reinforcement of control over their emission policies whereas environmental activists will access precious data to support their claims. All these interests, complementary and in opposition, will be expressed differently depending on time, space and social belonging influencing global governance.

The integration of satellite GHG observations in the Paris agreement governance raise significative multidisciplinary issues, besides technical considerations. From these case-study results, policy recommendations are addressed below.

3.3. Confronting the case study to the theoretical framework

The theoretical framework set in this research influenced the analysis of the case study, emphasizing the complexity of space-based data in global governance. Moreover, the master thesis tries to confront the case study and the theoretical framework to highlight broader perspectives on the role of scientific expertise and its articulation in the policymaking process. As mentioned in the theoretical framework, the matrix considers 5 entries: 3 voices (scientists, policymakers, citizens) and 2 concepts (expertise and responsibility).

3.3.1. Redistribution of expertise and responsibility

Based on elements of the case study research and the interviews, this section aims to address the complex synergy between the three voices of the expertise-responsibility diptych. The research suggests outputs that would fit in the understanding of science in public policies. Therefore, the context under study is that of *science for action*, excluding the scientific research for the sole purpose of knowledge.

3.3.1.1. Value chain of data: redistribution of expertise

A starting point of the analysis is data used in the public policy, such as space-based data, which are perceived differently by the three voices. The transversal analysis of the case study suggests that data have their own value. Therefore, the *value chain* of the data helps understand the link between voices and how scientific expertise is redistributed between them to support their own expertise.

Data production is set in a *value chain* following a process to produce added value. Within the chain different steps are involved[35]:

(i) creation of the medium to produce the data (for instance, the instruments and the satellites),
(ii) codification of data to establish homogeneity and comparability,
(iii) sharing of the data such as through an open-data policy,
(iv) diffusion of data products, services, visualization to users,
(v) strategic analysis of the data portfolio: which data are lacking or available? Which risks are associated?
(vi) evaluation of the process, quality assessment of data and their use.

Each phase involves different expertise and arbitration to produce added value. The three voices identified within the theoretical framework are involved differently by providing and capturing the value. Even if the division between scientists, citizens, and policymakers is porous[36], to provide a clear overview they will each be the object of following paragraphs.

3.3.1.1.1. The scientific expertise: a pivotal expertise

Earth system scientists remain the central expertise figure as they intervene in each step of the value chain.

Firstly, the collection of climate data is the result of scientific research needs. For instance, these data are required for the modelling of climate change phenomena, at the core of the rise of environmental policies (Aykut S., et al., 2015). Indeed, scientific concerns, expressed through institutions such as the IPCC or the WMO (*expertise of consensus*), are the starting point of global governance on climate change. Therefore, scientific expertise is advocating for means to enhance climate knowledge, including space-based remote sensing. Secondly, their *expertise of service* is needed to design satellites, codify data, conceive data products and services, and interpret space-based observations. As they are produced by scientific expertise, data products appear objective. The perception of objectivity and trustworthiness is an important part of the added value of EO products. By consequence, once modelled and interpreted, data are supporting the scientific discourse in the policy-making process and used to justify policies. Therefore, the scientist's voice is capturing the value of data as a token of objectivity.

When intervening in policy, the rationality of scientific expertise acts as a substitute for the subjectivity of opinion (Fontaine, P., 2008), and legitimates policy recommendations given by scientific bodies. Furthermore, scientific discourse is perceived as trustworthy when fulfilling the ideal of detachment (Feldman, J., 2002), between obtained results and

[35] The space-based observations *value chain* is inspired by the knowledge value chain defined by Ermine, J.-L. et al (2012).
[36] For instance, the scientist is also a citizen and its expert, influencing the expertise by ideology and personal opinion. This aspect is not ignored but has not been under enough investigation to be fully incorporated.

the person behind them. Science tends to erase the fact that knowledge is not self-existing but has been "discovered" or "built" by actual persons (ibid). Space observations are partially contributing to the detachment ideal by increasing the physical distance and homogenizing the means of data collection globally. As a result, outer space data would be perceived as more objective by some experts in the field. As observed during interviews within the research, scientific experts in this field frequently emphasized the inability of measurement instruments *to lie* by opposition to bottom-up methodologies involving multiple actors to collect data[37]. By contrast, the debate on investing in satellites instead of in-situ stations was not centred on the falsehood but on scientific uncertainty.

The interesting lead is how scientific expertise *dialogues* with other sources of expertise. Even if extensive investigations would be necessary to refine this affirmation, this research suggests that: (i) within the expertise network debates would lean towards using rationality to question other scientific expertise, (ii) scientific expertise tends to feed its own narrative of objectivity by their own production (such as space data) and by expressing doubts on other types of expertise.

However, the actual consequence of these trends is not to set the scientist in opposition with other expertise. On the contrary, the scientific expertise, because is perceived by modern society as objective, is easily diffused within other expertise. Hence, the scientific expertise is considered as a *pivotal* expertise in the value chain and between the different *voices.*

3.3.1.1.2. The policymaker expertise: an arbitration expertise

The expertise of the policymaker is not always considered as independent source of expertise. The identification of the policymaker as an expert is debatable, depending on the conception of expertise. This research retains a broad definition of expertise, policymakers are considered as a form of expert on the decision-making process. Thus, the "object" of their expertise would be the *arbitration* capacity to reach policy-objectives.

Following from the case-study, the integration of the policymaker in the value chain is quite straightforward and could be synthetized as: expressing the need for technical expertise, financing, ensuring the monitoring of space programmes, and exploiting the results in policy (e.g., conception, implementation, and evaluation). By intervening in the value chain, the policymaker's expertise provides a political and social value to produced data. This political/social value is important to highlight the benefit of scientific research to society and increase visibility of the outputs. On the other side, the objectivity of scientific expertise-based data legitimates policy choices. This way, the policymaker's expertise also captures added value from the data. In the case of space programmes, providing explicit operational application is a key stake to justify public funding (Odona, M., 2017). Thus, the policymaker's expertise serves to channel scientific expertise towards policy tools such as in the Copernicus programme. Indeed, space EO programmes overlap diverse objectives,

[37] For instance, the quality of the methodology depends on the possibility to rely on strong statistical infrastructures and on means invested to compile the inventory.

as described by Lamy et al. (2013): scientific, technologic, commercial, military, geo-strategic. All these *logics* are synthetized in a “logic of autonomy” towards other countries by conducting one’s own space programme.

The coexistence of different goals and the way they are articulated is directly implying the *arbitration* capacity of the policymaker’s expertise. This research suggests that the strong interconnectivity of heterogenous purposes has an ambivalent impact on scientific expertise. On one hand, political aspects in science-driven projects might discredit the scientific discourse, by weakening the ideal of detachment. On the other hand, the policymaker’s arbitration expertise encourages consensus, thus reinforcing scientific cooperation. Both dynamics have occurred in the IPCC. At first the intrusion of policymakers has been perceived as a threat to the quality of scientific outputs, while it eventually stimulated the will to build consensus on the topic of climate change and anthropogenic emissions (Rocle, R., 2009).

Finally, as suggested above, scientific oppositions are articulated around debate on different rationalities. As objectivity benefits scientific expertise, lack of scientific consensus leads to confuse other voices on which rationality to trust. This aspect, highlighted by the CITEPA and Ministry of Research interviews, alters the added value of data used in policies. Therefore, by choosing a given source of scientific expertise, the policymaker acts as a mediator between scientific expertise.

3.3.1.1.3. The citizen expertise: a “ground-based” expertise

Considering the citizen as the third voice is a complex statement. The *citizen* covers different realities and stands as the most porous category. Here, the “citizen voice” is considered as a narrative expressed by non-scientists and non-policymakers. The figure of the judge is also voluntary excluded, as it is perceived as neutral. To simplify the analysis, two main levers of actions influencing the policymaking process are retained: (i) private companies intervening on the same field as the scientist voice, (ii) advocating action of citizens explicitly looking to influence a specific policy.

Private initiatives are growing in the environmental field including on space based GHG emissions monitoring. For example, the company GHGSAT targets fossil energy industries to offers them a monitoring system of CH4 emissions via existing open datasets and its own micro-satellites constellation. The existence of private companies, by driving a market and participating to strengthen technical knowledge, is adding value to public policies acting on the same field. Also, as mentioned by the CNES expert (SCO), private initiatives push towards more innovative solutions. Enterprises are using their *ground-based* expertise to assess market needs and channel scientific expertise to answer them. The space field is particularly relevant a sector to witness the interaction between private companies, scientific experts and policymakers. For instance, the NASA develops conjointly with SpaceX the first commercial human lander on the Moon at the Horizon 2022 (NASA, 2021). On a more general approach, industries are producing the intermediary objects in scientific network cooperation. Industrial private companies are indispensable in science-drive policies. As a result, they are capturing value through public funding and the exploitation of data (policies' products). However, this involvement of private companies may also harm credibility of other expertise: scientific expertise appears less independent, and the arbitration capacity of policymaker's expertise is seen as biased.

Besides private initiative, citizens are taking part in the decision-making process through advocating for their positions or by looking for accountability. As underlined by Ministry of Research and of Ecological transition interviewees, citizens are the "last mile" for implementing policies; they embody a local form of expertise or as called here *ground-based* expertise. Acceptability is a condition of implementation of any policy and is influenced by the perception of the credibility of the other voices expertise. In this context, citizens are analysing the added value of data supporting the policy. Then, the synergy between all forms of expertise is determinant for the citizen to endorse policies. Multiple ways are used by scientists and policymakers to obtain citizens' approval. Firstly, user-friendly communication tools are a relevant way to increase awareness. As such, the field of "environmental communication" is a growing area of research and experimentation (Catellani, A. et al., 2019). Innovative medium of communication is then a lever of awareness such as the use of EO imageries. Recently, the Google Earth Time-lapse service was launched (April 2021) to observe evolution of satellite imagery from 1984 to 2021[38] and the impact of human activity on the environment. The launching video collected more than 2 million views in 5 days. Secondly, the *expertise of engagement* is expressed through co-constructive approach (participating to a better synergy between expertise and mutual acceptability). An example raised on the case study was the Copernicus co-constructive policy for data services and product. In the same way, Ministry of Research researchers highlighted the example French Citizenship Convention for the Climate[39] where all forms of expertise (citizens, policymaker, scientific) are engaging to define environmental policy in a same time and space. Through the approach of co-construction, citizens are producing (co-construction as a data user) and capturing value (co-decision making).

Finally, at the end of the value chain, data are used as an independent mean to challenge the accountability of policymaker's expertise. Accountability is based on (i) transparency, (ii) the possibility to evaluate. Both are carried by open-data policies. As the case study gives a substantial analysis of the former, this last section shall focus on policy assessment through data produced by scientific expertise. Related to the case study, the emergence of "satellite-based activism" supports the argument. "Satellite-based activism" is the use or remote sensing and visual representations collected from the outer space to monitor government engagements notably on human rights and on the protection of environment (Rothe, D. et al., 2018). The use of this medium shows how the citizen is capturing the value of the data to support its own interests. The research argues that the value of the data will become a rising consideration as citizen activism targeting policy accountability needs data as supporting evidence. This consideration is essential as citizens

[38] From Landsat and Sentinel-2 observations.
[39] Convention citoyenne pour le climat.

resort to legal proceedings to evaluate policy implementation, a growing consideration in the environmental field as mentioned in the interview of the government commissioner.

3.3.1.2. Different voices, different expertise: redistribution of responsibility

This research argues that the disconnection between the understanding of expertise distribution leads to confusion when addressing the issue of responsibility.

As mentioned in the theoretical framework, the notion of *responsibility* in environment policies is particularly decisive. On a broader perspective, assess responsibility is a key question to apprehend the role of each voices in policymaking process. In the case study, governance was seen to be significantly influenced by the change of paradigm between the Copenhagen COP and the Paris Agreement, partially because scientific expertise was not leading the project. This appraisal, supported by the WMO expert, is not unequivocal as discussed above. At its core, this debate questions the place of the scientist and the policymaker in the monitoring of policies.

Interviews have brought complementary assessments on a clarification of respective responsibility.

Ministry of Research interviewees argued for a clear distinction between responsibility of the scientists and policymakers taking the example of the Aquila earthquake (2009), where six scientists were charged as they expressed reassuring statements to the population before the disaster (Abbott A. et al., 2014). In this context, the responsibility of the scientist is to provide an expertise (*expertise of service / expertise of consensus*) but not to arbitrate the decision. The same way, a French MP interviewed, who is a member of the Parliamentary Office for the evaluation of scientific and technologic choices[40], claims that there is a need for a clearer role repartition of responsibility considering that the scientific expertise has a growing role in policies, especially concerning environment and health issues.

However, in practice, the respective position of scientists and policymakers is not as evident, inviting questions on the articulation of responsibility. First, interviewees working in policy-related institutions (ministries and national assembly) have scientific academic backgrounds and maintain strong links with scientific network. Secondly, as shown in the case study, governance bodies such as the IPCC or space agencies are both targeting political and scientific consensus. Both examples suggest that, in practice, decisions are a process of co-construction between different expertise, therefore responsibility cannot be entirely independent. This is why data and, more broadly, knowledge produced by scientific expertise should be considered as social and political objects. Moreover, the predictive aspect of science and its impact on policy implies a growing responsibility of scientific expertise pursuant to the precaution principle.

[40] Office parlementaire d’évaluation des choix scientifiques et technologiques.

The responsibility of citizens is more ambiguous. As underlined by the Ministry of Research researchers, their *ground-based* expertise, is crucial to construct policies at a local scale. As they participated, they bear a responsibility to permit the operational implementation of policies including in their economic activities. In the case study, this aspect is illustrated by the will to increase the monitoring of private enterprises' emissions such as mentioned in the Copernicus user interview. However, constructing a global or national significance to citizens expertise remains complex considering its local scale. Furthermore, as regards accountability, it could be further discussed if citizens have a responsibility to advocate for transparency and policy evaluation.

3.3.2. Global contributions to the articulation between scientific expertise and public policy

Even if the complex synergy between voices and the diptych expertise-responsibility cannot be fully addressed, the confrontation between the case study and the theoretical framework raises the following reflective avenues in accordance with hypothesis number 6:

(i) Technologic development, and more specifically that related to the outer space, influences the added value of knowledge and its insertion in the policymaking process. However, the added value of technical means should not be overestimated.

(ii) Scientific expertise has a growing pivotal position in global and national policies, but its understanding and evolution is co-dependent on the other types of expertise. Further investigations on citizens' expertise are also needed to clarify the link between scientific expertise accessibility and citizens' responsibility on the policymaker accountability.

(iii) Unclear division of responsibility weakens the credibility of expertise and the value of data / information provided by the expert. When responsibilities and expected outputs are not expressly defined, the decision-making process tends to be unsatisfying.

The output offers a potential, yet to be refined, framework:

Concept / Voices	Scientists	Policymakers	Citizens
Expertise[41]	Service – Consensus Pivotal	Consensus – Engagement Arbitration	Engagement Ground-based
Responsibility	Scale: multiple	Scale: limited to their mandate / may influence globally	Scale: mainly local to national
	Provide relevant data / information taking in account their social and political value	Ensure transparency and clarity on the distribution of responsibility and on the way, expertise is incorporated in the decision process	Transparency in their economic activities Provide their expertise to reinforce acceptability and policies implementation

4. Conclusion and recommendations

4.1. Main results and limitations

The Paris Agreement is a turning point as regards global GHG emissions monitoring. By setting the ambition mechanism, the requirement of GHG reporting is extended to all parties based on a bottom-up methodology. This method, by multiplying activity data by emission factors, gives an overview of the GHG balance (emissions / retrieval by sinks) at a national level. GHG inventories, already provided annually by Annex-I parties, are complementary with top-down methods. The latter provides measurements mainly from in-situ networks. Combining the two methodologies reduce incertitude on emissions and on carbon sinks, however only three countries (Australia, Switzerland and U.K.) are using top-down methodologies in their GHG inventories. Overall, considering uncertainties in the bottom-up reporting and knowledge gap on carbon cycle, data are lacking. To address this issue, space program such as Copernicus, through the COCO2 mission, are aiming to measure GHG anthropic emissions from space, contributing to a global monitoring and verification capacity to support the Paris Agreement ambition mechanism.

This research discussed this ambition, its impact on global governance and confronted it to theoretical framework. The following outputs are presented as an answer to the hypotheses and to indicate their limits:

(i) Hypothesis 1: Satellites are a relevant channel to provide data to complete top-down methodologies and support a global monitoring capacity. However,

[41] Presented as: Irène Thery / This research result.

technical uncertainties remain strong. Moreover, investing in in-situ networks remain a priority to reduce gap in GHG measurements.

(ii) Hypothesis 2: Earth Observation space programmes are strengthening scientific cooperation as they require an important mutualization of scientific expertise. More specifically, European space policy, such as through the Copernicus programme, adopts a cooperative, approach gathering EU members states and contributing missions led by non-EU states. Moreover, European projects explored in this research (e.g. CHE and VERIFY) are also bringing together international scientific experts. In this sense, satellites and space-based data are intermediary objects emphasizing scientific cooperation.

(iii) Hypothesis 3: Space-based data and their open-data policy is a tool to reinforce transparency. Examples of operational uses of Earth observation (e.g. ECVs monitoring from space, IAEA uses of imagery, satellite-based activism) suggests that GHG emission mitigation policies may benefit from space-based GHG monitoring in the future.

(iv) Hypothesis 4: Space-based data are perceived differently as they challenge traditional technology and the concept of sovereignty. However, unlike the first intuition of this research, outer space knowledge is polarizing.

(v) Hypothesis 5: The role of the scientific expertise is key under the Paris Agreement ambition mechanism especially when a global monitoring and verification capacity will be operational. Nonetheless, the presumed transfer of responsibility to scientists remains ambiguous. The Paris Agreement shifted the paradigm from a scientific led verification to cooperative approach between actors to help states towards mitigation. Moreover, interviews underline the need to set clear divisions between responsibilities in the decision-making progress. Further investigations would be required to consolidate this hypothesis.

(vi) Hypothesis 6: The confrontation of the case study to the theoretical framework allowed to highlight the complex synergy between three voices narratives (scientists, policymakers and citizens) and the diptych expertise-responsibility shaping the perception of scientific knowledge / data. As a result, the research suggests three categories of expertise: pivotal (scientists), arbitration (policymakers), ground-based (citizens). All of these sources of expertise are contributing to create added value to scientific data but are also capturing their value to strengthen their expertise. From this distribution, specific responsibilities emerged in the decision-making process.

Furthermore, other limitations must be underlined. This research only touched on technical considerations and the implication of the emergence of private industries (*New space*). These topics could be explored in detail to reinforce the relevance of the case study. Moreover, the theoretical output on the insertion of science expertise in public policies should be confronted to other case studies to ensure its applicability. Also, due to time constraints, interviews could not fully capture the relationship of citizens to EO.

Finally, space remains a complex, yet fascinating, source of knowledge, innovation and fantasies. Multi-disciplinary studies are essential to draw the edges of what it means for humanity to cross the final frontier: the outer space.

4.2. Recommendations

Based on the results, the following policy recommendations are made. The recommendations 1 to 6 are based on the case study whereas 7 and 8 aim to offer perspective for strengthening the theoretical understanding on new technologies and scientific expertise.

Recommendation 1: To reduce uncertainties and make the most of current available technologies, setting goals to integrate progressively top-down methodologies to more national GHG inventories.

Recommendation 2: Based on the Delhi declaration, clarifying the articulation between space-based observations and the Paris Agreement mitigation goals by addressing concerns on sovereignty. The modalities of integration of space-enabled measurement into the ambition mechanism should be explicit, especially if led by a regional political force (the EU).

Recommendation 3: As highlighted in the ESPI brief N.14, based on GEO work, implementing a governance system, specific to the Paris Agreement, of space-data / model integrity certification to ensure mutual trust on monitoring capacity.

Recommendation 4: As the ambition mechanism will incorporate non-Annex I Parties in the reporting synergy; the question of imported emissions should be addressed.

Recommendation 5: The integration of other actors, notably local authorities, industrial enterprises and citizens should be reinforced when setting new space missions.

Recommendation 6: A global emissions monitoring capacity should integrate social and economic indicators to ensure an equitable consideration of emissions at the light of development issues.

Recommendation 7: At a European scale, a study could be conducted on the perception of outer space knowledge / data by citizens.

Recommendation 8: Questions on expertise and responsibility could be confronted to further case studies to set a comprehensive framework for policies involving important scientific expertise input.

GLOSSARY

AD: Activity Data

AFOLU: anthropogenic emissions data from Agriculture, Forestry, and Other Land Use

CAMS: Copernicus Atmosphere Monitoring Service

CDS: Climate Data Store

CHE: Carbon Dioxide Human Emissions

CH4: Methane

CITEPA: Centre technique de référence en matière de pollution atmosphérique et de changement climatique

CLMS: Copernicus Land Monitoring Service

CMEMS: Copernicus Environment Monitoring Service

CNES: Centre National d'Etudes Spatiales, National Center for Space Studies

CNTBT: Comprehensive Nuclear-Test-Ban Treaty

COP: Conference of Parties

CO2: Carbon dioxide

CO2M: Copernicus CO2 Monitoring

CoCO2: Copernicus carbon dioxide service

C3S: Copernicus Climate Change Service

DLR: Deutsches Zentrum für Luft- und Raumfahrt, German Center for Air- and Space-Flight

DPRK: Democratic People's Republic of Korea

ECMWF: European Centre for Medium-Range Weather Forecasts

ECV: Essential Climate Variables

EDGAR: Emission Database for Global Atmospheric Research

EEA: European Environment Agency

EF: Emission Factors

EO: Earth Observation

ESPI: European Space Policy institute

ESA: European Space Agency

EU: European Union

EUMESTAT: European system meteorological satellites

GAFAM: Google, Amazon, Facebook, Apple, Microsoft

GAW: Global Atmosphere Watch

GCOS: Global Climate Observing System

GEO: Group on Earth Observations

GEOSS: Global Earth Observation System of Systems

GHG: Greenhouse Gases

Gifas: Groupement des industries françaises aéronautiques et spatiales, French Aerospace Industries Association

GOS: Global Observing System

GOSAT: Greenhouse Gases Observing SATellite

GST: Global Stocktake

H2020: Horizon 2020 programme

IAEA: International Atomic Energy Agency

IG3IS: Integrated Global Greenhouse Gas Information system

IPCC: Intergovernmental Panel on Climate Change

MVS: Monitoring and Verification Support

NASA: National Aeronautics and Space Administration

NDC: Nationally Determined Contributions

NIR: National Inventory Reports

NO2: nitrogen dioxide

OCO-2: Orbiting Carbon Observatory

OMI: Ocean Monitoring Indicators

PA: Paris Agreement

SCIAMACHY: Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY

SIAU: Satellite Imagery Analysis Unit

SBTSTA: Subsidiary Body for Scientific and Technological Advice

SCC: Social Cost of Carbon

SCO: Space Climate Observatory

SSM: Surface Soil Moisture

TFI: Task force on National GHG inventories

UK: United Kingdom

UN: United Nations

UNFCC: United Nations Framework Convention on Climate Change

USA: United States of America

VERIFY: Verifying Greenhouse Gas Emissions

WMO: World Meteorological Organization

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ANNEX

Figure 1 – Categories of Planet Boundaries

Source: Rockström, J., et al., (2009)

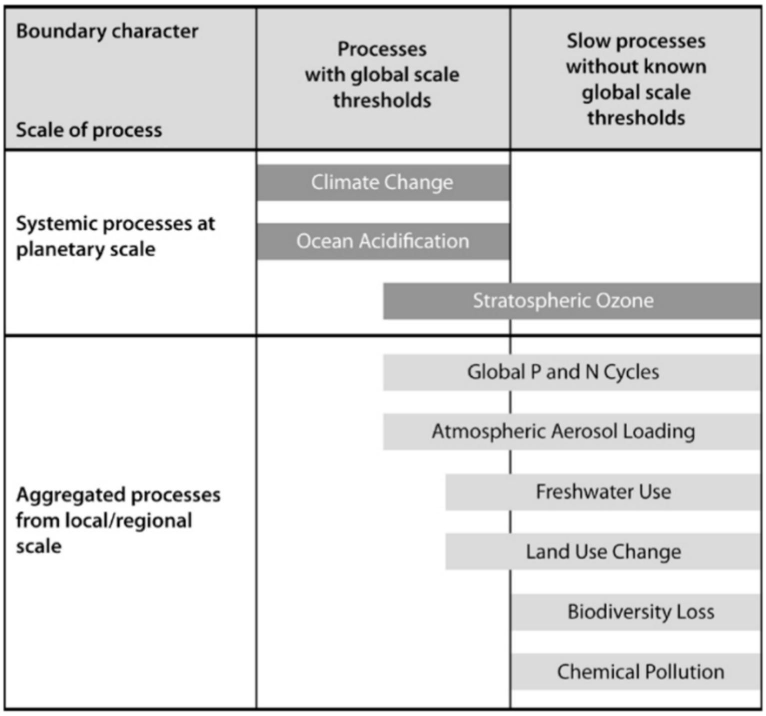
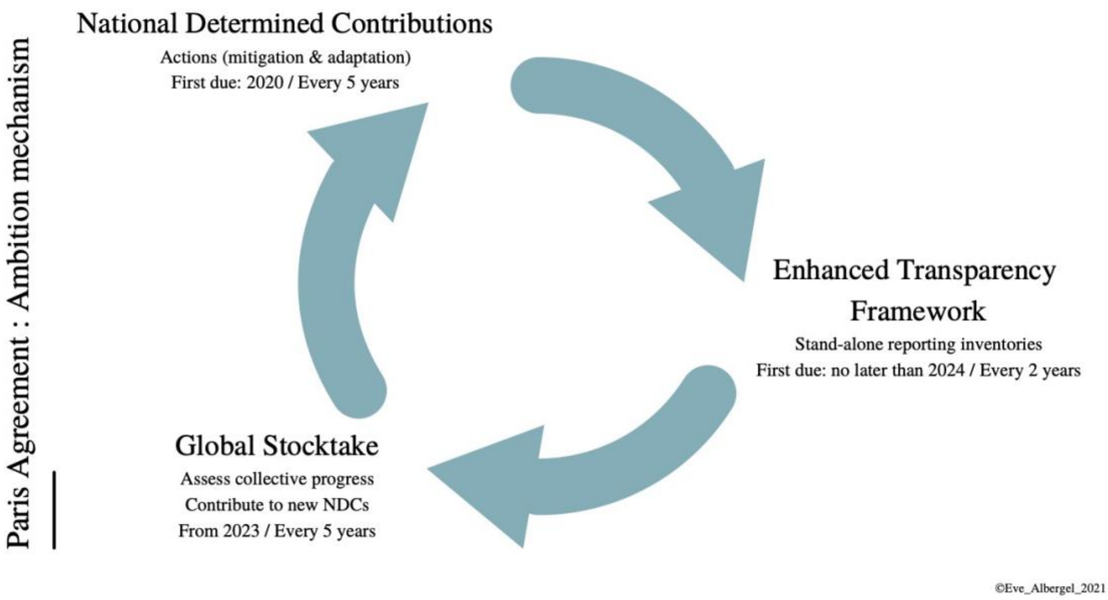
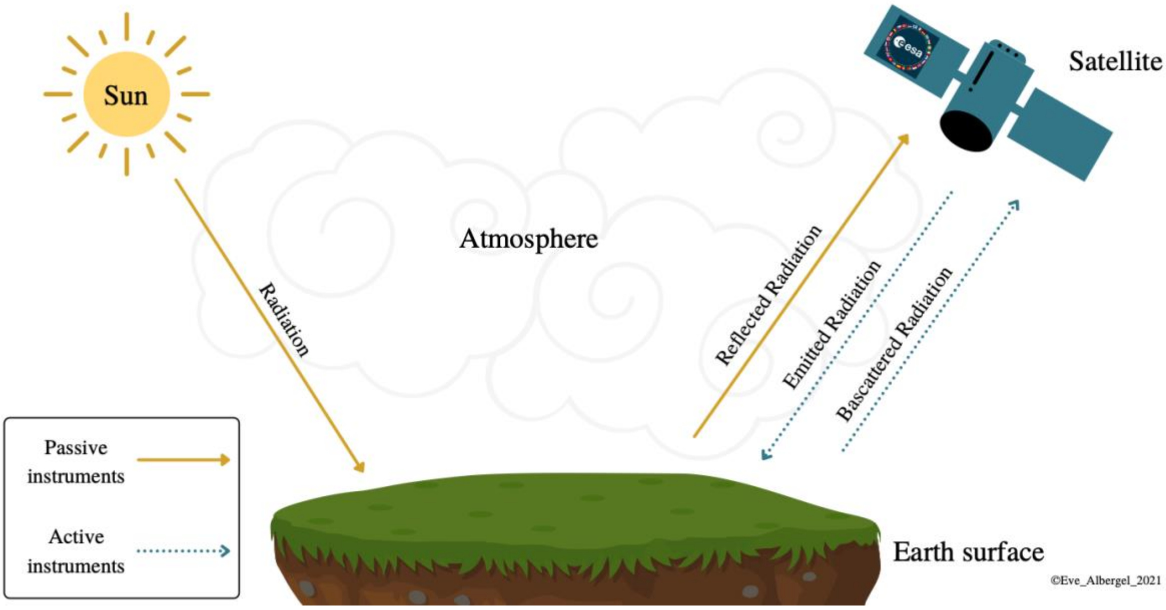


Figure 2 – Paris Agreement Ambition mechanism



(Made on Canva)

Figure 3 – Satellite Remote sensing



(Made on Canva)

Figure 4 – Diagram: CO2MSV capacity

Source: Janssens-Maenhout, G. et al., (2020)

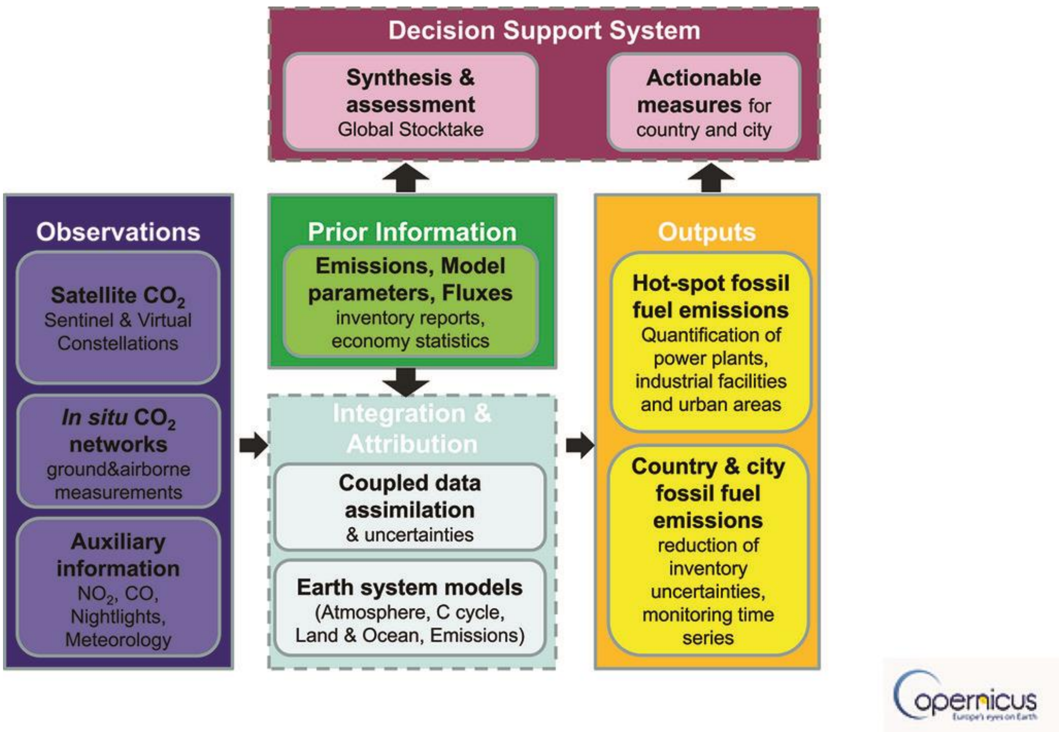


Figure 5 – CHE CO2 anthropogenic emissions monitoring system

Source: CHE website

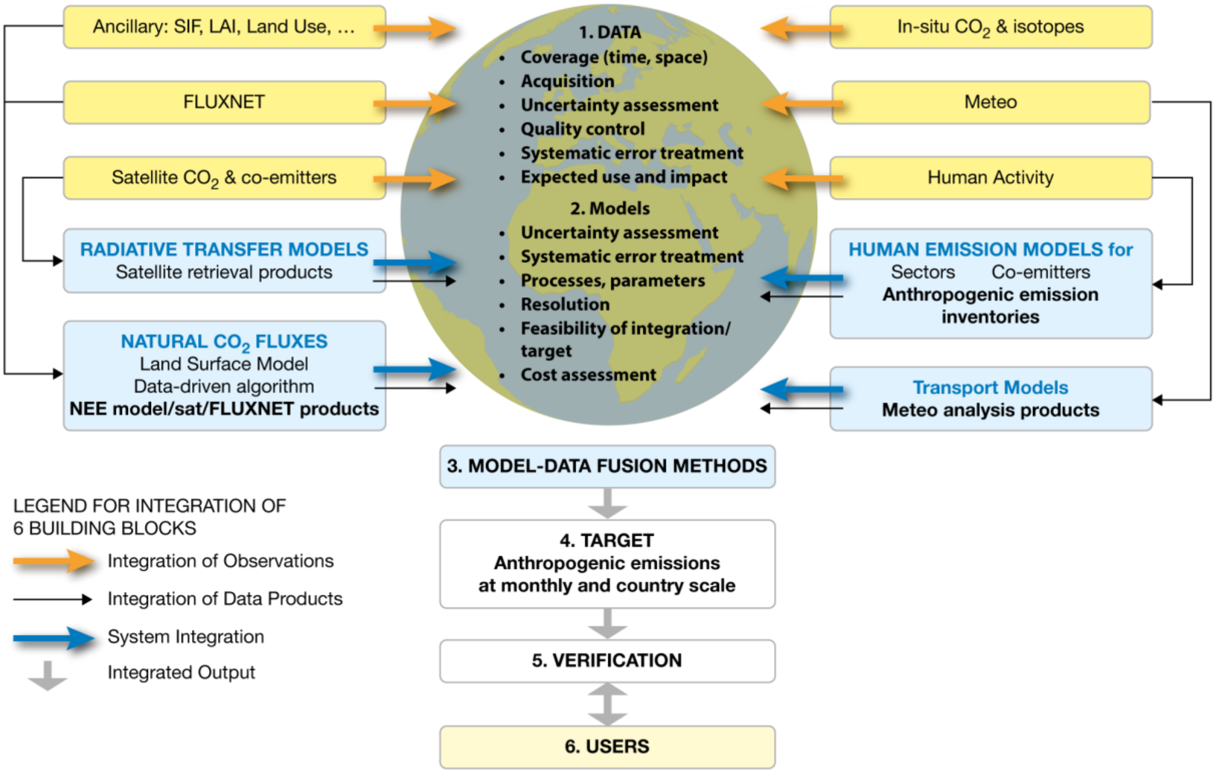


Table 1 – List of interviews

Presented in chronologic order. The function mentioned is the one gave by the participant / the one on which they were interviewed.

Function	Institution	Type of interview	Modalities
Legal counsel and public Affairs	Ariane Group	*Framing interview*	Phone call Language: French
Expert on atmospheric composition form Space	CNES Space Climate Observatory (SCO)	*Framing interview*	Phone call Language: French
Engineer, GHG inventory expert	CITEPA	*Framing interview*	In person Language: French
Government commissioner (Rapporteur public, 6ème chambre[42])	Council of State (Conseil d'Etat)	*Framing interview*	Video call Language: French
Diverse representatives of the French Aerospace industries association, Ariane Group and former French Minister of Research	Groupement des industries françaises aéronautoques et spaciales (GIFAS)[43]	*Workshop considered as in-depth interview*	Video call Language: French

[42] The 6ème chambre (Sixth Chamber) is, in particular, specialized on cases related to environment law.
[43] Referred as GIFAS interview in the research.

French coordinator of the national point-of-contact for the Horizon 2020 programme, cluster 4 (generic technologies and spatial industries)	CNES	*In-depth-interview*	Phone call Language: French
Head of the Mission “Climate, Earth Observation and evolution of the Earth system”, Member of the French delegation to the Copernicus User comity and to the ESA Progamme Board on Earth Observation	French Ministry of the Ecological Transition	*In-depth interview*	Video call Language: French
Policy officer to the “Climate change mission”			
Interministerial coordinator Copernicus and GEO	French Ministry of Research	*In-depth interview*	Video call Language: French
Head of department “Space and Defence policy” deputy			
Head of the Atmospheric Environment Research division at the WMO-GAW, Head of the IG3S Secretariat	WMO – UN	*In-depth interview*	Video call Language: English
Chief of Staff to the CEO	Sodern, ArianeGroup	*In-depth interview*	In person Language: French
French MP at the National Assembly, member of the Parliamentary Office for the evaluation of scientific and technologic choices	National Assembly	*In-depth interview*	Phone call Language: French
MSc Student in Carbon Management, Copernicus data user	University of Edinburgh	*In-depth interview*	Written form Language: English

Table 2 – States and European Space governance bodies

States	UE	ESA Parties	EUMETSAT	ECMWF	Contributing missions (Copernicus)
Austria	X	X	X	X	
Belgium	X	X	X	X	
Bulgaria	X	O	X	O	
Croatia	X	O	X	X	
Czech Republic	X	X	X	O	
Denmark	X	X	X	X	
Estonia	X	X	X		
Finland	X	X	X	X	
France	X	X	X	X	X
Germany	X	X	X	X	X
Greece	X	X	X	X	
Hungary	X	X	X	O	
Iceland			X	X	
Ireland	X	X	X	X	
Italy	X	X	X	X	X
Latvia	X		X	O	
Lithnunia	X	O	X	O	
Luxembourg	X	X	X	X	
Netherlands	X	X	X	X	
Norway		X	X	X	
Poland	X	X	X	X	
Portugal	X	X	X		
Romania	X	X	X	O	
Slovak Republic	X	O	X	O	
Slovenia	X		X	X	
Spain	X	X	X	X	X
Sweden	X	X	X	X	
Switherland			X	X	
Turkey			X	X	X
United Kingdom		X	X	X	X
Canada		O			X
Cyprus		O			
Malta		O			
Japan					X
U.S.A.					X
Serbia			O	X	
North Macedonia				O	
Morocco				O	
Algeria					X
Nigeria					X
China					X

Legend:
X = Parties / Member state
O = Contributing / Other status

Box 1 – Copernicus services: CMEMS and CLMS

The Copernicus Environment Monitoring service (CMEMS) is the marine service which tackles marine safety, by improving ship routing, and contributes to the understanding of the variation of related ECVs. These ECVs are meant to assess “the health of oceans” through the Ocean Monitoring Indicators (OMI). Acidity, temperature, sea levels are, for instance, essential variables to assess the CO2 absorption capacity of the ocean. According to the fourth Ocean State Report (2020), the ocean absorbed 20 to 30% of total anthropogenic emissions in the last two decades. Variables aim at evaluating the absorption of CO2, at understanding the impacts of an increase in such absorption on other components of marine equilibrium, and at anticipating future evolutions. For example, indicators such as the concentration of Chlorophyll-a are monitored through space-based remote-sensing and allow to assess the primary production (synthesis of organic carbon by organism such as phytoplankton), in turn giving information on CO2 fixation in oceans, available food for other organisms and oxygenation. Once applied to socio-economic consideration such understanding is a powerful indicator of the costs of environmental ocean alterations. The combination of models on CO2 absorption and the Social Cost of Carbon (SCC) estimates an economic value of the Mediterranean Sea as a carbon sink to 2,1Billion in 2018 (CMEMS, 2020).

As well as oceans, land is a carbon sink impacted by human activity. The Copernicus Land Monitoring Service (CLMS) provides bio-geophysical products of global land surface. Sink capacity of land depends on a broad range of variables such as surface soil moisture (SSM), surface temperature or land occupation (Green, J. et al., 2019). For instance, SSM is recognized as a ECV as it is: (i) a key element of water and heat fluxes between the ground and the atmosphere (impacting air temperature and humidity), (ii) a sensitive indicator to external variation which allows to assess climate change. Therefore, this indicator plays an important role in the understanding of the carbon cycle and in the evaluation of Earth energy. Notably, SSM is measured from space by the satellite Sentinel-1 C-SAR which allows for a global understanding but also a local assessment when combined with *in situ* data (Bauer-Marschallinger B. et al., 2018).

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Earth observation satellites: Monitoring greenhouse gas emissions under the Paris Agreement

Eve Albergel

Abstract

As anthropogenic greenhouse gas emissions are rising; climate change mitigation is becoming a top global priority. Under the Paris Agreement, Parties agreed on the ambitious goal of holding in the global average temperature below 2°C. However, capacity to monitor state GHG emissions mitigation performance remains unavailable globally. Through its Earth Observation programme, Copernicus, the European Commission aspires to contribute to close this gap and set a global monitoring verification capacity. Satellite measurements to track progress towards the Paris agreement raise issues on their feasibility and on the impact on global governance. This research, through a qualitative methodology, discusses these questions as a case study on how scientific expertise incorporates in public policies. Its outputs show that, in the future, satellite will provide valuable data to support a global monitoring capacity even if this technology should not be overestimated. On global governance, space-based observations may constitute a lever of transparency and cooperation but also raise concerns on sovereignty. Finally, to give a broader understanding of public policies, the case study results have been confronted to a theoretical framework on the diptych expertise-responsibility, suggesting insights on the articulation between science expertise and the decision-making process.

Key words

Paris Agreement, Climate change, Earth Observation data, Satellites