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POLLUTION AND CLIMATE CHANGES

FEEDBACK FROM SPACE FOR SUSTAINABLE CITIES AND COMMUNITES

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Abstract

Cities represent more than 50% of global population and are the main responsible of energy consumption in the world, accounting for more than 70% of CO^2 emissions deriving especially from energy and transportation sectors (Global Covenant of Mayors, 018). At the same time, also cities are negatively affected by Climate Change in terms of infrastructure, economy (e.g. agriculture), public services, urban planning and food security, all crucial dimensions for sustainable development.

In this scenario, urban planners and policy makers are called to identify innovative solution against crucial challenges related to the evolution of city and environment planning and management. Based on the City Sensing [1, pp. 10-13] approach, the aim of this thesis is to identify innovative technological approach that can support citizens to monitor the level the air pollutants and carbon emissions through the interrelation of Copernicus satellites, big data and cognitive techniques, in order to improve inclusive and sustainable urbanization and management of human settlements.

Satellites can help cities to become more resilient to climate change in terms of

- prevention of climate change through the development of risk management plans based on satellite data series
- adaptation to climate change thanks to the issue of ad hoc policies and interventions for each city
- communication of climate change in order to develop an informed decision making which foresees in climate change an opportunity rather than a risk.

The project will present how the combination of different technologies such as satellites, sensors, the internet drives the development of a new model of knowledge based on distributed acquisition of information whose combination with other already available data, provide a detailed, real time, dynamic and accessible framework for planning the future of a city. Moreover, the crystallization of these information within recorded blocks of blockchain can even create ‘shared value’ where certified data related to emissions and pollutants are associated with an economic value and resold on the market, in line with the carbon crediting system. In this way the pollutants stop being a problem to become for the cities and start being a solution.

ITA Version: Inquinamento e cambiamenti climatici. Feedback dallo spazio per città e comunità sostenibili

Le città rappresentano, con oltre il 50% della popolazione mondiale insediata, il principale responsabile del consumo energetico del pianeta, producendo oltre il 70% delle emissioni di CO^2 derivanti in particolare dai settori dell'energia e dei trasporti (Global Covenant of Mayors, 018). Allo stesso tempo, anche le città sono influenzate negativamente dai cambiamenti climatici con impatti sulle infrastrutture, economia (ad esempio agricoltura), servizi pubblici, pianificazione urbana e sicurezza alimentare, tutte dimensioni cruciali per lo sviluppo sostenibile. In questo scenario, gli urbanisti e i responsabili politici sono chiamati a identificare soluzioni innovative rispetto alle sfide cruciali legate all'evoluzione della pianificazione e della gestione della città e dell'ambiente.

L'obiettivo di questo lavoro è quello di identificare un approccio tecnologico innovativo, basato sull'approccio City Sensing, in grado di supportare i cittadini a monitorare il livello degli inquinanti atmosferici e delle emissioni di carbonio attraversol'utilizzo di fonti informative prodotte mediante l'interrelazione di satelliti Copernicus, big data e tecniche cognitive, al fine di migliorare l'urbanizzazione inclusiva e sostenibile e la gestione degli insediamenti umani.

I dati provenienti da satellitei possono aiutare le città a diventare più resilienti ai cambiamenti climatici in termini di:

- prevenzione dei cambiamenti attraverso lo sviluppo di piani di gestione del rischio basati su serie di dati satellitari
- adattamento ai cambiamenti grazie alla definizione delle politiche e degli interventi ad hoc per ogni città
- consapevolezza dei cambiamenti in atto al fine di sviluppare un processo decisionale informato che individua nel cambiamento climatico un'opportunità piuttosto che un rischio.

Il progetto presenterà come la combinazione di diverse tecnologie come satelliti per l'osservazione della terra, reti di sensori, Internet siano in grado di supportare lo sviluppo di un nuovo modello di conoscenza basato sull'acquisizione distribuita di informazioni, la cui integrazione con altre fonti già disponibili, fornirà un quadro dettagliato, in tempo reale, dinamico e accessibile per pianificare il futuro di una città. Inoltre, la cristallizzazione delle informazioni prodotte attraverso l'utilizzo della blockchain potrà anche creare "valore condiviso" dove i dati certificati relativi alle emissioni e agli inquinanti sono associati ad un valore economico, spendibile sul mercato, in line con il sistema di contabilizzazione dei crediti di carbonio. In questo modo il contenimento degli agenti inquinanti nelle città smette di essere solo un problema, potendo generare anche una nuova fonte economica.

1 Introduction

Key effects of climate change resulted in the doubling of catastrophic events for the period 1990-2016 [2], affecting especially the most vulnerable subjects: cities. These are the most populated areas of the world with more than 50% of inhabitants and the heart of decision-making process and socio-economic activities [3] [4]. Rapid urbanization and economic growth recognized cities as the locus of economy: sectors' interconnection and economies of scale have in fact improved urban centres' productivity, attracting more and more people [5] and this trend is expected to progress with 70% of the world's population living in urban areas by 2050 [6].

Although being the main driver of economic growth, cities have simultaneously contributed to the most serious increase of environmental degradation since 1990s [7]. The high concentration of population and economic activities as well as their size have critically exposed cities to a great aggregate risk, undermining social and economic development, access to basic services and citizens' quality of life. Economic losses related to climate change and air pollution are extremely high in urban sites, especially in developing countries, with higher indirect costs and extensive human capital loss [8]. On the one hand, strategic economic activities such as agriculture may be negatively impacted, with a subsequent decrease in biodiversity and productivity. On the other hand, both natural disaster and air pollution can lead to accidental and premature death. It has been largely demonstrated that exposure to a toxic mix of particles – particulate matter (PM) – deriving from air pollution is responsible for a wide spectrum of health issues that range from eye irritation to death correlated to cardiopulmonary and respiratory diseases [9, pp. 1-7]. This critical progressive correlation between air pollution and mortality trends not only endangers health security but it also affects economic development of cities as loss and enfeeblement of human capital not only lead to a subsequent lack of work force but also to an unbearable burden on public health with a cost of $5.11 trillion on world's economy in 2013. Moreover, unhealthy, unsafe and less productive urban environment stalls the competitiveness with the subsequent talents' drain toward more liveable sites, and unlocks inclusive prosperity and participation of the poorest segments of the population which are disproportionately impacted by air pollution [10]. International and European mitigation and adaptation policies have been launched since 1980s in order to set up air quality guideline and indicators about PM10 and PM2.5 [11][1]. Setting common standards in fact is expected to significantly reduce mortality and health disease. In Europe, for instance, reduction in PM10 and PM2.5 level according to set limits would lead to an estimated average benefit of €191 and €397 respectively per person per year with and even higher performance in terms of health status and quality of life in case of stricter objectives [12].

Nevertheless, despite standards and projections, in 2013 more than 80% of global population lived in urban districts which exceeded foreseen limits of particulate matter, underlining the lack or the inefficiency of implemented strategies in terms of air quality planning, public communication and regulatory compliance [13].

[1] WHO, 2005; Directive 96/62/EC; Directive 2008/50/EC; Directive 2004/107/EC

Therefore, the decision of this thesis to adopt a city scale approach is the result of a critical analysis and study that has identified urban centres as the main source of air pollution, the most vulnerable target and simultaneously the driver of decision-making and governance. Moreover, city scale research is easily associated to geographical and administrative boundaries resulting in distinct capacity and legitimacy to define policies and allocate resources combining top-down and bottom-up approaches.

However, while bottom-up initiatives for emissions reductions are quite frequent, the role of cities and the interactions with national and international response policies is still largely unexplored, especially in terms of mitigation interventions [14].

For this reason, the aim of this thesis is defining an innovative technological solution for cities against the burden of air pollution and climate change effects.

1.1 Motivation

Air pollution, especially in urban areas, have become one of the biggest negative influences on human health. The main harmful effects are on the environment, in particular carbon dioxide, nitrogen oxides, particulate matter and ozone are the major contributors to global warming today.
IoT sensor technologies and satellite imagery with machine learning algorithms can help us to collect and analyze high-quality data in outdoor air pollution, considering critical pollutants and environmental factors such as temperature or humidity. Furthermore, they can not only measure air pollutants, but can also actively participate in developing solutions for healthier cities of the future.
For this reason, the aim is to use satellite data as an analysis of the decision-making process for the health and economy sectors. Currently, it is not enough to simply report whether the city exceeds the pollution thresholds or not. Therefore, this thesis wants to make the air quality data as much as:

- Precise
- Complete
- Relevant
- Feasible

To do this, in addition to the satellite data, this work takes into account public and open-source monitoring networks, IoT sensors, other sets of environmental, health and economic data that can be defined as “Auxiliaries”. In recent years, the launch of satellite sensors for Earth Observation with spatial and temporal resolutions and, at the same time, with greater radiometric accuracy has paved the way for their use to support the study of air quality issues. The synoptic vision and in particular the daily cycle of measurement repetition of the new satellite sensors provides the potential to monitor the phenomenon of particulate pollution (PP). The issue presents considerable degrees of complexity due to various factors such as technological evolution that causes changes in the nature and quantity of pollutants or the evolution of legislation which, based on scientific evidence of the impact of pollutants on public health, modifies their tolerability thresholds.

Observation via satellite is a measurement method that deserves to be deepened: it is, in fact, a consolidated observation method for the study of atmospheric pollution phenomena on a continental scale but not yet used in a systematic way for monitoring atmospheric and local pollution.

Therefore, it has been largely discussed that the first objective of this thesis is the analysis of satellite data, combined with other technologies, to the detection of climate change and air pollution. However, this analysis is not independent per se: it is rather functional to the formulation of an innovative solution.

In recent years, green roofs have been the subject of study and interest for many. Today, anyone who speaks of green roofs or green infrastructures in the city always winks at the concept of "Garden City[2]", which was theorized for the first time by Ebenezer Howard in 1898. In the world, but in particular in Italy and China, they have begun to modify their cities with increasingly green projects. In fact, the general consideration for green technologies has changed, passing from being appreciated only for their aesthetic usefulness to being integrated into the construction of buildings, public and private, right from the design stage. They have therefore become an essential element of eco-sustainable architecture. Their widespread use is rooted in a pressing need: to make cities more liveable.

If looking at studies done on urban green vertex garden / vegetable roofs the results show that, if built correctly, green roofs can reduce noise and air pollution [15], reduce the "urban heat island[3] (UHI)" effect by 1- 2 ° C, improve the quality of rainwater runoff and alleviate the management loads of water regulation systems; increase the longevity of roofing membranes and reduce the energy consumption of the building [16]. However, only a small fraction, often scientific, points out that the substrates and plants on green roofs have a great capacity of sequestration of the carbon, which has a positive effect on the mitigation of climate change.
The problems due to intense and suffocating urbanization, are everywhere in the world: the city is tremendously hot, its air is unbreathable and noxious, its waterproof cement profiles make it a reservoir for rainwater. These phenomena not only affect the quality of life of citizens, but their very existence.

The solution proposed by this thesis is found in the installation of mosses in specific areas of the city: the mosses are chosen to overcome some limitations related to maintenance and installation. The whole work is driven by the motivation to create a WIN-WIN[4] project: the thesis, in fact, wants to quantify with the greatest possible precision the benefits that technological and non-technological solutions such as mosses and the blockchain are able to bring to each of the three problems set out above and highlight the influence that the climate has on them, through a comparison between different climatic contexts. Furthermore, their effectiveness was also evaluated in view of the future maximum expansion of green roofs, as expected by the cities under study.
The research of the data was mainly based on the estimates collected in the reports drawn up by the cities and, in their absence, they were calculated through consulting scientific publications.

[2] The garden city is a model of urban planning in which neighbourhoods and blocks are surrounded by "green belts", which contain proportionate areas of residences, industries and agriculture.
[3] An urban heat island (UHI) is an urban area or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities. The temperature difference is usually larger at night than during the day, and is most apparent when winds are weak. UHI is most noticeable during the summer and winter.
[4] Win-Win Negotiation: A win-win negotiation is a careful exploration of both the city, the environment and that of the private citizen, in order to find a mutually acceptable result that gives you to all actors involved as much as possible. If they leave the project satisfied with what you earned from the deal, then it's a win for everyone.

Lastly, in addition to the technological, environmental, and social aspects, a purely innovative motivation has led this research. Innovation means no longer thinking about reducing emissions, rather thinking about capturing them. It is important to define an inclusive and virtuous approach where all emissions that technologies still do not allow us to reduce are absorbed, on a planetary level.

The goal is therefore to find in sponge buildings[5] a profound ally to free cities from pollution.

In order to provide basic information for the construction of a new facility – the sponge buildings - in the city, the objectives of this study will be as follows:

- Monitor atmospheric pollutants from satellite
- Identify the most vulnerable areas by satellite
- Identify the buildings that can host "sponge" installations
- Select native plants for the construction and evaluation of the different green roofs
- Analyze the carbon sequestration of each plant-substrate combination.

1.2 Thesis structure

In compliance with the motivation above mentioned, the thesis follows this structure:

- The Introduction is divided into two main parts:

1) In the first part, the literature review of some importance on the topic studied during the research phase is drawn up, in order to define the state of art. The same literature allows us to define the fundamental aspects, problems, objectives and possible solutions related to the climate change and air pollution.

2) The second part defines the hypothesis of the thesis and therefore the scientific question to which this paper wants to answer: the detection and monitoring of pollution from Satellite was the fundamental and central aspect of the entire thesis work and drove the entire research.

- Motivation: it describes the reasons that triggered the investigation of air pollution and climate change. They are not personal reasons, rather scientific ones that have intrigued my person. Being a very crucial topic, especially from a scientific point of view, I was motivated to look for a solution applying remote sensing.

- Context: it presents the reference scenario where the problems and the possible approaches are formulated, including legislation, public policies, urban planning practices, but at the same time also the technological solutions and methodologies that will allow us to address the key problem. Many of these aspects are fundamental for the solution here illustrated and therefore an appropriate prominence is granted to them in this part of the thesis.

[5] the concept is explained below

- Objectives: Direct and indirect objectives are described: the context that precedes this part of the thesis allows the reader to better define which objectives had to be addressed. The objectives described will have followed throughout the thesis work.

- Approach and Methodology: After a definition of the problem and objectives, I move to the heart of the project by describing the entire technological process. This chapter defines the application of the satellite data approach to the topic and describes the methodology that is implemented to reduce the margin between new technologies and planning.

- State of the art: This chapter summarizes the entire research work carried out in the three years of the PhD. It illustrates the satellites' potential in terms of climate change monitoring, including the future perspectives. After a description of the data sources and possible services that can be used for the acquisition of the same, there is also an overview of the libraries and frameworks that can be used for an analysis of air pollution.

- Case Studies: In this chapter the description of the works and projects, available in the literature and correlated with the work proposed by this thesis is carried out. This chapter is essential for defining the starting point and the involvement of these existing projects into the technological approach here presented.

- The thesis project: This core chapter presents all the results obtained during the work carried out. Starting from the raw data acquired, it leads to the creation of the datasets used during the development of the models. The data preparation process is briefly described for each model. In the second part, there are some insights into the techniques used during the analysis, such as GridSearch, to search for hyperparameters, or CrossValidation, to validate the models; and performance evaluation metrics. The results are divided into two macro categories: 'pollutant prediction' and 'organic carbon calculation'. The latter are in turn divided into two categories: the cases that take into account all pollutants and the ones that consider the single pollutant.

- Comparison of experiments with existing realities: a comparative section of the thesis methodology with existing realities in the world is reported.

- Conclusions and future developments.

2 Context

2.1 Climate change

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "Climate change is directly or indirectly attributed to human activity that alters the composition of the global atmosphere and that is added to the variability of the natural climate observed in comparable periods of time". The alterations of the elements of the climate are due to the concentrations of gas in the atmosphere, which in the past were attributed solely to natural phenomena, and today are also linked to human activities. The effects of air pollution are multiple and cause a lot of damage to the environment and to humankind.

Air pollution can be defined as a situation in which substances are present in the atmosphere at concentration sufficiently high above their normal ambient levels to produce a measurable and undesirable effect on humans, animals, vegetation, or materials [17].The concentrations of pollutants in the atmosphere are a measure of air quality. The World Health Organization (WHO) estimates that exposure to ambient air pollution causes each year approximately 3.7 million premature deaths worldwide [18]. Under a business-as-usual socioeconomic scenario, it has been stated that the contribution of outdoor air pollution to worldwide premature mortality by 2050 could double [19] and that air pollution will be the top environmental cause of premature mortality [20]. Depending on the exposure, the effects of air pollution on human health range from subclinical and symptomatic events to increased morbidity and mortality [21]. The acute and chronic exposure to air pollutants–gases and aerosols has been positively associated with respiratory and cardiovascular sicknesses, and lung-cancer [22]. Recently, several European studies have highlighted that there are statistically significant positive associations between nitrogen dioxide (NO2) and Sulphur dioxide (SO2) concentrations with total, cardiovascular and respiratory mortality, particularly in urban areas [23]. Long-term exposure to tropospheric ozone (O3) and particulate matter (PM) has also been associated with increased death risk due to cardiopulmonary causes [24]. O3 is responsible of ~20000 premature deaths each year in the European Union [25].

The degradation of air also results in an increase of the burden of other related diseases, a reduction in life expectancy, and in the increase of health care public spending which convey to air pollution considerable financial and life-quality costs [26]. The United Nation Framework Convention on Climate Change states based on the fifth Intergovernmental Panel on Climate Change Assessment Report [27] that "the anthropogenic driven warming of the climate system is unequivocal, and that climate change is on top of the humankind major challenges". Climate change and air pollution are highly interlinked phenomena.

The radiative forcing (RF) of the atmosphere – a measure of the planetary radiation balance of which climate change relies on –strongly depends on the concentration of greenhouse gases (GHG) such as carbon dioxide (CO^2) and methane (CH4). However, RF is also sensitive to the concentration of short-lived atmospheric pollutants such as carbon monoxide (CO), non-methane organic volatile compounds (NMVOC), O3 (which is considered both a GHG and an air pollutant), and aerosols [28]. Whereas CO, NMVOC, and O3 have a positive RF that enhances climate change, the net contribution of aerosols is yet under discussion due to the complexity of the aerosol-cloud-radiation interactions that include light absorption and back scattering, and the formation of cloud condensation nuclei [29]. It is noteworthy that the implementation of air pollution abatement plans may lead to climate impacts. Air pollution is a threat for the environment affecting a wide range of ecosystems through a variety of processes including acidification, eutrophication or vegetation oxidation that can ultimately lead to a biodiversity and ecosystem services loss [30]. Moreover, particulate matter (dust, sand, ashes) deposit over solar panels require permanent cleaning that increase the facilities maintenance costs [31]. Visibility is another area impacted by atmospheric pollution during haze and smog events. Particles and gases in the atmosphere interact with light via scattering and absorption reducing visibility and thence, affecting citizen's life quality and altering on-road, marine and aviation safety [32].

Most of the effects, in fact, come from the city ecosystem. Cities are at the forefront of climate impact as they host more than half of the world's population. The highest concentrations of gases in the atmosphere from human activities correspond to the emissions of CO^2, which to date has increased three times its level compared to the beginning of the industrial revolution, and is considered responsible for about 64% of global warming. In general, climate change has serious consequences on food, water, health and housing sectors, and on the frequency and intensity of natural events. Although climate change is a global problem, its impact varies according to the geographic location in which exposure, vulnerability, and system resilience play a fundamental role.

2.1.1 Regulations and Policies

There are no real regulations on air pollution but over the years there have been agreements and treaties (international and European) on climate action. The main international agreement on climate action and climate change is the United Nations Framework Convention on Climate Change (UNFCCC), one of the three conventions adopted at the 1992 Rio Earth Summit[6]. At the time of writing, it has been ratified by 195 countries. Initially it represented a tool to allow countries to collaborate in order to limit the increase in global average temperature and climate change and to address its consequences. At the same time, other international agreements were also signed, for example the Kyoto Protocol which provided for stricter provisions to reduce emissions. Upon expiry of the protocol in 2012, the Doha Amendment was created which establishes a second commitment period to reduce greenhouse gas emissions in the period from 2013 to 2020.

The control and maintenance of atmospheric pollution and of the possible green solutions to be adopted are regulated, as seen, by national and international bodies. In recent years, the analysis of the legislation for adaptation to climate change also reached a community scale [33].

Kyoto Protocol

The Kyoto Protocol is an international treaty on environmental matters concerning global warming, drawn up and signed on 11 December 1997, in Kyoto, Japan, by more than 180 countries on the occasion of the third Conference of the Parties, (COP3), of the Framework Convention of the United Nations on Climate Change (UNFCCC). The Protocol entered into force on February 16, 2005, after the Russian ratification. As of May 2013, 192 states have signed up to the Protocol. According to what was stated by

[6] An international environmental treaty produced by the United Nations Conference on Environment and Development (UNCED), (also known as the "Earth Summit"), held in Rio de Janeiro in 1992.

the IPCC[7] and sharing the idea that anthropic activities are most likely responsible for the increase in global average temperature, the Protocol:

1. It provides for the obligation to implement a substantial reduction in the emissions of polluting elements;
2. Its objective is to stabilize the concentration of greenhouse gases on a planetary level. Gases capable of altering the greenhouse effect of our planet:

- Carbon dioxide (CO^2);
- Methane (CH4);
- Nitrous oxide (N2O);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs);
- Sulfur hexafluoride (SF6);

The Kyoto Protocol commits the listed countries to reduce annual greenhouse gas emissions by 5.2% compared to 1990 values, in the period 2008-2012, with different reductions for each country. In particular, the EU has a 8% reduction target.

The Paris Agreement

The Paris Agreement belongs to the UNFCCC framework and refers to greenhouse-gas-emissions mitigation, adaptation, and finance, starting from 2020. The Agreement entered into force on the 4th of November 2016, thirty days after the date on which at least 55 Parties to the Convention accounting in total for at least an estimated 55 % of the total global greenhouse gas emissions have deposited their instruments of ratification, acceptance, approval or accession with the Depositary. The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius, above pre-industrial levels, and to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. Under the Paris Agreement, each country must determine, plan, and regularly report on the contribution that it undertakes to mitigate global warming. No mechanism forces a country to set a specific target by a specific date, but each climate plan shall reflect the country's ambition for reducing emissions, considering its domestic circumstances and capabilities. The Paris Agreement requests each country to outline and communicate their post-2020 climate actions, known as their NDCs – National Determined Contributions.

European Union (EU) budget: Common Agricultural Policy (CAP)

With a budget of €365 billion, EU proposals make sure the CAP remains a future-proof policy, continuing to support farmers and rural communities, leading the sustainable development of EU agriculture and reflecting the European ambition on environmental care and climate action. Today's proposals give Member States greater flexibility and responsibility for choosing how and where to invest their CAP funding in order to meet ambitious goals set at EU level towards a smart, resilient, sustainable and competitive agricultural sector, while at the same time ensuring a fair and better targeted support of farmers' income. Climate change, natural resources, biodiversity, habitats and

[7] IPCC inducted to The Earth Hall of Fame Kyoto

landscapes are all addressed in the EU-wide objectives proposed today. Farmers' income support is already linked to the application of environment and climate-friendly practices and the new CAP will require farmers to achieve a higher level of ambition through both mandatory and incentive-based measures:

- Direct payments will be conditional on enhanced environmental and climate requirements;
- Each Member State will have to offer eco-schemes to support farmers to go beyond the mandatory requirements, funded with a share of their national direct payments' allocations;
- At least 30% of each rural development national allocation will be dedicated to environmental and climate measures;
- 40% of the CAP's overall budget is expected to contribute to climate action;
- In addition to the possibility to transfer 15% between pillars, Member States will also have the possibility to transfer an additional 15% from Pillar 1 to Pillar 2 for spending on climate and environment measures (without national co-financing).

The Green Deal

The most important novelty is certainly the initiative promoted by the new European Commission for a Green Deal, which aims to make the climate challenge and ecological transition an opportunity for a new development model, allowing Europe to exercise a leadership role on world scene. The goal is to become the first climate-neutral continent by 2050, strengthening the competitiveness of European industry and ensuring a socially sustainable and fair transition. Furthermore, the same legislation will aim at the protection of the natural environment and biodiversity, a strategy for sustainable food, a new action plan for the circular economy.

In particular, the following initiatives have been planned for 2020:

- Legislative proposals: European climate law, which establishes the climate neutrality goal for 2050 (presented on March 4, 2020);
- Proposal to extend the emissions trading system to the maritime sector and to reduce the allowances allocated to airlines;
- Border Carbon Tax: battery legislation in support of the strategic action plan on batteries and the circular economy (October 2020);
- The proposal to support zero-carbon steelmaking processes by 2030 (in 2020); or proposals for legislative reform on waste (from 2020);
- Revision of the directive on energy taxation. Strategies and action plans: the new EU industrial strategy (March 2020);
- Strategy for "green financing" and an investment plan for sustainable Europe;
- Plan to raise the EU's emissions reduction target for 2030 to 55%; Sustainable Food Strategy;
- Strategy to protect citizens' health from environmental degradation and pollution; o Strategy for biodiversity to 2030;
- New Action Plan for the circular economy (presented on 10 March 2020).
- Financing tools:

- Investment Plan and Just Transition Fund; role of the European Investment Bank (EIB) as a climate bank.
- Non-legislative initiatives:
- European Climate Pact;
- Global Conference of the Parties to the Convention on Biological Diversity; Initiatives to stimulate lead markets for circular and climate-neutral products in energy-intensive sectors (starting in 2020).

These rules introduce the Green Deal II within the framework of circular economy, launched by the EC in December 2019 and shared in the European Council by all national governments except the Polish one, provides a path for a fair and socially equitable transition by promoting a “New industrial revolution” that guarantees more sustainable and environmentally friendly production cycles, through a series of strategies, action plans and tools. The Plan launched by the Commission underlines how the European Green Deal must be aligned with a new industrial strategy to make the EU a world leader in the circular economy and clean technologies.

The action plan of the circular economy provides for the launch of a roadmap to promote the sustainable use of resources, starting with sectors with a high intensity of resources and a high environmental impact, such as textiles and construction. The Commission, with the aim of knowing the stakeholders' point of view, has promoted a consultation which, in addition to examining the context and identifying the critical issues that still hinder the development of the circular economy, aims to identify the actions necessary to accelerate the transition.

There is a need to raise environmental awareness, for the "public consumer" the Commission intends to propose mandatory minimum criteria and objectives on green public procurement (GPP) in sectoral legislation, gradually introduce a communication obligation to monitor the use of GPP, continue to foster capacity building through guidance, training activities and the dissemination of good practices and by encouraging public buyers to participate in the "Public buyers for the climate and environment" initiative, which will facilitate exchanges between buyers that intend to use green public procurement. Particular attention will be dedicated to the implementation of the circular bioeconomy strategy, to the promotion of the use of digital technologies for the traceability and mapping of resources and the use of green technologies thanks to a system of verification of environmental technologies with brand EU certification. The new strategy for SMEs will promote circular industrial collaboration between SMEs through training initiatives, consultancy, within the "Enterprise Europe Network", on collaboration between clusters and the transfer of knowledge through the European Center of Excellence for the efficient management of resources.

Other regulations on air pollution

In the territorial planning decision-making processes, the environmental component, combined with the technical and economic requirements, represents a discriminating element. The legislation already provides in the feasibility study of a public work, upstream of the three design phases, the production of documents aimed at justifying the choices made from an environmental point of view. All the design interventions carried out in the transport networks have a certain environmental impact on the various components of the context in which the work is inserted, among these there are certainly damage to the urban landscape, phenomena of noise and air pollution, deterioration of buildings of historical interest etc. Once the criticalities of the complex transport system have been identified, through appropriate evaluation methodologies, the planning process aims at identifying the best project scenario, submitting the different alternatives also to environmental assessment criteria.

The main legislative instruments to protect air quality are the Directives 008/50 / CE and 004/107 / CE, implemented in Italy with Legislative Decree 155/2010, which set limits to the concentrations of pollutants in the air and oblige States / Regions / Autonomous Provinces to prepare plans for the rehabilitation of air quality in the event of non-compliance, the Gothenburg Protocol, born under the "Convention on Long-Range Transboundary Air Pollution" and Directive 001/81 / CE (the so-called NEC Directive - National Emission Ceiling), implemented with Legislative Decree 171/2004, which set limits to national emissions. There is also a specific regulation that regulates the emission of the main pollutants from specific sources and sectors. Some of the main references are:

- the directives that introduce vehicle emission limits, including the Regulations (CE) 692/2008 and 595/2009 which introduce the most recent Euro standards (5 and 6);
- Directive 003/17/EC on the quality of petrol and diesel;
- Directive 1999/32/EC on the reduction of sulphur in liquid fuels;

In this context, the current legislation, Legislative Decree 155/2010, provides a unified regulatory framework for the assessment and management of air quality. The main purposes of the Decree are as follows:

- identification of environmental air quality objectives aimed at avoiding, preventing or reducing harmful effects on human health and the environment as a whole;
- assessment of ambient air quality based on common methods and criteria throughout the national territory;
- derive information on ambient air quality as a basis for identifying measures to be taken to combat pollution and the harmful effects of pollution on human health and the environment and to monitor long-term trends as well as improvements due to the measures taken;
- guarantee information on the environment to the public;
- to achieve better cooperation between European Union states in the field of air pollution.

2.1.2 Background theory

The European Environment Agency has found that the area of the Padano Basin, between the Alps, the northern Apennine chain and the Adriatic Sea, is the black jersey in Europe for atmospheric pollution. Particularly critical substances are particulate particles (PM10 and PM2.5), nitrogen oxides and ozone. In addition to damaging health and reducing life expectancy, poor air quality also causes economic losses, reduced agricultural yields and lower labour productivity. Attested the climatic and orographic peculiarities of the Po basin and the need for interventions at national level on sectors of state competence, the Regions belonging to the Po Basin - Emilia-Romagna, Lombardy, Piedmont, Veneto, Valle d'Aosta, Friuli-Venezia Giulia, Autonomous Provinces of Trento and Bolzano - signed an Agreement on 19 December 2013 with the Ministries of the Environment and Protection of the Territory and the Sea, of Economic Development, Infrastructures and Transport, of Agricultural, Food and Forestry and of Health in order to identify and implement homogeneously and jointly short, medium and long-term measures to combat atmospheric pollution in the areas of the Po Valley. Over the years, the Regions and the cities of the Po Valley have developed regional plans to respond to Legislative Decree no. 155 of 13 August 2010, transposition of the European Directive 2008/50 / EC on ambient air quality and cleaner air in Europe. In 2017, given the seriousness of the situation, the "New Program Agreement for the joint adoption of measures to improve the air quality of the Po Valley" was signed, with the aim of establishing new and more effective measures. In 2017, all the Regions that make up the Padano Basin in concert with the related regional agencies for the protection of the environment (ARPA) signed PREPAIR. This is a project funded by the European Union aimed at monitoring and coordinating the actions contained in the regional plans for better air quality in the territories in question. This work aims to compare the air quality remediation plans adopted by the regions belonging to the Padano Basin. The Air Quality Plans, according to the European directive, must identify the main emission sources that give rise to pollution and quantify the emissions. In the following I would like to verify whether the common objective of the New Padano Basin Agreement of 2017 has been achieved by comparing the four analysed plans, respectively of the regions: Piedmont, Emilia Romagna, Lombardy and Veneto. Piedmont Region (PRQA) uses the Regional Air Quality Detection System (SRRQA) consisting of 58 fixed stations for the acquisition of localized data based on the zoning of the territory pursuant to Legislative Decree 155/2010. The fundamental cognitive tool is the Regional Emissions Inventory for 2010, IREA Piemonte 2010B, which contains the annual emissions of macro and micro pollutants and constitutes the basic emission scenario. The operational air quality modelling chain is based on the application of Eulerian models of chemistry and transport (CTM) and was developed by the Piedmont Region in collaboration with ARPA Piemonte. The modelling information is integrated, by means of specific mathematical data assimilation techniques, with the values measured by the SRRQA stations in order to obtain an estimate of the air quality as realistic as possible. After the dispersion simulations, a post-processing module creates the thematic maps. The Piedmont plan has developed the sector-based modelling source apportionment technique in order to research the responsibility for pollution by sector of activity. The main emission sectors identified are: transport, heating, industry and agriculture. For each sector, the priority intervention actions to be carried out in were determined and analysed in detail on the short and long term.

Lastly, the expected effects on air quality are estimated using the scenario analysis methodology: that is, future or trend scenarios are planned, starting from a reference base, taking into account the application of emission reduction measures. The Italian GAINS-Italy model is the methodological reference taken and allows the analysis of a future scenario in 2030 where the regional emission trends of the main environmental indicators can be deduced. From the results obtained, I would like to identify the regional planning measures on which to focus more in order to obtain a better air quality and verify that, by defining the trend emission scenarios up to 2030, the limit values established by EU regulations are fully or at least partially respected. Subsequently, the Regional Integrated Air Plan, PAIR 2020, drawn up by the Emilia Romagna Region, the Regional Plan of Air Quality Interventions (PRIA, updated to 2018) adopted by the Lombardy Region and the Regional Plan for the Protection and Remediation of the Atmosphere (PRTRA) published by the Veneto Region have been analysed. In order to compare the four regional plans for air restoration, the methodologies used for the analysis of air quality were studied. All the Regions of the Po Basin started from a reference scenario based on current legislation, with the insertion of mitigation measures, from which a future scenario is built up to 2030. The methodology of the four regions is based on three main tools: the network of regional monitoring, the Regional Emissions Inventory and a regional modelling system. Furthermore, the methods of determining the emission sectors and the actions that have been planned were analysed.

The rehabilitation measures have been investigated in detail in order to derive those that Piedmont, Emilia Romagna, Lombardy and Veneto consider to be fundamental to adopt. The objectives of reducing emissions that the four regions are hoped to achieve and in particular the actions to be performed were also compared. Lastly, the effects that air pollution can cause on the health of the population residing in the basin area were examined. Over the last few years, numerous studies have found that air pollution causes significant effects on people's health, in particular the most vulnerable groups are the elderly, children and people with health problems. The pollutants under study are associated with effects such as the increase in respiratory symptoms, the aggravation of chronic cardio-respiratory diseases, lung cancer, increased mortality and the reduction of life expectancy. Today it can be said that the problem of air quality that affects the European, National and Regional territory is no longer negligible and it is essential that the bodies concerned act promptly and effectively.

2.2 Make cities inclusive, safe, resilient and sustainable

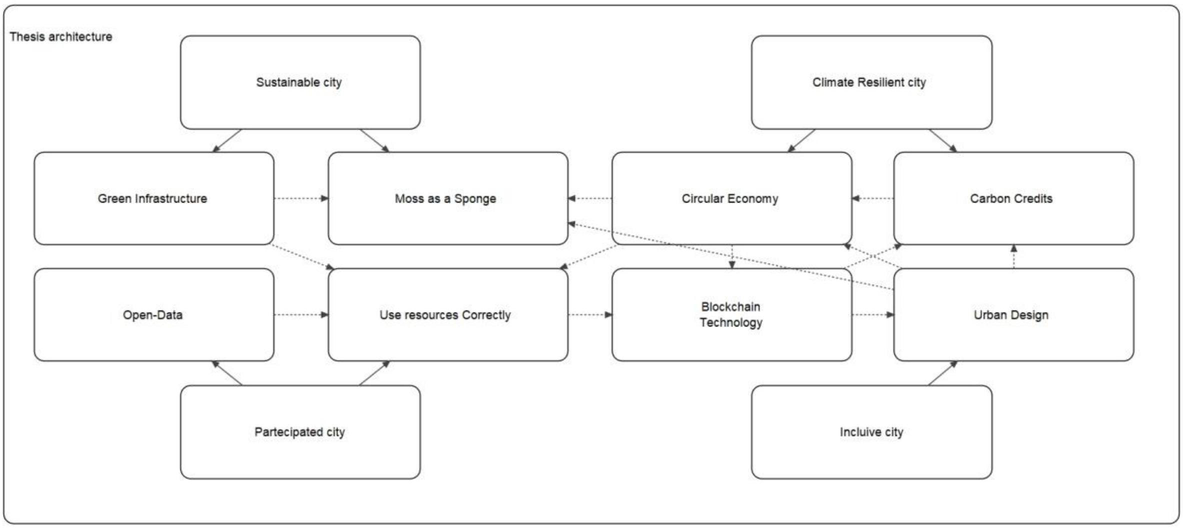
The work reported in this paragraph aims to comply with the 2030 agenda set by the SDGs, the Sustainable Development Goals [34]. There are 17 goals and 169 sub-goals. They take into account in a balanced way the three dimensions of sustainable development, namely economic, social and ecological. The Sustainable Development Goals will have to be achieved by 2030 globally by all UN member countries. This means that every country on the planet is called to make its contribution to jointly tackle these great challenges. Furthermore, incentives will have to be found to encourage non-governmental interlocutors to participate more actively in sustainable development. In particular, for the entire thesis, it will be followed objective 11 that is to *make cities and human settlements inclusive, safe, long-lasting and sustainable.*

The goals of objective 11[8] that will be tried to discuss are:

- **11.3** By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
- **11.6** By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
- **11.7** By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities
- **11.A** Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning

As a result, cities can lead the charge in supporting a green recovery to achieve those goals. In particular, the structure of this research will follow these topics:

- Sustainable city
- Climate resilient city
- Inclusive city
- Participated city



Summary diagram and their connections

The project will use the four types of cities in a synergistic way. And every single type will be accompanied by a technology.

2.2.1 Sustainable city

In the same decade where it became increasingly difficult to plan and create green areas with the desired quantities, positions and characteristics, paradoxically, the question of green and its multiple functions for sustainability has assumed

[8] https://www.un.org/sustainabledevelopment/cities/

unprecedented proportions. Conservative urban policy of the few green spaces left in the city and an obstruction towards new buildings can be observed nowadays. It almost seemed that the problem was land consumption. However, it is important instead to shift the focus of the problem to smart planning. Between the 70s and 80s, awareness grew that the production and consumption model of industrialized societies was no longer compatible with environmental protection. On a global level, the future of cities, where most of the population is now concentrated, and the need to think of the urban dimension in profoundly different terms is at the center of the political agenda of supranational, national and local levels of government. The growth of the urban population and the expansion of the city are phenomena that are not destined to end or slow down, and the city, with its concentration of economic activities, services, productive, residential, and working settlements, can represent the ideal scale from which to start to collect and resolve all the challenges and contradictions of sustainable development. So the aim of this paragraph will be to think of a sustainable city but at the same time technology. Without planning restrictions.

Solve the problem

The problems to be solved can be placed in two macro-areas, the first are related to buildings and the private citizen. The second macro-area includes the problems related to the city and its atmospheric pollution. The problems seem different but they are linked. The solutions to be addressed concern:

Buildings

- Encourage an ecological and eco-sustainable change
- Support green building standards or energy supply
- Encourage private investments
- Quantify the impact of overbuilding on climate change
- Efficient use of energy, water and other resources

City

- Combat Air Pollution
- Combat Rising City Temperatures (Heat Island)
- Fighting times of water runoff
- Encourage "Environmental" public policies
- Increase urban green
- Redevelop peripheral districts
- Reduce waste, pollution and environmental degradation

The added value

The solutions suggested here refer to Green infrastructures (GI) which give as added value:

- Environmental benefits (e.g. conservation of biodiversity or adaptation to climate change), social benefits (provision of water drainage or green spaces) economic benefits (e.g. job supply, credit exchange of carbon and rising property prices).
- Ecological, economic and social benefits through solutions in harmony with nature

- They will guarantee a citizen continuation of the network of natural and semi-natural areas and will provide ecosystem services, which are the basis of human well-being and quality of life.
- They facilitate integrated and synergistic planning that will ensure more sustainable planning

Green infrastructures can be used to reduce the amount of rainwater, increase the levels of carbon sequestration, improve air quality, mitigate the effect of urban heat islands, improve the cultural and historical landscape, giving identity to places and to the scenario of urban and peri-urban areas, where people live and work. In this paragraph, the reader will deal with green infrastructures, their legislation, how to install them and what they are used for the purposes of this thesis work and from a sustainable city perspective.

Green Infrastructures

Green infrastructures (GI) in the EU[9] support a full integration of such infrastructures into EU policies so that they can be established as a standard component of territorial development throughout the European Union. The strategy also recognizes that green infrastructure can contribute to a range of EU policies whose objectives can be achieved through solutions in harmony with nature and places the use of green infrastructure in the context of the Europe 2030 growth strategy.

Green Infrastructures better have the distinction of being multifunctional, which means that they can promote win-win solutions or combine large gains with small losses that provide benefits to a wide range of stakeholders. In addition, they can act as a catalyst for economic growth by attracting investment and generating jobs, while reducing environmental costs. The European community in the same document speaks of "green jobs" which currently already represent 5% of the labor market.

The main technologies used in the Green Infrastructures are:

- Green roofs
- Green walls
- Green areas of infiltration

Of course, in this work the focus will be on cities, so it will only deal with green roofs and walls. In the EU Member States there are already some transnational initiatives that have been successfully implemented, for example the European Green Belt[10] or Lower Danube Green Corridor[11]. More generally, there is scope for further integrating green infrastructures in a synergistic way into strategic planning tools, such as river basin management plans, Natura 2000 management plans, national air quality plans, programs of rural development and operational programs of cohesion policy. These plans could help establish an EU-wide green infrastructure network. This however

[9] Green infrastructures are also recognized in other EU policy contexts, notably under the 7th European Environment Action Program (7EAP), the 2014-2020 Regional Policy, the Water Framework Directive, The Nitrates Directive, the Floods Directive and the EU Strategy for Adaptation to Climate Change.
[10] https://www.europeangreenbelt.org/
[11] https://d2ouvy59p0dg6k.cloudfront.net/downloads/wwf_factsheet_ldgc.pdf

demonstrates that there is a network of large-scale programs but is lacking in city-scale projects.

In this work GI will be spoken in the city context using large-scale technologies: no reference will be made to the creation of new ideas to upholster buildings or to unite cities to the Natura 2000[12] network. However, a reference will be made to a study that, using pre-existing ideas, encourages the installation of mosses on buildings to improve the quality of urban life.

Green infrastructures are defined by the EU 2019[13] strategy as "*a strategically planned network of natural and semi-natural areas with other environmental elements, designed and managed in such a way as to provide a broad spectrum of ecosystem services. green (or blue, in the case of aquatic ecosystems) and other physical elements in land (including coastal areas) and marine areas. On land, green infrastructure is present in a rural and urban context* ".

The challenge of the European community is to include these infrastructures in territorial planning and development. Green infrastructures can be conceived as a set of "technological green" design solutions, underlining that technology has a series of environmental benefits for the management of resources and the mitigation of climate change [35].

The construction of green roofs, or roofs with vegetation, have to help to favor to:

- save energy
- mitigate the effects of the urban heat island
- increase the longevity of the roofing membranes
- improve the return on investment compared to traditional roofs
- reduce noise and air pollution
- increase urban biodiversity
- provide a more aesthetically pleasing environment
- a better quality of life and human well-being by providing a healthy environment in which to live and work
- promote biodiversity by reconnecting isolated natural areas
- protect people from climate change and other environmental disasters by mitigating floods, storing CO^2 and preventing soil erosion.
- encourage a smarter and more integrated development policy that ensures that the limited areas of Europe are used in the most efficient and coherent way possible.

The solution must be to integrate the GI in the energy balance. There could be a 2% reduction in electricity consumption and 9-11% in heating consumption[14]. Based on a model of a generic building with a green roof of 2000 m^2, these savings could vary over

[12] https://www.minambiente.it/pagina/direttiva-habitat
[13] EU Strategy on Green Infrastructure: Review of progress on implementation of the EU green infrastructure strategy COM(2019) 236 final
[14] Building energy simulation model supported by the U.S. Department of Energy.

the course of a year from 27.2 to 30.7 GJ of electricity saved and 9.5 to 38.6 GJ of natural gas for saved heating, depending on the climate and green roof design.

If considering the European averages of CO^2 produced for the generation of electricity and the combustion of natural gas [36], these figures translate into 491 g (year 2017) C per m^2 of green roof in electricity and 86 (year 2018) g C per m^2 of green roof in natural gas every year. Another 25% of reduction in electricity use may also occur due to the indirect reduction of the heat island achieved by the implementation of large-scale green roofs in an urban area [37].

Green roofs can also sequester carbon in plants and soil. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, this is a process commonly mentioned as sequestration of terrestrial carbon. Carbon is transferred to the substrate through plant litter and exudates. The length of time carbon remains in the soil before decomposition has not been quantified for green roofs yet, but, if net primary production[15] exceeds decomposition, this man-made ecosystem will be a net sink of carbon, at least in the short term.
The issue of carbon sequestration will be further developed in the following paragraphs.

Definition and design of green city infrastructures

Once green infrastructures in general have been defined, some researches have been conducted to identify which type of green crop and infrastructure worked best for the thesis' purpose. Generally, green roofs are divided into two possible types: extensive and intensive green roofs. An extensive green roof is defined when there are species that require a layer of earth between 8 and 15 centimetres and reduced maintenance interventions (once or twice a year). Their weight is generally less than 150 kg / m^2.

The surfaces are accessible only for routine maintenance. This solution is typically used for very large and impractical surfaces, so these structures are very suitable for covering entire sheds, shopping centers or other buildings whose roof is not used for the permanence of people. This is very important because it would guarantee the creation of sponge areas in industrial areas, which normally should represent the most polluted areas of the city. Low maintenance and easy installation made this product the ideal candidate for the entire research. It was also better to investigate the intensive green roof with species that require a layer of surface from 25 to 50 centimetres and constant maintenance or in any case more than 4-5 times a year. The weight exceeds 150 kg / m^2, but varies in relation to the design solutions adopted. The intensive green roof involves the planting of species suitable for accessible and practicable surfaces,

[15] Plants capture and store solar energy through photosynthesis. During photosynthesis, living plants convert carbon dioxide in the air into sugar molecules they use for food. In the process of making their own food, plants also provide the oxygen we need to breathe. Thus, plants provide the energy and air required by most life forms on Earth. Plant productivity also plays a major role in the global carbon cycle by absorbing some of the carbon dioxide released when people burn coal, oil, and other fossil fuels. The carbon plants absorb becomes part of leaves, roots, stalks or tree trunks, and ultimately, the soil.

requires a thicker substrate and has higher costs. The weight of the system can even reach up to 2,000 kg / m^2, with growing substrate greater than one meter. Clearly this solution is suitable for structures capable of carrying these loads.

Going deeper, the extensive green roof also gives the advantage of being light, with low maintenance required and cheap. It also has the characteristic of providing for itself after planting. The best green roof to achieve the aim of sponge buildings remains moss. In particular, in this paragraph, European realities that have developed real business on moss will be addressed. Sedum, for example, is a variety of aromatic plants and grasses which, after laying, survive without special care.

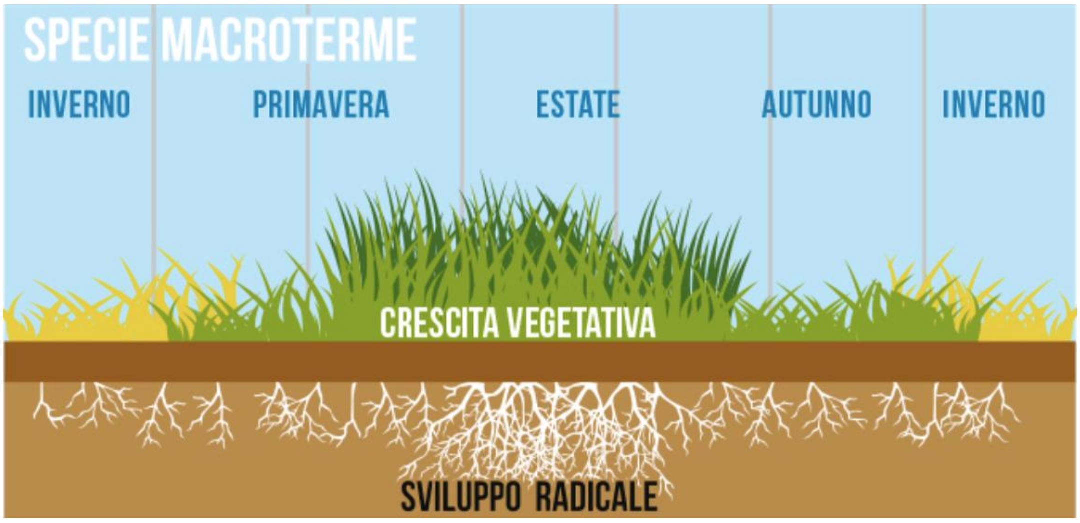
The benefits of extensive green roofs are [38]:

1. Longer lasting waterproof sheath because it is protected from strong UV radiation, high temperature ranges, driving rain and the formation of concretions.
2. Withholds rainwater (depending on the region and the type of green roof, from 30% to 90% of annual rainfall).
3. Reduction of waste water (shorter run-off times)
4. Natural summer-winter insulation
5. Ecological compensation area, recognized in compensation measures; increase in biodiversity thanks to the creation of new green areas and the expansion of habitats for plants and animals.
6. "Permeable" surface recognized by many administrations in the practices of ecological management of rainwater.
7. Improvement of the microclimate thanks to the evapotranspiration processes
8. Filtration and fixing of micro dust and volatile harmful substances
9. Improvement of the working / living environment, especially with usable or visible green roofs.
10. Urban / landscape design element that can be used on a large scale
11. Ballast for waterproofing insufficiently stabilized under wind load
12. Noise reduction thanks to the inertia to vibrations of the entire surface and thanks to the sound-absorbing power of the vegetation.
13. Reduction of electro-smog.

Before further mentioning the benefits and features and going through some similar case studies, it is important to mention that this work applies the satellite scale. Therefore, it was of fundamental interest to find a well-established technology (Musk) and adapt it to various city contexts.
The satellite, in fact, does not work on a local scale, but on a global one and choosing a technology that was not usable in most of the world would have been useless. Moss, on the other hand, fits to different climatic characteristics and can be installed at different latitudes. In conclusion, it was easier to create models that have moss as a starting hardware (HW).

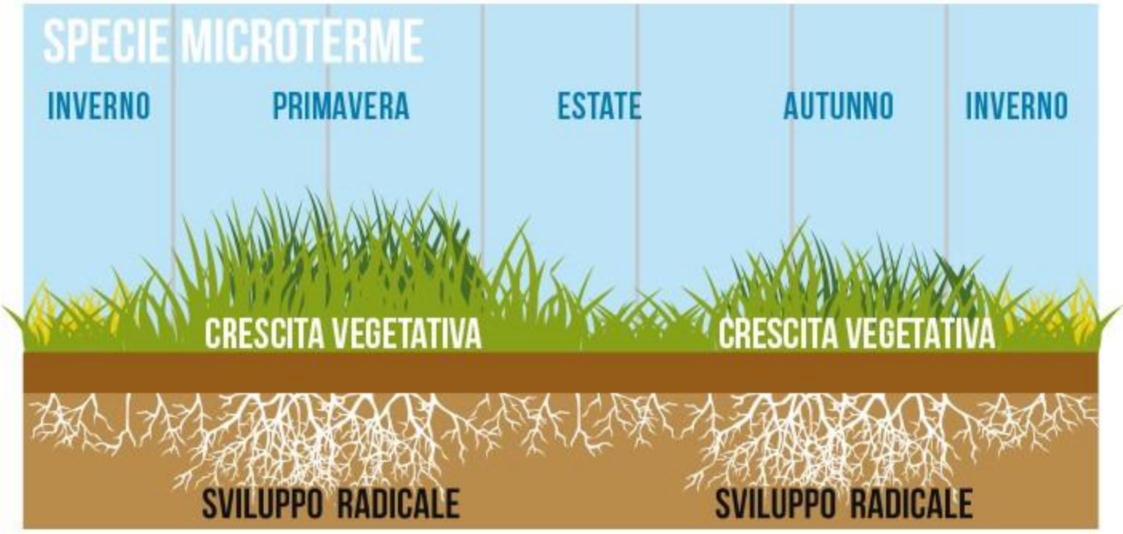
The climatic factors therefore allowed the division of the most suitable tree species into two macro categories:

- Micro-thermal species[16]: particularly suitable for temperatures between 15 and 25 ° C, with less tolerance to heat, drought and salinity, with greater growth in autumn and spring.



1 Image showing the Macro-thermal species **[39]**

- Macro-thermal species[17]: suitable for warmer climates and therefore not very suitable for those where temperatures can drop below 0 °. In this case they lose their green color and go into vegetative rest. The optimal growth temperature is between 25 and 35 ° C.



2 Image showing the Macro-thermal species **[39]**

Considering the whole "green package" [40], meaning the set of elements of the green roof, a green roof is structured as follows:

[16] The following species belong to this group: Festuca arundinacea, Lolium perenne, Poa pratensis◦Festuca rubra
[17] The following species belong to this group:Cynodondactylon, Paspalum vaginatum, Stenotaphrum secundatum, Zoysie

- Vegetation layer: vegetation varies according to the climatic zone as it strongly depends on temperatures, rainfall and other climatic factors
- Growing substrate: includes the layer where the plants will be planted and where they will root
- Filter element: the filtering layer is composed of a filter that prevents fine soil particles from entering the empty spaces of the drainage layer, with the risk of clogging and slowing down the drainage of water. Low degradability, strength to withstand the weight of the earth and root strength and flexibility are required
- Draining element: an appropriate drainage system must be chosen which allows water, which exceeds certain levels, to drain easily. It is mainly composed of materials of mineral origin and pre-formed plastic draining layers in plates or rolls
- Mechanical protection element: consisting of a protective mat which guarantees mechanical protection by means of a waterproof membrane
- Protection element: from the action of the roots to avoid cracks due to the digging action of the roots, an anti-root sheath is prepared, produced with synthetic substances such as PVC and polyethylene
- Sealing element (waterproofing): for a correct waterproofing of the concrete slab, membranes made with distilled bitumen and resins and elastomers are prepared to guarantee

An element for thermal insulation and a vapor barrier may also be provided.

Moss as a sponge

It has been identified air pollution as the sneaky and invisible problem that kills seven million people every year[18], which means that it represents the greatest risk to public health, worldwide. According to the World Health Organization, more than 80% of people live in urban areas in areas where the level of pollution is regularly monitored, but air quality measurements do not fall within the parameters set to safeguard their health.

The best solution would be to plant trees, which use their leaves to capture and absorb large amounts of harmful particles, however this is not always possible. Moss becomes the viable alternative to trees in the city. A German company, "Green City Solutions[19]", has designed a mobile system that helps reduce air pollutants. This plant is called "CityTree"[20] and has already been installed in many cities around the world, including Paris, Hong Kong, Oslo, Brussels.

CityTree is a HW that has quite small dimensions in height or in length. The average dimensions are 4 meters x 3 meters x 2 meters. These panels can be installed anywhere, the company even presents them on simple urban benches. According to

[18] Data reported by the United Nations report year 2019
[19] https://greencitysolutions.de/
[20] https://greencitysolutions.de/produkte/#section2

the German company, the panels provide an environmental advantage of 275 trees, occupying an evidently significantly smaller space.

These HWs have the particularity of being able to be "Itinerant": being panels of moss they can, if necessary, be moved by public administrations (PA) to neighbourhoods with higher pollutant rates. For example, to have a perfect city air filter, it would be necessary to put the air in contact with it. This is very difficult, because the pollution produced by the exhaust gases of cars, for example, is dispersed vertically for several kilometres. But having them within the city at various heights (roofs of buildings or benches at street level) would guarantee having sponge filters in the immediate vicinity of the source of pollution.

Furthermore, these panels can coexist with sensors that measure the soil moisture, monitor the quality of the surrounding air, the temperature and the quality of rainwater.

In conclusion it is not a tree, but a moss crop that can extend over a much larger surface area than the leaves of a tree, thus managing to capture more pollutants. Musk manages to capture fine dust, nitrogen dioxide and ozone gases present in the air, in a totally autonomous way. CityTree is able to absorb about 250 grams of particulate matter every day, and contributes to the capture of greenhouse gases, removing about 240 tons of carbon dioxide every year. Its cost is € 22,000.

2.2.2 Climate resilient city

Cities have the most to gain from getting funding for urban climate action and the most to lose if they do not. This is why it is time to increase investment in projects that transform pressing urban challenges into low-carbon opportunities. Climate resilience is a fundamental problem for cities. Today, cities account for over 70% of global energy-related CO^2 emissions and are highly vulnerable to the impacts of global warming. Despite all of this, cities rarely have access to the finance needed to build their resilience to climate risks and challenges exacerbated by high-speed urbanization. A city's ability to make climate smart investments often relies on reallocating existing budgets. Their ability to increase revenue and attract private finance is also limited by challenges such as creditworthiness, bankability and a lack of a viable project pipeline.

Cities can build climate resilience through investments in green urban projects, or create the internal economy that can self-sustain them through the revenues of green projects. The concept seems difficult but underpinning the central hubs of culture and commerce, low-carbon innovations in cities have far-reaching benefits: clean air, healthy citizens, new jobs and greater competitiveness. Supported by the right financing solutions, city-level decision makers can be agile to act and lead by example, lead national and global agendas on climate mitigation and adaptation. Subsequently, the same funding projects must return the expenditure and create added value for the citizen.

The city can thus become increasingly smart, setting ambitious goals and adopting a program to reduce CO^2 emissions. Funding must also extend to green building modifications. Then in a second moment from a Circular economy perspective, the blockchain that certifies and monitors the resistance of the buildings themselves comes to our aid. By placing them in ETS markets, they will generate income for citizens. The concept seems difficult, yet, if defined in detail, the concepts of circular economy, carbon credits and blockchain can be simpler to understand.

Solve the problem

The simple but effective solution to this impasse is to transform CO^2 from a cost to a revenue and subsequently contribute to the reduction of greenhouse gases.

To do this, starting with existing international regulations and standards on carbon dioxide emissions, the work provides a series of satellite services that transform the roofs of buildings into real "WALLETS":

- Certify and reward low carbon products and entities
- Improve the adoption of virtuous land management practices to increase their carbon sequestration capacity
- Support the trading of carbon credits in the regulated market.

The added value

Starting from the products already on the market, the solution has the advantages of:

- Being innovative in terms of technology (satellite images) and field of application (carbon sequestration in the city)
- Responding to the needs of users around the world
- Being reliable and incorruptible since it is based on secure automated processes of satellite image processing
- Being highly competitive on the market as it significantly reduces manual operations
- Promoting an approach that is beneficial to all citizens (e.g. improvement of land management that creates revenues instead of costs) and the environment (e.g. biodiversity, CO^2 balance)
- Presenting high-speed services (based on satellite review time versus manual sample collection and analysis)
- Designing a wide range of products to meet different customer needs to improve the customer experience
- Developing a database that serves at the same time the bodies responsible for enacting the regulations, those that must apply them and those that must monitor their compliance.

Therefore, the greatest value will be providing the world with the tools to monitor and safeguard the city and the environment through a sustainable system for reducing carbon dioxide emissions.

Circular Economy

Green spaces, today certainly more than some time ago, give the concrete possibility to start thinking in terms of urban economy. To do this, the involvement of urban actors must be integrated at every level. It is important to find a way to create a business improvement district, a real urban space that gives a decision-making experimentation, which keeps city government, private individuals and citizenship tied together. Linked by the common vision of managing the infrastructural ecosystem that sees the green of the city and shares it with the city in general. To implement this, an authentic circular economy regime has to be put in place, something that is beneficial both for the municipal budget and for private investments, and, last but not least, for the citizens' wallet, at the same time.

Starting from this, the aim is to exploit the European regulations that incentivize PAs and citizens to carry out projects in a Circular economy perspective.

Green building projects can give the opportunity to transform the economy and generate new competitive advantages. The roofs covered with moss will boost the competitiveness of the Union by helping to create both new business opportunities and innovative and more efficient ways of production and consumption. At the local level, this policy offers integration between citizens and social cohesion, will save energy and will help avoid irreversible damage in terms of climate, biodiversity and pollution of air, soil and water. The action on the circular economy front is therefore to facilitate green redevelopment projects for buildings and integrate them into environmental policies. For example, ETS carbon credits. The objective is to ensure the existence of an adequate regulatory framework for the development of the circular economy in the single market, to give clear signals to economic operators and to society in general on the way forward as regards the long-term objectives in carbon storage matter. By stimulating resilient activity, the plan will help unlock the growth and employment potential of the circular economy.

Carbon credits

As expressed in the previous chapter through the Kyoto Protocol, and then through the Paris Agreement, each country agreed to strengthen the global response to the threat of climate change. To achieve this ambitious goal, appropriate financial flows, a new technological framework and a strengthened capacity building framework have been put in place, thus supporting the action of developing countries and the most vulnerable countries, in line with their own national targets.

However, no mechanism obliges a country to set a specific target by a specific date, but each climate plan must reflect the country's ambition to reduce emissions, considering its domestic circumstances and capabilities.

These agreements have resulted in a set of initiatives, both institutional and commercial, aimed at achieving the objectives of the treaties:

- With a budget of € 365 billion, the EU proposals ensure that the Common Agricultural Policy (CAP) remains a future-proof policy, continuing to support farmers and rural communities, driving sustainable development of agriculture and reflecting the EU's ambition for environmental protection and climate action (40% of the overall CAP budget should contribute to climate action).
- The EU has developed an Emissions Trading System (EU ETS) as a key tool to reduce greenhouse gas emissions in a cost-effective way. The EU ETS works on the "cap and trade" principle. A limit is set on the total amount of certain GHGs that can be emitted by installations covered by the system. The limit is reduced over time so that total emissions decrease. Within the limit, companies receive or purchase allowances which they can trade with each other as needed. They can also purchase

limited amounts of international credits from emissions reduction projects around the world. The limit on the total number of allowances available ensures that they have value.

- In the United States, since 1990, land use, land use change, and forestry (LULUCF) activities have led to greater removal of CO^2 from the atmosphere than emissions. This initiative is based on the simple concept that CO^2 is exchanged between the atmosphere and plants and soil on earth and therefore a proper plan for land conversion and use can lead to massive CO^2 sequestration.
- The United Nations (UN) has developed a system for reducing greenhouse gas emissions based on United Nations Certified Emission Reduction Projects (CER) and the Clean Development Mechanism (CDM). CDM projects, located in developing countries, earn 1 CER for every metric ton of GHG emissions they reduce or avoid and are measured in CO^2 equivalent (CO^2-eq). These CERs can then be purchased by individuals and organizations to offset their emissions.
- On 1 June 2018, the European Commission proposed a whole series of regulations for the next Multiannual Financial Framework (MFF) 2021-27. One of these deals with the financing, management and monitoring of the common agricultural policy, COM (2018/393 final). These regulations make extensive reference to the term "climate change" and clearly state that the CAP needs to be modernized as climate change needs to be given a higher priority than before. In addition, great emphasis is placed on space programs ("Member States should continue to use data or information products provided by the Copernicus program, in addition to information technologies such as GALILEO and EGNOS, in order to ensure that comprehensive and comparable data are available in the whole of the Union for the purposes of monitoring the agro-climate policy ").
- Together with the initiatives promoted by the institutions, there are many private companies in the world that recognize the value of GHGs and above all the value of helping to reduce and certify the carbon footprint of individuals and / or companies. Examples of these private companies are:
    - Verra, a privately held company that develops and manages standards and frameworks to aid environmental and sustainable development efforts. Their product, the Verified Carbon Standard (VCS), "is the most widely used voluntary GHG program in the world and more than 1300 certified VCS projects have collectively reduced or removed more than 200 million tons of carbon and other GHG emissions from atmosphere".
    - Carbon Trade Exchange (CTX), which is a private company that exchanges carbon credits and offers carbon-related services including carbon offsetting, carbon neutrality certification, carbon project development and carbon footprinting.
    - In addition to the awareness of the Global Warning, the growth of human awareness of the relationship between health and food is increasing.
    - This social consciousness has slowly pushed agriculture towards new mechanisms that favor quality over quantity and therefore the

establishment of a wide variety of labels to certify better and safer environmental practices. Examples of these trends are:

- The consumption of organic (bio) food in Europe has steadily increased and consumers have more than doubled in the last decade.
- The Italian market of DOP, IGP, DOC and DOCG branded products has grown steadily reaching a maximum rate in 2018 when it went from 6% (2016-2017) to 8% (2017-2018).

For the purposes of the thesis project the carbon credits will be useful to generate economy. Once the carbon stored by green buildings has been calculated and monitored. It will be enough to re-monetize them using the voluntary carbon credit market. This will guarantee an extra economy to encourage and maintain urban green projects. The biggest limitations of this technology will be regulations, certification and monitoring. For monitoring beyond satellites, IoT technology could be used. For certification it is possible to rely on either on-site experts or on the Blockchain. Instead, for the legislation, the only option is to rely on the institutions.

In conclusion, voluntary carbon credits can also be generated on the roofs of our homes, by certifying and monitoring them. For monitoring, it will be discussed how to do it in the technical chapter related to the use of satellites. Instead, for certification, Blockchain technology will be explained in the next paragraph.

Blockchain technology

As seen from the two previous paragraphs, to implement a resilient economy project also from an economic point of view, regulations that incentivize stakeholders to believe in the circular economy and to take advantage of markets that care about climate change are needed. Of course, projects cannot be based only on the trust and goodwill of the citizen. Technologies that monitor the work and certify it are important as well. In addition to satellites, the blockchain technology will be included to certify the work and issue smart contracts for the voluntary carbon market.

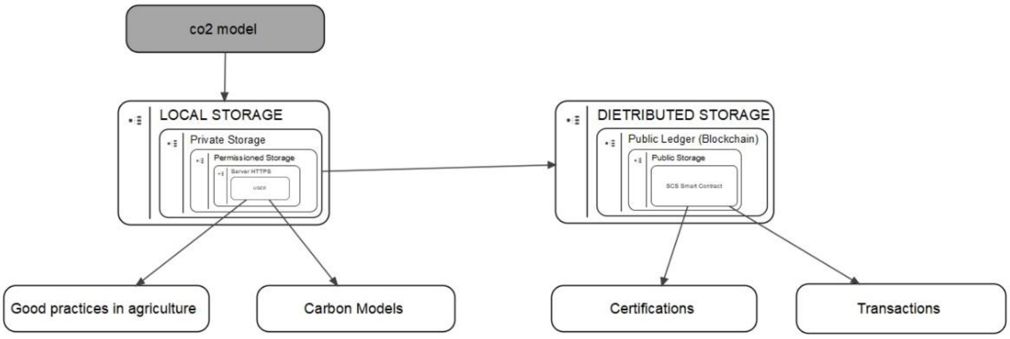
Without getting too involved in the Blockchain technology, it is possible to summarize its use in the following points:

- DFS Smart Contract[21]:
    - saving and managing data in IPFS and IPNS CIDs
    - management of IPFS repositories
    - management to guarantee the immutability of IPFS data
    - management to guarantee the ownership of IPFS data
    - management of the transfer of ownership of data
    - management of the sharing of ABE cryptographic keys
- DTP Smart Contract:
    - Transparent execution of training algorithms

[21] A smart contract is a computer program or a transaction protocol which is intended to automatically execute, control or document legally relevant events and actions according to the terms of a contract or an agreement. The objectives of smart contracts are the reduction of need in trusted intermediators, arbitrations and enforcement costs, fraud losses, as well as the reduction of malicious and accidental exceptions

- Saving and updating of the coefficients of neural networks
- Token (ERC23) Smart Contract:
  - Economic model of the Token
  - Token transfer from private citizens to the market

It can be predicted that at each stage of the carbon storage process, data will be collected and sent to a DATABASE (federated blockchain) that authenticates and stores the information. This solution will be able to guarantee both the authenticity of the data (detection of objective information processed in an automated and independent way) and the incorruptibility and transparency of the processing processes over time.



3 Graphic summary of the blockchain that should be used in this thesis work.

Federated blockchain combines different elements of both public and private blockchains. It is not controlled by an entity, but rather by a group. This group makes decisions regarding the carbon sequestration network. The system will be developed with a federated blockchain because the data related to satellite image processing will be written on a private blockchain, while the DB and the transition will be written on a public blockchain (cons: no double charges, false zero, write speed, access and security in the ledger).This system can also provide the necessary level of privacy for sensitive information - there will be no security concern in trusting a centralized authority as it is based on a decentralized architecture. Furthermore, the choice also depends on the environmental aspects: the federated blockchain was preferred, since public blockchains work on consensus algorithms that consume energy, thus emitting CO^2 (data extraction in fact requires a high level of computational power). Instead, the federated blockchain applies only a select group of nodes for validation, greatly reducing the complexity of the problem. Furthermore, it does not use the typical consensus algorithms, but a voting system to validate the nodes, which does not require a high level of computing power and therefore saves energy and consequently carbons.

2.2.3 Inclusive city

At the beginning of this chapter, it was said that SDGs set itself as an objective 11.7 on the inclusive city. By analyzing the concept in detail, a general definition can be

taken from the INU conference in May 2018 entitled *"Progetto Paese Città Accessibili a tutti"*[22] where article entitled, "*Città alla pari. Azioni, esperienze e memoria per la città inclusive"* was presented. In that text, the inclusive city is defined as a welfare vision towards a sustainable development perspective, working for an environment that creates autonomy, security and inclusion. Analyzing the problems expressed above and dwelling on the fact that it is necessary to create an autonomous economy, it was worth investigating the topic of inclusive cities.
Being a technician, I was able to transfer technologies from other worlds such as the Blockchain (Financial World), satellites (Space World) or carbon credits (Agricultural World) within the city planning mechanisms.

Solve the problem

The problems to be solved in order to get out of the city, historic center, neighborhood, suburb, urban green, agricultural green, etc. can be traced back to the following points:

- The city as a closed place
- Focus on the characteristics of the place and draw added value
- Need to face contradictions and problems that are instead a social product and, consequently, lose the reference to the strength of solidarity and the common good.
- Need to think about designing new forms of business, aimed at solving social and environmental problems.
- Budget problems mainly due to cuts in public spending, especially local, and with repeated manoeuvres that have penalized the municipalities.
- Loans and funds are often misused and have no financial return
- Need to create economic value from problems (environmental pollution) and create added value to combat the problem itself.

The added value

An inclusive city brings added value both for the environment and for the population but above all for the economy. We need to looking at a planned city and starts thinking about a preventive city. Giving a second purpose to all the works to be carried out.

- Private projects and public works can easily create economy
- Projects carried out on private buildings create added value for public places.
- The citizen has the opportunity to earn and in the same way contribute to cleaning up the environment
- The inclusive city can create extra income for the PA
- The inclusive city can create Beauty, Design and redevelopment

[22] http://www.urbanisticainformazioni.it/IMG/pdf/citta_alla_pari.pdf

In detail, it is important to deepen two aspects that are linked to the inclusive city. The first is a purely architectural concept and concerns the design aspect that involves the thesis project. The second, on the other hand, is much more engineering and wants to explain how economy can be created from a garden roof made of moss.

Service Design for urban inclusion

The common thread that connects all the types of cities explained in this chapter is the pollution of urban areas. This project addresses the problem of pollution and urban decay in a holistic way, that is, treating a specific part of the city as an "ecosystem" that includes buildings and people, with the possibility of identifying possible advantageous variables of urban regeneration with benefits in terms of environmental well-being by inserting, when possible, economic facilitation devices. The technological solution provides a suite of services for different stakeholders; this solution, if properly connected, selects an integrated and synergistic use of technological, methodological, economic and social resources.

The approach adopted is that of Service Design whose concept is linked to economic and financial discipline and indicates an activity of integration and organization of different types of resources, including communication artefacts and materials relating to a specific service, aimed at improving the relationship between supplier and end user. In other words, Service Design can be seen as an interdisciplinary approach to the design of a service in which user-centered design assumes central importance in giving the service greater usability, desirability, accessibility and attractiveness and is recently described by some research [41] as a key factor in the innovation of services.

One of the essential elements of the approach is for example the use of satellite data [42]. Demonstrate to use digital tools and georeferenced data, combined with a co-design approach, interactively connecting between citizens, stakeholders and decision makers in the approach to urban problems as it provides a common information base and methods efficient communication and exchange of information between the various subjects. Salinas, [42] underline among the main vulnerabilities, the frequent and well known difficulty of making understandable the more technical aspects of the processes and the very different actors.

The approach to Service Design is applicable on many aspects, however a rather well-known aspect, but less applied on a large scale, is certainly linked to the reliability and quality of the information that feeds digital strategies; in this regard, the idea that the blockchain can make a substantial contribution is very widespread and shared, however, examples of application of this technology are still rare. In the future evolutionary prospects of this research, the blockchain has a central function in Service Design as it involves automating the process that guarantees the origin of the information generated by the processing of the data provided by the satellite platforms, whose reliability and quality is consolidated.

When satellite data is attributed an economic value, the need for a transfer register is evident, which generates the related costs and impacts on the service economy; alternatively, a self-certified blockchain-based tracking system can be used which is practically free. The same technological platform, in addition to the structured register, must also perform the important function of a meeting place between sellers and buyers of carbon credits by developing a market in which the financial resources of the real market are introduced.

The foregoing lays the foundations for the development of a process in which an owner of a property to be redeveloped is convenient to carry out a "green intervention" thanks to the guarantees of return on short investment times, as well as bringing an environmental benefit to guarantee the community.

Organic matter of roofs for urban inclusion

The main node becomes the green which, in addition to being an active lung of the city, can become an economic source for those who live there. To stop and reduce net land use and increase urban quality and preserve the environment, it is necessary to promote inclusive spatial planning and environmental management to increase policy coherence. To do this, it is necessary to identify and monitor vulnerable areas, monitoring the air breathed daily, identifying critical areas. In addition, soil consumption, the quality of urban greenery and the carbon sequestration capacity of urban environmental ecosystems must be monitored weekly. It will be necessary to promote sustainable and resilient primary production through actions aimed at spreading more effective models for the conversion of urban areas into green areas, facilitating the transformation of traditional buildings into green buildings, facilitating the creation of urban gardens, roof gardens and vertical green walls.

To encourage people not to consume land and encourage citizens to transform their roofs into green areas, here it has been developed a cognitive and interpretative model of urban complexity supported by a system of digital data and information whose main objective is to provide a certain and reliable quantification of phenomena and dynamics normally considered unnecessary or not useful. It is therefore possible speak of the “Data-Driven Sustainability Model” referring to a technological system for monitoring and evaluating phenomena on an urban scale that allows the development of real economies aimed at reducing negative impacts and improving the quality of the environment and urban space. The undervalued, unnecessary and not useful aspects are attributable to the organic substance of the soil. It is made up of any material produced by living organisms, plants or animals, which returns to the soil and undergoes decomposition processes. So even moss can be used to store carbon.

To transform carbon into economic value, it is necessary to calculate the atmospheric CO^2 storage capacity of an urban green area and its direct removal into the atmosphere through photosynthesis and carbon fixation in plant litter and root exudates. CO^2 sequestration in plants and soil has already been quantified by several models [43] [44] [45] [46] [47], showing that an ecosystem can act as a carbon sink for a sufficient period of time.

The energy saving potential of green roofs, on the other hand, has been extensively studied [48] [49] [50] [51] [52] [53] [54] and they have also developed a web tool [55] , the "Green Roof Energy Calculator ”, to promptly estimate the annual energy savings for buildings with a green roof. In contrast, other studies [56] [57] have measured the ability of green roofs to sequester carbon in plants and substrates and efforts to quantify carbon sequestration.

These studies compared the environmental burden and benefits of green roofs and assessed their overall environmental impact. In particular, a study by Bianchini [58] indicated that the annual reduction of air pollution (NO^2, SO^2 and O^3) from a green roof will offset the emissions associated with its production after 13-32 years. The study calculated the amount of air pollution created by the production of the polymers of a typical green roof system and compared their results with its pollution removal capacity [59].

2.2.4 Participated city

The participatory city has also been mentioned in the previous paragraphs, it provides that an important part of planning must be represented by the experimentation of public participation processes so that the local community is sensitized and can strengthen its sense of responsibility and belonging towards the territory, as well as being able to hypothesize new economic opportunities and use of territorial resources. In our case, on the other hand, participation is not expressed in the planning stage but it is an active participation. Citizens, knowing the problem of air pollution, mobilize with private projects (on their buildings) and participate in the reduction of pollutants. In this way the private project becomes an initiative capable of enhancing and improving the territory. The role of the PA remains that of coordinating the strategies aimed at guaranteeing the enhancement of the environment and the birth of compatible economic activities, the identification of priorities and specific indications to be taken into account in the project, as well as the possible elaboration of ideas for the future management of the territory.

Therefore, the goal is to have a voluntary participation that gives the concrete possibility of gaining economic benefits. Human capital and the democratic participation of citizens are dictated by common interests, and, as anticipated, this thesis aims for a win-win approach.

In this paragraph two fundamental aspects for participation will be deepened. The first concerns the degree of involvement of the citizen, who must be trained and prepared in order to participate. To train them, it is necessary to encourage the involvement of citizens in Free technologies (use MOOC *Massive Open Online Courses* or contact training) and to prepare them, it is necessary to provide citizens with greater transparency and open data. The second concerns financial aspects, a citizen to participate actively must be able to derive profits from his actions. Earnings must be an incentive to participate but at the same time they must encourage them to do more and more.

Solve the problem

- Need to help citizens to use data and understand their use
- Encourage the active participation of citizens in environmental projects
- It is necessary to help the citizen to finance environmental projects and to obtain income from them
- It is necessary to solve the problems of housing and social relations by using “parallel” resources that come from environmental projects
- Encourage private projects that look to a common gain
- Private individuals must be encouraged to take advantage of public funds, but only if they are able to obtain an environmental or economic gain for the community.

The added value

- To stimulate virtuous and democratic processes.
- If a community can recognize and recognize itself in the choices that are planned and in the relationships that are established, it will be able to look forward to the principles of sustainability, equity and development.
- A participatory decision can produce (although it does not necessarily produce) qualitatively better results.
- The quality of life will not depend not only on resources, but also on their distribution and use.
- Participation will have as its purpose the expansion of everyone's ability to share choices.
- It increases the consensus of the institutions.
- It is an antidote to forms of pressure on non-transparent decision makers, to promote partisan or corporate interests.
- Participation enhances the "social capital" of a local community.
- It makes local "short networks" more solid, but also their ability to connect with supra-local "long networks"[23]
- It tends to prevent a conflict that blocks development potential.
- Contrasts the tendencies towards the destruction of human (and non) localized resources

Open data and Satellite data

The existence of several variables to be taken into consideration makes planning adaptation strategies extremely complicated in terms of involving stakeholders in the decision-making process as well as in terms of developing a consolidated framework for adaptation and mitigation. In 2020 there is an urgent need to make the potential of data known to everyone. Almost ten years after the Malmo[24] Declaration and the Open

[23] The first conceptual step, by no means trivial in non-metropolitan contexts, was to understand the territory as a network, as a continuous relationship between short and long networks, between intangible and material networks. http://www.urbanisticainformazioni.it/Processi-di-rigenerazione-reti-corte-e-nuovi-paradigmi-per-le-reti.html
[24] Malmo Declaration on eGovernment policies of 2009 to propose a first path of opening up European administrations in 5 years.

Government Partnership[25], which incentivize a concrete commitment by governments to promote transparency, empower citizens, fight corruption and strengthen governance through technology.

It has been realized that local authority sites have many open databases, but very few know how to use them. The thesis will make use of those databases and at the same time make them "understandable", which means the use of data diffusion in a graphic form compared to a table form. It will aim to produce new approaches that can help urban planners and citizens themselves to transform cities into smart and sustainable centers through the combination of Technology Information and Communication (ICT)[26].

The digitization of information and the creation of digital data archives contribute to the rapid dissemination of knowledge and improve the availability, quality and accuracy of data. The possibility of transcribing, collecting new data and interconnecting them with existing databases reveals new interpretations of the city, creating virtual and digital models of urban space. Sensors placed on roofs or satellite data will become an integral part of open data[27]. The City Sensing approach will be used, which will have a widespread and pervasive method to understand the dynamics of the contemporary city and share them with the main stakeholders in order to install an interactive, simplified but complete decision-making process: participatory modelling of the city allows projections and forecasts of future cities.

In City Sensing, a heterogeneous set of data coming from system technologies and the direct consultation of citizens made possible by ICTs provide information on specific parts of the city with variable spatial and temporal resolution, the sensing of which makes it shared [60]. On the one hand, the application of ICT ensures an informed decision-making process and therefore a better resilience of the city and adaptability. On the other hand, ICTs enable territorial governance: the dissemination of information catalyzes communication between local governments, communities and all interested parties [61]. Using remote sensing data integrated with specific datasets from on-site surveys and official EUMETSAT[28] databases, this thesis aims to create a reliable, reproducible and cost-effective system for measuring air pollution values. In recent years, the launch of satellite sensors for Earth Observation (EO) with spatial and temporal resolutions and, at the same time, greater radiometric precision has paved the way for their use to support the study of air quality problems. The synoptic view and in particular the measurement frequency of the new satellite sensors provide the potential to monitor particulate pollution: despite its consolidation potential of the analysis on a continental scale, EO is not yet systematically used on a local scale for monitoring. air pollution.

For this thesis all the Open-Source satellites of the Copernicus Mission were used. The satellites will allow to analyze urban air pollution and estimate the sequestration capacity of green areas. In particular, the 5P satellite can provide access to

[25] Italian initiative of 2011 on open-data

[26] They are the set of methods and technologies that make up the information transmission, reception and processing systems (including digital technologies).

[27] they are data freely accessible to all whose possible restrictions are the obligation to quote the source or to keep the database always open. Open data refers to the broader discipline of open government, that is a doctrine according to which the public administration should be open to citizens, both in terms of transparency and direct participation in the decision-making process.

[28] The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is an intergovernmental organisation created through an international convention agreed by a current total of 30 European Member States.

tropospheric pollution data through the TROPOMI sensor[29]. In the methodology part, it will be possible to understand in detail how they are processed, validated, integrated with the data on the ground and how they are returned to the end customer.

Use resources correctly

Citizens have become very aware of air pollution problems, especially those involving fine particulate matter. Residents, visitors, scientists and policymakers are finding that open access to air quality data could help people warn them when all children, seniors, and even healthy adults should stay indoors due to dangerous pollution. In part, it has to thank laws on open data, and satellite data is an example of this: data is key in the dialogue between citizens and government to clean up the air in the years to come.

To use data and engage citizens, it is necessary to plan projects that see the use of data to create solutions, not to solve problems. The fusion of the wide variety of technologies available for air quality monitoring and the development of innovative applications and business models can improve the urban context.

Given the relatively cross-sectoral nature of air quality and the ability of our data to apply to a wide range of applications, it is easy to find projects that create environmental and market benefits. To face this challenge, the thesis work will have two target markets as its objective and will have a sustainable process to convey new product and market requests in the development and sales pipeline.

The participatory budget will have the task of channelling funding to support the mitigation and adaptation projects to climate change selected by citizens. The lines of development, downsizing and replication of innovative financing solutions will have to take into account the capital needed to structure low-carbon and climate-resilient projects.

Citizens who are committed to tackling climate pollution will need to receive support to develop their proposals through an economic contribution or the technical advice of city finance experts at the main public and private organizations. Climate initiatives and funding often included an Energy Performance Contracting (EPC)[30] scheme

- a method of financing energy efficiency improvements and renewable projects that do not have the funds to do so
- for the profound modernization of buildings, a tool for self-assessment of the climate risk for cities and a prize card for citizens who invest in energy efficiency measures.

The project's vision wants to incentivize to give also direct financing to mitigate the climate, not only to finance works that will have an impact on it in the long term. The vision is to push environmental data into mainstream decision making, consisting of a

[29] The TROPOspheric Monitoring Instrument (TROPOMI) is the satellite instrument on board the Copernicus Sentinel-5 Precursor satellite. The Sentinel-5 Precursor (S5P) is the first of the atmospheric composition Sentinels, launched on 13 October 2017, planned for a mission of seven years.

[30] Energy performance contracting (EPC) is a mechanism for organising the energy efficiency financing. The EPC involves an Energy Service Company (ESCO) which provides various services, such as finances and guaranteed energy savings. The remuneration of the ESCO depends on the achievement of the guaranteed savings. The ESCO stays involved in the measurement and verification process for the energy savings in the repayment period. ESCO and energy performance contracting are mostly found in the public sector and to a lesser extent in the industrial and commercial building sectors (Hilke and Ryan, 2012).

distinct set of relevant skills and experiences, which will involve both B2B marketing and direct supply chains.

3 Research objectives

This thesis does not want to have as its main objective the monitoring of pollutants or to introduce the methodology and tools necessary to monitor the atmosphere. It does not just want to describe the problem or a possible solution to solve it: the thesis, instead, aims to use technological skills to support, plan, improve and create added value to the problem of air pollution in the city.

It is possible set therefore the following objectives in terms of environment, city, public administration, citizens and the companies.

- I aim for the Public Administration to involve it in the transition towards sustainability and the use of new methodologies that come from the integration of traditional technologies with advanced space management technologies.
- As far as the city, I can recall three words Circular-Green-Satellite. The three keywords describe the goal which is to identify new opportunities to increase the level of circularity of their solutions, adapt to climate change and improve the comfort of public spaces and production areas in the area using new satellite technologies.
- In terms of environment, I foresee three sub-paths, the first is to integrate and participate in all the actors and technologies in a single project. The second path must be to transform project funding for climate change into self-financing projects for climate change. Third and last path always sees the environment as a common thread, it must be the one that allows to integrate projects through observatories and make the environment known through knowledge and policies of the territories.
- The goal for citizens and companies is to find an ideal solution that helps them improve the performance of their buildings and helps them monitoring consumption and their impact on the city itself, and where possible also create an economic value.

The 5 key dimensions of the thesis are:

1. **Implementation** of a project that is able to observe the principles of the Circular Economy
2. The resilient **vision** that facilitates the circular model, increasing the quality of life of stakeholders
3. The **dissemination** of best practices to increase efficiency in the use of technologies for citizen problems.
4. The **planned** management of cities and buildings with innovative and sustainable methods that promote reuse and resilience
5. **Support** for the development of environmental awareness, involving stakeholders in virtuous mechanisms

By intersecting these five dimensions with a single project, this thesis work will also be able to stimulate 5 indirect objectives for the city:

Understand the city, manage the city

In a world increasingly immersed in digital and technological transformation, the challenge is to create a thesis project capable of organizing and managing the huge amount of data and information available and constantly changing to improve the city based on the real needs of citizens and public administrations.

The solutions must allow to:

- Know the **problem and the real demand** for services and infrastructure
- Help to **make decisions** based on up-to-date data and statistics
- Give the opportunity to **view** data through interactive maps and graphics, encouraging communication and citizen **participation**

Greener buildings, greener cities

- Monitor consumption through satellite **management information** systems
- **Reduce urban pollution**
- Obtain significant **savings in energy** consumption
- Offer a more **functional environment** to citizens and employees, enabling a series of value-added services of public utility
- Making access to the **new flexibility market possible**, actively participating in the network to reduce pollutants and generating extra revenues that can be invested in additional services.

Circular economies for the city

The thesis must target the cities of tomorrow: resilient buildings, reduction of environmental impact, technology to facilitate every activity, resilience to guarantee the safety of all and economic growth. A project that can be defined as Circular is smart when it manages to identify the current level of circularity in the city and offers a roadmap of innovative solutions to be able to increase it.

To do this it is necessary to:

- Directly **support** public administrations on their path towards circularity by offering an evaluation tool that analyses the city according to some key dimensions and identifies and addresses areas for improvement. And once the path is cleared, the circular city becomes close and concretely achievable.
- **Educating, implementing and disseminating** the principles of the circular economy, in the multiple role of responsible citizenship and managing private assets also at the service of the community.

Objectives of the thesis

The general objective of this thesis is to bring clarity on the question of the definition, classification, collection and dissemination of data on atmospheric pollution in urban areas, on the use of roofs and on the possible economic value. The more specific objectives are:

Do a literature review of existing definitions and classifications used in various domains, whether statistical, administrative, scientific, and more.

a. Use the data obtained through the Copernicus mission, Sentinel-5P, to carry out a study on air quality and create models that allow to make predictions on the concentration of pollutants in the atmosphere

b. Do a literature review on existing methodologies for estimating sponge building storage and estimating pollutant fixation in cities, including a review of methodologies currently applied by countries;
   - make recommendations for
      i. potential definition of strategies,
      ii. building classification schemes and
      iii. methods for quantifying the production of terry roofs.
   - Analyze green building production data.
   - Create a set of recommendations on how to collect data on green cities, so that they allow for the creation of consistent datasets.

Information	Data to be Collected	Method of Collection	Data source
Atmospheric Pollution Information	Identification of main polluting indices in the city of Munich	Satellite + EEA	Satellite Data
Create economic value	Calculate the carbon credit of buildings and their market value	Blockchain + Satellite	Satellite Data
Building information	Total green roof area	GIS Software	OSM- GOOGLE API
	Determination of optimal plant species for green roofs at Munich	Literature Review	
Buildings capable of supporting a green roof within the city of Munich.	Carbon sequestration potential of specific plant species	Literature Review	Satellite Data + OSM-GOOGLE API
	Calculate the initial carbon credit to build a garden roof	Literature Review	
	Total Carbon sequestration potential of Munich	Gis Solftware	
	Total carbon sequestration potential of the entire city of Munich	Data analysis	

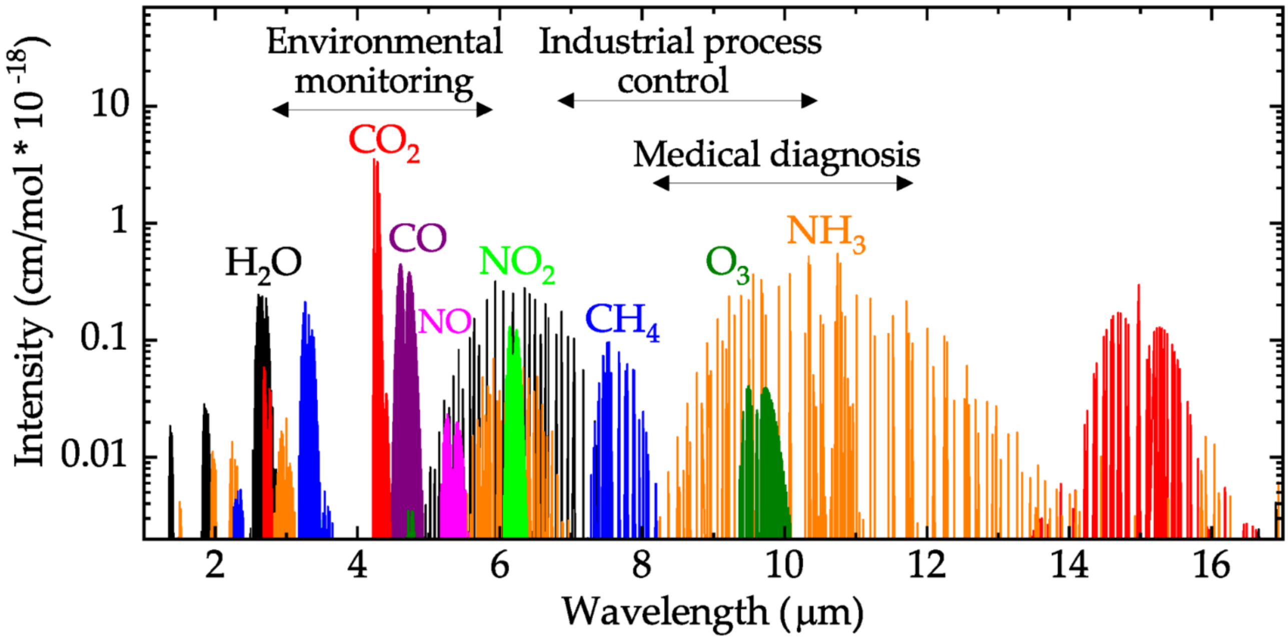
1 Table of thesis objectives

4 Research approach and methodology

The first chapter of this thesis helped us to identify the topic and helped us understand what the objectives are. This chapter instead has the task of defining the state of the art of atmospheric pollution. By defining the characteristics of pollution, the types of monitoring with particular detail on the satellite and other terrestrial technologies. The second part will introduce the model for defining and identifying air pollution and will focus on the added value of satellites and how to integrate the data within the city context.

4.1 How to monitor pollution from space

The remote sensing instrumental techniques dedicated to the monitoring of atmospheric gas concentrations have significantly improved and grown over the last few years. Now there are many satellites that allow probing even in the lower layers of the troposphere and contribute to the evaluation of air quality. In the next chapter I will define the state of the art in detail. In this chapter it is important to address how to monitor atmospheric composition from space. Satellite observation tools currently are mainly in the form of spectrometers with high spectral resolution. In the past, global space observations of trace gases from space were devoted to measurements of water vapor and ozone. With the improvement of measurement techniques and species concentration recovery algorithms, it is now possible to provide quantitative information on many concentrations of trace gases and pollutants at regional or even local scales and with ever finer vertical resolution.

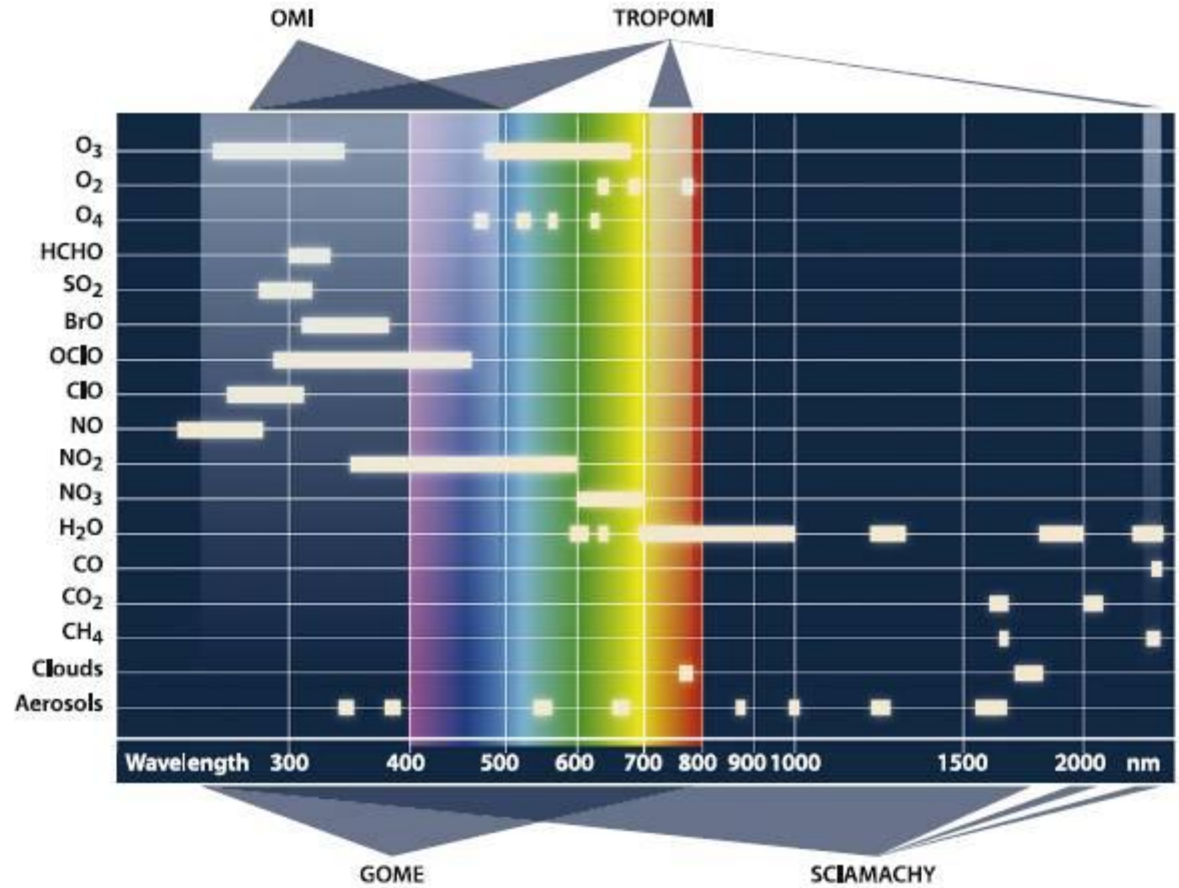


4 Mid-infrared absorption spectra of some gases **[62]**

To observe air pollutants, the satellites' passive remote sensing instruments measure atmospheric spectra resulting from the interaction between solar radiation or radiation emitted by the Earth or atmosphere and their molecules. The exploitation of these signals containing specific characteristics or signatures of the different molecules allows to recover their concentrations at different altitudes (for strong absorbers) or their total concentration in the column (integrated along the vertical, for weak absorbers). Each molecular absorption / emission line (in the IR) or cross section (in the UV) in a spectrum has a characteristic signature: the position indicates the identity of the molecule and the intensity infers the atmospheric concentration. To properly recover atmospheric concentrations from any raw satellite spectrum, other parameters are required, such as instrument characteristics (detector, optics, etc.), spectroscopic data, ancillary data such as temperature or air mass factors, and a transfer algorithm atmospheric radiative.

There are currently many satellite instruments capable of measuring air pollution. The state-of-the-art instruments that use UV-visible and thermal infrared radiation are TROPOMI (TROPOspheric Monitoring Instrument) and IASI (Infrared Atmospheric Sounding Interferometer) respectively [63].

OMI's spectrometer pioneered TROPOMI's Push Sweep Spectrometer has a greater number of spectral bands, which allows it to measure in longer wavelengths and, therefore, can have direct access to more atmospheric gases. While OMI measures between 270 and 500 nm (UV and visible), TROPOMI will also measure in the near infrared (675–775 nm) and short wave infrared (2305–2385 nm). With this extended range, TROPOMI already observes the greenhouse gas methane (CH4) and carbon monoxide (CO) as well as ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), formaldehyde (HCHO) etc. measured by OMI. TROPOMI also has a better signal-to-noise ratio than OMI (better measurement quality), as well as a better ability to detect clouds and fine particles (aerosols) and their altitude [64].



5 Spectral ranges for TROPOMI and the heritage instruments OMI, SCIAMACHY and GOME (Veefkind et al., 2012).

4.2 Urban Planning from the space

Air pollution is a major health risk factor. In order to know the real extent of this phenomenon and the related risks, it is necessary to adapt the innovative monitoring techniques and promote interdisciplinary scientific analyses that include different studies (satellites and IoT sensors on site). As seen from the previous paragraph, European countries have adopted regulations on pollution, with measures aimed at obtaining the reduction of emissions through structural interventions. Therefore, as a target I will identify the real extent of the risk deriving from exposure to atmospheric pollutants and the incidence of concomitant factors. Cities are also adversely affected by climate change in terms of infrastructure, economy, public services, urban planning and food security, all crucial dimensions for sustainable development. In this scenario, urban planners and policy makers are called to develop a comprehensive knowledge model that provides a detailed, real-time, dynamic and accessible framework for planning a city's future.

Therefore, a prototype will be presented which will serve as a support for decision making. In addition, it will explain how to integrate satellite imagery into different technologies and how to achieve added value. Finally, this work will use the same technology to create economic value in the city: the data will be crystallized within registered blockchain blocks to create a "shared value" where certified emissions data can be associated with an economic value and resold on the market in a win-win approach.

This thesis has a socio-urban purpose: it aims to give birth to a new concept of "Smart-Cities" defining them as "urban centers that integrate technologies and cybernetic infrastructures to create environmental and economic efficiency by improving the general quality of life". With this approach, the project aims to manage buildings, which represent 72% of electricity consumption, 39% of energy consumption, 38% of all carbon dioxide emissions (CO^2), 40% of raw materials used, 30% of waste production (136 million tons per year) and 14% of drinking water consumption for the benefit of "green buildings" that can reduce energy consumption by 24-50%, CO^2 emissions by 33- 39%, water consumption up to 40% and solid waste increasing to 70% during the life cycle of the building [36].

Consequently, the need to construct "green buildings" within Smart Cities will minimize the impact on human health and the environment, as well as reduce life cycle costs.

The chapter suggests that planning can be done from space. Fortunately, this is possible thanks to the Copernicus program[31], currently the most ambitious Earth observation program in the world and made up of different satellite systems. ESA makes all Satellite data available completely free of charge. This program provides accurate, timely and easily accessible information to improve environmental management, understand and mitigate the effects of climate change, and ensure civil safety. The program is coordinated and managed by the European Commission, while the development of the infrastructures takes place under the control of ESA and EUMETSAT (Sentinel 3 and 6) for the space components. The thematic areas in which the services linked to the Copernicus program are inserted are six:

- Land
- Sea
- Atmosphere
- Climate change
- Emergency management
- Safety

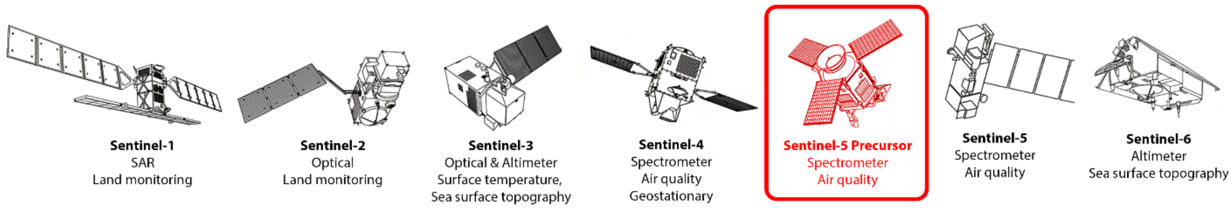
These services support an infinite number of applications including environmental protection, urban area management, land use planning, agriculture, forest management, fisheries, transport, sustainable development, civil protection and tourism.

For the specific needs of the program, the Sentinel project was developed, which envisages the launch into orbit of 12 satellites that will form the space component of the Copernicus program.

The primary purpose of the Sentinel satellites is to support the operational needs of Global Monitoring for Environmental Security (GMES). The satellites of the Sentinel missions represent the space component of the Copernicus program and also constitute the European contribution to the Global Earth Observation System of Systems GEOSS.

[31] Europe's Copernicus programme sets out to fulfil the growing need amongst European policy-makers, businesses, scientists and individuals to access timely accurate information services. By delivering vast amounts of Earth observation data through a unified system, this innovative programme starts a new chapter in the way we manage the environment, understand and mitigate the effects of climate change and ensure civil security for a safer and more sustainable future (http://www.esa.int/Applications/Observing_the_Earth/Copernicus/Overview3).

Each Sentinel mission is based on a constellation of a pair of satellites, constantly moving in different orbits, to meet the review and coverage requirements, resulting in reliable datasets for Copernicus services. Sentinel missions are as follows:



6 Copernicus Sentinel satellites In red sentinel S5p object of study in this thesis work ©ESA

- Sentinel-1: is a C-band synthetic aperture radar imaging mission for land and ocean monitoring independent from weather conditions. It is composed of two satellites, in polar orbit, which operate both day and night.
- Sentinel-2: like the previous one, it is made up of a family of two satellites in polar orbit. It aims to monitor the land surface, coastal areas and changes in vegetation. The satellites are equipped with a multi-spectral instrument, which provides thirteen different spectral bands for each acquisition.
- Sentinel-3: this mission focuses on the study of the topography of the sea surface, the temperatures of the land and sea surface, the color of the earth and the ocean, with the aim of monitoring changes in both the climate and the environment. It is a multi-instrument mission and, unlike the previous ones, it is made up of three satellites in polar orbit.
- Sentinel-4 (not yet in orbit): its mission is to monitor the atmospheric composition in order to obtain an analysis of the air quality. The SENTINEL-4 UVN instrument is an Ultraviolet-Visible-Near-Infrared (UVN) light spectrometer that will be mounted on board the third generation METEOSAT satellites[32], managed by EUMETSAT. The data provided will be used to support monitoring and forecasting in Europe;
- Sentinel-5 (not yet in orbit): dedicated to monitoring air quality. The Sentinel-5 UVNS instrument is a spectrometer that will be mounted on the second generation MetOp satellites. It aims to continuously monitor the Earth's atmosphere, providing global, large-scale data.
- Sentinel-5P: is a precursor satellite mission that aims to fill gaps due to the withdrawal of the Envisat satellite and NASA's Aura mission and the launch of Sentinel-5. It aims to measure some atmospheric parameters with high space-time resolution, concerning: air quality, ozone, UV radiation.
- Sentinel-6 (will be launched by the end of this calendar year 2020): It will carry a radar altimeter to measure the global height of the sea surface. It involves the collaboration of Europe and the United States.

[32] The Meteosat series of satellites are geostationary meteorological satellites operated by EUMETSAT under the Meteosat Transition Programme (MTP) and the Meteosat Second Generation (MSG) program. The MTP program was established to ensure the operational continuity between the end of the successful Meteosat Operational Programme in 1995 and Meteosat Second Generation (MSG), which came into operation at the start of 2004 using improved satellites. The MSG program will provide service until the MTG (Meteosat Third Generation) program takes over.

Specifically, in this thesis the data of the Satellites will be used:

Sentinel-2

The Sentinel-2 mission consists of two multispectral platforms (Orbit Heli-synchronous[33]), the first Sentinel-2A was launched into orbit on June 23, 2015, while the second Sentinel-2B was launched on March 7, 2017. They will launch also Sentinel-2C and 2D satellites. The Sentinel-2 mission provides multi-spectral images (13 bands) with high and medium spatial resolution depending on the specific band.

The Sentinel-2 satellites are placed in continuity, as an image type, with the SPOT and LANDSAT satellites, providing the Copernicus program with data necessary for a wide range of applications, also in combination with radar data from the Sentinel-1 mission, such as:

- Climate change, images from Sentinel-2 satellites can be of great support (given the reduced review time of up to 5 days) for monitoring deforestation or desertification.
- Territory monitoring has the same application fields as the Sentinel-1 mission and together with it can provide data for the drafting of land cover and use maps.

The satellites weigh approximately 1200 kg and are designed for a life of approximately 7 years, although the batteries and propellants have been charged for 12 years of operation, including end-of-life orbital maneuvers.

7 Graphic model depicting Sentinel-2A and 2B ©ESA

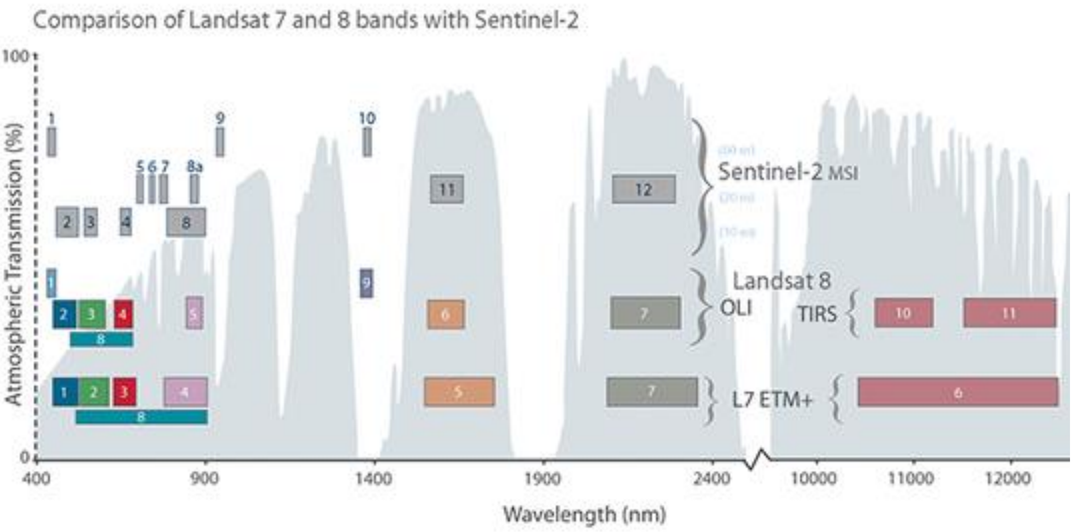
The MSI (Multispectral INstrument) sensors mounted on the platform work passively, the incident light rays are divided and filtered on separate focal planes, one for the visible bands (VIS), one for the near infrared band (Near-InfraredNIR) and one for "short wave" infrared (Short Wave InfraredSWIR). The choice of the sun-synchronous

[33] A Sun-synchronous orbit (SSO, also called a heliosynchronous orbit) is a nearly polar orbit around a planet, in which the satellite passes over any given point of the planet's surface at the same local mean solar time. More technically, it is an orbit arranged so that it processes through one complete revolution each year, so it always maintains the same relationship with the Sun.

orbit was made because in this way the impact of shading on the ground is minimized. The orbit is kept stable by a dedicated propulsion system and through the measurements of a dual frequency GNSS receiver of revisitation is 5 days at the equator (2-3 days at medium latitudes) in the same setting conditions, this value decreases if referring to different setting conditions, due to the lateral overlap of the acquisitions. Sentinel-2 systematically acquires data on land and coastal areas in a band ranging from 56 ° South latitude to 84 °.

Sentinel-2 satellites are equipped with a multispectral sensor, MSI, a push-broom instrument that acquires data lines perpendicular to the swathe uses the forward movement of the satellite to acquire new data strings. The incident radiation is deflected by a “beam-splitter” system on various focal planes according to the filters applied. The swath is 290km. In order to guarantee this, both the VNIR and SWIR sensors are composed of 12 detectors placed in two horizontal rows.

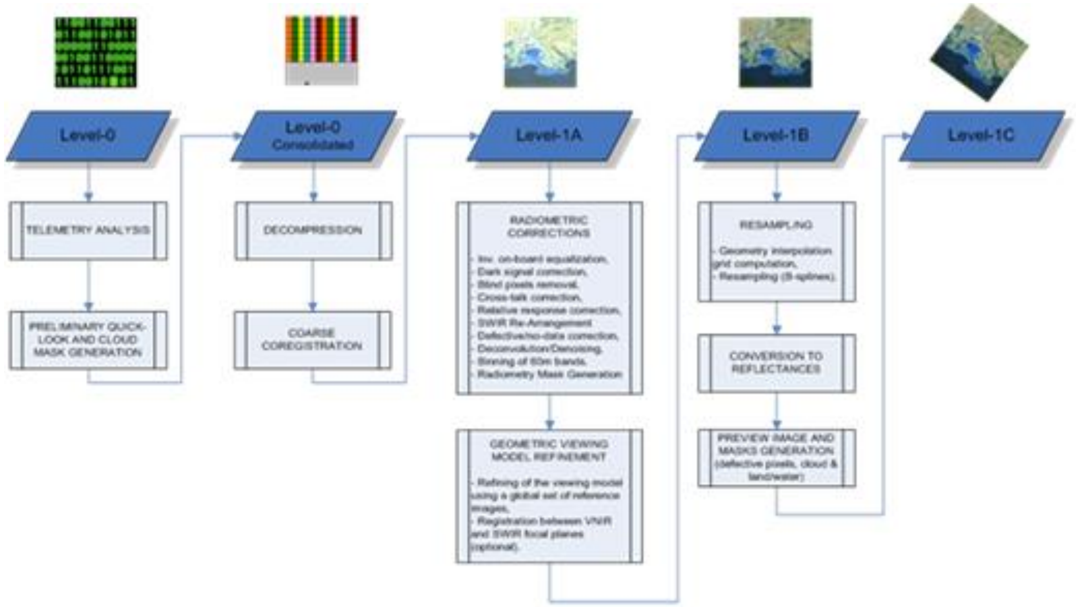
Sentinel-2 sensors are capable of receiving information on 13 spectral bands at different spatial resolutions.



8 List Of Band Combinations For Sentinel 2, Landsat 8 e Landsat 7 ETM+ © STEP Forum

In general, the Sentinel-2 bands are narrower than its predecessors such as the LANDSAT[34], this serves to limit the atmospheric influence on the reception of light waves. The 8th near infrared band is specially designed with a "narrow" width to avoid contamination due to water vapor present in the atmosphere; despite this, it is able to describe the plateau of the spectral curve of the vegetation in the infrared and is sensitive to iron oxides in the soil. Band 1, in the blue field, is necessary for the precise correction of the deformations induced by the atmospheric aerosol. The radiometric resolution of the MSI is 12 bits with the ability to acquire images in a range of light intensity values ranging from 0 to 4095. Sentinel-2 data is available in various processing levels as follows:

[34] The Landsat program is the longest-running enterprise for acquisition of satellite imagery of Earth. It is a joint NASA/USGS program. On July 23, 1972 the Earth Resources Technology Satellite was launched. This was eventually renamed to Landsat. The most recent, Landsat 8, was launched on February 11, 2013.



9 Processing levels from Level-0 to Level-1C. (Level-0, Level-1A and Level-1B products are PDGS internal products not made available to users.) © ESA

The data is provided in a special format (SAFE[35]) which includes, in addition to the JPEG image, quality indicators, auxiliary data and metadata. Level 2A contains orthorectified products with Bottom-Of-Atmosphere (BOT) reflectance information and a basic classification (including cloud classes). This kind of products are generated by users of 1C products. At levels 1C and 2A there are "granules" (also called tiles) of 100 sq km. At level 1B there are images covering areas of about 25 sq km, this is the minimum level of data provided and contains information of all the spectral bands.

In addition to Sentinel-2 data, Landsat-8 images will also be used to study the surface temperature of cities and exhaust fumes.

Sentinel-5P

Sentinel-5P is the Copernicus mission precursor of Sentinel-5. The first mission of Copernicus which aims to monitor the Earth's atmosphere by performing atmospheric measurements with high space-time resolution. As explained by the official ESA website [65], the Sentinel-5P mission, in addition to providing data to study the concentration of pollutants in the atmosphere, "*will also contribute to services such as the monitoring of volcanic ash for air safety and for services that warn of high levels of UV radiation that can cause damage to the skin. Furthermore, scientists will also use the data to improve our knowledge of important processes in the atmosphere related to climate and the formation of holes in the ozone layer*".

This project was born from the collaboration of ESA with: the European Commission, the Dutch Space Office. The satellite was launched on 13 October 2017 from the Plesetsk Cosmodrome in Russia. The acceleration phase ended on March 5, 2019,

[35] format, including image data in JPEG2000 format, quality indicators (e.g. defective pixels mask), auxiliary data and metadata.

and has been carrying out routine operations ever since. The satellite is designed for a total useful life of 7 years and has a weight of 980 kg. The data supply and release plan include:

Level 1B

- total columns of ozone, nitrogen dioxide, carbon monoxide; cloud and aerosol
- Total columns of ozone, formaldehyde, sulfur dioxide
- Total columns of tropospheric ozone, columns of methane
- Aerosol Layer Height
- Release of Ozone Profile

The predicted orbit is sun-synchronous near-polar[36], at an altitude of 835 m and an orbital cycle duration of 16 days. Thanks to its very wide swath (2600km) the instrument will provide a daily coverage of the earth's surface for latitudes greater than 7 ° and less than -7 °, while for the band between those two latitudes values the coverage will be 95%. Sentinel-5P's orbit is calculated in such a way that it is followed by Suomi-NPP, NASA satellite of the NPP mission started in 2011, in such a way that the zone observed by Sentinel-5P remains within the zone examined by Suomi-NPP.

The main instrument brought into orbit by the satellite will be called TROPOMI, a push broom with nadiral vision sensor. The "TROPOspheric Monitoring Instrument" (TROPOMI) which combines the strengths of instruments already used for the observation of the atmosphere, such as: SCIAMACHY (ENVISAT), OMI (AURA) and fills the gaps between them and the future mission of Copernicus Sentinel-4 and Sentinel-5 through the use of advanced technologies that allow to obtain performances not obtainable through the instruments already present in the space. The main features of the instrument are[37]:

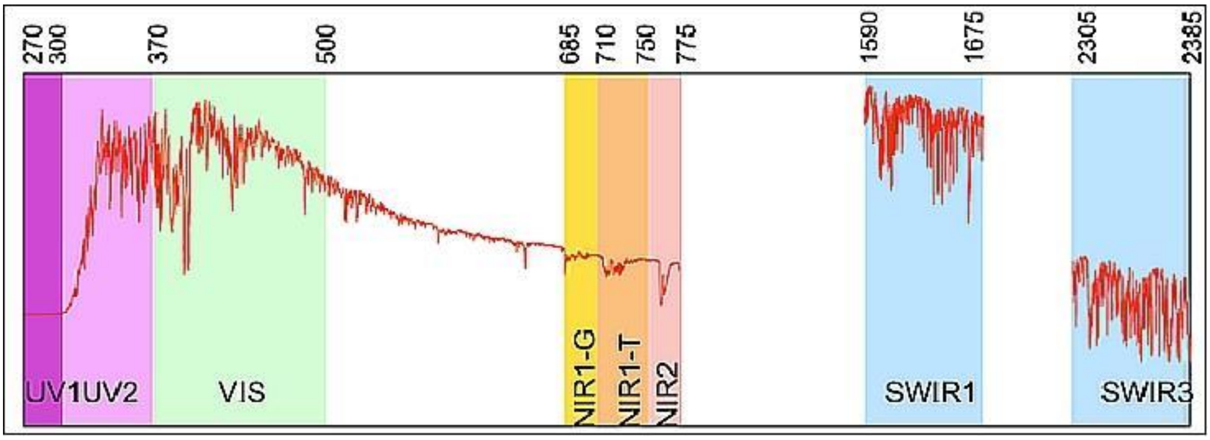
- Configuration: broom staring (non-scanning) in nadir viewing
- Swath width: 2,600 km
- Spatial sampling: 7x7 km
- Spectral: 4 spectrometers, each electronically divided into two bands (2 in UV, 2 in VIS, 2 in NIR, 2 in SWIR)
- Radiometric accuracy (absolute): from 1.6% (SWIR) to 1.9% (UV) of the measured terrestrial spectral reflectance.
- Passive grid imaging spectrometer

[36] Due to the rotation of the Earth, it is possible to combine the advantages of low-altitude orbits with global coverage, using near-polar orbiting satellites, which have an orbital plane crossing the poles. These satellites, termed Polar Orbiting Environmental Satellites (POES) are launched into orbits at high inclinations* to the Earth's rotation (at low angles with longitude lines), such that they pass across high latitudes near the poles. Most POES orbits are circular to slightly elliptical at distances ranging from 700 to 1700 km (435 - 1056 mi) from the geoid. At different altitudes they travel at different speeds. "High inclination" means that the subsatellite point moves north or south along the surface projection of the earth's axis. If the orbit is designed correctly, the subsatellite point can be largely in the day side (or night side) of the planet during the entire orbit. Such an orbit is termed "sun-synchronous" and more details on that are given below. Obviously, in order for this to happen, the orbital speed of the satellite (and its orbital altitude) would have to be phased with the rotation of the earth. The result is that the orbit of the satellite can be phased so that the satellite maximizes its coverage of the the day side of the planet.

[37] Copernicus : s5p instrumental payloadhttps://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p/instrumental-payload

- Total mass: 204.3 kg excluding ICU (16.7 kg)
- Dimensions: 1.40 x 0.65 x 0.75 m
- Duration of the project: 7 years
- Average absorption: 155 W
- Data volume generated: 139 Gbit per full orbit.

It is composed of four spectrometers, each of which sensitive to two spectral bands, for a total of eight bands: 2 in UV, 2 V, 2 NIR, 2 SWIR. It will have a spatial resolution of 7 km in "along track" acquisition, in "acrosstrack" mode the spatial resolution varies between the bands:



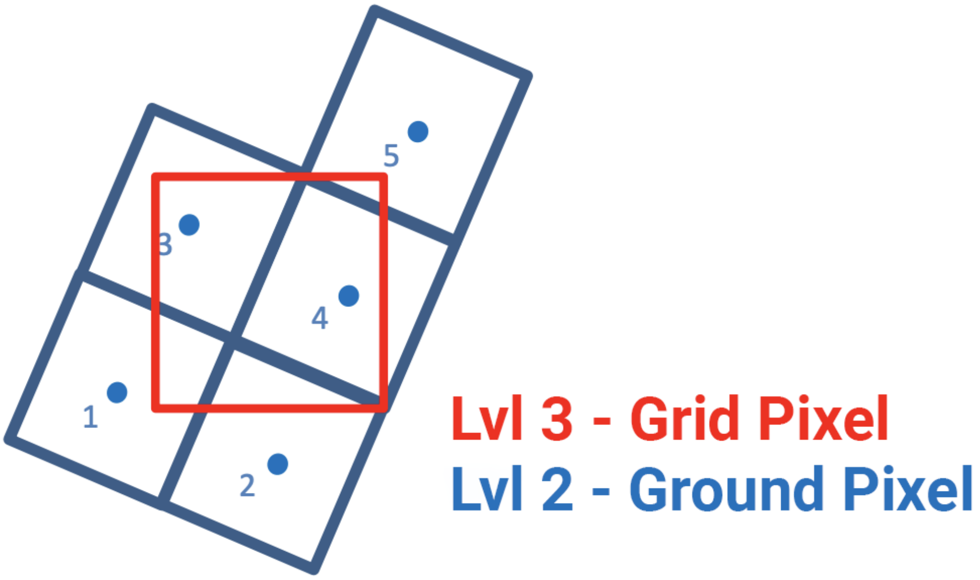
10 Sentinel-5 spectral band definition (spectral radiance of SWIR bands not in scale) © ESA

TROPOMI products are distributed on two levels, in this work they will be processed at a level 3 to correct the pixel and will explain the procedure:

- Level-0, represents the raw data acquired by the instrument.
- level-1b, contain radiance and irradiance for each pixel at each wavelength.
- Level 2, directly provide geophysical atmospheric parameters.

• Level 3, Orthorectification and repositioning of the pixel on square grid: Processing from level 2 to level 3 is performed because ESA provides predefined level 2 data without a fixed grid (unlike, for example, Sentinel-2 images that use the EPSG Geodetic Parameter Dataset military grid reference system). The pixels in Sentinel-5P Level-2 products are defined by latitude and longitude, forming an irregular grid that makes combining multiple images more difficult. This can be solved by converting to processing level 3: the data is resampled into a normal grid of spatial pixels, using the HARP[38] software toolkit.

[38] Data harmonization toolset for scientific earth observation data



11 Sentinel-5P Level-2 ground pixel (blue) vs. Level-3 grid pixel (red) ©RUS Copernicus edited [69]

Level 2 data includes:

- Total column of ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, formaldehyde and methane
- Tropospheric column of ozone
- Vertical ozone profiles
- Cloud and aerosol information

In addition, three data processing is provided:

- Near real time NRT
- OFFL offline
- Reprocessing

In the first case the data is available within three hours of detection, this service is offered for most products. In the second case, the times differ depending on the product considered: 12 hours for level 1B, up to five days for level 2 products.

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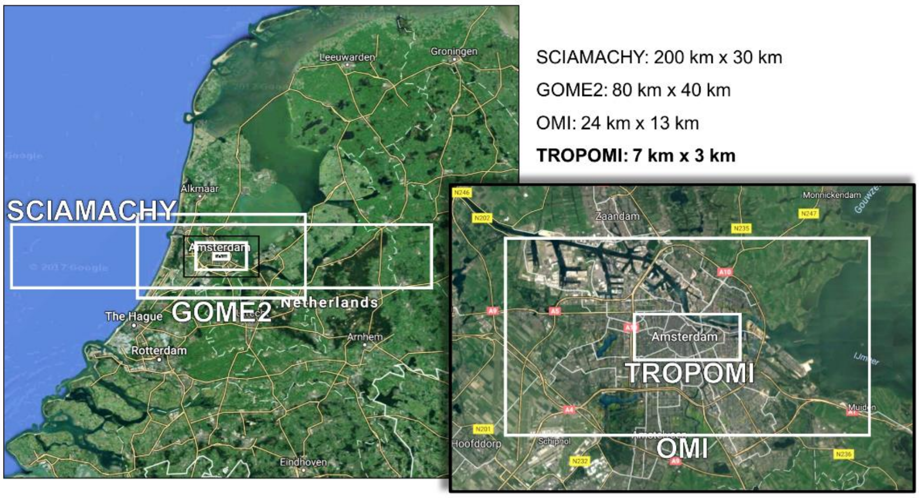
difficult. This can be solved by converting to processing level 3: the data is resampled into a normal grid of spatial pixels, using the HARP software toolkit[39].

Measurements for urban scales

It has seen previously that the measurements have improved. By improving the sensors, the scales have also improved. Sentinel 5P has a pixel size of approximately 7 km x 3 km. This is considerably smaller than its predecessor, OMI, which has a pixel size of around 24km x 13km, and certainly much smaller than GOME2 (80km x 40km) and SCIAMACHY (200km x 30km). The smaller pixel size means it is possible to start solving city-scale air quality. All this helps to use this data even in urban contexts. With such fine resolution, it is possible to get a better idea of the regional variability in air quality, as well as the different sources of pollutants in the atmosphere. In addition to the best resolutions, significantly more measurements are available while OMI acquires around 1 million spectra per day, Sentinel-5p's Tropomi sensor will provide around 20 million. With TROPOMI it is therefore possible to open a new era of challenges regarding big data and the processing capacity of city air pollution [66].

Satellites have improved resolution and revisit times. The pixel size of about 7km x 3km, which allows us to see at much finer city scales and resolutions than in the past. However, a smaller pixel does not mean less coverage of the Earth, on the contrary, the new satellites, despite having smaller pixels, have increased the swath width by 2700 km, thus providing greater global coverage every day.



12 The TROPOMI instrument has a pixel size of around 7 km x 3 km, allowing us to see on city scales, and much finer resolutions than its predecessors **[67]**

[39] HARP is a toolkit for reading, processing and inter-comparing satellite remote sensing data, model data, in-situ data, and ground based remote sensing data. https://atmospherictoolbox.org/

5 State of the art

5.1 Atmospheric aerosol

Air pollution is believed to occur whenever harmful or excessive amounts of defined substances such as gases, particulates and biological molecules are introduced into the atmosphere. These excessive emissions have obvious consequences, causing disease and death of populations and other living organisms and damaging crops. Air pollutants can be solid particles, liquid droplets or gases, classified as follows: Primary pollutants, which are emitted from the source directly into the atmosphere. Sources can be natural processes, such as sandstorms, or human-related processes, such as industry and vehicle emissions. Any modification of the normal composition or physical state of atmospheric air, due to the presence in it of one or more substances in quantities and with characteristics such as to:

- alter the normal environmental conditions and air healthiness
- constitute a danger or direct / indirect damage to human health
- undermine recreational activities and other legitimate uses of the environment
- altering biological resources and ecosystems and public and private material goods.

The substances emitted into the atmosphere are very numerous and new ones are synthesized every year by human activities. The main air pollutants are:

- carbon monoxide (CO)
- nitrogen oxides (Nox)
- sulfur oxides (Sox)
- Hydrocarbons (CxHy)
- suspended particles (PTS)
- ozone (O3)

Not all of them are visible from satellite, but in this thesis I will refer not only to the main pollutants, but also to less known pollutants that affect the climate of cities:

- Carbon Monoxide (CO)
- Formaldehyde
- Methane
- Nitrogen Dioxide
- Sulfur Dioxide
- Ozone (O3)

For these substances, with the exception of hydrocarbons, there are standards that establish acceptability limits and establish “air quality” standards for concentration values over an entire reference year. These limits are of a health nature: above them the conditions for protecting public health are lacking, with the consequent possibility of the onset of various types of pathologies. To control these parameters, starting from the 1970s, monitoring networks were set up based on automatic detection control units, fixed (mainly) and mobile. Furthermore, in those years, space agencies also began to monitor the atmosphere from space. In this chapter I will define the state of the art of satellite technologies. It should be remembered that for the other contaminants not present in the list above, however, no real tolerability limits have been set and therefore there are no, with few exceptions (some hydrocarbons) limited to the main cities, which have control units set up for their control. As far as the emission sources are concerned, the anthropogenic ones can be traced back to five main business sectors:

- Transportation
- Thermoelectric power stations
- Industry
- Domestic and tertiary sector
- Agriculture and fisheries

It is possible to distinguish between sources of the Italian Legislative [68] and in widespread environmental emission standards[40] (transport, domestic and tertiary sector, agriculture and fishing), with discharge at a more or less low height, and concentrated sources of emissions[41] (industries and thermoelectric plants) with high discharge height and total[42] emissions with combined exhaust. Diffuse sources play a predominant role in the emissions of carbon monoxide and hydrocarbons, and prevalent in those of nitrogen oxides and suspended particles, while industries and thermoelectric power plants are the main culprits of sulfur dioxide emissions. Once released into the atmosphere, the toxic substances are transported by air currents to different altitudes for more or less long times and distances. In this case, the satellite is the only technological tool capable of constantly monitoring them. A significant part is deposited, within a distance between a few tens of meters and a few kilometers. The rest of the load falls at greater distances, up to 1000 km or more, after undergoing several chemical transformations (mainly oxidation and photolysis processes). Impacts can be monitored on agricultural or forest land adjacent to city areas. Relapse to the ground can occur in two ways:

- Dry fallout: deposition of residual forms of gaseous species or, in the form of particles, of some salts;
- Wet fallout: affects acids and most salts and comes mainly from rain and snow.

The meteorological conditions are decisive for the dry relapse.

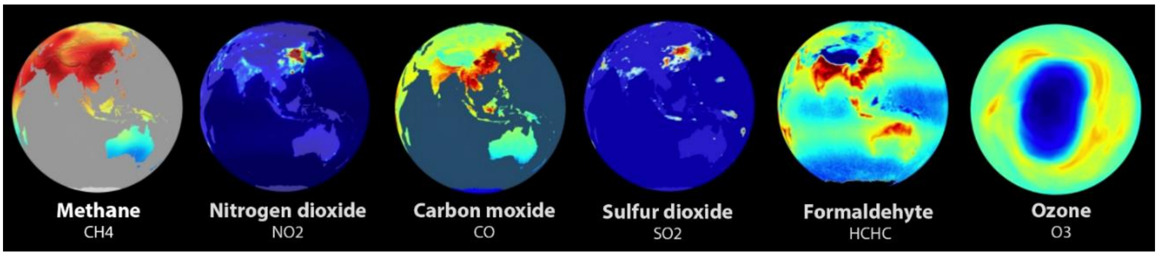
Making distinction between the type of pollutants, it is possible to distinguish them into primary and secondary. Primary are those which manifest their harmful action in the form and state in which they are released into the atmosphere. The substances that, on the other hand, derive from the reaction between primary pollutants, possibly with the participation of natural components of the atmosphere, under the influence of chemical or physical catalysts, are secondary pollutants.

5.1.1 Classification and composition

The directives of the European Union on air quality identify SO2, NO2, PM10, CO and ozone as indicators of preferential use for health impact assessments. The European

[40] diffuse issue: issue other than that falling under letter c); for the activities referred to in Article 275, diffuse emissions also include the solvents contained in the products, without prejudice to the different indications contained in Part III of Annex III to part five of the Italian Legislative Decree no. 152
Environmental regulations;
[41] technically conveyable emission: diffuse emission that must be conveyed on the basis of the best available techniques or in the presence of situations or areas that require particular protection;
[42] total emissions: the sum of diffuse and channeled emissions;

Commission, in 2013 and updated in 2018, adopted the proposal “Aria pulita per tutti [69]”, a set of measures favorable to the reduction of atmospheric pollution. Below are some of the pollutants mentioned in the "clean air" proposal that are currently of greatest concern.



13 Sentinel-5P data products ©ESA

- **Ozone (O_3):** the ozone present in the atmosphere can be classified as "good" or "bad" depending on where it is located. The "good" ozone in the stratosphere protects the Earth from ultraviolet radiation from the sun, which allows the splitting of O2 atomics. While the one in the troposphere, therefore in contact with the ground, causes respiratory diseases. Tropospheric ozone is the result of chemical reactions between nitrogen oxides (NOx) and volatile organic compounds, favored by solar radiation and high temperatures. In addition, the winds allow the transport and accumulation of this polluted, which can therefore also reach rural areas.

- **Formaldehyde (HCHO):** I am talking about urban formaldehyde non indoor chemical compound, which belongs to the so-called volatile organic compounds. Formaldehyde is present in many places and represents a real danger to the body. In the early 2000s it was included in the group of carcinogens with which humans can come into contact by inhalation.

- **Methane (CH_4):** second only to carbon dioxide (CO2) as a greenhouse gas resulting from human activities. Methane is a short-living greenhouse gas, for about 12 years in the atmosphere. It is also considered a very potent greenhouse gas, because its ability to retain heat in the atmosphere is 23 times that of carbon dioxide. Studying methane allows us to keep the heat islands under control. Over the past two centuries, the concentration of methane in the atmosphere has more than doubled. The concentration in the atmosphere is determined by the balance between the inbound rate and the outbound rate. The rate of methane entering the atmosphere has increased due to human activities; the rate of methane removed is determined by the effectiveness of the "sink", the systems that absorb and neutralize greenhouse gases.

- **Carbon monoxide (CO):** is a colorless and odorless gas, which when inhaled in large quantities becomes harmful to health. It is created during the combustion process, an example may be the combustion of fossil fuels carried out by cars, aircraft, machinery or, inside homes: fireplaces, ovens, stoves. The presence of CO in the air reduces the percentage of oxygen that can be inhaled, creating problems for the body. A high concentration of CO, in the air inhaled by a human being, causes low oxygenation of the blood flow and in extreme conditions can cause dizziness, loss of consciousness and death. Situations that do not require a high level of concentration in subjects who already have heart and respiratory problems.

- **Sulfur dioxide (SO_2):** belongs to a larger group of components: gaseous sulfur glyoximes SOx. SO2 is used as an indicator for the entire group since it is the component that creates the greatest concern given the higher concentration. The concentration of SO3 is lower because the reaction that generates it is much slower than the one resulting in SO2. [S + O2-> SO2, 2SO2 + O2-> 2SO3] also SO3 has a high reactivity with water (H2O) whose ration leads to the formation of sulfuric acid H2SO4, which has a liquid or oily consistency depending on the ambient temperature. The sources of creation of these pollutants are common to the entire group, among the most important there are: the combustion of fossil fuels carried out in industries and power plants and volcanic eruptions. Exposure to high concentrations of SOx can cause respiratory problems. The aspect that is most frightening, considering the impact on human health, is the propensity of sulfur oxides to react with other compounds present in the atmosphere that lead to the creation of small particles, which contribute to particulate pollution (PM). The small particles can be inhaled and this allows them to penetrate the respiratory tract up to the lungs. Or they can settle on statues and monuments causing damage to the stone and damaging cultural assets. The effects of the presence of SOx in the atmosphere are not only important for humans, but also for plants and entire ecosystems, being the main cause of acid rain.

- **Nitrogen dioxide (NO_2):** The entire group of nitrogen oxides (NOx), which includes nitrogen dioxide, is highly reactive. They are mainly produced during combustion. Nitrogen dioxide is not released directly into the atmosphere, but is the product of chemical reactions that take place in the atmosphere. The reactions of nitrogen dioxides together with other substances present in the atmosphere leads to the formation of particulate matter and ozone. Nitrogen dioxide is four times more toxic than nitrogen monoxide for human health. The tools made available for monitoring and studying pollution are many and different from each other. Mainly it is possible to distinguish them in two gross macro categories: ground instruments, which allow for more detailed information on a more restricted area; satellite technologies, which provide an overview.

5.1.2 Risk assessment

Having identified the pollutants and their composition, now the need arises to explain what the association between pollution and state of health is in order to define the risks. All countries have carried out research on both topics, to document the cautions and find affinities. For example, in Italy through the MISA[43]-1 e MISA-2[44] studies or at the global level through the WHO[45] report, it has been shown that there is a close relationship between pollution and the harmful effects related to human health. Although many studies have been done, there are also criticisms at a global level. In addition to the Human risk, I would like to underline in this work that there is another risk linked to pollution. I would call it Technological Risk. Not all countries in the world have ground control units to monitor pollution. For example, China does not provide data on atmospheric quality to its citizens. The reasons are manifold but often simply due to the lack of ground air quality control units in many regions. However, China is not an isolated case, other areas of the world are also affected by the same problems. Even when governments measure air quality, however, it is faced a technological risk that can be classified on the nomenclature and on the scale of different parameters, such as NOx or PM10, or with the risk that the measurements may not be well calibrated. It should also be remembered that some countries[46] have no monitoring programs at all. Governments need these data trends to make policy decisions on air pollution. It is known that there were not enough ground tools in China and around the world to anticipate these trends. So, there are significant problems to consistently measure air quality around the world so that policy makers can best address the sources of this problem both globally and locally.

This thesis aims to develop a way to use satellite data to monitor the amount of pollutants and the quality of the area on a global and no longer local scale. Aerosol Optical Depth (AOD) data from MODIS (Moderate Resolution Imaging Spectroradiometer) and Multi-Angle Imaging Spectroradiometer (MISR) sensors on the NASA Terra Satellite have started air quality calibrations for several years.

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[43] Meta-analysis of Italian studies on the short-term effects of atmospheric pollutants (Original Name: Meta-analisi degli studi italiani sugli effetti a breve termine degli inquinanti atmosferici)

[44] The MISA study reported short-term impact estimates of PM10 for 11 Italian cities in the period 1996-2002; corresponding to a fraction attributable between 1.3% and 1.7% of deaths from all natural causes, considering as the no-effect threshold the maximum concentration value among the minimum values observed in the study period (11.9 µg / m3 registered in Palermo). In the period 2006-2009, in all the 23 cities covered by the EpiAir study, the number of deaths attributable to the short-term effects of PM10 concentrations above 20 µg / m3 was equal to 0.9% of mortality from natural causes and the impact of PM2.5 concentrations above 10 µg / m3 resulted in 0.8% of mortality from natural causes. The impact of PM10 and PM2.5 dust concentrations is concentrated in the cities of the Po Valley, the Florentine Plain and in large metropolitan areas as a percentage of deaths (1.0% versus 0.4% in the other cities analyzed).

[45] The WHO report, considering PM10 concentrations higher than 20 µg / m3, estimated an attributable fraction of 1.5% .

[46] See chapter 8 table 7

5.1.3 Ground sensors for the air quality index

Once the direct or indirect effects of atmospheric pollution have been defined, it is necessary to know and introduce how to monitor the air quality index starting from satellite data and even talking about in situ data. The Air Quality Index allows users to better understand the air quality in the place where they live, work or travel. By viewing up-to-date information, users can obtain information on air quality in individual countries, regions and cities. The index is based on concentration values for up to five key pollutants, including:

- particulate matter (PM_{10});
- fine particulate matter ($PM_{2.5}$);
- ozone (O3);
- nitrogen dioxide (NO_2);
- sulphur dioxide (SO_2).

In the case of weather stations, the index can be calculated every hour for more than two thousand air quality monitoring stations across Europe, using updated data reported by EEA[47] member countries. The data is not formally verified by the countries. Stations can be classified in relation to the predominant sources of emissions, including traffic, industry and the context in which the level of pollution is not dominated by either traffic or industry. The interweaving of data allows the user to be informed about individual stations or single areas of the city. European Union legislation sets air quality standards for both short-term (hourly or daily) and long-term (annual) air quality levels. The standards for long-term levels are stricter than those for short-term levels, as serious health effects can occur from long-term exposure to pollutants as seen from the chapter on risks.

Therefore, it should be remembered that the air quality index is not a tool for verifying compliance with air quality standards and cannot be used for this purpose. To calculate the Index, "up-to-date" air quality data is used and officially communicated hourly by EEA member countries, supplemented where possible and necessary with modeled air quality data provided by the Copernicus Atmosphere Monitoring Service (CAMS)[48] of the European Union. The concentration values in scientific methodology predict a maximum of five key pollutants to determine the index level that reflects the air quality at each monitoring station. The index corresponds to the poorest level for any of the five pollutants.

[47] The European Economic Area (EEA) was established via the Agreement on the European Economic Area, an international agreement which enables the extension of the European Union's single market to member states of the European Free Trade Association. The EEA links the EU member states and three EFTA states (Iceland, Liechtenstein, and Norway) into an internal market governed by the same basic rules. The United Kingdom benefits from this relationship during the transition/implementation period planned by the treaties.These rules aim to enable free movement of persons, goods, services, and capital within the European Single Market, including the freedom to choose residence in any country within this area. The EEA was established on 1 January 1994 upon entry into force of the EEA Agreement. The contracting parties are the EU, its member states, and Iceland, Liechtenstein, Norway, and the United Kingdom.

[48] The Copernicus Atmosphere Monitoring Service (CAMS) is a service implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), launched in November 11, 2014, that provides continuous data and information on atmospheric composition. CAMS, which is part of the Copernicus Programme, describes the current situation, forecasts the situation a few days ahead, and analyses consistently retrospective data records for recent years. This service has around 10 years of developments, and its current precursor project, MACC-III (Monitoring Atmospheric Composition and Climate - Interim Implementation), is delivering the pre-operational Copernicus Atmosphere Service.[1] CAMS tracks air pollution, solar energy, greenhouse gases and climate forcing globally.[2]

The positions of the air quality monitoring stations are located by the authorities on the territory, according to the needs and proximity of particular sources of pollutants. In most cases of the European network, the stations are located near the motorways or in the city center (to better monitor traffic pollutants) and those in industrial areas. The colors reflect the quality of the air at a given hour.

Stations that monitor traffic only monitor data for NO2 and PM (PM2.5, PM10 or both). This is because SO2 concentrations can be high in localized areas and distort the image of local air quality, while ozone levels are normally very low in this type of station. Instead the industrial and "background[49]" stations the index is calculated for those stations with data (measured or modeled) for at least the three pollutants NO2, O3 and PM (PM2.5, PM10 or both).

Stations on site record pollutants constantly 24/24, but the average time for pollutants must be taken into account. Usually NO2, O3 and SO2, have hourly concentrations, instead PM10 and PM2.5, data are released with an average of 24 hours.

In addition to the average time, missing data must be taken into account. In this thesis they are approximated or "filled in" using air quality data modelled by CAMS. Of course, filling methods are used to replace it:

- NO2, PM2.5 and PM10 the difference method[50].
- O3 multiplicative method.

Of course, thanks to the use of technologies such as Machine Learning, which in the next chapter I will describe in detail, the forecast values can be calculated for the next 24/48 hours, the air quality data modelled by CAMS are used and corrected using the methods of filling the spaces described above.

Finally, as defined by the World Health Organization in its report on the health risks of air pollution in Europe (HRAPIE project report [70]) the data bands must be based on the relative risks associated with short-term exposure to PM2.5, O3 and NO2. The relative risk of exposure to PM2.5 should be given as a guideline for the index, in particular the increased risk of mortality due to a 10 µg / m3 increase in the daily concentration of PM2.5.

Assuming linearity between the relative risk functions for O3 and NO2, the relative concentrations of pollutants that pose a relative risk equivalent to an increase of 10 µg / m3 in the daily average of PM2.5 can be calculated.

For PM10 concentrations, for example a constant ratio of PM10 to PM2.5 of 1:2 is assumed, it must be in line with the air quality guidelines of the World Health Organization for Europe.

For SO2, the bands reflect the limit values set by the EU Air Quality Directive. The bands and their limits are shown below.

[49] background are stations located in such a position that the level of pollution is not influenced mainly by specific sources (industries, traffic, residential heating, etc.) but by the integrated contribution of all sources upwind of the station with respect to the predominant wind directions in the site ;

[50] Difference Method: The value is approximated by taking the CAMS modeled value and adding or subtracting a correction difference. This correction is the average difference between the previously measured values and the CAMS modeled value for the same hour for at least three of the previous four days.

Pollutant	Index level (based on pollutant concentrations in µg/m3)					
	Good	Fair	Moderate	Poor	Very poor	Extremely poor
Particles less than 2.5 µm ($PM_{2.5}$)	0-10	10-20	20-25	25-50	50-75	75-800
Particles less than 10 µm (PM_{10})	0-20	20-40	40-50	50-100	100-150	150-1200
Nitrogen dioxide (NO_2)	0-40	40-90	90-120	120-230	230-340	340-1000
Ozone (O3)	0-50	50-100	100-130	130-240	240-380	380-800
Sulphur dioxide (SO_2)	0-100	100-200	200-350	350-500	500-750	750-1250

2 Air Quality Standards ©EU

Of course, a conventional scale is given ranging from Good to Extremely poor: air quality measurements that exceed the maximum values in the "extremely poor" category are not taken into account for the index calculation, as the latter are generally declared incorrect. The index bands are also complemented by communications that determine health-related information and provide recommendations for both the general population and sensitive populations[51].

AQ index	General population	Sensitive populations
Good	The air quality is good. Enjoy your usual outdoor activities.	The air quality is good. Enjoy your usual outdoor activities.
Fair	Enjoy your usual outdoor activities	Enjoy your usual outdoor activities
Moderate	Enjoy your usual outdoor activities	Consider reducing intense outdoor activities, if you experience symptoms.
Poor	Consider reducing intense activities outdoors, if you experience symptoms	Consider reducing physical activities, particularly outdoors,

[51] The latter includes adults and children with respiratory problems and adults with heart problems.

AQ index	General population	Sensitive populations
	such as sore eyes, a cough or sore throat	especially if you experience symptoms.
Very poor	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat	Reduce physical activities, particularly outdoors, especially if you experience symptoms.
Extremely poor	Reduce physical activities outdoors.	Avoid physical activities outdoors.

3 The ranges and meanings of each air quality index (AQI) level, as defined by the EPA © EPA

European stations data are taken from the portal developed jointly by the European Commission's Directorate-General for the Environment and the European Environment Agency to inform citizens and public authorities on the recent state of air quality in Europe.

5.1.4 Sources of aerosols/ origin of the aerosols

The measurements and monitoring of atmospheric pollutants in cities started around the 60s and 70s, the attention was totally dedicated to the measurements of the total suspended particulate (Pts), the totality of particles present in the atmosphere, without any selection of dimensional fractions. At the end of the 1900s and the beginning of the 2000s, interest shifted, driven by the growing epidemiological evaluations of the impacts on health, towards the fraction of less than 10 μm aerodynamic diameter (PM10), to the point that the monitoring of this type of aerosol as European standards have been explicitly inserted [71].

The 2000s began with the awareness that, in addition to what was seen previously, it was also necessary to monitor aerosols with smaller dimensions. In previous years, in fact, the scientific literature had shown wide interest from different points of view on how the pollutants were distributed in the various dimensional fractions but it never deepened or involved the final actors. It should also be remembered that the growing knowledge of exposure from the 1960s to the present days has significantly changed the measurements of air pollutants. It has begun to have the goal of knowing the impact on public health of atmospheric pollution by paying attention to the smallest particles and to the physio-chemical phenomena of formation and transformation. Particulate matter has long confirmed the thesis that the penetration of atmospheric particles into the human body from the respiratory tract to the lungs was higher because of their smaller size [71].

For these reasons, in addition to the pollutants already considered in the European legislation of previous years, particulate matter less than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) was added to the regulations of the beginning of the century [72]. In addition to the latter, in the same period and although they had not been expressly included in the law on air quality, it has begun to consider and study even the smallest particles, those able to penetrate deep into the alveoli: PM1, lower PM at 100 nm ($PM_{0.1}$), down to nano-sized particles, slightly larger than the size of the gas / vapor molecules from which they can derive for phase transformation. Naturally it should be remembered that this type of particles can only be monitored with sophisticated instruments and not with satellite technology. The requests of the new community legislation and above all the requests for scientific articles have helped to understand and deepen the environmental, physical, chemical, biotoxicological, epidemiological, health aspects that have been, and still are, imported for monitoring. In addition to monitoring, their objective is to acquire useful information and make it public, to support the administrators of the territories and citizens in their government decisions and behavior on these issues [68].

However, speaking in a non-differentiated way of particulate matter within the meaning of the legislation and of nanometric particles below 100 nm is certainly a bet, given the great differences that exist in the two types of aerosols considered. It is therefore necessary to specify that, when referring to PM2.5 according to regulatory requirements, it is usually mentioned its mass concentration per unit of air volume and the unit of measurement normally used is: µg/m3. As for very small particles, up to the size of 100 nm and, in some more general cases up to the sub-micrometric aerosol (PM_1), what is used to measure is the number of particles per volume of air and not plus the mass. In the smaller dimensional intervals, the mass concentration becomes negligible while the concentration becomes relevant in numerical terms [73].

For the latter the unit of measurement normally used is: npc / m3. Atmospheric aerosol with a diameter of less than 1 µm is generally divided into three-dimensional intervals (trimodal distribution) defined as:

- nucleation range (3-25 nm)
- Aitken nucleus range (25-90 nm)
- accumulation range (90-1000 nm)

The main physicochemical phenomena responsible for almost all the processes of formation and transformation of atmospheric particulate occur in these intervals. In the nucleation range the particles are generally newly formed, due to the gas / particle reaction involving the phase transition just around 1-2 nm. In the context of nuclei, on the other hand, the particles can undergo phenomena of growth and transformation or aggregation with pre-existing particles. In the range above 90 nm, the particles undergo growth, condensation and coagulation phenomena reaching dimensions such as to make their contribution important in terms of mass concentration [73].

Aerosols are classified into two categories:

- Aerosol of natural origin
- Aerosol of anthropogenic origin

Natural aerosols are produced by volcanoes, sea spray, sand or wind-induced soil erosion. Anthropogenic aerosols are the result of human activities, such as dust from agricultural activities, smoke from burnt biomass and fossil fuels, and photochemical smog mainly due to vehicle emissions [74]. Photochemical smog is an atmospheric condition that develops when primary particles, particularly nitrogen oxides and bi-products of combustion, react in the presence of sunlight to produce dangerous secondary particles. It is known to affect most of the major cities of the world in sunny, hot and dry weather [75]. Although most aerosols are found in the troposphere, where they are removed within days of precipitation and interaction with the earth's surface. Large volcanic eruptions can inject aerosols and trace gas much higher into the stratosphere where they can remain for a long time [76]. Aerosols are classified according to their origin, concentration, size range, structure and chemical composition [77].

The lack of detailed knowledge of aerosol properties makes aerosol one of the major uncertainties in assessing climate forcing. Atmospheric aerosol monitoring is a fundamentally difficult problem. The aerosol can be distinguished in:

- primary: set of particles emitted directly into the atmosphere from the different sources
- secondary: particles not directly introduced but formed by conversion processes in the atmosphere

The secondary aerosol is formed in the presence of the so-called precursors, e.g. gaseous compounds of various origins that are chemically transformed and oxidized in the atmosphere with the production of particles. These low-volatile compounds can deposit on particles (condensation) or join together, forming aggregates made up of several molecules that grow into particles. This process is called nucleation. Aggregates can also join together and form larger particles through the coagulation process.

Aerosol of natural origin

Even if man-made pollution is the most attributed to the deterioration of air quality, it should not be forgotten the importance of pollution of natural origin. There are many sources of natural pollutants that often take on greater significance than their anthropogenic counterparts. For example:

- Marine spray: aerosol particles released into the atmosphere following the explosion of air bubbles produced by the wave motion of the seas and oceans
- Volcanic eruptions: they are able to release large quantities of aerosols into the atmosphere

- Transport of Saharan dust: every year large masses of air transport hundreds of millions of tons of Saharan sand to the West and to Europe.
- Erosion of rocks
- Emission from vegetation
- Forest fires

Natural air pollutants have always accompanied human history. Dust and gases emitted by volcanoes, forest fires and the decomposition of organic compounds enter the atmosphere at regular intervals and in some cases at levels that can cause dramatic effects on the climate. In any case, it must be emphasized that natural pollutants do not necessarily represent a serious problem as pollutants generated by human activities can, because they are often considerably less dangerous than man-made compounds and are never concentrated in large cities. Natural sources of sulfur dioxide include volcanoes, organic decomposition, and forest fires. The precise quantity of natural emissions is difficult to quantify: in 1983 it was estimated that sulfur dioxide emissions were around 80-290 million tons (anthropogenic sources in the world emitted about 69 million tons per year) [78]. In addition to anthropogenic sources, some "pollutants" also have natural origins such as ozone which forms near the ground level following a series of chemical reactions catalyzed by light. In any case, about 10-15% of ground-level ozone comes from the upper layers of the atmosphere (stratosphere) where it is formed by the action of UV rays from molecular oxygen. The importance of natural particulate sources, on the other hand, is less important than anthropogenic ones, since they originate particles of such size that they cannot cause significant damage to the respiratory system. Sources of this type do not cause particularly acute episodes of pollution as pollution generally occurs on a relatively short time scale and does not expose people to prolonged exposure. There may be exceptions with the explosion of Saint Helens volcano in May 1980, for example, which caused a marked deterioration in air quality in the United States and throughout the Northeast Pacific for months after its eruption, with repercussions also on the global climate. Even in Europe, Sahara dust travels through the air annually for thousands of kilometers and then arrives not only in relatively neighboring countries such as Italy and Greece, but also in more remote areas such as the United Kingdom. There are also pollutants emitted by plants, such as pollen (considered components of atmospheric particulate matter) and everyone is aware of the allergic effects that these substances can cause in predisposed subjects. In conclusion most of the gaseous compounds in the air are part of natural cycles, which is why ecosystems are able to maintain the balance between the various parts of the system. This is very important to make us understand that the earth is able to be resilient to these pollutants. However, it should be remembered that the introduction of large amounts of additional compounds can also permanently compromise the natural pre-existing biochemical cycles. Since man can do very little with regard to natural pollution, the greatest concern must be to reduce the polluting emissions produced by human activities.

Aerosol of anthropogenic origin

Man has always used the resources at his disposal almost indiscriminately, without paying any attention to the environmental repercussions that his presence could have had in the various natural cycles. Destruction and environmental pollution have always gone hand in hand with the evolution of the so-called civilization. The human population in the past was much less represented and the environmental impact was practically irrelevant, at least in the global sphere. Now, unfortunately, the enormous demographic increase and the densification of housing in some specific areas leads to a considerably higher polluting action locally and globally, extremely worrying and often particularly harmful both for man and the environment. More air pollution is what humans produce to meet their civil and industrial needs. Air pollution of anthropogenic origin is released by:

- Industrial processes (industries, plants for the production of electricity and incinerators)
- Small stationary sources
- City processes: (domestic heating systems) and from mobile sources (vehicular traffic)
- Use of fossil fuels
- Spreading of salt

Many of these sources are closely related to energy production and consumption, particularly fossil fuels. The use of fossil fuels for domestic heating, in particular heavy fuel oils, biomass and coal is a significant source of environmental pollution from particulates and sulfur dioxide, especially in temperate regions (especially China and Eastern Europe) [79]. Traffic also contributes to a large extent to the emissions of these pollutants in cities characterized by great vehicular congestion, and this due to the presence of an immense series of vehicles using gasoline with a high sulfur content (especially in Asia). As for the other main pollutants, it should be emphasized that anthropogenic sources play a fundamental role as much as natural ones in the emission of ozone and volatile organic compounds; combustions generally represent the main cause of nitrogen oxide emissions. Transport vehicle engines are typically the main cause of carbon monoxide emissions. In addition to the substances that are produced as a result of the various combustion processes, all those pollutants that are produced during particular technological cycles must be reported. These compounds are released in significantly lower quantities and for this reason have little relevance as a global impact globally; in any case they are often highly toxic and their presence is particularly important at the local level.

The approach strategy is clearly different: the specific pollutants of industrial origin are in fact found not after their diffusion into the environment (atmospheric inputs), but at the moment of their release (emissions into the atmosphere). The impact of pollutants on humans depends on the area of production of the pollutants and their dispersion. Large stationary springs, often located far from larger inhabited centers, are dispersed in the air at great heights, while domestic heating and traffic produce pollutants that are released at ground level in densely populated areas. Consequently, small mobile and stationary sources contribute more to air pollution in urban areas and, consequently, damage public health much more than can be assumed by a simple quantitative comparison between the various types of emissions.

Remote sensing and Aerosol

Obviously, the broad acceptance of optical models based on the simplified hypotheses described above reflects the limitations of current knowledge on aerosols and does not mean that aerosols actually exist as a set of chemically homogeneous particles of regular shape. Clarifying the details of the physical and chemical aerosol structure and their connections to optical properties requires the involvement of physical and chemical aerosol analysis, which is provided by many types of in situ aerosol measurements. Consequently, in the present thesis, I will verify and enrich the properties of aerosols derived from ground remote sensing of aerosols with respect to the information available on aerosol in situ.

Remote sensing of aerosol on the ground does not provide global coverage; however, its large angular and spectral measurements of solar and sky radiation are best suited to reliably and continuously derive detailed optical properties of aerosols at key locations. Despite the high spatial and temporal variability of aerosols, there are a rather limited number of general categories of aerosol types with distinctly different optical properties. The following four general aerosol types are associated with different sources and emission mechanisms and are expected to show significant differences in optical properties:

- urban industrial aerosol from the combustion of fossil fuels in populated industrial regions
- aerosol that burns biomass produced by forest and meadow fires
- desert dust blown into the atmosphere by the wind
- aerosol of marine origin.

Satellites make it possible to use knowledge of the physics and chemistry of atmospheric aerosol to model aerosol optics and, conversely, to deduce some information about physical and chemical aerosol from optical measurements. However, adequate modelling of the full complexity of the interrelation of optical, physical and chemical aerosol properties is a challenging fundamental task. On the other hand, the optical properties show clear sensitivity to a rather limited set of physical and chemical characteristics of the aerosol. Therefore, the optical models [80] employ the following limited set of aerosol parameters: particle size (particle size distribution), composition (complex refractive index) and shape [81]. Consequently, both in aerosol modelling and in applications there are many efforts to explain the absence of sphericity by particles [82]. However, no sphericity and inhomogeneity are not fully elucidated issues in atmospheric aerosol modelling and most aerosol applications are based on an optical model that considers aerosol as a mixture of homogeneous spherical particles of different sizes with composition characterized by the complex refractive index. Scientific experience indicates that, in many cases, these hypotheses allow the models to adequately reproduce the radiation fields affected by the observed aerosols. This was more or less the beginning of modern aerosol science.

Today there are still models but they are improving as well as the tools, the way they work and the measurement possibilities are much more developed. Where in the most ancient space missions only optical cameras were used are the modern ones and the future ones are better combined with echo sounders, imagers, laser instruments and multiband spectrometers.

Since the early nineties the satellite world has intensified the collection of satellite data for the study of the earth-ocean-atmosphere system using polar orbit satellites, so-called environmental as they are aimed at "observing the earth". The European Space Agency collaborated with the ERS-1/2 satellites, and the Envisat platform, in the early 2000s. There have been numerous programs such as Earth Living Planet that have developed missions aimed at both the study of the Earth-ocean system and the atmosphere. In addition to the programs, "repository" platforms have been created that have begun to host Atmospheric data such as Earth Explorer aimed at collecting data to be used operationally by Earth Watch. In the following paragraphs, each mission will be illustrated in detail. The most important missions were the Meteosat satellites now in their third generation (during my PhD I was able to collaborate in the realization of the same with the L2PF project[52]), developed by the European Agency and Eumetsat, another very important mission is that of Copernicus which establishes the Agency's role as a provider of Earth Observation (EO) data. The Sentinel satellites (1-6) were born from that mission and the need to ensure continuity in the supply of such data in open-source format also arises. Among the projects that use satellite data, the Moses project (Managing crOp water Saving with Enterprise Services) is funded under the "pillar" of societal challenges, relating to the thematic area "water", in the context of the European Research and Innovation Program Horizon 2020.

Sensors, problems and added value of Remote Sensing

The collection, processing and return of data from satellite is another element of the atmosphere section, with important applications in the field of monitoring aimed at determining the state of health of the territory. Remote sensing tools are of two main types: active and passive.

Active sensors provide their own source of energy to illuminate the objects they observe. An active sensor emits radiation in the direction of the target to be examined. The sensor then detects and measures the reflected or backscattered radiation from the target.

A sensor that emits electromagnetic radiation itself is said to be active, of which it will then receive a fraction reflected / diffused by the target (regardless of the lighting

[52] The Level 2 products will be partially centrally generated via the L2PF and partially generated by the Satellite Application Facilities network.

conditions). Such sensors require transmitting equipment and high signal strength. Among the active sensors are placed, for example, the LIDAR and the RADAR[53] .

Passive sensors, on the other hand, detect the natural energy (radiation) that is emitted or reflected by the object or scene observed. Reflected sunlight is the most common source of radiation measured by passive sensors. A passive sensor does not emit any radiation and only measures the electromagnetic energy naturally diffused by the observed medium. These sensors are independent from the radiation emitting apparatuses and generally require low power; at the same time, they strictly depend on an external source in most cases the sun.

There are numerous satellites and payload numbers on board. But the added value is found in the dissemination and classification of the data. For example, atmospheric pollution is expressed, in the various countries, by different air quality indexes (e. g. dimensionless values calculated with different methods), in order to compare the pollution between two countries or compare the absolute values measured for the main pollutants from local detection networks or, more simply, satellite maps can be used.

The downside of satellites is that the measurements provided are difficult to calibrate, so comparisons over time or the determination of absolute measured values are anything but simple. Furthermore, unlike the sensors used by ground stations, satellites do not measure pollutants directly: the data they provide is the result of a conversion dependent on theoretical models and relative accuracy.

On the other hand, satellites make it possible to monitor a variety of phenomena on a daily and global basis, including long-distance or intercontinental transport of air pollutants. The monitoring of atmospheric pollution is therefore added to the meteorological one, the stratospheric ozone level, the temperature of the planet, climate change and extreme phenomena, etc.

In general, satellite sensors for remote sensing measure the energy reflected, diffused or emitted by the analyzed object. They consist of a transducer, that is a device capable of receiving and responding to a signal or stimulation with an electrical signal. In the case of environmental monitoring, the stimulus can usually be: temperature, pressure, humidity, etc. but most sensors "work" (record) with electromagnetic radiation.

Therefore, the information on an object, a phenomenon, a territory is obtained by measuring the electromagnetic radiation coming from a source (usually the sun) of energy, subsequently reflected (or emitted) by the objects themselves.

In practice, the sensors capture the electromagnetic radiation reflected (but also emitted) by an object placed on the earth's surface and convert it into an electrical signal proportional to the amount of EM energy it receives; the product of the transformation are images that are the recording of discrete Digital Number values associated with the investigated unit.

[53] RAdio Detection And Ranging.

5.1.5 First satellites and data

In these paragraphs I will reconstruct the stories of the satellites that monitor our planet using the sources of the various European space agencies. I will rank them as past, present and future satellites. The time frame will be established by the gold period in orbit. All the sources in these three paragraphs are purely descriptive and have the task of reconstructing the history of air pollution seen from satellite. As a premise, it should be remembered that the most important have been listed and will find them in a random order. The large satellites of the past have mainly been launched by the European Space Agency (ESA) and the United States Space Agency (NASA), to collect environmental data that can be incorporated into various models, databases and other tools for the use by policy makers and various national bodies with comprehensive global observations of our planet.

In addition to the traditional measurement of temperature and water vapor, the constellations allowed the monitoring of a variety of atmospheric pollutants:

- Ozone (O3)
- Carbon monoxide (CO)
- Carbon dioxide (CO^2)
- Nitrogen oxide (NO)
- Nitrogen dioxide (NO2)
- Nitric acid (HNO3)
- Methane (CH4)
- Formaldehyde (HCHO)
- Etandiale (CHOCHO)
- Sulfur dioxide (SO2)
- Acetonitrile (CH3CN)
- Formic acid (HCOOH)
- Methanol (CH3OH)
- Ammonia (NH3) heavy water (HDO), aerosol.

Aerosol information “over water” has been available from AVHRR aboard NOAA satellites since 1981. TOMS has provided a long time series of the Aerosol Index (AI) over both water and land, starting in 1978. AI is a measure of the wavelength-dependent reduction of Rayleigh scattered radiance by aerosol absorption relative to a pure Rayleigh atmosphere [83]. A near UV algorithm to retrieve AOD and SSA has been applied to the TOMS record from 1979 to 2000 and several thesis discussing the algorithm, AOD validation analyses and the climatological AOD record have been published [84]. Other instruments have been used to provide such information, such as OCTS, ATSR-2, and SeaWIFS [85]. However, none of the mentioned instruments were designed for the retrieval of aerosol properties, which over water could only be obtained because of the dark surface. Over brighter surfaces, and over most land surfaces, satellite remote sensing of aerosols was not possible. This situation has significantly improved during the last decade, when methods were developed to retrieve aerosol properties over land, utilizing multiple views, polarization and multi-spectral information from instruments that were designed for the retrieval of aerosol properties, such as POLDER, MODIS, MISR, and other instruments that offered such features, in particular ATSR-2. ATSR-2 combines a nadir and forward view, which can be used to eliminate the effect of the land surface reflection, with four spectral bands that are suitable for determining the aerosol properties. Algorithms have been developed that apply over land.

ENVISAT (ESA)

Since 2012 is no longer operational, the global pollution maps were provided by Envisat, the world's largest satellite for environmental monitoring, with its 10 instruments on board. Envisat was launched in February 2002 by the European Space Agency (ESA) [86], of which it was a flagship. The absorption spectrometer for atmospheric image scanning mapping was able to record the spectrum of sunlight passing through the atmosphere. The results were then carefully filtered to find traces of spectral absorption of trace gases. Its purpose was to perform global measurements of these gases in the troposphere and stratosphere. In 2004, after 18 months of observations, Envisat provided the famous global atmospheric map of nitrogen dioxide (NO_2) pollution, which clearly shows how human activities affect air quality. Nitrogen oxides, in fact, are produced by emissions from power plants, heavy industry and road transport, as well as by the combustion of biomass and biogas.

The map shows that the Po Valley was, at the time, one of the three areas with the most polluted air on the planet, together with the area around Beijing and New York. Localized in situ measurements of atmospheric nitrogen dioxide are conducted in many western industrial countries, however, terrestrial data sources are generally limited to ground level and geographically.

Nitrogen dioxide is a predominantly human gas, but lightning strikes in the air also create nitrogen oxides, such as microbial activity in the soil, whose excessive exposure causes lung damage and respiratory problems, and is often underestimated. It also plays an important role in the chemistry of the atmosphere, because it leads to the production of ozone in the troposphere, the lowest part of the atmosphere, which extends up to an altitude between 8 and 16 kilometres.

(A)ATSR (ESA)

ATSR-2 onboard ERS-2 and AATSR onboard ENVISAT are dual view imaging spectrometers with seven wavelength bands, four in the visible and NIR (0.555, 0.659, 0.865, and 1.6 μm) and three in TIR (3.7, 11, and 12 μm). The resolution of these instruments is 1 x 1 km^2 at nadir view and the swath width is 512 km, resulting in a return time of three days at mid-latitudes. The nadir view and the forward view at 55º incident angle to the surface allow for near-simultaneous observation of the same area on the Earth's surface through two different atmospheric columns within a time interval of approx. 2.5 minutes. Algorithms for the retrieval of the aerosol optical depth (AOD) and derived parameters from ATSR-2 measurements have been developed and applied by TNO, The Hague, The Netherlands, for a variety of locations that are representative for the occurrence of characteristic aerosol types. The single view algorithm is applied over water surfaces and uses either the nadir or the forward view. The dual view algorithm is applied over land surfaces, which in general are brighter than water surfaces. In the dual view algorithm, the two views are combined to eliminate the effect of the land surface reflectance and the total reflectance received by ATSR at the top of the atmosphere (TOA) [86]. The actual retrieval is similar for both algorithms once the surface contribution has been accounted for. A radiative transfer model is applied to calculate the TOA reflectance (Doubling-Adding method at KNMI (DAK). This is done for several aerosol models and the results are stored in look-up tables (LUTs). The calculated TOA reflectance is compared with the measured values and by selecting different LUTs the error function, describing the difference between model and measurement, is minimized to find the most suitable aerosol model. This procedure is applied for the ATSR-2 wavelengths of 0.55 μm, 0.67 μm, 0.87 μm (only over water) and 1.6 μm) and hence the optimization procedure determines the aerosol mixture that best fits the measurements over the applicable wavelength range. Thus, the parameters determined are the AOD at the suitable wavelengths, the Ångström parameter describing the wavelength dependence of the AOD. The aerosol type and mixing ratio, given by the most suitable aerosol model, are retained as well.

MERIS (ESA)

The MERIS FRS and RR data were acquired through a bulk-data-exchange agreement between NASA and ESA. Global RR Level-1B data were transferred via ftp from the ESA UK-PAC data distribution facility. FRS data were provided by ESA to the LAADS group at NASA on tapes. FRS files were extracted from tape by LAADS and transferred to OBPG for higher-level processing. The data exchange agreement between NASA and ESA included the rights to redistribute the ESA Level-1B data and derived products. MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command. The instrument scans the Earth's surface by the so called "push-broom" method. Linear CCD arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction [86]. MERIS is designed so that it can acquire data over the Earth whenever illumination conditions are suitable. The instrument's 68.5° field of view around nadir covers a swath width of 1150 km. This wide field of view is shared between five identical optical modules arranged in a fan shape configuration [87].

GOMOS (ESA)

GOMOS is a medium resolution spectrometer covering the wavelength range from 250 nm to 950 nm. The high sensitivity requirement down to 250 nm has been a significant design driver leading to an all-reflective optical system design for the UVVIS part of the spectrum and to functional pupil separation between the UVVIS and the NIR spectral regions (thus no dichroic separation of UV). Due to the requirement of operating on very faint stars (down to magnitude 4 to 5), the sensitivity requirement to the instrument is very high [86]. Consequently, a large telescope (30 cm × 20 cm aperture) had to be used to collect sufficient signal, and detectors with high quantum efficiency and very low noise had to be developed to achieve the required signal to noise ratios [88].

SeaWiFS (GeoEye/NASA)

The OV-2 spacecraft and the SeaWiFS sensor were owned and operated by GeoEye(now DigitalGlobe). The data were purchased by NASA under “data buy” contracts. The initial contract covered the period from the initial imaging through five years after initial commissioning [89]. After that date, a series of contract extensions were negotiated between NASA and GeoEye, up to the end of the mission. The SeaWiFS data were collected and acquired by two overall scenarios: onboard data recording and direct broadcast. SeaWiFS also had unique restrictions on data distribution because of the terms of the data buy contract [90].

PARASOL/POLDER (CNES/JAXA)

PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar) is a French (CNES) science mission of the Myriade series, put forward by CNRS/LOA [91], with the general objective to study the Earth's atmosphere. Of particular interest in this study is the role of clouds and aerosols (fine particles in suspension in the air) in climate mechanisms (which effect has global warming on cloud cover? How do clouds and aerosols interact?). The PARASOL mission flies the POLDER-derived instrument as its main payload with the objective to improve the microphysical and radiative property characterization of clouds and aerosols for model improvement. Clouds and aerosols play an important role in direct and indirect radiative forcing of the Earth's energy budget. The study of the dynamic processes and interactions between liquid and solid particles (radiative properties of clouds and aerosols) in the atmosphere is therefore a major goal. PARASOL (POLDER) complements CALIPSO (Lidar) and NASA's Aqua and Aura (MODIS, CERES) missions, it also makes use of the CloudSat (CPR) radar data. The instruments form a so-called “train of satellites,” all in the same orbits and in a PM sequence (a loosely-coupled constellation), provide a unique opportunity of near-simultaneous observations, by collecting data in different spectral domains (optical and microwave regions) and at various FOVs (Field of Views) [92].

TOMS (NASA) OMS (Total Ozone Mapping Spectrometer) Missions

Initial spaceborne ozone (O3) observations started with the BUV (Backscatter Ultraviolet) sensor, a demonstration instrument flown on Nimbus-4 of NASA (launch April 8, 1970; sun-synchronous near-circular polar orbit, perigee = 1092 km, apogee = 1108 km, inclination = 80.1º, period = 107.2 minutes). The BUV instrument consisted of a double monochromator containing all reflective optics and a photomultiplier detector. The double monochromator was composed of two Ebert-Fastie-type monochromators in tandem. The objective was to monitor the vertical distribution and total amount of atmospheric ozone on a global scale by measuring the intensity of UV radiation backscattered by the Earth/atmosphere system during day and night in the spectral band of 25-34 nm. - The new measurement technique of BUV total column ozone data led to its acceptance by the international ozone community as a possible data source comparable to the Dobson instrument in ground observations.

1)Prior to the development of TOMS (Total Ozone Mapping Spectrometer) and its predecessor BUV on the Nimbus-4 satellite, ozone measurements were obtained via ground-based Dobson spectrophotometer stations (local measurements only). Global observations of ozone on a daily basis were provided with TOMS, first flown on the Nimbus-7 mission of NASA (launch Oct. 24, 1978).

2)During its lifetime on Nimbus-7, the analysis of TOMS data helped make” ozone” a household word through its false-colour images of the “Antarctic Ozone Hole.”[54].

3)At about the same time the TOMS group at NASA also noticed unusual ozone values in the Antarctic. Satellite measurements then confirmed that the springtime ozone loss in the Antarctic was a continent-wide feature. In fact, TOMS has been a key instrument

[54] The Antarctic Ozone Hole was first noticed by a research group of the British Antarctic Survey (BAS) from data obtained with a Dobson ozone spectrophotometer at Halley Bay Station, Antarctica (latitude 75º 35', longitude 26º 34', since 1956) in the time period 1981-1983. Joseph Farman, Brian Gardiner and Jonathan Shanklin, are the BAS scientists who discovered the Antarctic ozone hole. They reported the average daily value of ozone at Halley Bay Station for the four latest complete observing seasons during Antarctic springtime (October 1980 to March 1984) in 1985

for monitoring ozone levels on a global scale. Even after 14 years of operations (1992), TOMS was testing new concepts such as nowcasting of winds at flight altitudes and volcanic ash clouds. Nowcasting refers to real-time ozone mapping that occurs when satellite data is processed and displayed on a computer screen simultaneously as the satellite passes overhead. In April 1993, during an early morning pass of NASA's Nimbus-7, scientists were able to take real-time ozone readings from TOMS.

The following chapters provide an overview of the various missions with TOMS as a payload instrument. The TOMS program is managed by NASA/GSFC, Greenbelt, MD, within the ESE (Earth Science Enterprise) program, formerly known as MTPE (Mission to Planet Earth) a long-term, coordinated research effort to study the Earth as a global environmental system. Although TOMS-EP is the last operational NASA mission with a TOMS instrument, continuity of NASA ozone observations is provided with OMI (Ozone Monitoring Instrument) on Aura (the EOS/Chem-1 mission). OMI is a sensor contribution of NIVR (Netherlands Institute for Air and Space Development) of Delft in collaboration with FMI (Finnish Meteorological Institute), Helsinki, Finland. OMI is a nadir-viewing hyperspectral instrument, a UV/VIS imaging spectrograph, which measures the solar radiation backscattered by the Earth's atmosphere and surface over the entire wavelength range from 270 to 500 nm, with a spectral resolution of about 0.5 nm (see eoPortal description under Aura). A launch of the Aura mission took place on July 15, 2004 on a Delta-2 vehicle from VAFB, CA.

SAGE-III (NASA)

The Stratospheric Aerosol and Gas Experiment III-ISS (SAGE III-ISS) is among the first NASA Earth research and payloads sent to the space station to measure the composition of the central and lower atmosphere. The orbit offers a unique point of view for making ozone and aerosol measurements.

The SAGE program has had a long tradition and was one of NASA's longest-running Earth observation programs, which provided continuous long-term data to help understand the earth's atmosphere. The SAGE II data was fundamental to confirm the human-induced changes to ozone and therefore contributed to the 1987 Montreal protocol which banned certain harmful chemicals. SAGE II also saw ozone stop decreasing in response to this action [93].

RADIOMETER-2 (NASA)

Using data from the Along Track Scanning Radiometer-2 [94]on the ERS-2 satellite, the Advanced Along Track Scanning Radiometer and the Medium Resolution Imaging Spectrometer on Envisat and the Spinning Enhanced Visible & InfraRed Imager (SEVIRI) instrument on the Meteosat Second Generation, GlobAerosol has produced a global aerosol dataset going back to 1995. The full dataset is available on the GlobAerosol website.

Mission	Instrument	Sponsoring Agency	Traced Gases									Altitude	Time Span	Measuring	Principle of instrument	Resolution	Date of Launches	Revisit Times
			CO_2	CO	O2	O3	NO2	NO3	SO2	H2O	aerosoles	Orbit	Start–finish					
Past																		
ENVISAT	(A)ATSR	ESA										767	20.05.2002 - 08.04.2012	troposphere, atmosphere	Radiometer	1km x 1km 500km swatwidth		
ENVISAT	ENVISAT SCIAMACHY	ESA	•								yes	767	1.03.2002–08.04.2012	troposphere, atmosphere	imaging spectrometer		1.03.2002	35D
ENVISAT	MERIS	ESA										767	17.05.2002 - 08.04. 2012					
ENVISAT	GOMOS	ESA			•	•	•	•		•	yes	767	17.05.2002 - 08.04. 2012					
Nimbus 7	SeaWiFS	GeoEye/NASA								•		n/a	18.08.1997 - 11.12.2010	bio optical attributes of oceans	8 wave lengths camera	1.1km x 4.5km (LAC x GAC)	1.08.1997	
PARASOL	POLDER (3rd G)	CNES/JAXA									yes	Sun-synchronous circular orbit, altitude = 705 km, inclination = 98.21º, the local equator crossing time is at 13:30.	18.12.2004 - 18.12.2013	Troposhere	Radiometer		18.12.2004	
TOMS-EP	TOMS	(NASA) OMS (Total Ozone				•					UV absorbing aerosoles	493 × 511 km, 97.44°	02.07.1996 - 02.12.2006	Troposhere	Spectrometer		02.07.1996	
ISS	SAGE III-ISS	NASA				•	•	•			Yes			Stratosphere		5km vertical	19.02.2017	

4 Summary table, the satellites, the past, their payload and their characteristics are described

5.1.6 Current satellites and data

The launch of ADEOS in August 1996 with POLDER, TOMS and OCTS instruments on board and the future launch of EOS - AM 1 in mid-1998 with MODIS and MISR instruments on board symbolized the beginning of a new era in aerosol remote sensing as part of a new remote sensing of the entire Earth system. Finally, satellites that monitor pollution even on land are beginning to emerge. Envisat had been the pioneer. Today, multispectral, multangular and international space polarization measurements, combined for the first time with automatic and routine international ground-based aerosol monitoring, will represent a step forward in our ability to observe the highly variable global aerosol. This capability has been contrasted with current single channel techniques for AVHRR, Meteosat and GOES which, although poorly calibrated and poorly characterized, have already generated important global aerosol maps and regional transport assessments.

These new data have significantly improved the atmospheric corrections for the aerosol effect on remote sensing of the oceans and have been used to generate the first atmospheric corrections in real time on land. This special issue summarizes the science behind this change in remote sensing and studies on the sensitivity and application of new algorithms to data from satellite and airborne instruments. The discussion concluded that early remote sensing of aerosols simultaneously from different space platforms with different observation strategies, together with continuous validations worldwide, should be of significant importance to test remote sensing approaches to characterize the complex and highly variable aerosol field. So far, it is possible to have only a partial understanding of the information content and accuracy of the reversal of radiative transfer of aerosol information from satellite data, due to the lack of sufficient theoretical analysis and applications for adequate field data. This limitation will make the new expected data even more interesting and challenging. One of the main concerns was the current inadequate ability to detect aerosol uptake from space or soil. Absorption is a critical parameter for climate studies and atmospheric corrections. For the oceans, the main concerns are the effects of white caps and dust on the correction scheme. Future improvements in aerosol recovery and atmospheric corrections will require improved climatology of aerosol properties and an understanding of the effects of mixed composition and particle shape. The main ingredient missing from the planned remote sensing of aerosols are spatial and terrestrial lidar observations of aerosol profiles.

MODIS (NASA)

The ODPS started acquiring MODIS data in 2003. The MODIS data (from both Terra and Aqua) have been acquired via two means. Originally the data were acquired from NOAA in near-real-time, with the GESDAAC and the MODIS Adaptive Processing System (MODAPS) as backups. More recently, MODAPS has become the primary source of the MODIS data. The Level-0 files are processed to generate Level-1A, geolocation and Level-1B (calibrated) products, using software provided by MODAPS. The geolocation processing also requires attitude and ephemeris data files that are acquired from the GESDAAC. All of the Level-1 products follow the standard MODIS formats, including HDF-EOS metadata. The daytime granules are processed to generate the Ocean Color products, and all of the granules are used to generate SST products. The MODIS-VIIRS Atmosphere Discipline Team develops and maintains imager remote sensing algorithms for the creation of long-term climate data records of derived geophysical parameters pertaining to atmospheric properties of the Earth (aerosols, clouds, water vapor). The Atmosphere Team traces its roots to the EOS flagship Terra and Aqua missions, launched in 1999 and 2002, respectively, and specifically in support of the twin Moderate-resolution Imaging Spectroradiometers (MODIS). As these missions and sensors age, NASA is supporting the extension of key EOS-era MODIS climate data records to NOAA's next-generation polar orbiting imager VIIRS, the first of which was launched on the Suomi NPP platform in 2011. Both MODIS and VIIRS provide wide spectral range (narrowband channels from visible to infrared), high spatial resolution, and near-daily to daily global coverage of the Earth and its atmosphere. To support climate data record production from two different sensors, two product streams are available, both archived at the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Centre (DAAC): the EOS-heritage MODIS Standard Products, and the Continuity Products derived from VIIRS. While in many cases the Continuity algorithms are direct descendants of the MODIS Standard algorithms, in some cases (e.g., clouds) they are not.

MSG (EUMETSAT/ESA)
The sensors that study the aerosol in the MSG missions are: GOME-2, IASI, AVHRR. The multi-sensor polar product for optical aerosol properties (PMAP) provides optical aerosol depth (AOD) [86], aerosol type (fine mode, coarse mode (dust), volcanic ash) on ocean and land surfaces. It also provides information on the optical depth of the cloud (COD) and on the maximum cloud temperature on a global scale. The AOD product has an operational status [95].

AURA (NASA)
The Aura satellite was successfully launched on July 15, 2004 in a synchronous, almost polar orbit (with an inclination of 98.2 degrees). It orbits 705 km (438 miles) above Earth with a repeated cycle of sixteen days and 233 laps per cycle. The ascending node is in daylight and crosses the equator at approximately 13:45 [96]. Aura is flying in formation with other Earth observation satellites called A-Train[55]. The Aura satellite also has the ability to transmit directly through a smaller downlink antenna. This capability allows an investigator to receive data almost instantly. The small building with the dome (top right) is the Finnish direct transmission station that receives the OMI data while the satellite passes over its head. The direct transmission data is processed at the Finnish Meteorological Institute FMI and distributed shortly after the Aura overpass. Aura allows studies on the horizontal and vertical distribution of the main air pollutants and greenhouse gases and how these

[55] Aura flies in formation about 15 minutes away from Aqua in the constellation of satellites "A-Train" which consists of several satellites flying in the immediate vicinity. Every single mission has its scientific objectives; all of them will improve our understanding of the Earth's climate. The synergy expected to be achieved by flying in the immediate vicinity should allow the overall scientific results of the Afternoon constellation to be greater than the sum of the science of each individual mission.

GCOM-W1 Global Change Observation Mission-Water (Jaxa)

GNOM-W1 [97] is part of the constellation of Japanese satellites which have the task of observing all environmental changes on Earth for present and future generations. The "Global Change Observation Mission" (GCOM) aims to build, use and verify systems that allow continuous observations on a global scale (for 10-15 years) of geophysical parameters effective to elucidate global climate change and the circulation mechanisms of water. The GCOM mission is a series of two satellites, GCOM-W for observing changes in water circulation and GCOM-C for climate change. The GCOM-W with an onboard microwave radiometer will observe precipitation, amount of vapor, wind speed over the ocean, sea water temperature, water level in land areas and snow depth.

CLOUDSAT (NASA)

CloudSat is a NASA remote sensing satellite, launched from a Delta II rocket on April 28, 2006. It uses a radar to measure the height and properties of clouds, adding information on cloud and climate relations to help solve the problem of global warming. CloudSat was part of the "A-Train" satellite formation, with several other satellites: Aqua, Aura, CALIPSO and the French PARASOL. CloudSat's main tool is the Cloud Profiling Radar (CPR), a 94 GHz radar that measures the backscattering power from clouds as a function of the distance from the radar itself. The instrument was designed at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, with the contribution of the Canadian Space Agency [98]. The overall design of the CPR is simple, well understood, and has a strong legacy from the many cloud radars already in use in terrestrial and aerial applications. Most of the design parameters and subsystem configurations are almost identical to those for the airborne Cloud Radar, with which NASA's DC-8 has been flying since 1998. CloudSat is managed by the Jet Propulsion Laboratory. The University of Colorado provides scientific direction, data processing and distribution.

OCO-2 Orbiting Carbon Observatory

The three grid spectrometers of the satellite Orbiting Carbon Observatory (OCO-2) allow global and space observations of the concentration of carbon dioxide (CO^2) integrated in the column, a critical greenhouse gas for global warming. This satellite is mapping carbon dioxide in the atmosphere with unprecedented detail: scientists are learning more about how this greenhouse gas is released by burning fossil fuels, but also how plants work and how the earth and oceans suck in and release CO^2. About 25% of human emissions are absorbed by the ocean and another 25% by plants. Today as huge amounts of this gas is pumped into the atmosphere it is important to understand if these processes will continue. The OCO-2 satellite can be used to track CO^2 in very small areas, such as volcanoes and cities like Los Angeles or Paris. Therefore, it can be used not only to better understand the pollution of the city, but also to predict when volcanoes erupt. Carbon dioxide is higher in urban areas, where there are more cars and power plant emissions than in suburban areas, and it is higher in winter when plants absorb less CO^2 and more plants die than in summer.

MetOp (EUMETSAT/ESA)

The current MetOp series of EUMETSAT has three identical satellites. Launched in 2006, MetOp-A is Europe's first polar-orbiting mission dedicated to operational meteorology, and will be followed by MetOp-B in 2012 and MetOp-C in 2016. - These first three MetOp satellites guarantee the continuous delivery of high-quality data for medium- and long-term weather forecasting and for climate monitoring until at least 2020 [86]. The EPS-SG (EUMETSAT Polar System-Second Generation) Phase System baseline has been agreed by Council in June 2010 and is based on a Two-Satellite In-orbit Configuration. In 2011, ESA, in partnership with EUMETSAT, embarked upon the initial steps (industrial studies, Phase A) towards developing concepts for the next generation of MetOp -SG satellites. While the three satellites in the first series are identical, the current concept for MetOp-SG, also known as 'Post-EPS', will comprise two different satellites orbiting as a pair. It is envisaged that each satellite will carry a different, but complementary, instrument package. In November 2012, the EUMETSAT Council successfully concluded the approval process for the EPS-SG (EUMETSAT Polar System Second Generation) Preparatory Program with all 26 Member States having now firmly committed themselves. On May 20, 2014, the first documents signalling the go-ahead for Europe's fleet of MetOp Second Generation weather satellites were signed by Volker Liebig, ESA Director of Earth Observation Programs, and Michael Menking, Head of Airbus Defence & Space's Earth Observation, Navigation and Science Programs in the presence of the German Chancellor Angela Merkel at the Berlin Air Show. With the first contractual documents now signed, the ‘A' satellites will be developed and built by Airbus Defence and Space in Toulouse, France, while the ‘B' satellites will be developed and built at the company's facilities in Friedrichshafen, Germany. However, under the leadership of Airbus Defence and Space, a large industrial consortium of many different companies around Europe will be involved. MetOp-SG encompasses the objective of obtaining consistent, long-term collection of remotely sensed data of uniform quality for operational services for meteorology and climate monitoring state analysis, forecasting and operational service provision, in the context of the EUMETSAT's EPS-SG system.

Sentinel-3 OLCI

The main objective of the Sentinel-3 mission is to provide a sustained operational capability to measure sea and land surface temperature, sea surface topography, sea ice freeboard/thickness, and ocean- and land surface colour/reflectance with excellent accuracy and reliability in support of Copernicus Services. In order to satisfy the large coverage and high revisit requirements, the Sentinel-3 mission is designed as a constellation of two identical satellites, Sentinel-3A (S3A) and Sentinel-3B (S3B).

Using the twin-satellite constellation full coverage of all ocean surfaces is achieved in 2 days. The Sentinel-3 constellation operates in a sun-synchronous near polar orbit inclined at 98.65° at 815 altitude km with a local time at descending node of 10:00 am (giving a 7 day repeat cycle) [86]. Each satellite flies on the same orbital plane separated by 140°. Both S3A and S3B are designed for a nominal lifetime of 7 years, with consumable for up to 12 years. S3A was successfully from Plesetsk, Russia in February 016 and S3B was launched in April 018. Sentinel-3 carries four instruments that work in synergy: optical and radar. The Optical instruments are composed by the Sea and Land Surface Temperature Radiometer (SLSTR) and the Ocean and Land Colour Instrument (OLCI) to which correspond the processing chain to generate products. Furthermore, a combination of SLSTR/OLCI data allows to generate Synergy products e.g. ocean colour and land reflectance, aerosol optical depth, land and sea temperature, and vegetation core products. The products are delivered with different latencies to users: Near Real-Time (NRT) is delivered in less than 3 hours after data acquisition, Short Time Critical (STC) is delivered within 48 hours after data acquisition, and Non-Time Critical (NTC) typically delivered within 1 month after data acquisition. The selection of a product type in terms of delivery time is a trade-off between real-time needs and the final accuracy needed. Some Level-2 parameters depend on consolidating auxiliary and ancillary data such as orbit, platform or wet and dry tropospheric corrections.

SAGE III-ISS

External observation systems and sensors, such as those included in the SAGE III-ISS survey, have the potential to provide future designers and engineers with important information on the longevity of the components for the systems operated in the external space environment. The objective of SAGE III-ISS is to measure stratospheric ozone, aerosols and other trace gases. These measurements improve our understanding of the Earth's atmosphere and allow national and international leaders to make informed political decisions. When the ozone breaks down, all the inhabitants of the Earth are affected. Humans, plants and animals are exposed to the most damaging rays of the sun, which can cause long-term problems such as cataracts and cancer in humans and crop reduction. The operations of SAGE III-ISS are highly autonomous with the payload of the instrument performing most of the planning of events and the execution of scientific measurements. The payload of the instrument uses the broadcast accessory data to determine when the next scientific event occurs and where to point the instrument. SAGE III-ISS generates about 1.8 GB of data per day, including integrity and status telemetry data. Data is stored on a solid-state memory card and downlink on a daily basis through ISS communication systems. Scheduling and uploading commands are performed on a weekly basis. The general operations of SAGE III-ISS, including the development of commands and coordination with the Payload Operations Integration Centre (POIC), are performed at the Flight Mission Support Centre at the Langley Research Centre in Hampton, Virginia. The SAGE III-ISS survey starts on two separate EXPRESS pallet adapters (ExPA) inside a SpaceX Dragon Vehicle trunk. SAGE III-ISS is assembled on the ELC-4 site (ISS starboard nadir) via the remote space station manipulation system (SSRMS). No crew involvement is required.

MISR (NASA)

No instrument like MISR has flown in space before. Viewing the sunlit Earth simultaneously at nine widely spaced angles, MISR provides ongoing global coverage with high spatial detail. Its imagery is carefully calibrated to provide accurate measures of the brightness, contrast, and colour of reflected sunlight. MISR provides new types of information for scientists studying Earth's climate, such as the partitioning of energy and carbon between the land surface and the atmosphere, and the regional and global impacts of different types of atmospheric particles and clouds on climate. The change in reflection at different view angles affords the means to distinguish different types of atmospheric particles (aerosols), cloud forms, and land surface covers. Combined with stereoscopic techniques, this enables construction of 3-D models and estimation of the total amount of sunlight reflected by Earth's diverse environments [99].

CALIPSO (NASA/CNES)

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) was launched on April 28, 2006 to study the roles of clouds and aerosols of climate and weather. It flew in the international "A-Train" constellation for coincident Earth observations until September 13, 2018 when CALIPSO began lowering its orbit from 705 km to 688 km (428 miles) above the Earth to resume formation flying with “CloudSat” as part of the “C-Train”. The CALIPSO satellite comprises three instruments, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP Lidar), the Imaging Infrared Radiometer (IIR), and the Wide Field Camera (WFC). CALIPSO is a partnership between NASA and the French Space Agency, CNES.

OMI (NIVR/FMI/NASA)

MI is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the EOS Aura mission. It will continue the TOMS record for total ozone and other atmospheric parameters related to ozone chemistry and climate. OMI measurements will be highly synergistic with the other instruments on the EOS Aura platform. The OMI instrument employs hyperspectral imaging in a push-broom mode to observe solar backscatter radiation in the visible and ultraviolet. The Earth will be viewed in 740 wavelength bands along the satellite track with a swath large enough to provide global coverage in 14 orbits (1 day). The nominal 13 x 24 km spatial resolution can be zoomed to 13 x 13 km for detecting and tracking urban-scale pollution sources. The hyperspectral capabilities will improve the accuracy and precision of the total ozone amounts. The hyperspectral capabilities will also allow for accurate radiometric and wavelength self-calibration over the long term. The expanded wavelength characteristics will provide the following features.

GOES (NOAA)

The Geostationary Operational Environmental Satellite-R Series (GOES-R), the latest generation of geostationary weather satellites, significantly improves the detection and observation of environmental phenomena, resulting in improved public safety, more accurate forecasts, better protection of property, and greater assurance on our nation’s economic health and prosperity. GOES-16 replaced GOES-13 as the operational GOES-East Satellite on 18 December 2017 and GOES-17 became operational on 12 February 2019. GOES-15 will still be sending data a little while longer before it is decommissioned later in 2019. GOES-T and GOES-U are planned to be launched in the future and will extend the availability of the operational GOES satellite system through 2036 [100].

AVHRR (NOAA/EUMETSAT)

NOAA/NESDIS has been routinely estimating aerosol amount over the world's oceans from the Advanced Very High-Resolution Radiometer (AVHRR) onboard the NOAA polar orbiting operational satellites. The products are daily, weekly, and monthly global one-degree maps of Aerosol Optical Thickness [86]. The weekly products are based on a composite of one week's worth of data, and the monthly average products are based on the average of each week's data for the month. Currently they are created from AVHRR channel 1, 2 and 3 optical thickness retrievals from AVHRR 4-km global area coverage (GAC) data [101].

AEOLUS

Launched on 22. August 2018 is the first satellite mission to acquire profiles of Earth's wind on a global scale. These near-realtime observations will improve the accuracy of numerical weather and climate prediction and advance our understanding of tropical dynamics and processes relevant to climate variability. Many aspects of our lives are influenced by the weather. It goes without saying that accurate forecasts are important for commercial undertakings such as farming, fishing, construction and transport and in general it makes easier to plan the days ahead. In extreme circumstances, knowing what the weather will bring, can also help saving lives and protect property. Although weather forecasts have advanced considerably in recent years, meteorologists urgently need reliable wind-profile data to improve accuracy further. Aeolus wind mission will demonstrate that measuring global wind-profiles from space, using laser technology, can meet this requirement. Aeolus is the fifth in the family of ESA's Earth Explorer missions, which address key scientific challenges identified by the science community and demonstrate breakthrough technology in observing techniques. Named after Aeolus [86], who in Greek mythology was appointed 'keeper of the winds' by the Gods, this novel mission will not only provide much-needed data to improve the quality of weather forecasts, but also contribute to long-term climate research. The Aeolus satellite carries just one large instrument – a Doppler wind lidar called Aladin that will probe the lowermost 30 km of the atmosphere to measure the winds sweeping around our planet.

Himawari-8 AHI

Himawari-8 AHI is a multiple wavelength imager with 16 bands ranging from visible to infrared wavelength (3 visible bands, 3 near-infrared bands and 10 infrared bands), providing observations over the Asia–Pacific region with a temporal resolution of 2.5–10 min and a spatial resolution of 0.5–2 km [102]. Currently, Himwari-8 has released Level 3 (L3) Version 3.0 hourly aerosol product, including AOD at 500 nm and Ångström Exponent (AE) with the spatial resolution of 5 km. The L3 AOD product provides AOD_Pure and AOD_Merged subsets. To be specific, AOD_Pure is the result of applying the rigorous cloud screening to L2 AOD retrievals, and AOD_Merged is the result of interpolating AOD_Pure based on spatial and temporal variability information from L2 AOD. AOD_Merged generally has fewer missing values than AOD_Pure because of interpolation and has a higher accuracy than L2 AOD due to successful elimination of cloud contamination [103].

Mission	Instrument	Sponsoring Agency	Traced Gases									Altitude	Time Span	Measuring	Principle of instrument	Resolution	Date of Launches	Revisit Times	Period
	Running																		
Terra	MOPITT	NASA		•							No	705	18.12.1999	Troposhere					
Terra	MODIS	NASA									No	705	18.12.1999	Troposhere					
Aqua	MODIS	NASA									No	705	04.05.2002	Troposhere					
	MSG	EUMETS																	
Sentinel 3 A/B	OLCI	EUMETS AT/ESA													Spectrometer				
GoSat	GOSAT TANSO-FTS	JAXA-MOE-	•								Yes /see link to paper	667/666	2009–ongoing	troposphere, atmosphere	SWIR /Tanso FTS /spectrometer		23.01.2009		
GoSat2/ Ibuki2	GOSAT-2 TANSO FTS-2	JAXA-MOE-	•	•							Yes /see link to paper	624/622	2018–ongoing	troposphere, atmosphere	TANSO-FTS-2/TANSO-CAI-2		29.10.2018		
OCO-2	OCO-2	NASA	•									711	2014–ongoing	troposphere, atmosphere					
ISS	OCO-3	NASA	•									370/420km -precessing (ISS)	2019–ongoing	troposphere, atmosphere					
TanSat	TanSat ACGS	CAS-MOST-CMA	•								yes	726/697	2016–ongoing	carbon oxid distribution changes during the year	Atmospheric Carbon-dioxide Grating Spectroradiometer (ACGS)	(1km/pix) x (1km/pix) , swatwidth 20km	21.12.2016		
Sentinel 5P	TROPOMI	ESA	•	•		•	•		•		yes	824	2017–ongoing	troposphere, atmosphere	Tropomi		13.10.2017		
Fenyun 3	Feng Yun 3D GAS	CMA-CNSA	•									836	2017–ongoing		Sounders, Imager, Spectrometers, Photometer		14.11.2017		
Prisma	Prisma	ASI										614	2019 -		spectrometer 250		22.03.2019	29d	99 min
MetOp	MetOp	EUMETS	•	•		•	•	•	•		Yes	820	10.2006 ->				19.10.2006		
ISS	SAGE III-ISS	NASA				•	•	•			Yes								
MISR (NASA)	MISR (NASA)	NASA									Yes								
CALIPSO (NASA/CNES)	CALIPSO (NASA/CNES)	NASA									Yes	703/701	28.04.2006				28.04.2006		
AURA	OMI (NIVR/FMI/NASA)	NASA				•		•	•		Yes	709	14.10.2004	stratosphere, troposphere, atmosphere			15.07.2004		98.83 min
GOES (NOAA)	GOES (NOAA)	NOAA										675	26.04.2013				26.04.2013		
Himawari-8 AHI	Himawari-8 AHI																		
AEOLUS	AEOLUS											328/316	22.08.2018				22.08.2018		90.8 min

5 Summary table Describes the satellites, currently in orbit, their payload and their characteristics.

Sentinel-5P

Sentinel-5P is the forerunner of Sentinel-5's Copernicus mission. The first Copernicus mission that aims to monitor the Earth's atmosphere by performing atmospheric measurements with high space-time resolution [86]. This project is the result of ESA's collaboration with the European Commission, the Dutch Space Office and was launched on October 2017. Its characteristics have been reported several times in this thesis and this short paragraph wants to guide the reader to understand where it is historically located.

5.1.7 Future satellites

EarthCARE

The EarthCARE (Earth Cloud, Aerosol and Radiation Explorer) satellite mission is the next evolution in multi-sensor, space-borne observations and synergistic data products. With an expected launch date in mid-2022, this joint mission between the European Space Agency and the Japanese Aerospace Exploration Agency aims to observe interactions among radiant energy transfer, clouds, aerosols and precipitation, so for better understanding: controls on Earth's energy budget. Based on the robust heritage of satellites and satellite constellations, the EarthCARE payload includes four instruments operating on a single platform to provide coincident measurements: a high-spectral-resolution lidar (ATLID), the first ever space-born Doppler radar (CPR), a multispectral imager (MSI), and a broadband radiometer (BBR). The novel features of the satellite (e.g. coincident measurements, higher radar sensitivity, Doppler capability, and measured lidar extinction) provide an exciting opportunity to perform more accurate and informed analysis than before [86]. For more information on the mission, instrumentation, and data products, please visit ESA's Earth Explorers EarthCARE page. The Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite mission will advance our understanding of the role that clouds, and aerosols play in reflecting incident solar radiation back out to space and trapping infrared radiation emitted from Earth's surface.

Energy in the atmosphere is balance between incoming light from the Sun, which heats Earth, and outgoing thermal radiation, which cools Earth. Clouds and, to a lesser extent, aerosols reflect incident solar light back out to space, but they also trap outgoing infrared light. This leads to a net effect of either cooling or heating of the planet. The effect of clouds on atmospheric heating and cooling is not only much stronger than the effect of greenhouse gases such as carbon dioxide, but also much more complex owing to the complicated structure of clouds. Furthermore, the life cycle of clouds depends on the temperature, moisture and dynamics of the atmosphere. In addition, aerosols influence the life cycle of clouds, and so contribute indirectly to their radiative effect. The effect of clouds on atmospheric heating and cooling is not only much stronger than the effect of greenhouse gases such as carbon dioxide, but also much more complex owing to the complicated structure of clouds. Furthermore, the life cycle of clouds depends on the temperature, moisture and dynamics of the atmosphere. Clouds remain one of the biggest mysteries in our understanding of how the atmosphere drives the climate system. An improved understanding and better modelling of the relationship between clouds, aerosols and radiation is therefore one of the highest priorities in climate research and weather prediction. EarthCARE is the largest and most complex Earth Explorer mission to date. The data will be used in numerical weather prediction models to study how cloud profiles can improve weather forecasts. The EarthCARE lidar and radar instruments are the most advanced cloud and aerosol profiling instrument ever flown in space. The lidar will be able to distinguish clouds and different types of aerosols. The radar will be able to detect vertical motion within clouds, which will lead to a much better understanding of convection and ice & rain fall speed, leading to improved drizzle, rainfall and snowfall rates. EarthCARE (Earth Cloud Aerosol and Radiation Explorer) will provide global profiles of clouds and aerosols along with measurements of solar radiation reflected from the planet and thermal radiation emitted from the planet. To do this, the satellite carries two large instruments: a lidar to measure vertical profiles of aerosols and thin clouds, and a radar to measure vertical profiles of thick clouds and precipitation. Furthermore, two other instruments, a cloud imager and a broadband radiometer that measures the reflected solar radiation as well as the emitted thermal radiation of the clouds, complete the satellite's suite of sensors. The use of these instruments means that 3D cloud and aerosol scenes can be directly related to reflected solar and emitted thermal radiation. EarthCARE will acquire global datasets of cloud and aerosol profiles at the same time. This will help to evaluate and improve how clouds are represented in atmospheric models. emitted thermal radiation.

MERLIN

MERLIN (MEthane Remote sensing LIdar missioN) is a French-German collaborative minisatellite climate mission. The primary objective is to obtain spatial and temporal gradients of atmospheric methane (CH4) columns with high precision and unprecedented accuracy on a global scale. Methane (CH4) and carbon dioxide (CO^2) both cause global warming, although the impact of methane is 5 times more powerful than the one of carbon dioxide on a timescale of 100 years [86]. The satellite is set to measure concentrations of methane in Earth's atmosphere with unprecedented accuracy. Methane LIDAR (Light Detection and Ranging), the core part of the instrument is a laser, which can send out light pulses on two different wavelengths and thus measure the methane concentration at all latitudes with great precision regardless of sunlight. The launch is foreseen for December 021 [104].

MicroCarb

MicroCarb [86] is a CNES microsatellite mission with the goal to monitor the fluxes of carbon dioxide (CO^2) at the surface between the atmosphere and the oceans and vegetation. A better knowledge of the carbon flux is needed to:

- Understand the functioning of the vegetation (yearly cycle, response to meteorological anomalies)
- Identify and quantify the terrestrial ecosystem Carbon sinks and sources at yearly scales (where are the Carbon sinks/sources; how do they evolve with the climate changes)
- Quantify the oceanic Carbon sources and sinks at yearly scales and their responses to the announced climate changes
- Contribute to the measurement of Carbon emission linked to fossil fuels use.

Biomass ESA

The Earth Explorer Biomass will provide global maps of the amount of carbon stored in the world's forests and how this change over time, mainly through absorbing carbon dioxide, which is released from burning fossil fuels. Biomass will also provide essential support to UN treaties on the reduction of emissions from deforestation and forest degradation. Forest type and forest cover worldwide can be detected by today's satellites, but Biomass will take the information to the next level. the satellite will carry the first P-band synthetic aperture radar, able to deliver accurate maps of tropical, temperate and boreal forest biomass [86]. The global mass of trees is not obtainable by ground measurement techniques. The five-year mission will witness at least eight growth cycles in the world's forests. The launch is foreseen in 2021. Observations from this new mission will also lead to better insight into rates of habitat loss and, therefore, the effect this may have on biodiversity in the forest environment.

GeoCARB

The Geostationary Carbon Observatory (GeoCarb), targeted for launch in the early 2020s, will build on the success of NASA’s Orbiting Carbon Observatory-2 (OCO-2) mission by placing a similar instrument on a commercial SES-Government Solutions communications satellite flying in geostationary orbit. NASA has selected a first-of-its-kind Earth science mission that should playing a role in the US greenhouse gases and vegetation health from space to advance our understanding of Earth’s natural exchanges of carbon between the land, atmosphere and ocean. GeoCarb will collect 10 million daily observations of the concentrations of carbon dioxide, methane, carbon monoxide and solar-induced fluorescence (SIF) at a spatial resolution of about 3 to 6 miles (5 to 10 kilometres) [105]. The primary goals of GeoCARB are to monitor plant health and vegetation stress throughout the US, and to probe, in unprecedented detail, the natural sources, sinks and exchange processes that control carbon dioxide, carbon and methane in the atmosphere [86]. The investigator-led mission will launch on a commercial communications satellite to make observations over the Americas from an orbit of approximately 35,400 kilometres above the equator. The GeoCarb instrument views reflected light from Earth through a narrow slit. When the slit is projected onto Earth’s surface, it sees an area measuring about 1,740 miles (2,800 kilometres) from north to south and about 3.7 miles (6 kilometres) from east to west. In comparison, OCO-2’s swath is about 6.2 miles (10 kilometres) wide. GeoCarb stares at that area for about 4-1/2 seconds, then the slit is moved half a slit width -- 1.9 miles, or 3 kilometres -- to the west, allowing for double sampling. With this technique, GeoCarb can scan the entire continental United States in about -1/4 hours, and from Brazil to South America’s West Coast in about -3/4 hours. It is not designed to observe the oceans, as reflectivity over the oceans is too low to provide useful data. The mission was competitively selected from 15 proposals submitted to the agency's second Earth Venture - Mission announcement of opportunity for small orbital investigations of the Earth system. GeoCARB is the second space-based investigation in the Earth Venture - Mission series of rapidly developed, cost-constrained projects for NASA's Earth Science Division [106].

Mission	Instrument	Sponsoring Agency	Traced Gases									Altitude	Time Span	Measuring	Principle of instrument	Resolution	Date of Launches	Revisit Times	Period
	Planned																		
Gaofen 5	Gaofen 5 GMI	CNSA	•									695/677	2018–2026	atmosphere	6 instruments		8.05.2018		
BIOMASS	BIOMASS	ESA	•	•								672/635	2022-		P-Band SAR		2022		
MicroCarb	MicroCarb	CNES-UKSA	•	•								650	2020–2025	atmosphere, surface land and sea	LIDAR		2020?		
MERLIN	MERLIN	DLR-										500	2024–2027		LIDAR		2024?		
MetOp-SG Sentinel 5	MetOp-SG Sentinel 5	EumetSat	•	•								LEO	2021–2025		spectrometer		2022		
GeoCarb	GeoCarb	NASA	•	•								GEO	2022–2025				2022		
EarthCARE	EarthCARE	ESA									•	393	2021 - 2023		LIDAR, RADAR, MSI		2021	25 d	

6 Summary table, The satellites, future, their payload and their characteristics are described.

5.1.8 Other spaceborne remote sensing technologies

In addition to satellite data, the Copernicus program offers information services based on satellite Earth observation and in situ (no-space) data.

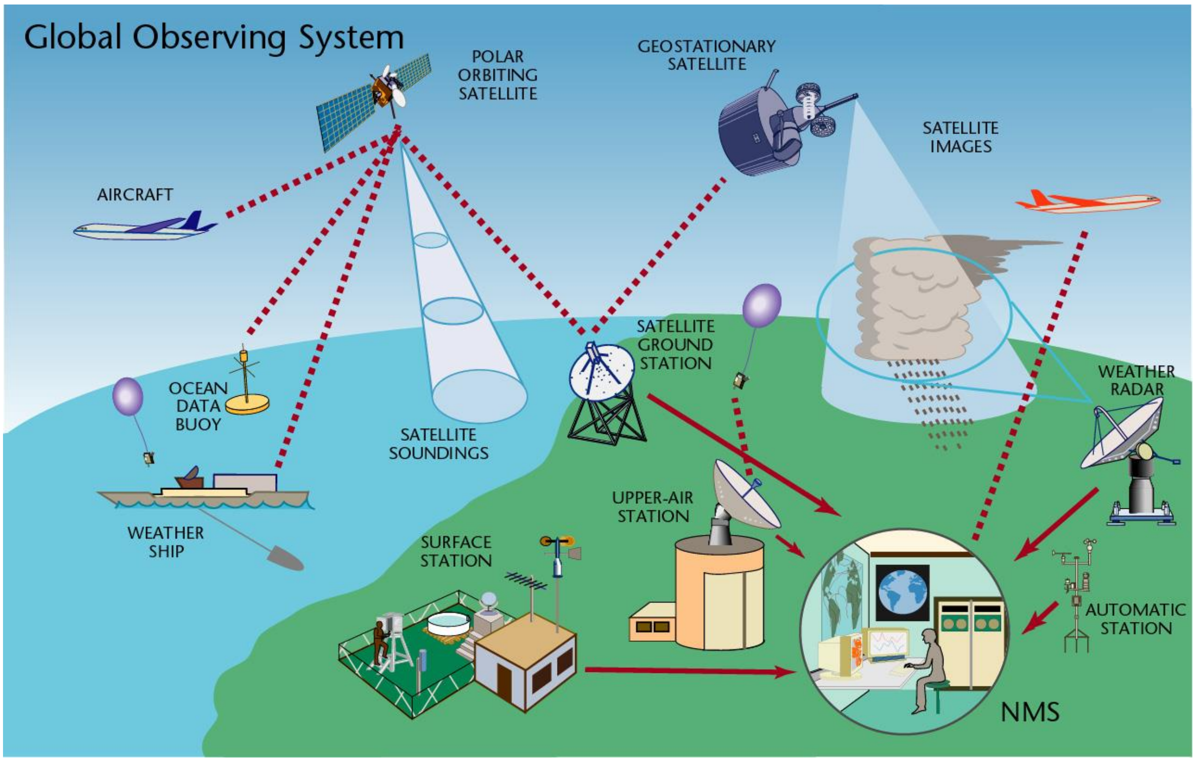
The large amounts of global data come from satellites and terrestrial, aerial and marine measuring systems. They are used to provide information to help service providers, public authorities and other international organizations to improve the quality of life of European citizens. The information services provided are freely and openly accessible to its users. Users are provided with reliable and up-to-date information through a range of Copernicus services related to environmental and security issues. These include:

- Copernicus Global Land Service (CGLS),
- Copernicus Marine Environmental Monitoring Service (CMEMS)
- Copernicus Land Monitoring Service (CLMS)
- Copernicus Atmospheric Monitoring Service (CAMS)
- Copernicus Emergency Management Service (CEMS)
- Copernicus Climate Change Service (C3S)

The services provide critical information to support a wide range of applications, including environmental protection and atmosphere quality management. In particular, the Copernicus Atmosphere Monitoring Service (CAMS) provides consistent, quality-controlled information on air pollution and health, greenhouse effect and climate forcing, anywhere in the world. CAMS is implemented by the European Centre for Medium Term Weather Forecasting (ECMWF). CAMS has the added value of being a data repository that combines data from satellites with data from in situ sensors. CAMS combines information from different payloads with computerized models of the atmosphere to generate an accurate estimation of atmospheric variables such as temperature, ozone concentrations and the amount of aerosol particles. Using these estimates as a starting point, the models can then produce forecasts. The observations are also used to evaluate the quality of CAMS products. The atmosphere is continuously observed by more than 40 satellites, thousands of ground and air observation stations, ships and balloons. Together they measure meteorological parameters such as temperature, clouds and winds, and also atmospheric components such as ozone, carbon monoxide and aerosols. Non-satellite observations are often grouped into a category called "in situ observations".

In-situ observations include:

- measurements of air quality in and around cities;
- measurements made by commercial and research aircraft;
- measurements of vertical distribution of pollutants and aerosols using balloon probes or ground instruments



14 The atmosphere is continuously being observed by more than 40 satellites, thousands of ground-based observation stations, and aircraft, ships and balloons and in situ observations [110]

These in situ observations are used by CAMS to improve daily forecasts, to assess forecast quality and to monitor the exchange of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) on the Earth's surface. The data is available to users completely free of charge.

5.2 Models in urban pollution monitoring

The use of Earth observation has made it possible to monitor air pollution in different geographical areas and has given rise to numerous studies aimed at determining the optical thickness of aerosol (AOT) using indirect methods using Landsat TM / ETM +, ASTER, SPOT, ALOS, IRS etc. If wanted to define also a state of the art of AOT models it should surely start from the one in 1990 [107] that developed an algorithm to determine the optical thickness of the aerosol, the model was based on the reflectance of the surface between the images of the clear day and those of the nebulous day. In 1992 [108] they used SPOT images to estimate the distribution of air pollution in the city of Toulouse in France, they developed an equation to calculate the optical depth difference of the aerosol between a reference image (acquired under clear atmospheric conditions) and a polluted image. Their method foresaw that after correction of solar variations and angle of observation, the residual deviation of apparent radiation was due to pollutants. Only in 1998-1999 [109] showed that an evaluation of air pollution in Athens could be obtained using the Landsat TM 1 band correlating the optical thickness of the aerosol with the acquired air pollutants. Since the early 2000s the sensors began to field and with it also the models. In 2009 [110] they developed a method that combines the DOS (Darkest Object Subtraction) principle and radiative transfer equations to find the AOT value for the Landsat TM 1 and 2 bands. The method to determine the AOT was based on the use of atmospheric correction of light and dark pixels. To determine the optical thickness of the aerosol by applying the contrast tool (maximum contrast value), radiative transfer calculations and 'tracking' the darkest suitable pixel in the scene for Landsat, SPOT and high resolution images such as IKONOS and Quickbird. Also in those years MODIS images, despite their low pixel resolution, were used to extract the optical thickness values of the aerosol for the 550 nm band. MODIS data were extended and correlated to PM10 [111] in different study areas with improved correlation coefficients but with different limitations. It was also discovered that PM2.5 can also be monitored by satellite by correlating the MODIS data using new improved algorithms [102].

From the literature it is expected that future satellite technologies will provide data with finer spatial and temporal resolutions and more accurate data retrieval [112]. In addition, the advanced ability to discriminate aerosol species in satellite technologies will further contribute to health effects studies investigating species-specific health implications [112].

Air quality monitoring is one of the most complex problems in the field of environmental protection and is aimed at determining concentrations of compounds potentially hazardous to human health and the environment [113].

The emission models of pollutants

The key parameter to evaluate the air pollution model that can be found in air pollution studies is the optical thickness of the aerosol. The AOT is a measure of the aerosol load in the atmosphere, high values of this index suggest a high concentration of aerosol and therefore air pollution. The use of Earth observation is based on the monitoring and determination of both direct and indirect AOT as an instrument to assess and measure air pollution. The models are the instrument able to represent reality, used to predict and describe the evolution of a real phenomenon. There are three main requirements that are required from a model:

- The model must be able to predict the evolution of a phenomenon taking into account any disturbances that have induced it.
- it must include every knowledge a priori.
- it must be consistent with the theory that presides over its construction.

The models have become a primary tool of analysis in most of the assessments of the quality of the air mainly for the following reasons:

- It is possible to obtain an image of air quality in an area, in contrast to the limits in the spatial coverage of air quality measurements.
- The relationship between air concentrations and the emissions that cause them can be established explicitly and quantitatively using models, which are very important to support air quality management.

This type of methodology is the only tool available if you want to study the impact on air quality of possible future sources or alternative future emission scenarios. Air pollution models can be used in a complementary way to air quality measurements, taking due account of the strengths and weaknesses of both analysis techniques. Model applications can be distinguished on the basis of many criteria, such as underlying physical concepts, time and spatial scale, source type, component type and application type.

The local-regional scale models [114] are in principle related to the mesoscale[56]. It has been recognized that, particularly in southern Europe, urban-scale problems (local circulation systems, such as sea and land breezes) can only be successfully treated with the help of mesoscale air pollution models in a sufficiently large model domain. The time scale, on the other hand, requires both short-term models (maximum hourly concentrations) and long-term models (annual average concentrations). Meteorological statistics are necessary for the calculation of percentiles and or exceedance frequencies.

Although atmospheric models are a key tool in air quality assessment studies, their limits should always be taken into account. Therefore, before attempting to select or apply a model, it is necessary to keep in mind that uncertainties in the model results may be large, introduced by the model concept and/or input parameters. In particular:

- There is no model that can adequately address all imaginable situations even for a broad category such as point sources.
- The meteorological and topographical complexities of the area, which are usually associated with a potential exceedance of air quality standards, are rarely sensitive to a single mathematical treatment; case-by-case analysis and judgments are often required.
- Consistency in the selection and application of models, input data and air quality data are very important. It is useless to calculate an air quality field with a spatial resolution much higher than the emission field.

It is necessary to find a balance in detail and accuracy of the data involved: emission inventory, meteorological data and air quality data. The availability of appropriate data should be examined before applying any model. A model that requires detailed and accurate input data should not be used when such data is not available. The representativity of model results may be limited; in most models a spatial and temporal average is introduced which may complicate a direct comparison with measurements in a given place and time. The involvement of specialists is necessary whenever more sophisticated models are used or the area of interest has complicated meteorological or topographical features.

[56] Mesoscale meteorology is the study of weather systems smaller than synoptic scale systems but larger than microscale and storm-scale cumulus systems. Horizontal dimensions generally range from around 5 kilometers to several hundred kilometers. Examples of mesoscale weather systems are sea breezes, squall lines, and mesoscale convective complexes. Vertical velocity often equals or exceeds horizontal velocities in mesoscale meteorological systems due to nonhydrostatic processes such as buoyant acceleration of a rising thermal or acceleration through a narrow mountain pass.

5.2.1 The models of dispersion of pollutants

The deterministic models describe the behaviour of the phenomena of a real system, through algorithms able to schematize the urban air pollution system. It is possible to distinguish two classes of deterministic models, according to the different way of observing atmospheric pollution:

- The Lagrangian dispersion models are the models that refer to a mobile coordinate system that follows the movements of air masses whose behaviour has to be reproduced. Among them it is possible to distinguish trajectory and particle models. In the trajectory models is simulated the evolution of a column of air that moves under the action of the average component of the wind speed (for horizontal hypothesis and uniform with the altitude).
- The Eulerian models refer to a fixed coordinate system; they are based on the integration of the differential equation of the diffusion, obtained from the mass balance applied to an infinitesimal volume of air under certain assumptions. Depending on how the differential equation is solved, it will lead to analytical models (puff and Gaussian), boxing models and grid models. The most important phenomena in the atmospheric field are illustrated below, on which the model algorithms are built.

The models of deterministic type are proposed to reconstruct in quantitative way phenomena that determine the space-time evolution of the concentration of pollutants in air.

Lagrangian Dispersion Models
[115]

General equation of transport and diffusion [116]**:** The equation 1 obtained through the mass balance, on an infinitesimal volume (dxdydz), during the time interval dt in its complete form results:

$$\frac{\partial C}{\partial t} = -\nabla(vC) + \nabla \cdot (K \cdot \nabla C) + \nabla \cdot (D \cdot \nabla C) - R + S$$

1 General equation of transport and diffusion

Indicating with:

C = pollutant concentration at the receptor in g/m3

v = vector of wind speed at reference height in m/s

D = molecular diffusivity coefficients in m2/s

K = turbulent diffusivity tensor in m2/s

R = removal factor in g/(m3-s)

S = source factor in g/(m3-s)

Dry deposition: Continuous phenomenon described by the deposition rate defined as:

$$v_d = \frac{F}{c(z)}$$

2 Dry deposition

Where:

v_d = deposition speed in m/s

F = flow of pollutants removed per unit area in g/(m2-s)

c(z) = concentration of pollutant near the ground in g/m3

Wet deposition: includes all processes by which air pollutants are transported to the ground through various forms of precipitation (rain, snow, fog). Of these models there are two most used: the rainout, in which the pollutant inside the clouds becomes the condensation core of the water drops and the washout, in which the pollutant under the clouds, bumping the water drops, is dragged to the ground; in both cases, the water-pollutant interaction characterizes the process.

$$Q(t+dt) = Q(t)e^{-l_w dt}$$

3 Wet deposition

where:

Q(t) = the amount of pollutant instantly t

l_w = the washout coefficient. The coefficient l_w is a function of the rain intensity P(t) expressed in (mm/h) and assumes the value of:

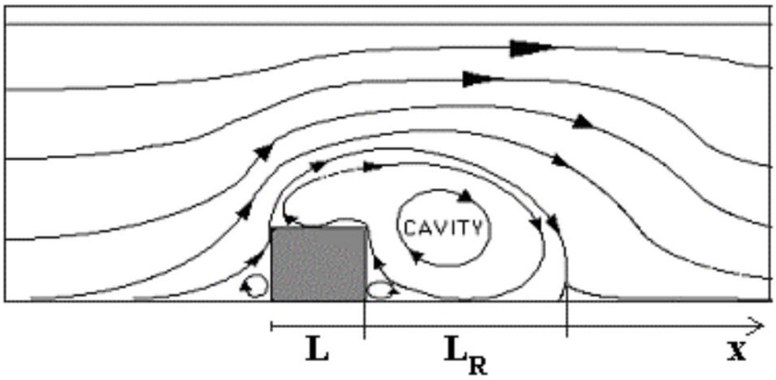
$$l_w = l_{wo}P(t)^a$$

4 washout coefficient

l_{wo} = constant that depends on the type of pollutant

a= exponent, generally assumes a value between (0,75÷1)

Downwash phenomenon: Occurs in the presence of buildings, can affect the dispersion of the mass of pollutant emitted. The wake of buildings within a wind field, generates an increase in mechanical turbulence and therefore an increase in total turbulence.



15 Downwash phenomenon

16 It is represented the trend of the flow lines, modified by the presence of a building. It is also represented the cavity, a highly turbulent area where the pollutant tends to accumulate [120]

In the precedent image it is possible to see an area, called a cavity, in the downwind part of the building, where it is assumed that the flows, due to the high turbulence, are completely mixed. The algorithms are not able to predict the concentration of pollutant in the cavity, so the calculation is performed at distances that are not influenced by the cavity. The algorithms that describe the downwash phenomena, are activated only if the source falls in a well-defined area near the building:

- $C = C_N$ → per $L \leq x \leq L + 0.85{*}L_R$
- $C = \lambda{*}C_N + (1 - \lambda){*}C_F$ → per $L + 0.85{*}L_R \leq x \leq L + L_R$
- $C = C_P + \lambda{*}C_N + (1 - \lambda){*}C_F$ → per $L + L_R \leq x \leq L + 1.15{*}L_R$
- $C = C_P + C_F$ → per $x \geq L + 1.15{*}L_R$

5 Downwash phenomenon in which λ descends linearly by 1 for $x = L + 0.85{*}L_R$ and 0 for $x = L + 1.15{*}L_R$

The calculation of the concentration on the ground, downwind of the building, is then made according to the distance from the building.

CF = concentration due to the part of the captured plume, considered as a volume source

CP = concentration due to the part of the plume not captured, calculated as in the absence of downwash.

Eulerian Dispersion Models
[117]

Puff models

The puff models allow to reproduce the trend of a pollutant in no-homogeneous and non-stationary conditions. The emission is discretized into a series of individual puffs. Each of these units is transported within the calculation domain for a certain time interval by the wind field present at the centre of gravity of the puff at a certain time. They are the models that have allowed to calculate the dispersions of the pollutants within this thesis work. The turbulent diffusion is simulated assuming that the pollutant is distributed within each unit with Gaussian law (law that varies in space). The concentration at a certain instant t is the sum of the contribution of each single puff. Considering only one puff, with centre of gravity in (x_p,y_p,z_p) the concentration at any point of the domain will be:

$$C(x,y,z)=\frac{M}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{(x-x_p)^2}{2\sigma_x^2}-\frac{(y-y_p)^2}{2\sigma_y^2}\frac{(z-z_p)^2}{2\sigma_z^2}\right]$$

6 Puff models

There are also other types of models. The models described in this paragraph have helped to define together with GIS[57] software the dispersion of pollutants in the city environment.

5.3 Data acquisition and processing tools and techniques

In the previous chapters I have defined the EU air quality directives identify SO2, NO2, PM10, CO and ozone as preferential use indicators for health impact assessments. I have identified which are the satellites that can help us monitor and control air quality. I have established how to approach the air quality models and their diffusion in the

[57] A geographic information system (GIS) is a conceptualized framework that provides the ability to capture and analyze spatial and geographic data. GIS applications (or GIS apps) are computer-based tools that allow the user to create interactive queries (user-created searches), store and edit spatial and non-spatial data, analyze spatial information output, and visually share the results of these operations by presenting them as maps

atmosphere. In this chapter I will define the set of environmental data used for the work and how they can be processed and validated [118].

Data collection procedures

Data and information were collected mainly from three sources

1. Satellite data

2. In situ data

3. Auxiliary Data

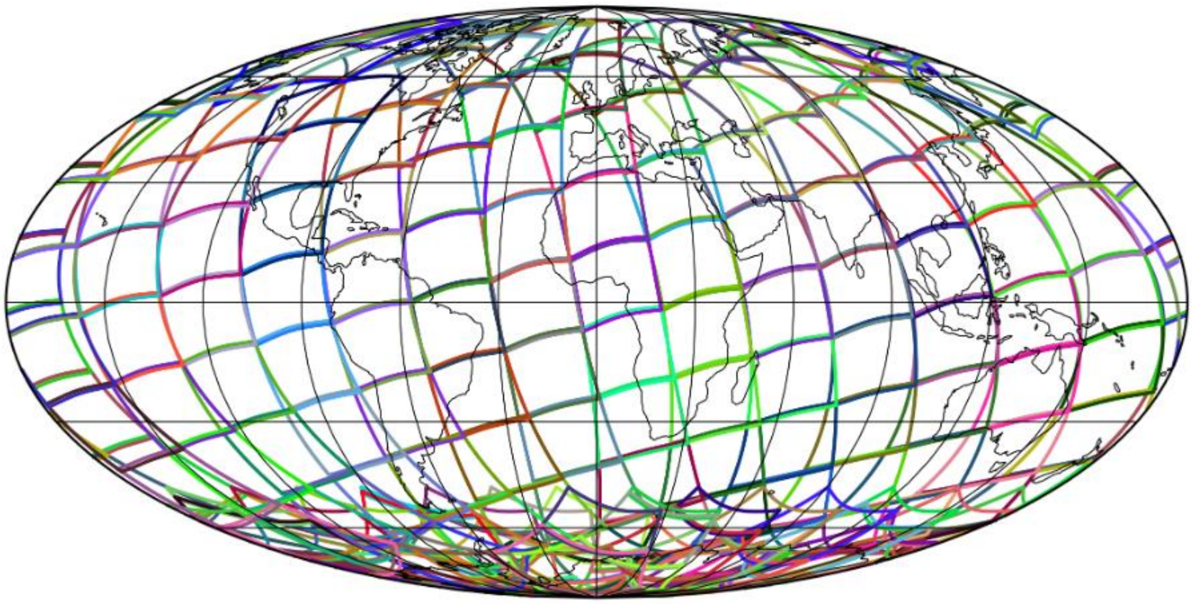
The data and information have been organized according to their quality. Satellite data and ancillary data are reprocessed to meet the needs of the project. On the other hand, the data in situ are corrected and validated. Correction and validation follow the methodologies retrieved from the literature review and contain a fair number of expert and professional opinions.

5.3.1 Satellite data used for pollutants analysis

The data described in this paragraph for air quality monitoring comes mainly from Sentinel 5P and European control units. The advantage of remote air pollution data includes broad coverage with useful spatial and temporal resolution. Sentinel 5P is a fairly new source of remote sensing data, but it requires a compute-intensive download and processing that is often an obstacle to public use. The shared workflow repository, however, contains other air pollutants including ozone (O_3), sulphur dioxide (SO_2), carbon monoxide (CO). The spatial resolution of the measurements (3.5 × 7 km^2 for all trace gases except CO and methane (CH_4) which is 7 × 7 km^2) allows observation and mapping of air pollution on a smaller scale. end. As already mentioned in chapter 1, the products that I will consider in this work are those of level 2 and with an OFFL (offline) processing. Level 2 products are manufactured using Level 1B radiation with geolocation and irradiation. In addition, they are based on auxiliary input data:

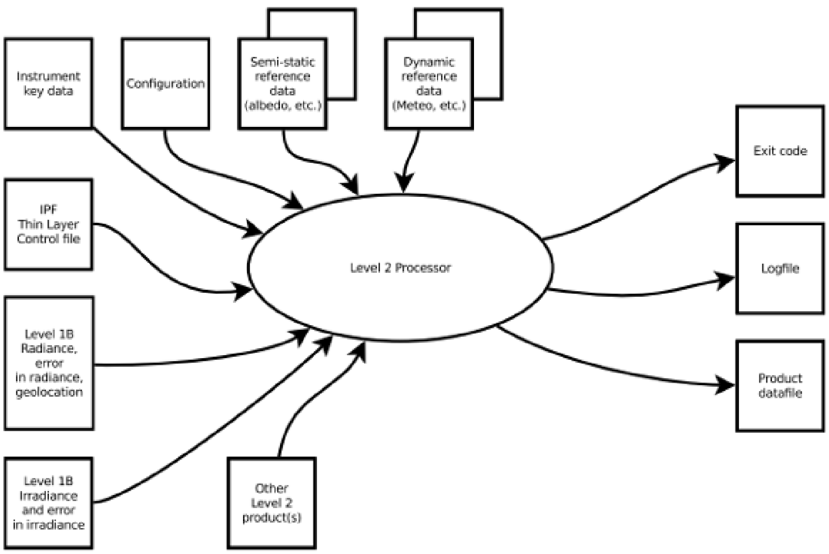
- dynamic (e.g. Weather fields from a numerical weather forecast model)
- static (e.g. Reference spectra of the absorption cross section).

From these inputs the ESA processor produces a TROPOMI Level-2 output file, such as NO_2 columns or O_3 profiles.



17 Outline of the granules. The image shows the different orbits traveled by the sentinel-5P satellite © ESA

The orbits of SENTINEL-5P are orbits with an inclination (approximately 98.7 °). The inclination of the orbit is the angular distance of the orbital plane from the equator. Ascending orbits tilt equatorial at 13:30 mean local solar time. In a sun-synchronous orbit, the surface is always illuminated with the same solar angle. The orbital cycle is 16 days (14 orbits per day, 227 orbits per cycle). The reference altitude of the orbit is approximately 824 km. Mainly 2 daily orbits are used to map the whole of Europe.



18 Generic Overview of a TROPOMI Level-2 Processor © ESA

The processor also produces a log file and an exit code so that the processing system can verify the results of the processing. I will use them as part of the data validation and validation.

Most of the TROPOMI processors/algorithms made by ESA exploit a calculation, which is based on the measured reflectance spectra. Its formula:

$$R(\lambda) = \frac{\pi I(\lambda)}{\mu_0 E_0(\lambda)}$$

7 TROPOMI processor/algorithms © ESA

The measured reflectance spectrum is adapted from a modelled reflectance spectrum in order to retrieve the geophysical (atmospheric concentration, surface albedo) and instrumental (wavelength assignment of spectral pixels) parameters of the model to the geolocation (earth pixel coordinates) and the time of measurement.

ESA also tells that the entire workflow for translating data from level 1 to level two is based on algorithms that describe the processing of a single pixel on the ground. In TROPOMI level 2 processors, they are integrated into a loop that covers all (valid) ground pixels of the input level 1B product.

The Level 2 products used in this work are recovered based on the UV-VIS-NIR spectral ranges from bands 1 to. In detail they are:

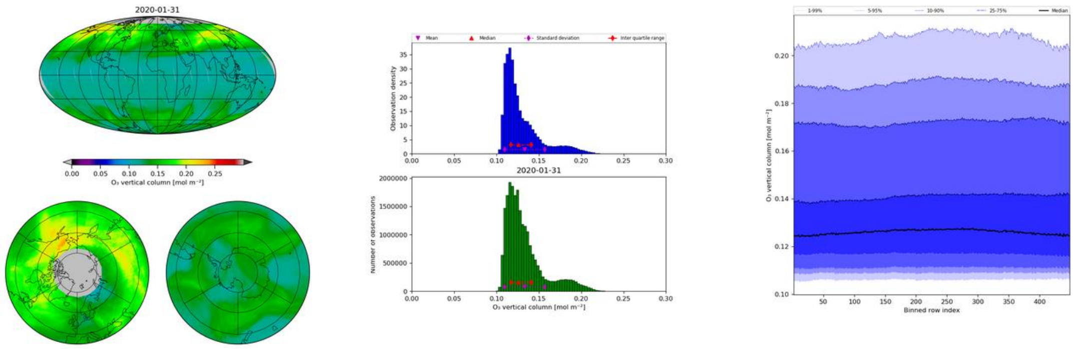
Ozone (O3)

[119] which has two output products of the O3 vertical profile:

- Complete O3
- Tropospheric O3

The recovery algorithm used by ESA is similar for both products and uses an Optimal Estimation Method (OEM) [120]. For the recovery of the complete O3 profile, the wavelength range used for the adaptation is 270 - 320 nm (spectral bands 1 and 2). The recovery of the tropospheric profile of O3 uses the wavelength range between 300 - 320 nm (spectral band 2).

Due to the difference in spatial sampling the O3 profile also differs in spatial resolution. The complete O3 profile has a spatial resolution of 21x28 km2 (ALT x ACT) spatial limit of the spectral band 1 (270-300 nm). The tropospheric profile O3, on the other hand, uses the spectral band 2 (300 - 320 nm) and has a maximum spatial resolution of 7x7 km2.



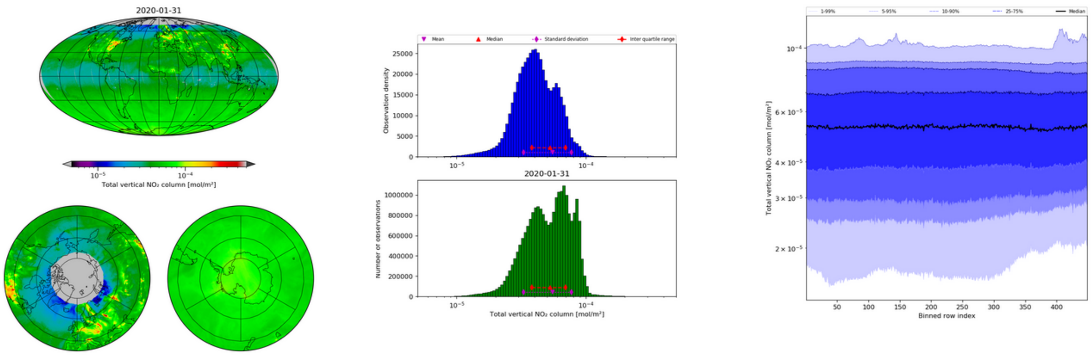
ozone_total_vertical_column_count	22402815
ozone_total_vertical_column_mean	0.1332729607820511
ozone_total_vertical_column_standard_deviation	0.02379138581454754
ozone_total_vertical_column_min	0.008746105246245861
ozone_total_vertical_column_max	1.38080632686615

19 Map of "O3 Sentinel 5P vertical column precision" for 2020-01-31

Nitrogen Dioxide (NO2)

[121] The TROPOMI NO2 recovery algorithm is based on the OMI NO2 recovery algorithm (called DOMINO) [122]. This algorithm is a three-phase DOAS[58]:

- Phase 1: inclined column
- Phase 2: Separate the total inclined column into stratospheric and tropospheric parts. The wavelength range used for NO2 recovery is 405 - 465 nm and uses spectral band 4. It is the same as the OMI tool (DOMINO algorithm).
- Phase 3: Vertical column translation



nitrogendioxide_total_column_count	22980850
nitrogendioxide_total_column_mean	5.506249362952076e-05
nitrogendioxide_total_column_standard_deviation	2.2243018975132145e-05
nitrogendioxide_total_column_min	2.1654361717082793e-06
nitrogendioxide_total_column_max	0.0024058776907622814

20 Map of "NO2 Sentinel 5P vertical column precision" for 2020-01-31

[58] For space borne applications the DOAS (Differential Optical Absorption Spectroscopy) method consists of two steps. The DOAS method is used to fit the differential absorption cross-sections to the measured sun-normalized Earth radiance spectrum, to obtain the slant column density. The slant column density is translated into the vertical column density using the air mass factor. This air mass factor can include a correction for cloud effects, in order to account for the trace gas amount obscured by clouds.

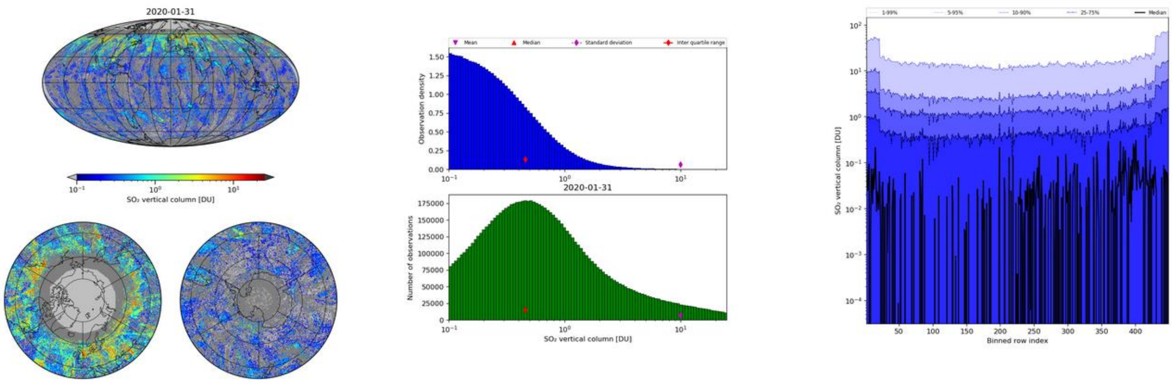
Data on nitrogen dioxide has been used in research to assess air quality and potential trends in industrial activity. Cars, trucks, power plants, and other industrial plants emit nitrogen dioxide (NO2) as a product of burning fossil fuels. Nitrogen dioxide can rapidly transform into ground level ozone, a major respiratory pollutant and one of the main ingredients of summer smog. Nitrogen dioxide levels drop when companies and factories close or when there are fewer vehicles on the road. This was visible in the Covid-19 lockdown period and at night when vehicular traffic decreases. The data is available on a daily time frame (one view per day, when clouds allow) from TROPOMI and OMI using Earthdata Search. Giovanni and Worldview can be used to explore and visualize the data.

Earthdata Search provides OMI NO2 data in daily cross-linked products (0.25 degrees latitude x 0.25 degrees longitude) and non-cross-linked products at native resolution (minimum pixel size of 13x24 km2). The data is in Hierarchical Data Format Release 5 (HDF5) and can be opened using the freely available NASA tool, Panoply. Data is generally provided with a 48 hour delay.

Sulphur dioxide (SO2)

[123] **:** Also this general method used the derivation of the density of the vertical column SO2 is the DOAS method. The SO2 columns are mainly derived from bands 2 and 3.

The bands between 312-326 nm are ideal for small column densities. Wavelengths of 325-335 nm allow recovery of moderate SO2 columns. Instead, between 360-390 nm they are more suitable for the recovery of extremely high SO2 columns.

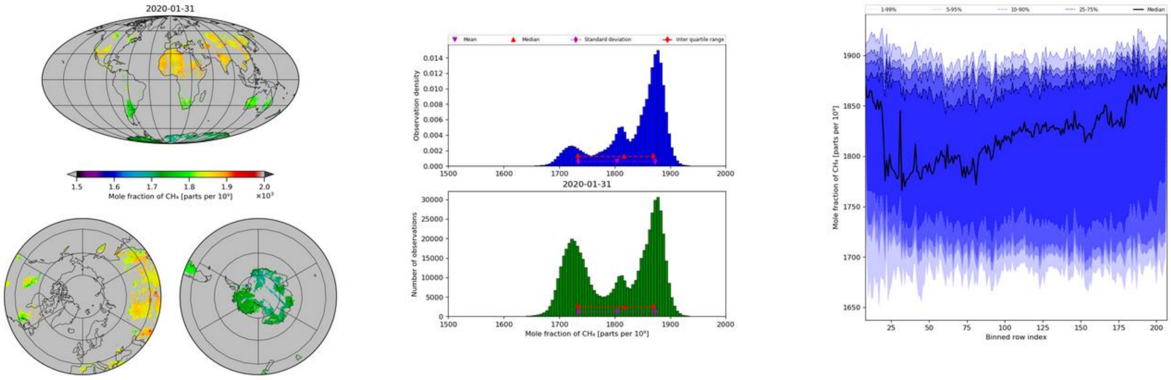


sulfurdioxide_total_vertical_column_count	21350267
sulfurdioxide_total_vertical_column_mean	-0.5654256730941453
sulfurdioxide_total_vertical_column_standard_deviation	10.603398193406363
sulfurdioxide_total_vertical_column_min	-961.9025675520302
sulfurdioxide_total_vertical_column_max	818.206319962442

21 Map of “SO2 Sentinel 5P vertical column precision” for 2020-01-31

Methane (CH4)

[124] The algorithm for recovering methane columns from the SENTINEL-5P instrument is based on previous developments of a CO^2 and CH4 recovery algorithm from Greenhouse Gases Observing Satellite GOSAT [125]. The algorithm retrieves the CH4 column of the aerosol quantity from the level 1B reflectance measurements in the SWIR band and also in the NIR band between 757-774 nm (O2 A-band). It also takes into account the adaptation parameters such as the surface albedo and its first order spectral dependence in the two bands and the total columns of carbon monoxide and water vapor respectively. The adaptation window is based on the O2-A bands 755-775 nm (spectral band 6) and 2324-2338 nm (spectral band 7).

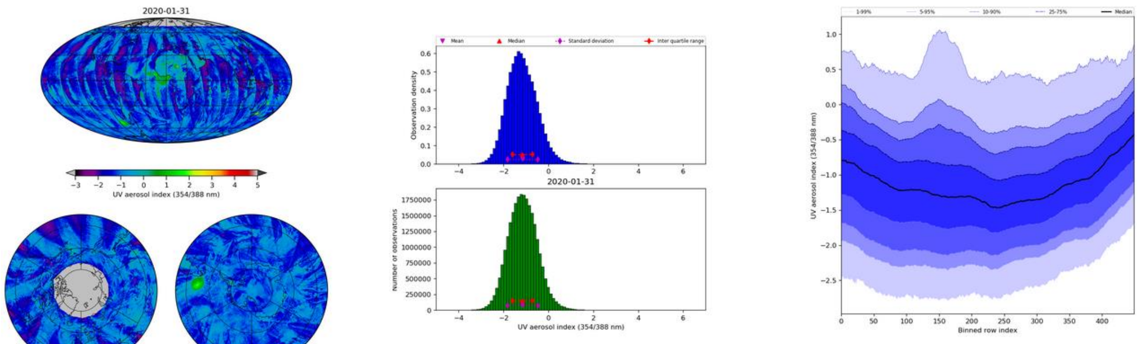


methane_mixing_ratio_count	584120
methane_mixing_ratio_mean	1803.84375
methane_mixing_ratio_standard_deviation	69.53557586669922
methane_mixing_ratio_min	1314.2337646484375
methane_mixing_ratio_max	2053.52197265625

22 Map of "CH4 Sentinel 5P vertical column precision" for 2020-01-31

Aerosol Index (AI)

[126] It is a qualitative index that indicates the presence of high aerosol layers with significant absorption. The relatively simple calculation of AI is based on wavelength changes in Rayleigh scattering in the UV spectral range where ozone absorption is very small. For a given pair of wavelengths, a ratio is calculated from the measured Top Of Atmosphere (TOA) reflectance and the calculated theoretical reflectance for a Rayleigh diffusion-only atmosphere and a residual value is obtained. Positive values of this residue indicate the presence of aerosol that absorbs UV rays.



aerosol_index_354_388_count	25432232
aerosol_index_354_388_mean	-1.1411616802215576
aerosol_index_354_388_standard_deviation	0.6713845729827881
aerosol_index_354_388_min	-9.763019561767578
aerosol_index_354_388_max	34.11167907714844

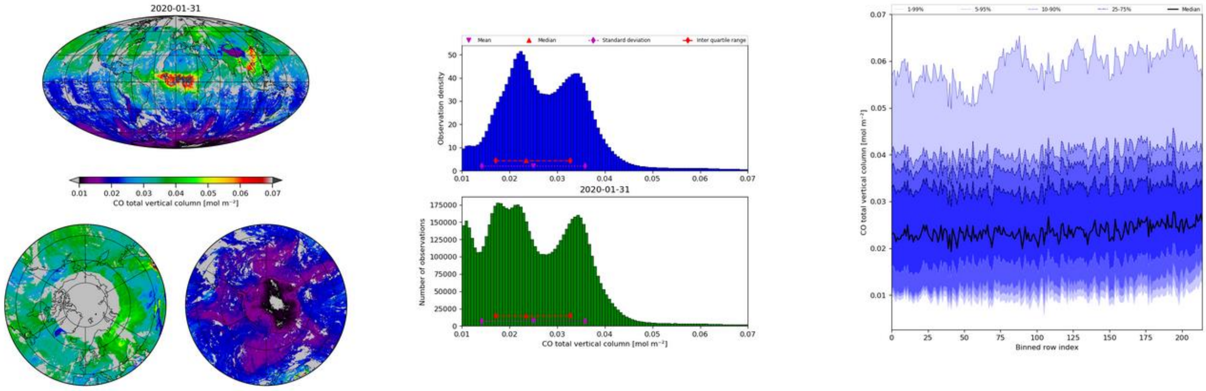
23 Map of "AI Sentinel 5P vertical column precision" for 2020-01-31

Carbon Monoxide (CO)

[127] The TROPOMI SWIR sensor measurements help us to define the CO column estimate. Recovery is done in two stages:

- As part of the SWIR preprocessing module, the vertically integrated amount of methane is recovered from the SWIR band between 2315 and 2324 nm using a non-diffusing radiative transfer pattern.
- The second uses a full physical recovery approach SICOR[59] is used to deduce the CO columns from the adjacent spectral window, 2324-2338 nm

[59] Shortwave Infrared Carbon Monoxide Retrieval (SICOR) algorithm for the processing of CO total columns from S5Pand S5 shortwave infrared measurements. Carbon monoxide total column retrievals from TROPOMI shortwave infrared measurements. Available from: https://www.researchgate.net/publication/309516357_Carbon_monoxide_total_column_retrievals_from_TROPOMI_shortwave_infrared_measurements [accessed Oct 01 2020].

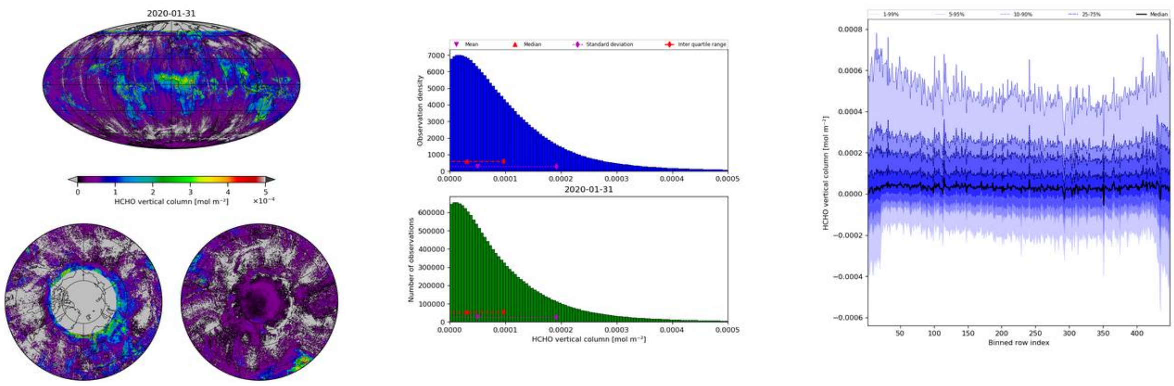


carbonmonoxide_total_column_count	7361843
carbonmonoxide_total_column_mean	0.025014515966176987
carbonmonoxide_total_column_standard_deviation	0.010830073617398739
carbonmonoxide_total_column_min	-3.21673846244812
carbonmonoxide_total_column_max	1.4277592897415161

24 Map of “CO Sentinel 5P vertical column precision” for 2020-01-31

The ESA processor also deals with di **Aerosol Layer Height** [128] and **Formaldehyde (HCHO)** [129] but will not consider it in this thesis.

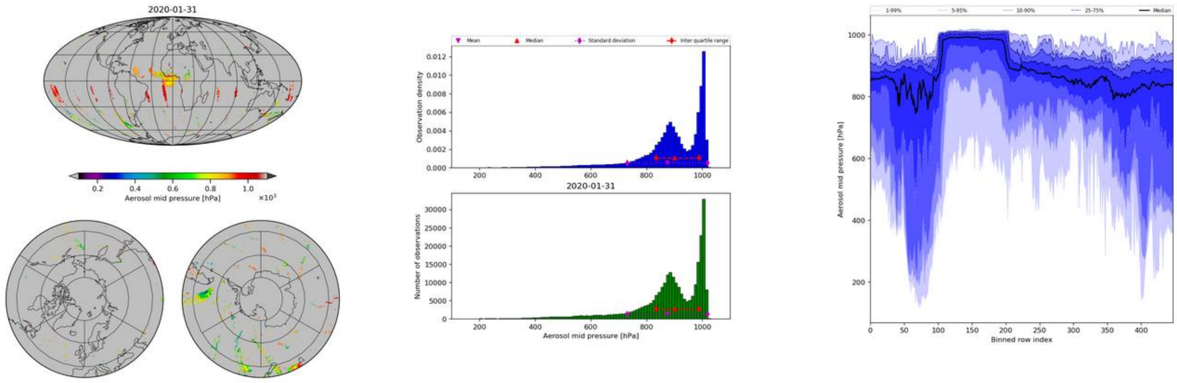
Formaldehyde (HCHO)



formaldehyde_tropospheric_vertical_column_count	24401478
formaldehyde_tropospheric_vertical_column_mean	5.018075171392411e-05
formaldehyde_tropospheric_vertical_column_standard_deviation	0.0001413890568073839
formaldehyde_tropospheric_vertical_column_min	-0.00606963038444519
formaldehyde_tropospheric_vertical_column_max	0.009351924993097782

25 Map of “HCHO Sentinel 5P vertical column precision” for 2020-01-31

Aerosol Layer Height (ALH)



aerosol_mid_pressure_count	271145
aerosol_mid_pressure_mean	874.3845845887862
aerosol_mid_pressure_standard_deviation	144.26271878161376
aerosol_mid_pressure_min	0.030943162441253662
aerosol_mid_pressure_max	1024.045

26 Map of “ALH Sentinel 5P vertical column precision” for 2020-01-31

Level 2 processed by ESA has been described but as mentioned in chapter 1 the search will be based on Level 3 of the data.

5.3.2 Integration of satellite data with in-situ data

Particulates, in addition to being produced by natural processes such as volcanic eruptions or the action of wind on the ground, can originate from industrial processes (construction sites, foundries, cement factories), from agricultural processes (sowing), from wear asphalt, tires, brakes (asbestos) and clutches, as well as vehicle exhaust. Suspended particles can cause irritation and allergies to the mucous membranes of humans and other animal organisms, but they can also act as condensation nuclei for gaseous air pollutants which are thus concentrated in the particulates. The largest particles (> 10 µm) are usually the least dangerous as they lodge in the nose and throat. Among the combustion residues, very dangerous for health are the ashes made up of heavy metal oxides, such as cadmium, copper, lead and vanadium. Many heavy metals, in fact, in addition to being able to penetrate directly into organisms through respiration, can also be assumed through food, due to the known ability to accumulate in the tissues of plants and animals. The presence of particulates in the air can also be responsible for phenomena such as the reduction of visibility and the acceleration of the formation of clouds, rain, snow (acting as condensation nuclei).

Not all of them are visible from satellite and it was worth identifying why and at what time of day they should be detected in the city. For this reason, ground control units are used. In this research I take data issued by the EEA. A map and forecast data are collected using federal references or equivalent monitoring techniques or techniques approved by national or local monitoring agencies. To keep the maps "in real time", the data are displayed after the end of each hour. Although preliminary data quality assessments are performed, the EEA data is not fully verified and validated through the quality assurance procedures that monitoring organizations used to officially submit and certify EPA Air Quality System (AQS) data.

This sharing and centralization of data creates a single source for real-time and forecast air quality data. Benefits include quality control, consistency of country reports, access to automated mapping methods, and distribution of data to the public and other data systems.

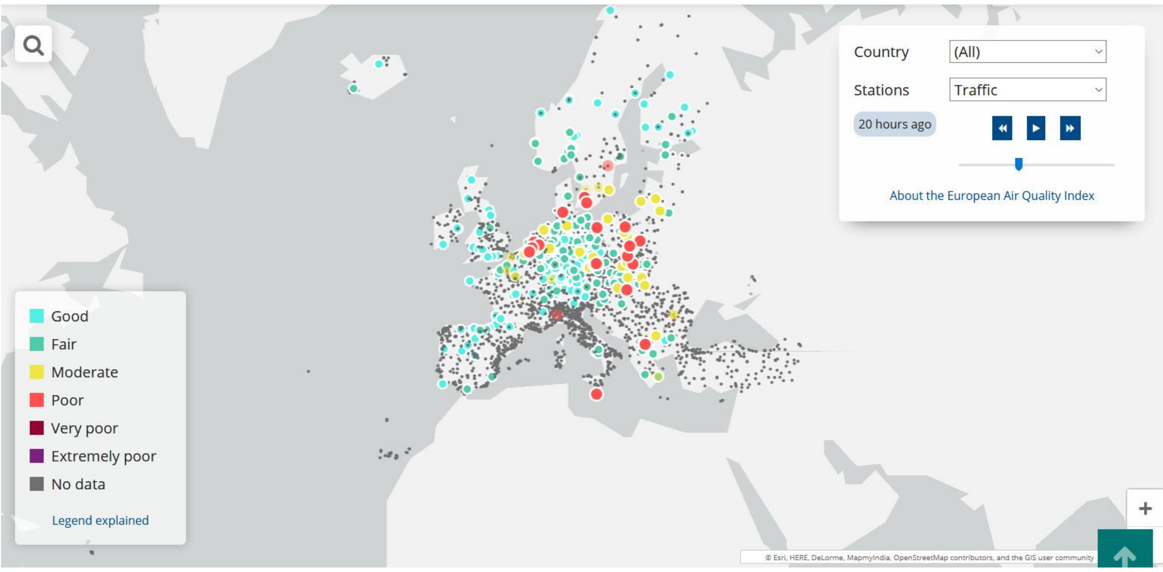
The control units produce an air quality index (AQI) is an index for reporting the daily air quality. It tells how clean or polluted the air is and what associated health effects may be of concern. AQI focuses on the health effects may be experience within hours or days of breathing in polluted air.

According to the criteria of the European Environment Agency (EEA), air quality measuring stations are classified according to the type of station and area and the characteristics of the area [130]:

- *Traffic (T) stations located in such a position that the level of pollution is mainly influenced by traffic emissions from neighbouring roads with medium-high traffic intensity;*
- *Background (or background, B) stations located in such a position that the level of pollution is not influenced mainly by specific sources (industries, traffic, residential heating, etc.) but by the integrated contribution of all the sources upwind of the station with respect to predominant wind directions at the site;*
- *Industrial (I) - stations located in such a position that the level of pollution is mainly influenced by individual industrial sources or by adjacent industrial areas;*
- *Urban (U) - fixed station inserted in a continuously or at least predominantly built area;*
- *Suburban (S) - fixed station inserted in a largely built-up area where there are both built-up and non-urbanized areas;*
- *Rural (R) - station inserted in non-urban and non-suburban contexts. If it is located more than 50 km away from the emission sources the station is defined as remote rural*

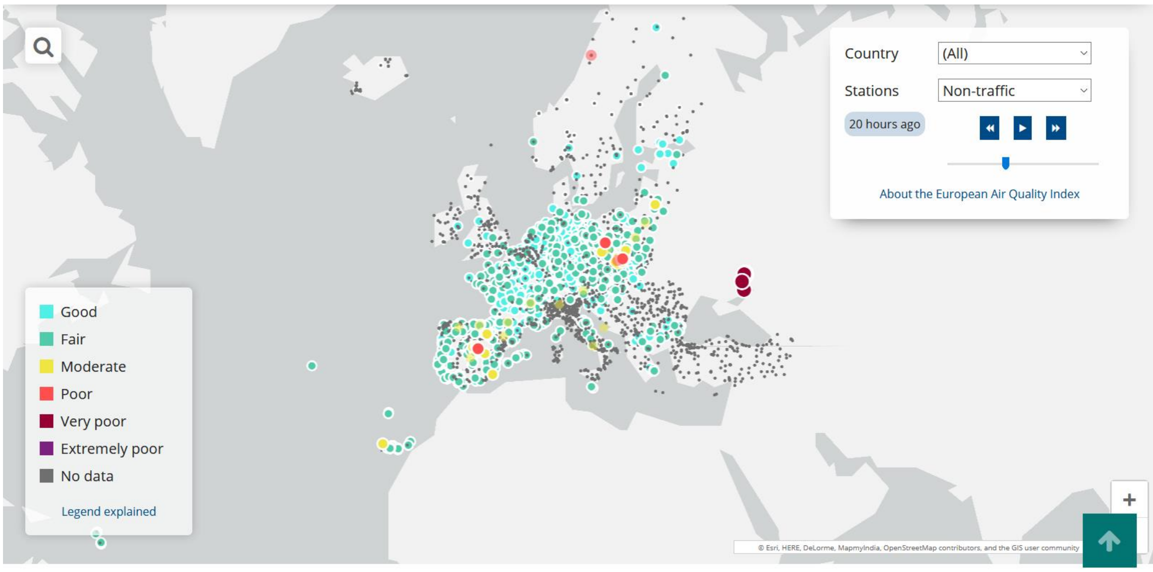
The stations are therefore classified through a combination of the characteristics listed above (for example TU station located in an urban area close to a traffic route; BS station not directly in proximity to a particular emission source, in a peripheral area of the agglomeration urban).

Control units TU



27 Atmospheric control unit that highlights motorway stations across Europe. The colours describe the state of pollution.

Control units B-S-R

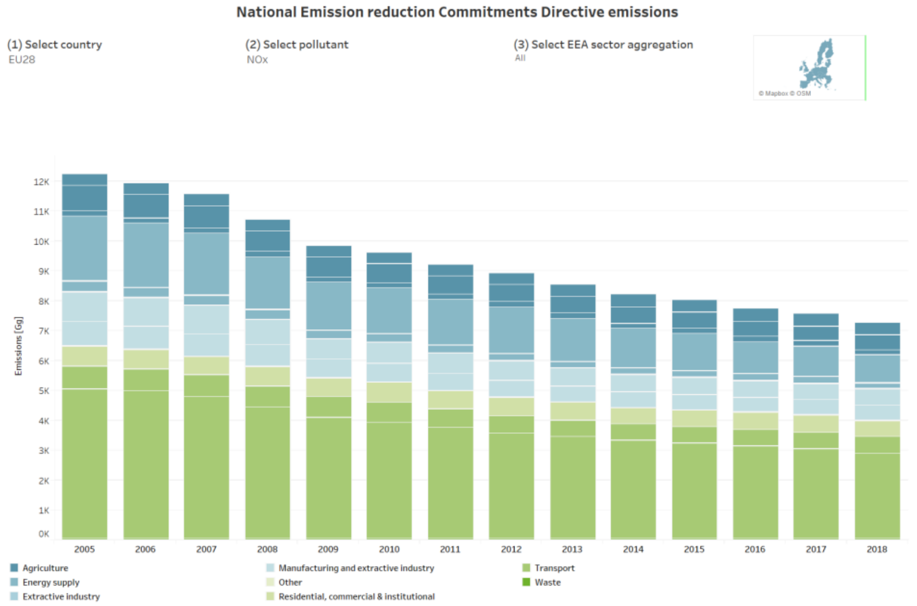


28 Atmospheric control unit that BSR stations across Europe. The colours describe the state of pollution.

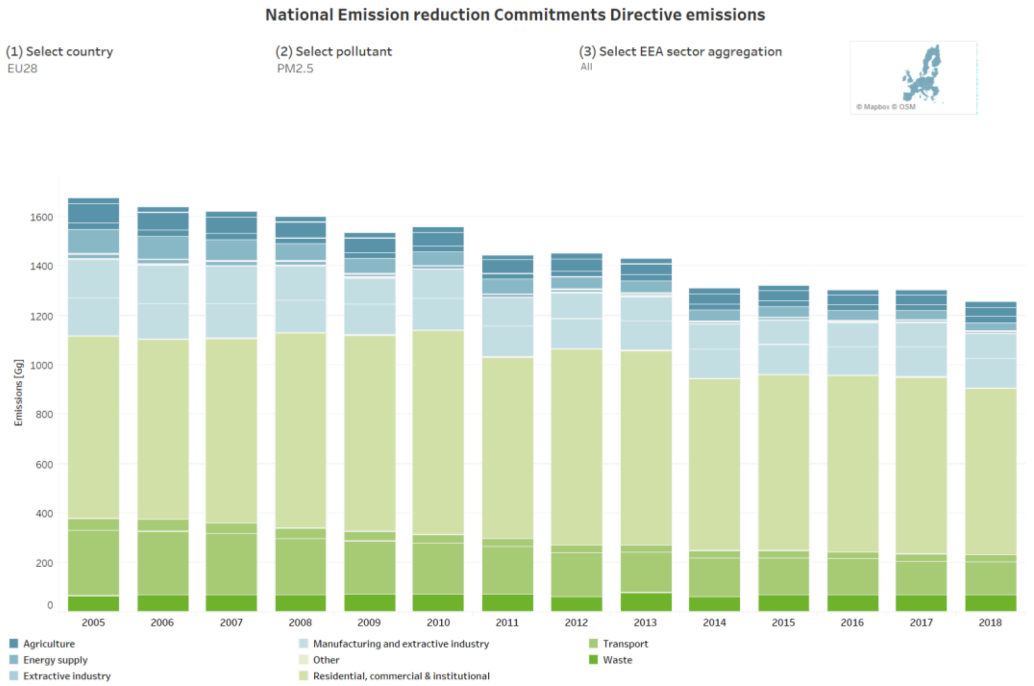
5.3.3 Auxiliary Data

5.3.3.1 Historical data

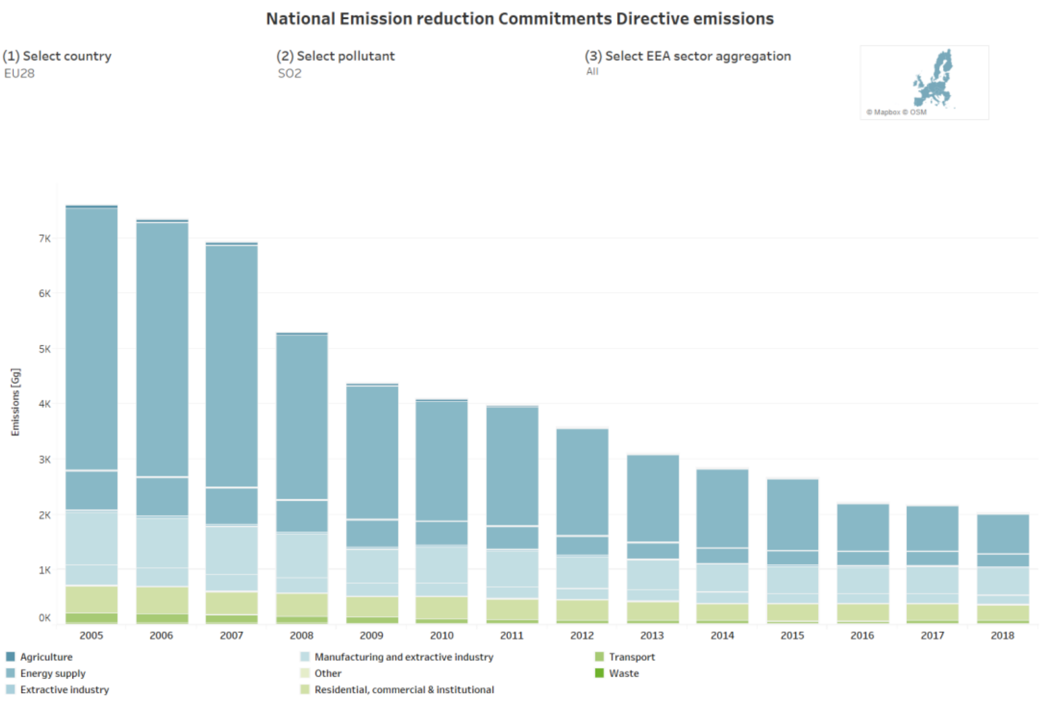
Historical data is obtained from the database of the European Environment Agency (EEA) which is responsible for documenting and evaluating the trend of pollution, the measures and policies applied to it. Data from the European Environment Agency shows that emissions in Europe have decreased substantially in recent decades, resulting in better air quality. However, the concentrations of pollutants are still too high and problems related to air quality persist. Historical data is entered within the methodology to better train the neural network. Thanks to historical data, the behavior of pollutants in certain conditions and areas can be predicted in greater detail. The graphs of the EEA [131] demonstrate this:



29 NOx Reduction of European indexed emissions **[131]**



30 PM2.5 Reduction of European indexed emissions **[131]**



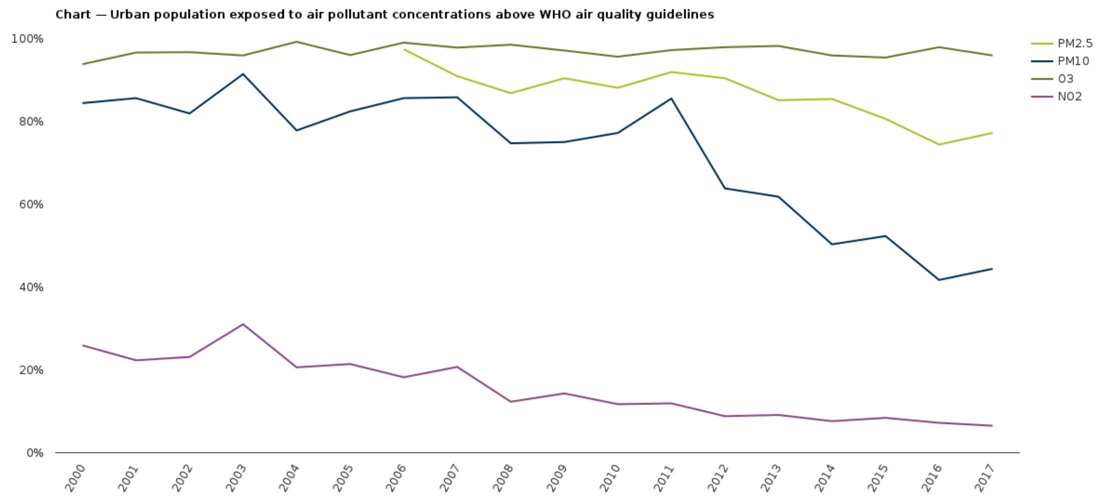
31 National emissions reduced after the directives applied since 2005 **[131]**

Population

There are also a number of data comparing population to air pollution.This map compares the relationship between the average annual air quality data of particulate matter 2.5 (PM 2.5) for the United States between 1998 and 2016 with the percentage of the population minority. Population data is from Esri's updated demographics, and air quality data is from NASA SEDAC grid data aggregated to states, counties, convention districts, and 50km hex containers.

The exposed population:

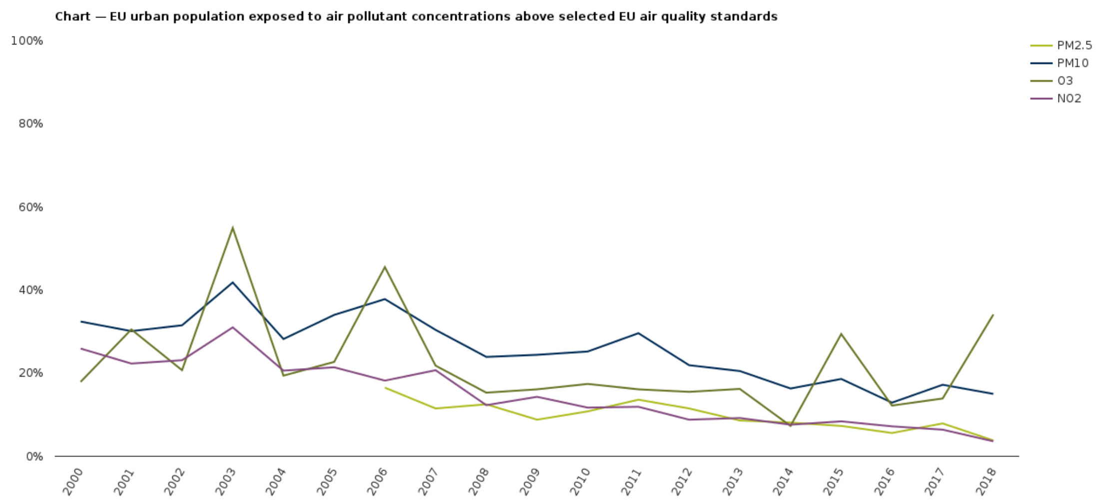
- PM2.5 - population exposed to annual concentrations higher than 10 µg / m3;
- PM10 - population exposed to annual concentrations greater than 20 µg / m3; O3
- population exposed to average maximum daily concentrations over 8 hours above 100 µg / m3 for at least 1 day per year; NO2 - population exposed to annual concentrations above 40 µg / m3



32 [136]

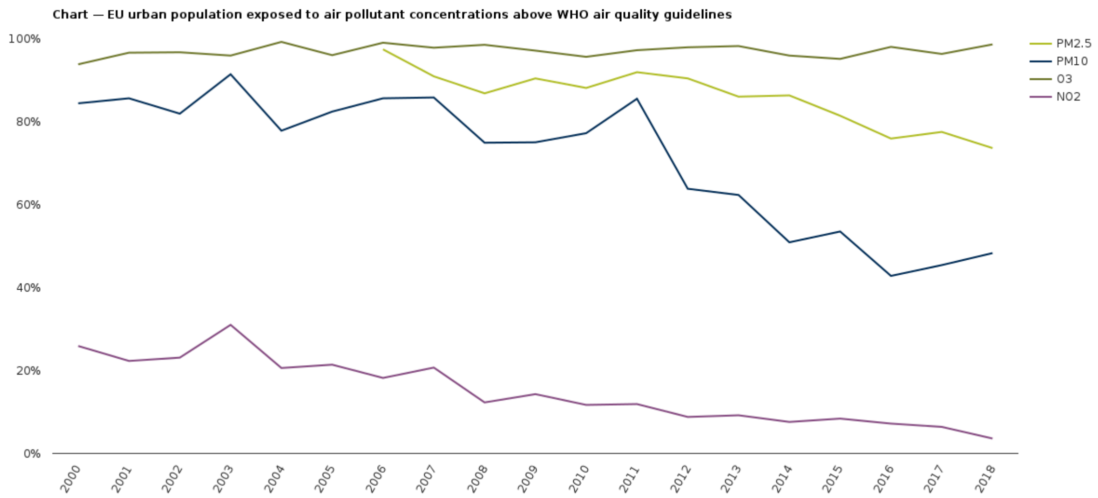
In the second graph, the criteria for each pollutant are: PM2.5 - population exposed to concentrations higher than 25 µg / m3; PM10 - population exposed to daily concentrations above 50 µg / m3 for more than 35 days a year; O3 - population exposed to average maximum daily concentrations over 8 hours above 120 µg / m3 for more than 25 days a year; NO_2 - population exposed to annual concentrations above 40 µg / m3. These criteria are based on the limit values (for PM and NO_2) and target values (for O3) set out in the Air Quality

Directive.



33 **[131]**

PM2.5, particulate matter with a diameter of less than 2.5 µm; PM10, particulate matter with a diameter of less than 10 µm; O3, ground level ozone and NO2, nitrogen dioxide.



34 **[131]**

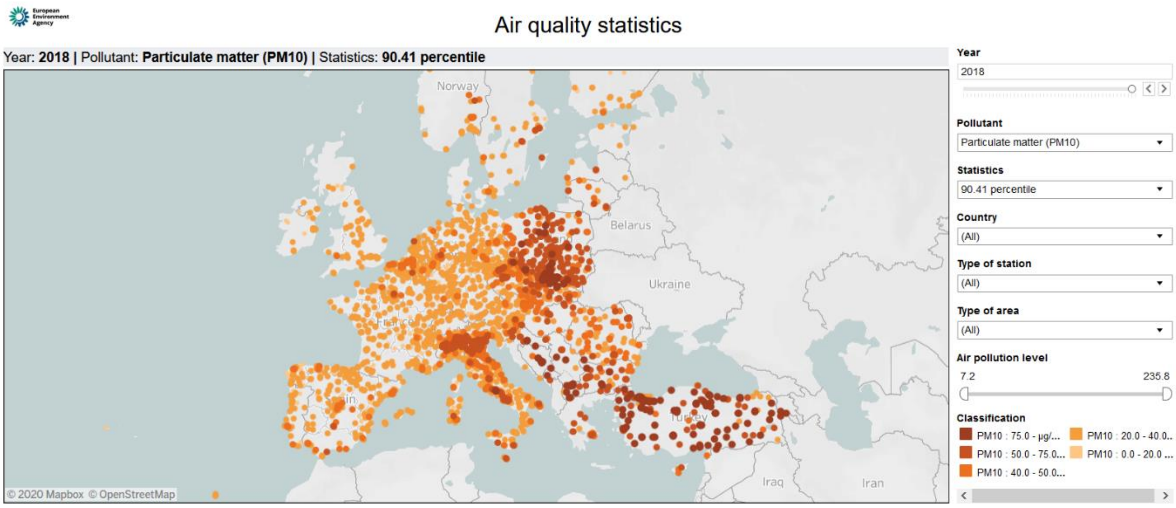
The rationale for the selection of pollutants and the corresponding WHO guidelines are provided in the specification section of the indicator CSI 004.

Criteria:

- Population exposed to annual concentrations of PM2.5 above 10 µg / m3.
- Population exposed to annual concentrations of PM10 above 20 µg / m3.
- Population exposed to 8-hour average maximum daily O3 concentrations above 100 µg / m3 for at least one day per year.
- Population exposed to annual NO2 concentrations above 40 µg / m3.

Statistical Studies

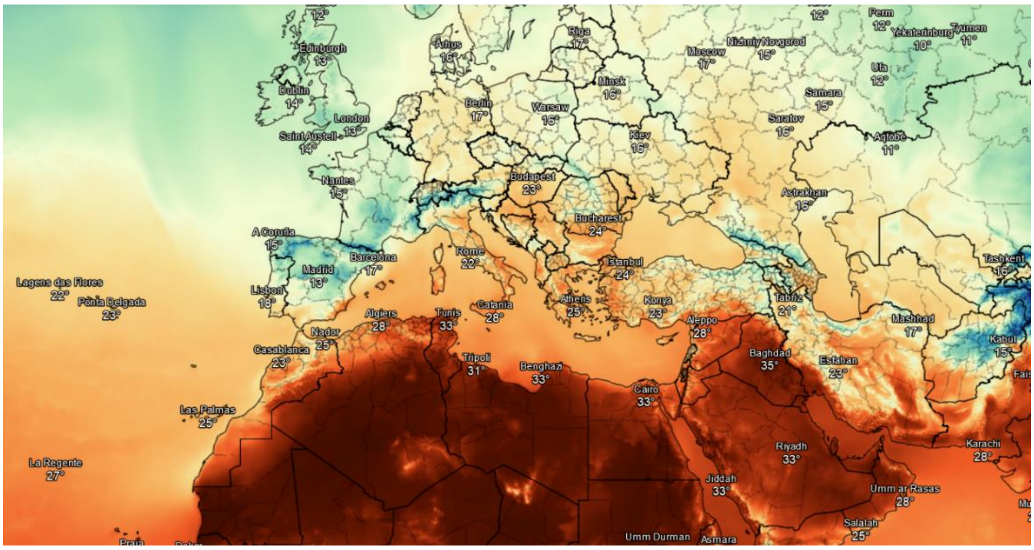
In addition to air quality monitoring studies, there are several short-term studies incorporated into EEA planning. Research studies also focused on environmental management, legal framework and environmental monitoring. The online information from the monitoring stations was designed to be massively disseminated to the public. All studies include a complete analysis of air pollution, including the development of the emissions inventory, modelling the dispersion of current and future emission scenarios up to 2020 and the analysis of the health impact of the scenarios. The highest concentrations in the data represent the areas with the highest industrial density. An example of the PM_{10} study provided by EEA is shown below.



35 Key air quality statistics for the main air pollutants © EEA

5.3.3.2 Meteorological data

The collection and quality of meteorological data (temperature and relative humidity) do not pose particular problems within the study. The comparability and reliability of these data, for which long historical series and valid and standardized international measurement and collection procedures are available, is good. In addition, the Dark Sky [132] service was used which provides weather information via the open source API. From the APIs it is possible to find information on past observations, current weather conditions and even weather forecasts.

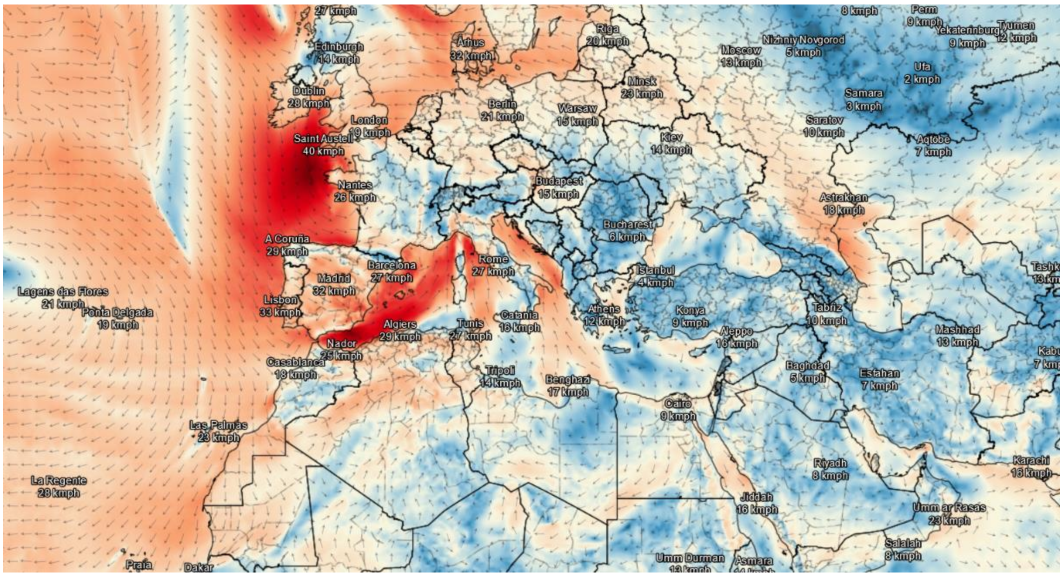


36 Real-time temperature maps of all European countries **[132]**

The Dark Sky API is based on information gathered from a wide range of sources. Some of them are [133]:

- Canadian Meteorological Center and US NCEP, provides global coverage;

- "gfs": US NOAA forecasting system, with global coverage;
- German Meteorological Office, which also provides global coverage;
- Integrated Surface Database NOAA.

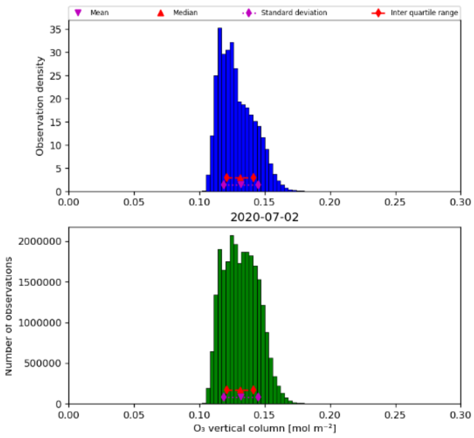


37 Wind and Precipitation Maps in real time of all European countries **[133]**

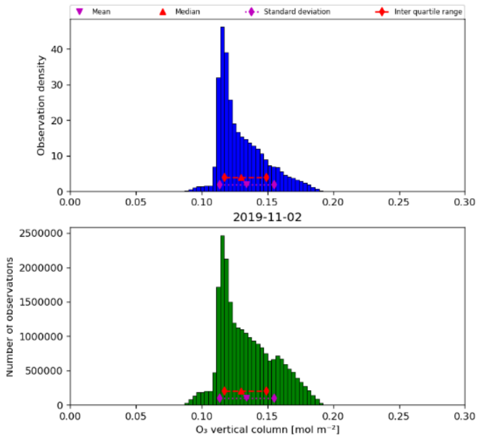
5.3.3.3 Graphic Analysis

I will now move on to graphically analyse the variables listed above. Based on these graphs I will be able to understand which the components are most present in the air and which, therefore, could influence the number of short-term deaths.

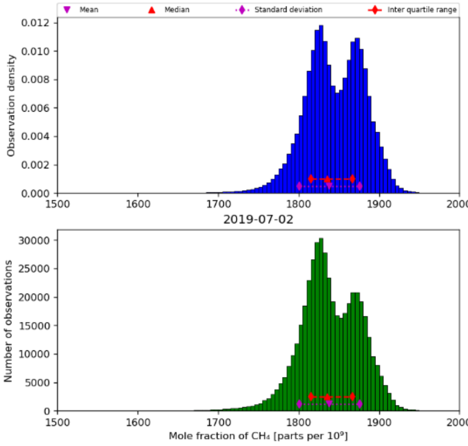
Frequency histograms



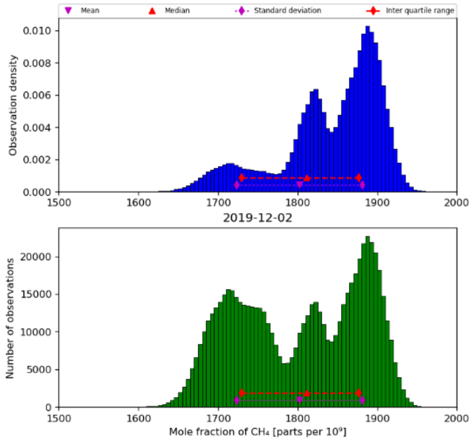
39 Summer histogram O3



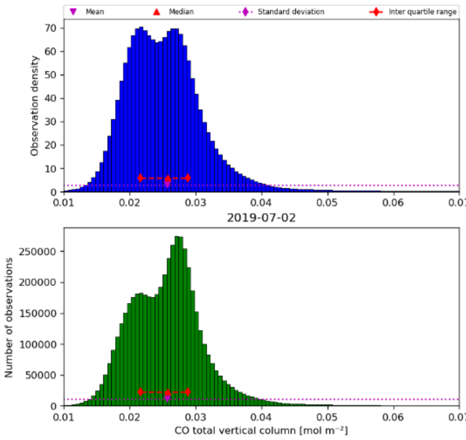
38 Winter histogram O3



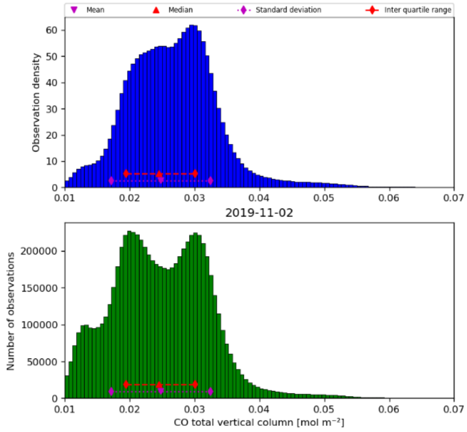
40 Summer histogram CH4



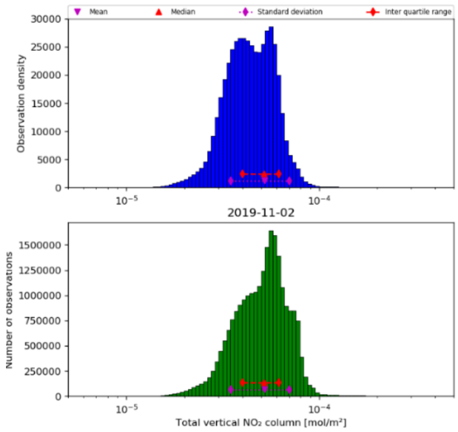
41 Winter histogram CH4



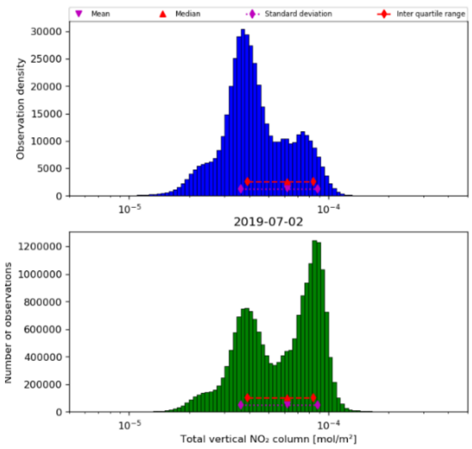
42 Summer histogram CO



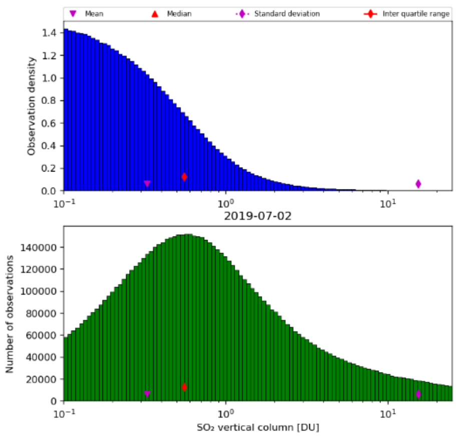
43 Winter histogram CO

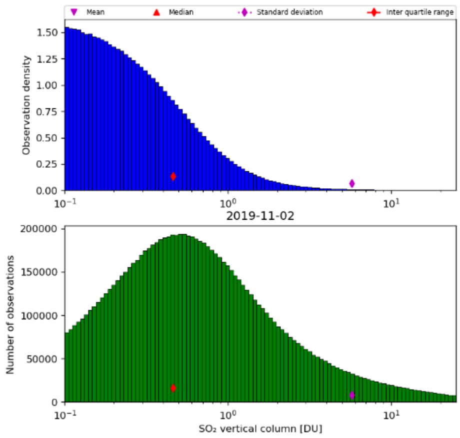


44 Sammer histogram NO2



45 Winter histogram NO2





46 Sammer histogram SO2

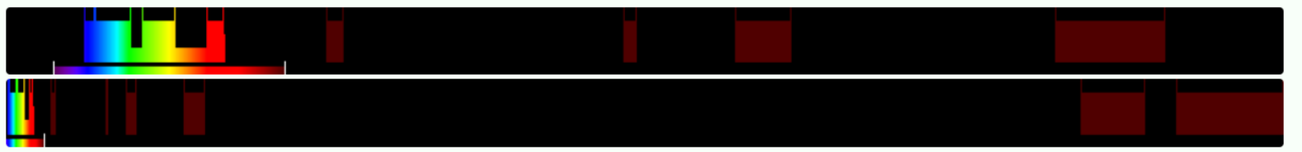
47 Winter histogram SO2

From the Graphs it can be seen that most pollutants have a higher frequency for low values, while O3 and CH4 follow an asymmetric distribution in the summer period.

5.3.3.4 Land surface

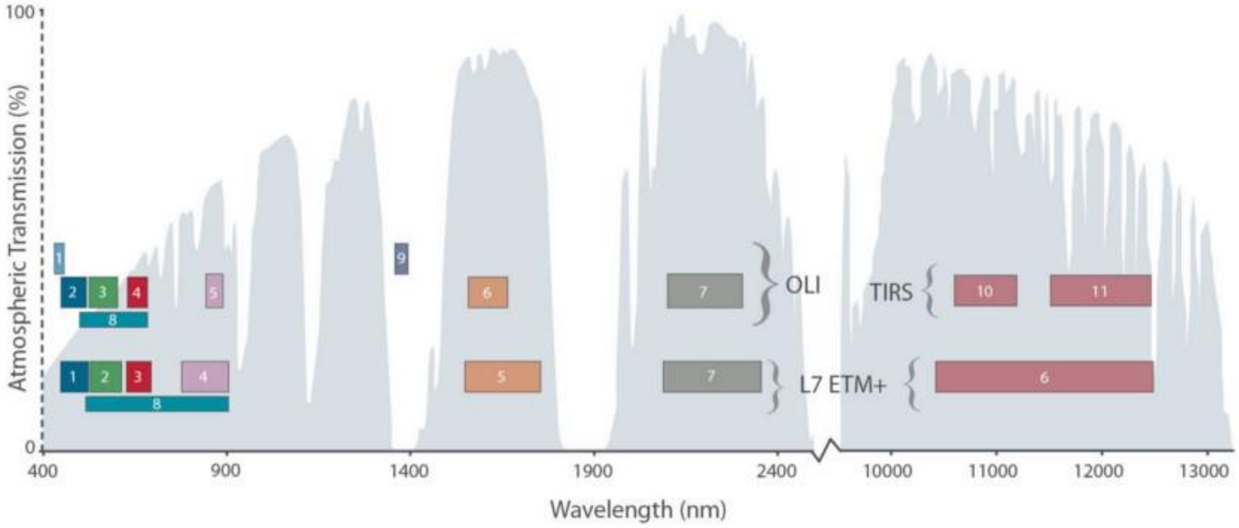
Temperature

The Earth's surface temperature (LST) is an important variable within the Earth's climate and atmospheric system. It describes processes such as the exchange of energy and water between the earth's surface and the atmosphere and affects the speed and timing of plant growth. LST is also very useful for keeping the problem of heat islands in the city under control. Accurate understanding of LST at the global and regional levels helps to evaluate the Earth's surface-atmosphere exchange processes in models and, when combined with other physical properties such as vegetation and soil moisture, provides a valuable metric of the surface status.



48 LST spectrum ©Index database

LST is derived from Band 1 of the Landsat-8 satellite. Below you can look at the spectral band of the Landsat-8 satellite.



49 Comparison between ETM + and OLI + TIRS sensor bands ©USGS

Sentinel-2 satellites
Mainly sentinel-2 data were used to calculate the vegetation resistant to atmosphere index (ARVI, NDVI, SOC and TOC) The ARVI index is a vegetation-based index that minimizes the effects of atmospheric dispersion due to aerosols such as rain, fog, dust, smoke or air pollution. To use this index, your images must have bands that collect data at wavelengths between 650nm and 865nm. ARVI has been useful in all regions with a high atmospheric aerosol content.

50 ARVI spectrum ©Index database

The Normalized Difference Vegetation Index (NDVI) is a graphical indicator which has had the task of locating urban green areas. The index exploits the different response of the vegetation cover to the spectral bands of the visible (red) and the near infrared, and provides a dimensionless numerical value, theoretically between -1 and +1. This value has been shown to be closely related to the health of the vegetation, understood as biomass and leaf area (Leaf Area Index), and to the biochemical processes related to it (photosynthetic activity).

51 NDVI spectrum ©Index database

SOC (Soil organic Carbon) and Total Organic Carbon had the task of monitoring and controlling the sequestered organic carbon by satellite. The only limitation was the pixel resolution of the Satellite Sentinel 2 10mX10m. Sentinel-2 together with Landsat-8, being optical satellites, helped to monitor cities every day with a frequency of 6 days.

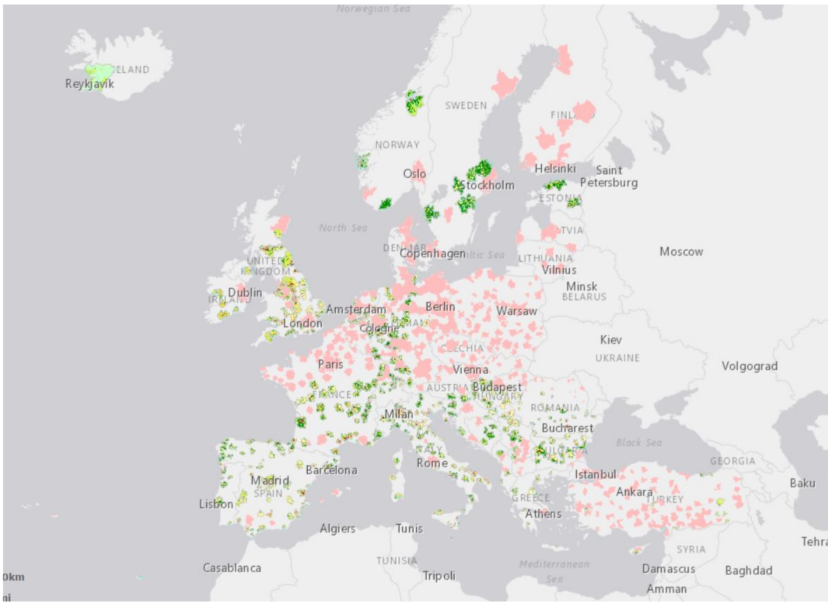
5.3.3.5 Buildings

For the delimitation of urban areas, the 2018 Urban Atlas was used, created with Copernicus data and updated every 6 years. The complete dataset, completed, covers 27 European countries + EFTA countries + Western Balkans + Turkey + UK. It currently consists of 438 Functional Urban Areas (FUAs).

The products are:

- The 2018 edition of Urban Atlas' Land Cover / Land Use product [60].
- The 2012-2018 modification product and The revised 2012 edition of Urban Atlas
- Street Tree Layer (STL)

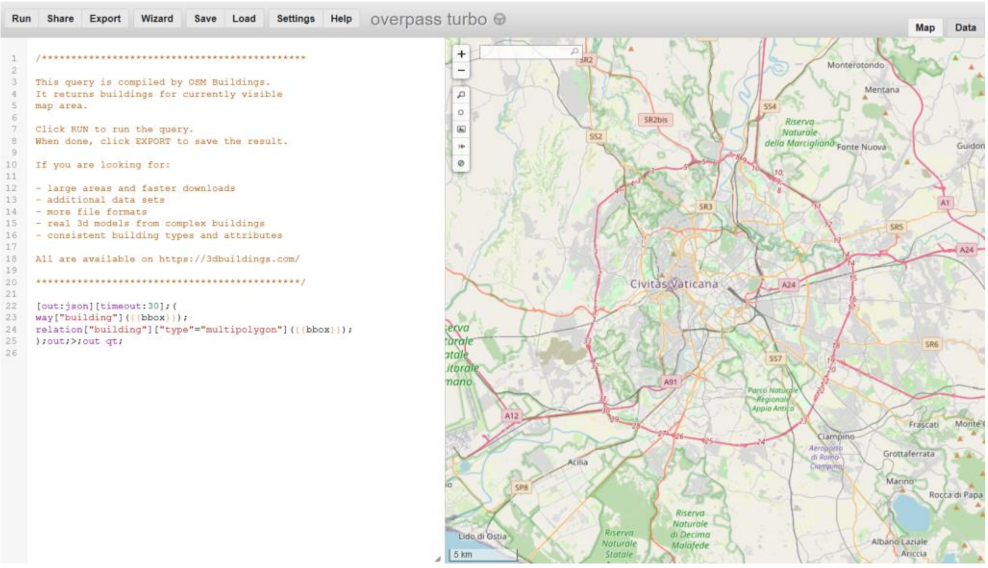
The Land Cover / Land Use product nomenclature includes 17 urban classes with MMU 0.25 ha and 10 rural classes with MMU 1ha. The population estimates for each polygon in the 2018 Urban Atlas dataset were produced by the JRC in collaboration with DG Regio.



52 Shapefile European land use file from the European Copernicus database **[134]**

[60] The Metadata tab in the product pages provides the key meta information (aligned with INSPIRE) about the product. Complete and INSPIRE compliant metadata of the core Copernicus land products are stored in the metadata catalogue of the European Environment Agency. This catalogue is INSPIRE enabled discovery service compliant with Open Geospatial Consortium (OGC) Catalogue Services Web (CSW) 2.0.2 and its facilities are provided through GeoNetwork, an open source metadata catalogue service. Copernicus Land Monitoring Service supports a virtual endpoint of this service.

In addition to the delimitation of the area, I have deepened the study by integrating the OSM[61] building bees to classify and georeferenced all the buildings, their shape, position and use.



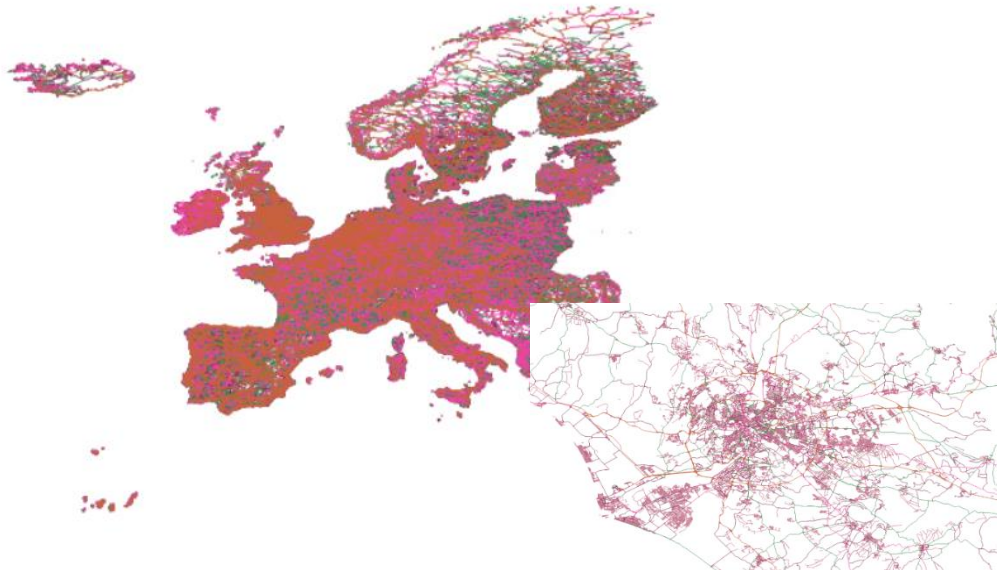
53 Built OSM Cartography

5.3.3.6 API

Among the most used auxiliary data are data concerning the geographical coverage of Bing Maps and Google, in particular the traffic API. Both platforms contain different levels of geographic coverage for each country / region of the world. The APIs contain as metadata:

- Road data/Routes (driving and walking). This type of data has detailed road data available in the most populated centres and most of these have been checked for accuracy. Coverage is updated frequently. In remote areas some road information may be missing. The data are useful for our project to identify fragile areas of the city and to advise PAs on how to possibly improve mobility in terms of atmospheric pollution.

[61] It is possible to download map data from the OpenStreetMap dataset in a number of ways. The full dataset is available from the OpenStreetMap website download area. It is also possible to select smaller areas to download. Data normally comes in the form of XML formatted .osm files. If you just want to use a "map" (e.g. for a GPS device) then you likely do not want to download this raw data, instead see other OSM download options. Some things to consider: The entire planet is a huge amount of data. Start with a regional extract to make sure your setup works properly. Common tools like Osmosis or various import tools for database imports and converters take hours or days to import data, depending largely on disk speed. OpenStreetMap is a federative project. That means that a lot of essential resources are provided by third party providers. Be bold, try to download there first. The official servers aren't huge data centres and don't have ample resources. They are rather dedicated to keep the data flow in sync.

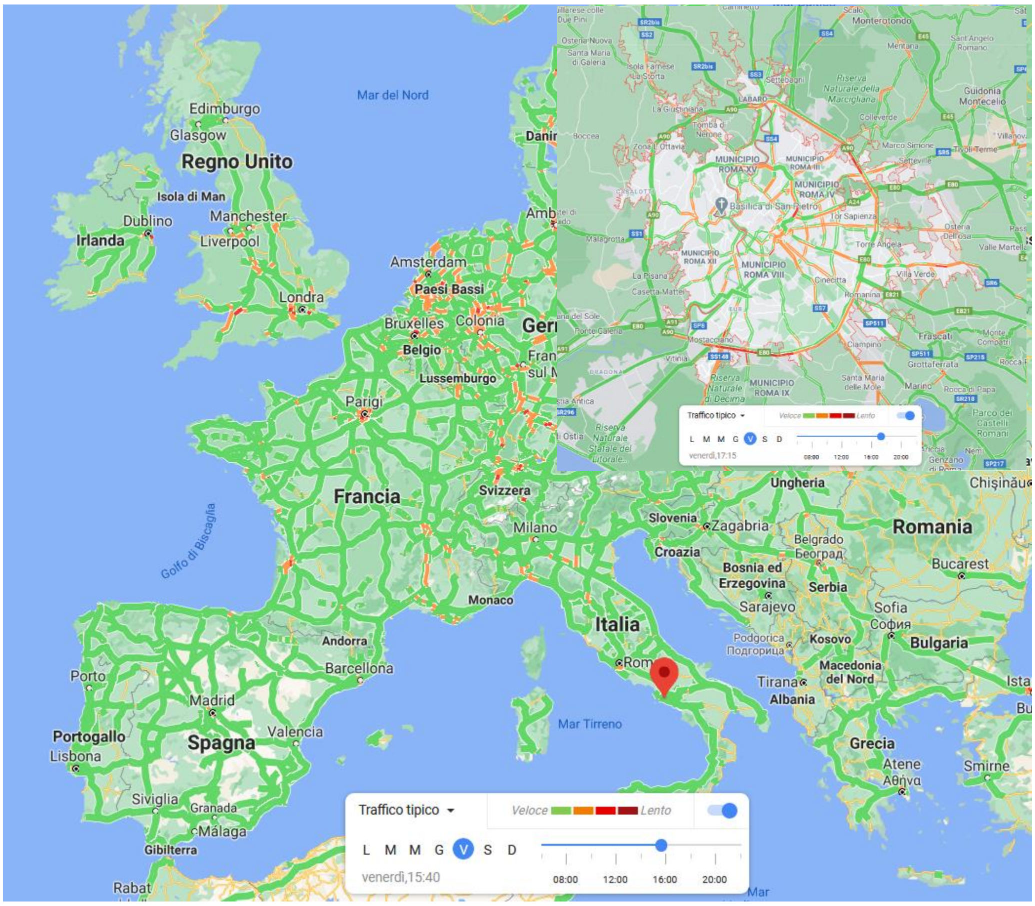


54 Shapefile European buildings with detail of the city of Rome

- The road maps made it possible to map the pollutants emitted by the cars and the air quality. The polluting fumes do not have a limited impact on those who are in the immediate vicinity of the motorway perimeter, but can extend for hundreds of kilometres and affect distant communities. The analyses can be done both starting from the motorways and starting from the fumes detected by satellite. Both help us to define the origin with certainty.

55 Intersection of roads, traffic and buildings show the impact of air pollution in the city

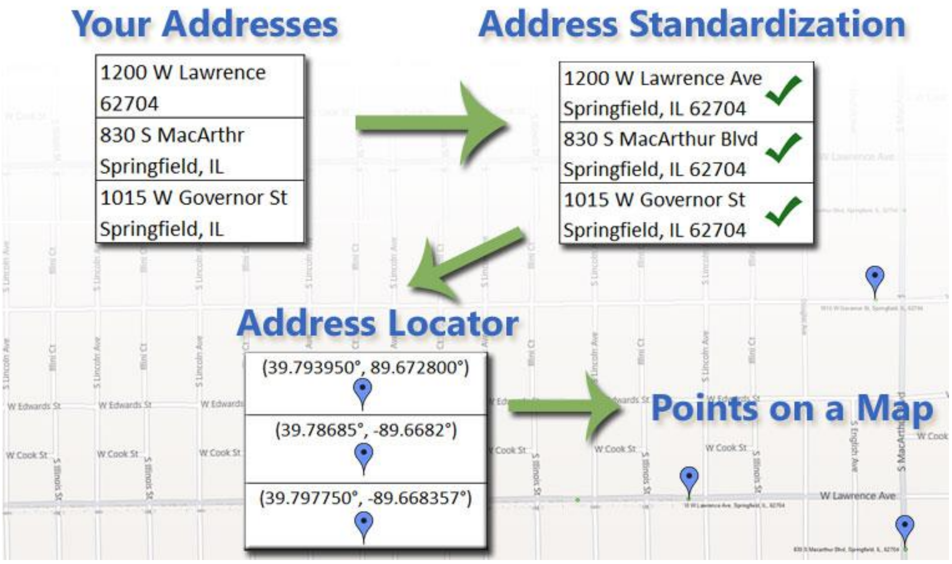
- Traffic: APIs provide traffic coverage for all of Europe. Traffic flow can be illustrated by coloured lines representing different levels of traffic congestion displayed on a map. The traffic flow can also be used by the routing APIs. In this work it is used to locate the major pollutants in the city. Furthermore, a time check is made with the traffic control units presented previously.



56 Road chart with traffic Api provided by google maps. Rome detail top left

- In addition to attributes on the road axes and on the cars that drive them. The data from these large search engines can help us locate truck routes. Having the dimensions of the tracks and using the API Truck Routing it is possible to provide routes that can be travelled by trucks such as dimensions, weight and type of load. This is important as not all trucks can travel the same routes as other vehicles. And it allows us in a large city to locate industrial areas and their atmospheric effects on neighbourhoods.

- The last metadata used is Geocoding. More than metadata, it can be defined as a technology that allows to locate most addresses in the latitude / longitude coordinate at the centre of the batch of addresses (property border). It is very useful for locating public and industrial buildings on maps.

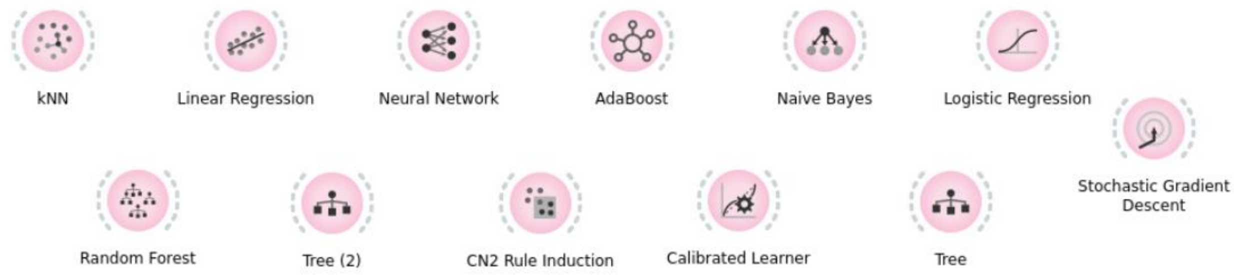


57 Graph showing how geocoding works **[135]**

5.3.4 Data Correction and processing model

The previous paragraphs explained how and what data to use to carry out a study on air quality and create models that allow to make predictions on the concentration of pollutants in the atmosphere. Sentinel-5P offers a wide range of products that characterize the atmospheric composition, but I have also understood that it is crucial to consider the possibility of enriching the entire data set by adding additional features. To do this, it was necessary to deepen the study of pollution to understand what factors could be correlated with its manifestation and its variations. The difference between the sources has imposed the correlation between the meteorological and historical information on pollutants. One year, from January 2019 / January 2020, this was considered as the reference period. Sentinel acquisitions have different granularities depending on the product considered. Acquisitions of pollutants such as NO2, SO2 and HCHO can be represented with patches of size 3.5x7 Km2; other pollutants such as CO and O3 with patches of 7x7 Km2. Machine Learning is used to solve correlation problems between sources. Machine learning is a branch of computer science in close connection with artificial intelligence, based on the assumption that, through data, machines can acquire knowledge by identifying models independently. In fact, ML was born from the theory that a computer can learn through the recognition of a considerable amount of data. Machine learning could be defined as the set of mechanisms that allow an intelligent machine to improve its capabilities and performance over time. The code learns to perform certain tasks by improving.

Furthermore, the prediction of air quality is a complex task due to the dynamic nature, volatility and high variability over time and space of pollutants and particulates. At the same time, the technologies available are able to model, predict and monitor air quality, especially in urban areas. There are many methods of machine learning.



58 Image with the major Machine Learning models

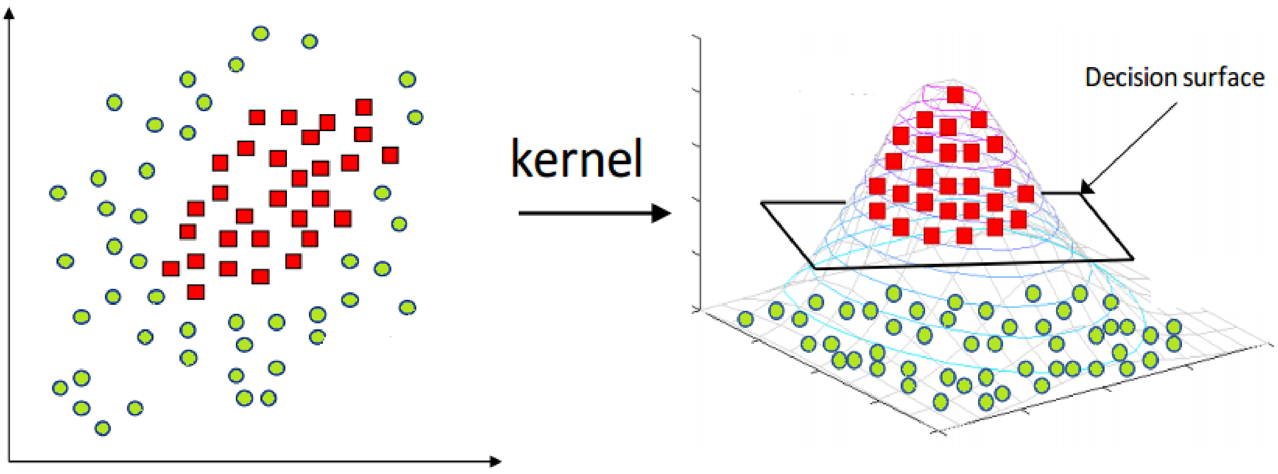
Among the automatic learning models used to study air pollution, certainly the most popular is the one that supports vector regression (SVR), to predict the levels of pollutants and particulate matter and to predict the air quality index (AQI). Among the various alternatives, the radial basis function (RBF) is also possible, the type of kernel that allowed SVR to obtain the most accurate predictions.

There are a number of published contributions that exploit the use of support vector machines (SVMs) to predict time series, and several authors have applied SVM to generate models to predict air quality and pollutant level. The first study is from 1997 [136] and it proposed a variant of SVM, to be applied in regression problems, called support vector regression (SVR), which may be particularly appropriate for this type of activity. In the same year, Müller [137] conducted another study in which SVR was compared with ANNs. The authors concluded that overall SVR performance was better. Only in 2003 Cao [138] presented a hybrid approach to time series prediction, combining ANN to partition the input space and SVM to model each portioned region. Results showed that this hybrid approach achieves high prediction performance and enables efficient learning for pollutants. Finally Wang [139] in 2009 it used SVMs to predict daily air pollutants in the city of Macau.

Regarding the forecasts of air quality in time series, a study was presented in 2005 [140] which applied SVMs to predict air quality in central Hong Kong. The results showed that the SVM model offers more promising results than other ML approaches. In 2012 Vong [141] developed a model to predict air pollution levels in Macau using SVM. In this approach as in those of Sotomayor-Olmedo [142] the authors concluded that SVMs provided flexibility and scalability to predict air quality when applied to dynamic and nonlinear data.

Support Vector Regression

Support Vector Machines (SVMs) were introduced in the 1990s [143], for classification problems. The goal was to find the optimal separation hyperplane between classes. The points that lie on the boundaries of the classes are called support vectors and the space in between is called a hyperplane; when a linear separator is unable to find a solution, the data points are projected into a higher dimensional space, where the previous non-linearly separable points become linearly separable, using the kernel functions.



59 Kernel **[144]**

Kernel is widely used in the Support Vector Machines (SVM) model to link linearity and non-linearity. It converts the nonlinear lower dimensional space to a higher dimensional space, so we can get a linear classification. So, I am projecting the data with some extra features so it can convert to a higher dimensional space.

Suppose that if wanted to classify polluted air particles in red and points of non-polluted area in green and it is impossible to differentiate them because it is in non-linear form (even in the real world the data is scattered and it is impossible to separate them). So, I can use a decision surface where it can rank both green points and red squares. Kernel uses only the original feature space because as the size space increases it becomes more and more complex to classify.

Steps involved in SVM:

• Collects data and tracks it accordingly

• Apply the kernel trick

• Learns the linear line that classifies the data

• Projects support data

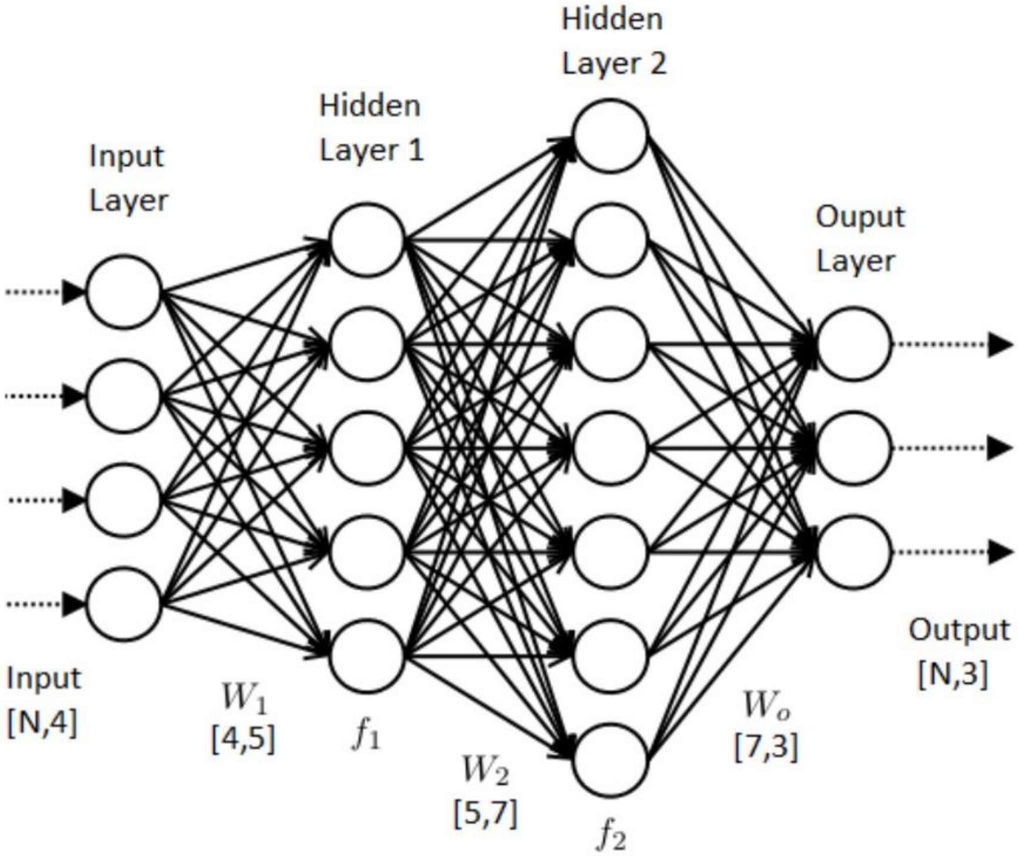
Finally, the Kernel converts the nonlinear classification into a linear classification by moving the space of the lower dimensions to a higher dimensional space. There is a lot of math involved in Kernel to learn the linear line that classifies data. Mercer's theorem helps convert nonlinear data points into a higher dimensional space.

Neural Networks

Neural networks are complex models made up of interconnected neurons. The first works date back to the Eighties and take inspiration from a human brain composed of neurons (elementary units) and synapses (connections between units). The neuron is the basic element of neural networks. The neuron is a non-linear model.

For its functioning it needs:

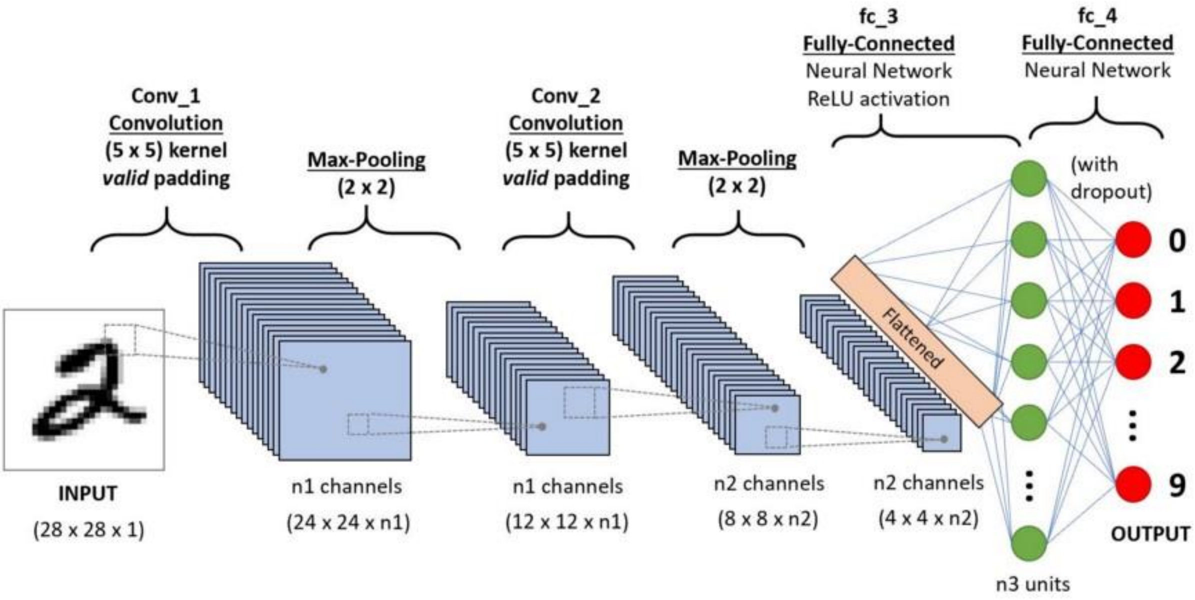
• Of an input vector
• The input data of a weight vector are multiplied with the weight vector;
• A bias value, offset that allows you to change the action potential of the input;
• Of an activation function (eg: step function, sinusoidal function).



60 Artificial Neural Network ©VIASAT

Neural Network CNN

Convolutional neural networks, or ConvNet CNN are a deep learning algorithm. Later I will explain in detail the meaning of Deep learning. They are especially used in the field of computer vision. The structure of convolutional neural networks respects that of generic neural networks, the difference lies in the fact that each layer hosts a kernel of dimension n ∗ m. The kernel is multiplied by a portion of the input resulting in an output matrix of the same size, if a zero padding technique is used, or smaller, given by the sum of all multiplied elements.



61 A CNN sequence to classify handwritten digits **[145]**

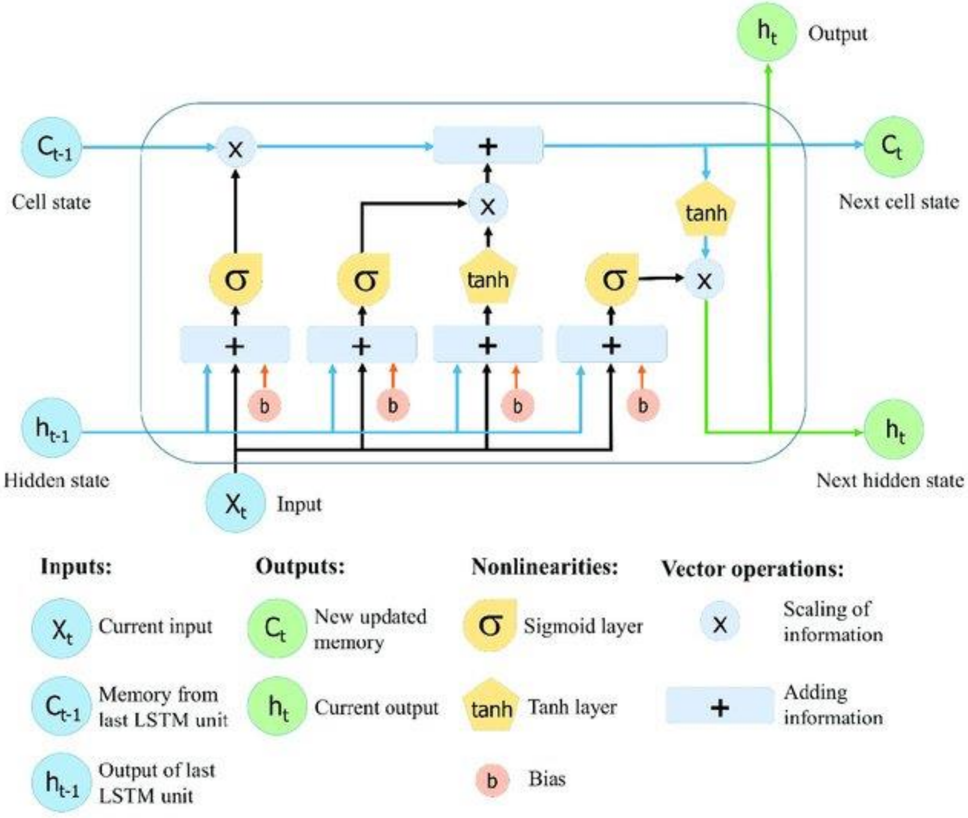
The output is generated by sliding the kernel over the entire input image, obtaining a feature map. Unlike fully connected networks, in which neurons are connected to all neurons of the previous level, in this case each neuron is connected only to a sub-portion of the input volume.

Long Short Term Memory

LSTMs are used to classify, process and forecast time series. They are based on the back propagation mechanism. Structurally it is possible to consider three fundamental elements:

• Input Gate: A sigma function assigns a value of 0 or 1 to the input values, in order to decide which values are passed. The function attributes a weight included in the range [-1,1] to each input value.

• Forget Gate: defines which details are to be considered using a sigma function applied to the input data and the previous state.



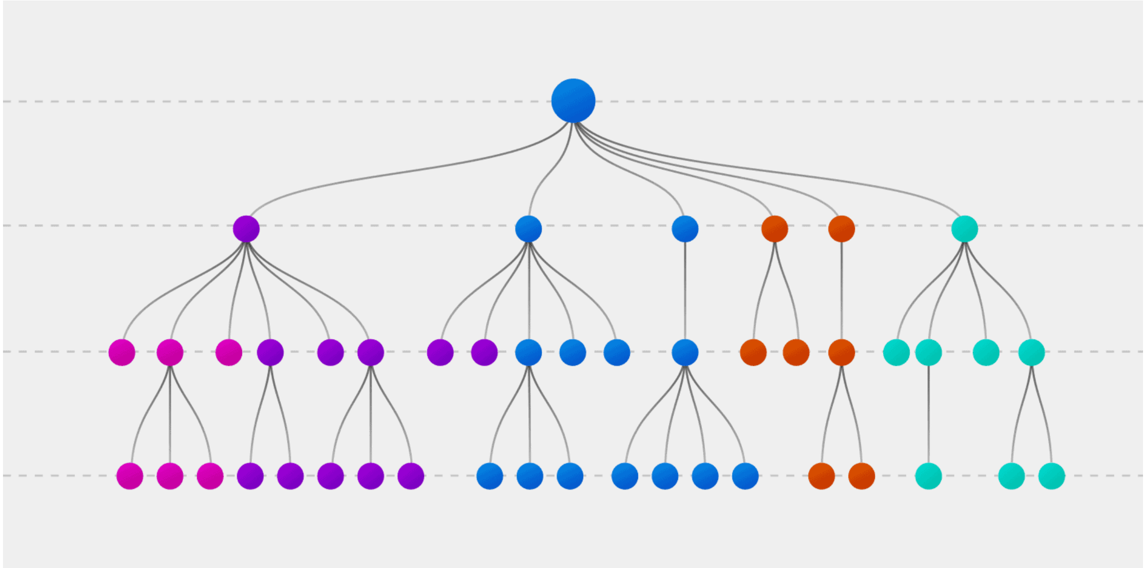
62 The structure of the Long Short-Term Memory (LSTM) neural network. Reproduced from Yan **[146]**

The output has a value between 0 (discarded) and 1 (taken). Also in this case a sigma function is used per capile which are the allowed values, and which are weighted through a tanh function[62].

Decision Tree

It is an algorithm for supervised learning based on decisions structured in a sequential and hierarchical manner. In the tree structure, each node depicted, which is not a leaf node, represents a feature. The exit branches of a node represent a division of the starting dataset based on the value of the feature analyzed in that given node.

[62] In mathematics, hyperbolic functions are analogues of the ordinary trigonometric functions defined for the hyperbola rather than on the circle: just as the points (cos t, sin t) form a circle with a unit radius, the points (cosh t, sinh t) form the right half of the equilateral hyperbola.
Hyperbolic functions occur in the calculations of angles and distances in hyperbolic geometry. They also occur in the solutions of many linear differential equations (such as the equation defining a catenary), cubic equations, and Laplace's equation in Cartesian coordinates. Laplace's equations are important in many areas of physics, including electromagnetic theory, heat transfer, fluid dynamics, and special relativity.



63 Decision Tree **[147]**

Trees are characterized by the number of branches coming out of the nodes. Binary trees are trees with two outgoing branches for each node. The tree nodes are differentiated into root and intermediate nodes, explained above, and leaf nodes. The leaf nodes represent the assigned output. The use of this learning mechanism involves the division of work into two phases:

Training: in which the tree is created. The approach used in this phase is of the following type: Gready, the split attribute is chosen locally and not globally;

Test: each instance of the test set, it is possible to go through the tree built in training phases until you reach the leaf node that represents the predictive value attributed to that instance.

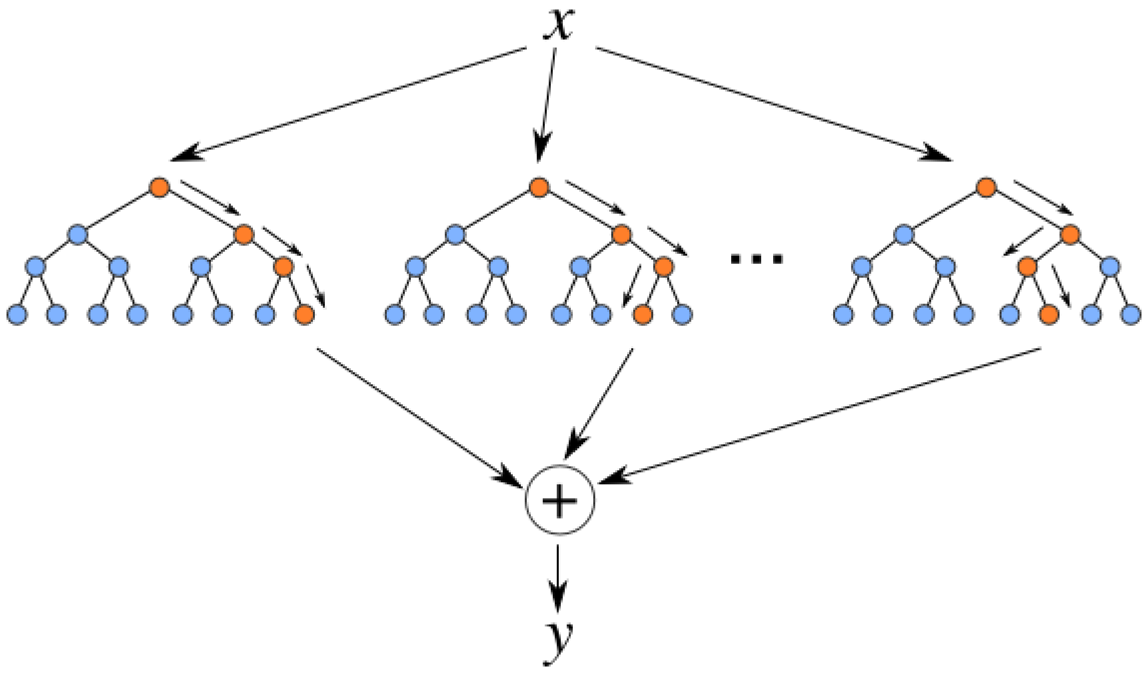
Random Forest

It is the combination of multiple machine learning algorithms that allows for a more accurate prediction than the models considered individually. There are two types of Esemble models: Boosting and Bagging.

• Bagging (Bootstrap aggregating) is a resampling technique, it is used to resample training data several times. Given a training set of N units, it selects N units at random with repetition, resulting in many datasets, all of size N to be used for model estimation.

Random Forest is a supervised learning algorithm used for both classification and regression. The Random Forest algorithm allows to overcome some limitations present in the use of the decision tree. In fact, trees with high depth: are very sensitive to training data; they have a high computational cost and a high risk of overfitting.

• Dibagging (Bootstrap aggregating), is a technique where the decision trees that make it up are performed in parallel without any dependence and interaction between them.



64 Random Forest Regression **[148]**

Operation is as follows:

• generation of different datasets with bootstrap;

• estimate of a tree for each dataset;

• application of regression and classification techniques for forecasts

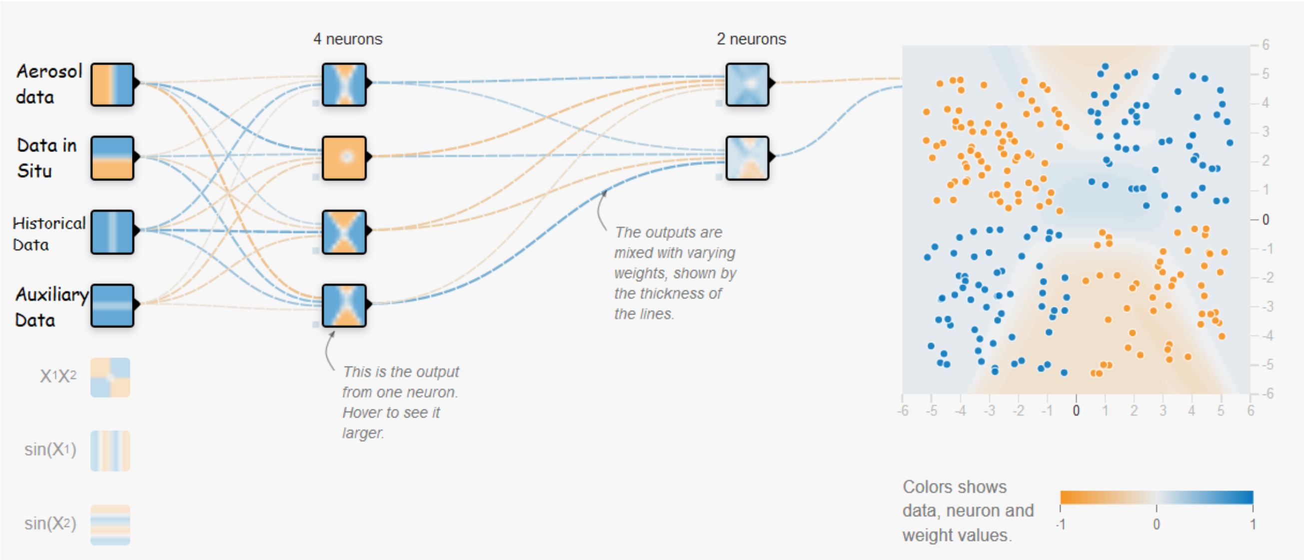
Random Forest is only considered a random subset of features, so that the most important features are not always chosen first.

Each tree extracts a random sample from the original dataset allowing you to add an additional element of randomness that prevents over-fitting. During execution, the model combines the results obtained from the individual decision trees, producing a single output

Machine learning tasks are usually classified into three categories, or paradigms:

Supervised Learning

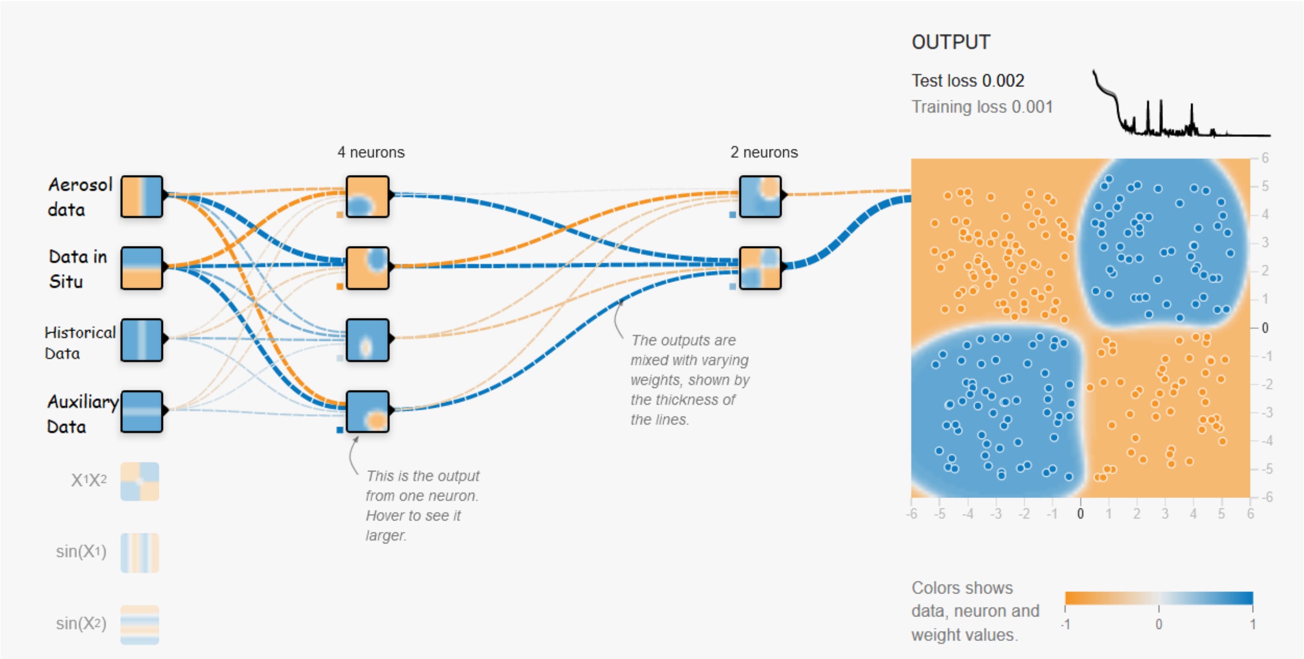
Supervised learning: examples of the desired inputs and respective outputs are provided with the aim of extracting a general rule that associates the input with the corresponding output. It is a technique that allows you to train the model using labelled data. In the training phase, an input-output mapping function is created based on the supplied (useless, output) pairs. This function will then be used in the test phase to assign an output to data, input, not yet labelled. Depending on the output domain it is possible to distinguish two cases: if the output domain is finite and consists of discrete values, then the model will implement a classification; if the output domain is continuous it will perform a regression.



65 Supervised learning of this thesis work

Unsupervised Learning

This technique is used when the deep learning model is given the dataset without explicit instructions, what to do with it. The model then tries to automatically find the structure in the data by extracting the characteristics and analysing the structure. The inputs provided have neither a defined structure nor associated outputs. The purpose of the calculator is therefore to identify patterns in the inputs in order to reproduce or predict them.

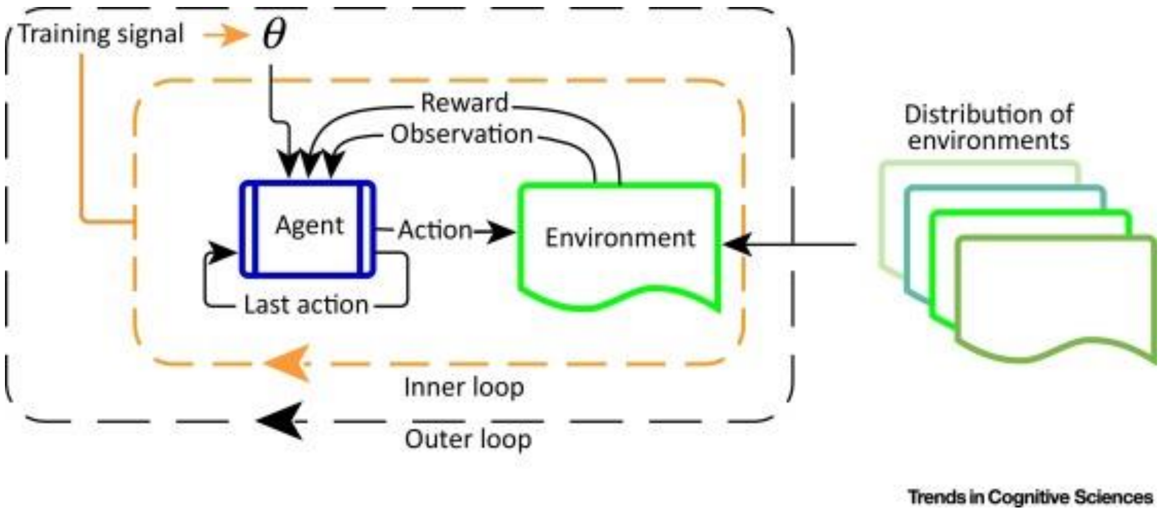


66 Unsupervised learning of this thesis work

It can organize data in various ways like Clustering, Anomaly Detection, Association, Auto-Encoder. This type of classification aims to extract information from unlabelled data and whose structure is not known a priori. clustering algorithms and algorithms for dimensionality reduction (PCA, t-SNE).

Reinforcement learning

Reinforcement learning is a machine learning technique that aims to create autonomous agents able to choose actions to be taken to achieve certain objectives through interaction with the environment in which they are immersed. This type of learning is usually modelled through decision-making processes and can be carried out with different types of algorithms, classifiable based on the use of a model that describes the environment, on the methods of gathering experience (in first person or by of third parties), the type of representation of the system states and the actions to be performed (discrete or continuous).



67 Reinforcement Learning **[149]**

It foresees a System (agent) that starts from an initial state. An action is then applied. On the result of this action, metrics are calculated to evaluate its performance. This rating is sent as feedback to the system, which changes its status.

Deep Learning

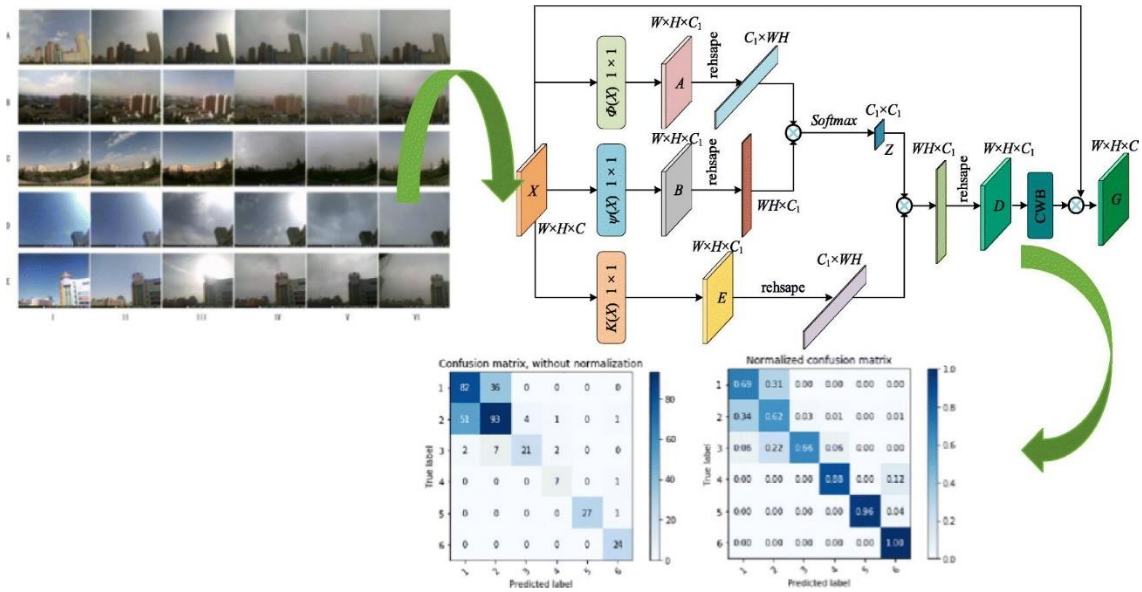
Deep learning is a set of methods attributable to the machine learning family that are able to provide high-level abstraction models for a wide range of non-linear phenomena. These techniques have led to the achievement of important advances in various disciplines such as computer vision, natural language processing, facial and speech recognition, and signal analysis in general. Deep learning relies on different models to represent objects. An image, for example, can be processed as a simple vector of numerical samples or with other types of representations. Specifically, it could be described starting from:

• the intensity of the pixels

• the edges of the elements that compose it

• its different regions, with particular shapes

Using the right representation makes the learning task more efficient. Research in this area therefore strives to build models of reality as efficient as possible with the aim of extrapolating the best representations from vast collections of unstructured data. Numerous deep learning techniques are expressly influenced by neuroscience and are inspired by the information processing and communication models of the nervous system, with particular attention to the way in which connections are established between neurons based on received messages, neuronal responses and characteristics of the connections themselves.



68 Deep Learning **[150]**

5.3.5 Validation

The validation process used is in principle simple, the actual implementation represents a large process in which every single phase is subject to various assumptions and potentially requires user decisions which could make it a subjective approach. To avoid this, established methods for validating satellite-derived data products follow steps described in the scientific literature. In the domain of terrestrial products, validation is defined as the process of evaluating by independent means the accuracy of the terrestrial products derived from the satellite and quantifying their uncertainties by analytical comparison with reference data [151]. Furthermore, the guidelines for the definition of validation by the Committee on Earth Observation Satellites (CEOS) have been studied and "the process of evaluating, by independent means, the quality of the data produced by the system outputs" [152].

The validation was performed from an idealized perspective, the input data x and y (for example, satellite data and reference data) on validation follow a process that can be traced back to the reference standards. The CEOS working group [153] on calibration and validation defines the guidelines for validating the data retrieved from the satellite of the biogeophysical variables. As shown in the table below, they define the following validation steps:

Validation stage	Definition
0	No validation. Product accuracy has not been assessed. Product considered beta.
1	Product accuracy is assessed from a small (typically <30) set of locations and time periods by comparison with in situ or other suitable reference data.
2	Product accuracy is estimated over a considerable set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.
3	Uncertainties in the product and its associated structure are well quantified from comparison with reference in situ or other suitable reference data. Uncertainties are characterized in a statistically rigorous way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature.
4	Validation results for stage 3 are systematically updated when new product versions are released and as the time-series expands.

7 Validation stages as defined © CEOS

To carry out an internal validation of satellite data, it must find a compromise between the number of sample units and the representativeness of the results on the quality of atmospheric data at European level.

A validation good practice protocol consists of the following steps:

• The selection of reference data

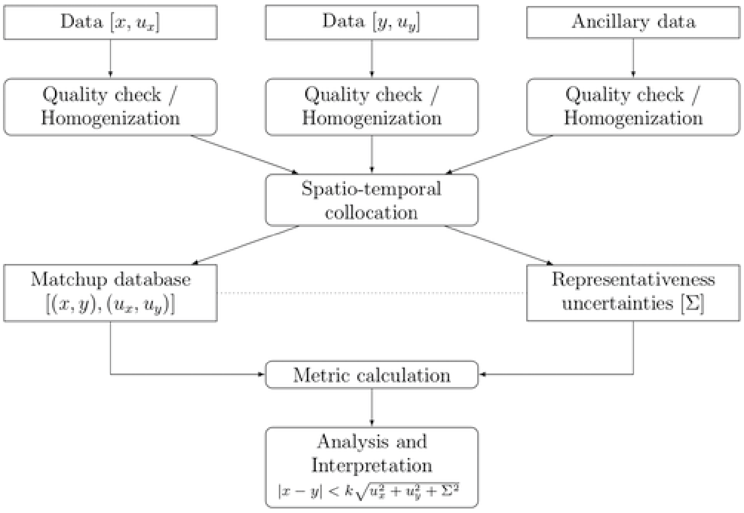
• Data pre-processing phases

• The selection and implementation of appropriate metrics

• Presentation of the validation results

Steps for Validation

The following phases of the generic validation process have been described in detail in the scientific article "Validation practices for satellite-based Earth observation data across communitie" [151].



69 Schematic overview of the general validation process

The diagram shows the generic structure of the comparison part within a validation process. Below I will describe the different steps, highlighting the user's decisions and assumptions. In particular, these assumptions are discussed which may cause additional uncertainties affecting the validation results. "

Data

"From an idealized perspective, the input data x and y (e.g. satellite data and reference data) for the validation process would be traceable to the SI reference standards. In practice this is rarely the case, and the choice of reference data in particular, it is often a pragmatic decision. Typical considerations in this regard include the following questions:

• Do the data provide scientifically meaningful estimates of the investigated geophysical quantity?

• Does this data sufficiently cover the potential parameter space?

• Should the data be accurate enough to draw the desired conclusions from the validation process?

• Is the data available and publicly accessible?

These points are all critical to maintaining end-to-end traceability in the validation process. Currently, many of these considerations may not be adequately addressed and the choice of data is often based on practicality or what is deemed most suitable for the validation process. These decisions therefore affect the overall credibility of the validation results. [151]. "

Quality check

“Once a data set is chosen, a quality assessment is required, which is also applicable to any ancillary data. Many in-situ atmospheric control unit suppliers include data quality information within their datasets. Data quality information can be provided as simple binary flags (good / poor data quality) or graduated flags representing a range of different quality levels. Alternatively, the data can be provided with quantitative uncertainty measures and, in some cases, these can also be combined with a description of the quality level. Thresholds are commonly applied to quality level descriptors or uncertainty information to determine which data to use in the validation process. In some cases, additional checks may be necessary such as checking the physical plausibility of a given measurement, visual inspection of the data or testing for temporal consistency. In some communities, the data can also be checked against a climatology to ensure that the values are within normal seasonal limits.

The decisions made here are generally application specific and can be based on the volume of data available. They can lead to a reduction in the space-time coverage of available data and can affect the representativeness of the data set " [151].

Spatiotemporal Collocation

“The space-time location is one of the most challenging aspects of a validation exercise on non-temporal data chosen to keep track of it with the Blockchain technology that will explain in the next paragraphs. In time and space placement the following concerns must be addressed:

1. The placed measurements should be close to each other with respect to the space-time scale on which the variability of the geophysical field becomes comparable to the measurement uncertainties, especially when considering intermittent and highly variable parameters (eg convective precipitation).

2. If possible, differences in space-time resolution (horizontal, vertical and temporal) should be minimized.

3. Placement criteria should take into account the need for a sufficient number of collocated pairs for robust statistical analysis. This need often conflicts with the first concern and a compromise must be found.

In general, there are two categories of placement methods:

the. those that keep the data on their original grids and select the closest matches

ii. those that use interpolation and aggregation techniques (e.g., regridding, resampling, and kriging) to bring both datasets to the same grid and time scale.

The interpretation of "closer" in the first approach can lead to a wide variety of colocation criteria, from simple metrics based on physical separation (distance, time) to more advanced methods such as the use of backward trajectories or ancillary data, providing further assurance that the geophysical field is measured under similar circumstances (e.g., potential vorticity constraints in the atmospheric domain). This may also include statistical tests for the representativeness of a dataset based, for example, on geostatistical analyses [154] provide an example for characterizing the spatial representativity of point-like observations in situ for the validation of satellite surface albedo data products. Their approach is based on a semivariogram analysis.

Additionally, when returning a dataset, several options are available, ranging from linear interpolations to advanced upscaling and downscaling schemes that mandate mass / surface / energy conservation and resolution harmonization of the actual measurement. Note that the latter is not always the same / similar to the adopted sampling grid.

Whichever colocation approach is chosen, a residual mismatch is almost inevitable, due to differences in resolution and field of view, or even just a simple offset in the measurement position, such as, for example, caused by the fact that the Satellite sounder has a sampling pattern that does not result in an exact flyover at the ground station. When the resulting differences cannot be corrected in the comparison, an additional uncertainty term must be taken into account in the consistency check represented here by Σ.

This collocation uncertainty can be estimated by various methods such as triple collocation analysis [155], the use of structure functions or uncertainties derived from the simulation experiments of the observation system. " [151].

Homogenization

“In many cases, further homogenization between the two data sets is necessary before actual differences can be computed. For instance, unit and other representation conversions are often required, and these can introduce additional uncertainties, in particular, when ancillary data are used. For comparisons of measurements that rely on retrieval methods such as optimal estimation, this step could include the harmonization in terms of resolution and prior contribution using the Averaging Kernels, for instance, following the recipe [156].

Metric Calculation

“The choice of metrics used within the validation process depends on the application and the data available. A series of metrics used to validate the data relating to the atmosphere are illustrated below:

Metric	Definition	Assumptions	Sensitive to
Measures of systematic differences			
Bias	$\hat{\mu}_x - \hat{\mu}_y$	S, G	sm, sr
Median difference	$p_x^{50} - p_y^{50}$	S	sm, sr
Measures of statistical spread			

RMSD	$\sqrt{E[(x-y)^2]}$	A, S, G, L, IE, O	sm, sr, rm, rr
cRMSD	$\sqrt{E[((x-\hat{\mu}_x)-(y-\hat{\mu}_y))^2]}$	A, S, G, L, IE, O	sm, sr, rm, rr
Triple collocation measures			
R^t	$\sqrt{\frac{\hat{\sigma}_{xy}\hat{\sigma}_{xz}}{\hat{\sigma}_x^2\hat{\sigma}_{yz}}}$	A, S, G, L, IE, O	rm, rr
RMSE	$\sqrt{\hat{\sigma}_x^2-\frac{\hat{\sigma}_{xy}\hat{\sigma}_{xz}}{\hat{\sigma}_{yz}}}$	A, S, G, L, IE, O	rm, rr
SNR (dB)	$-10\log\left(\frac{\hat{\sigma}_x^2\hat{\sigma}_{yz}}{\hat{\sigma}_{xy}\hat{\sigma}_{xz}}-1\right)$	A, S, G, L, IE, O	rm, rr
Statistical dependency measures			
Pearson's *R*	$\frac{\hat{\sigma}_{xy}}{\sqrt{\hat{\sigma}_x^2\hat{\sigma}_y^2}}$	A, S, G, L, IE, O	rm, rr
Spearman's *ρ*	$\frac{\hat{\sigma}_{r_{xy}}}{\sqrt{\hat{\sigma}_{r_x}^2\hat{\sigma}_{r_y}^2}}$	A, S, IE, O	rm, rr
Kendall's *τ*	$\frac{n_c-n_d}{n_0}$	A, S, IE, O	rm, rr
Mutual information, *I*	$\iint f_{x,y}(x,y)\log\left(\frac{f_{x,y}(x,y)}{f_x(x)f_y(y)}\right)\mathrm{d}x\mathrm{d}y$	A, S, IE, O	rm, rr
Temporal stability measures			
Absolute temporal stability		L	

8 Summary of Common Metrics Definitions as well as their inherent assumptions and sensitivities

*Abbreviations: **S**, stationarity; **G**, Gaussianity; **L**, linearity; **IE**, independence of error terms; **O**, orthogonality; A, additive error model; **sm**, systematic measurement uncertainties; **sr,** systematic representativeness differences; rm, random measurement uncertainties; **rr**, random representativeness differences.*

Analysis and Interpretation

"Once the final metrics are obtained, to complete the validation it is necessary to judge whether the results are in accordance with the requirements. Following the definition of validation, this implies verifying that the satellite set and the in situ data sets are suitable for their correlation. However, in many cases there is no single application and the requirements can be numerous and hence a validation objective must be defined, which could then be verified for compliance on an individual basis.

In its most basic form, the consistency check between the differences between two measurements and the reported measurement uncertainties can be written as [157]:

$$|x - y| < k\sqrt{u_x^2 + u_y^2 + \Sigma^2},$$

where x and y are the reference measurements and of EO, ux and uy the respective uncertainties, k the so-called coverage factor and Σ the additional variance of the differences due to the colocation mismatch, e.g. differences in the representativeness of both measurements. The coverage factor allows you to adapt the combined uncertainties to a particular confidence level. Where k = 1, the combined uncertainty is consistent with 1 standard deviation. The value k = 2 is often used to provide a 95% confidence level (assuming a normal distribution of the combined uncertainty) [158]."

6 Study cases

The analysis of air quality is a problem that has often been addressed in recent years using different technologies and methodologies. There are many works that try to study the phenomenon to create models that allow for predictions for the future. Most of these projects use data from sensors placed on the ground, therefore they have a different application field from the project reported in this thesis work. The main difference lies in the fact that ground sensors consider restricted areas and above all that the reported values only represent a narrow band of the troposphere. All this makes data not comparable with satellite data, which consider the entire atmospheric column, or in special cases, the entire tropospheric column. As for the minority part of works that analyse satellite data, these obtain data from different technologies and therefore it is easy to be in the condition in which the observed granularity, both at a spatial and temporal level, are not comparable with those obtained by the Sentinel-5P satellite. Remote sensing has been recognized throughout the world as an effective technology for monitoring and mapping air pollution and environmental change. The main advantage of satellite remote sensing is its repetitive and synoptic coverage which is a lot very useful for the study of the urban area. In this chapter I will address some realities that have used remote sensing to help create a base of information on land use, land cover distribution, detection of urban change, monitoring of urban growth and urban environmental impact assessment.

In the first part, two projects funded by NASA and the European Space Agency that are based on satellite applications and GIS systems will be addressed. In the second part, priority will be given to innovative projects that allow to study air quality with a methodology that differs from traditional ones. In particular, these technologies will be able to work in tandem with those proposed within this thesis work. In addition to remote sensing, most projects are also based on the geographic information system (GIS). Basically, an information system that deals with spatial and non-spatial data. Geographic information system provides input, coordinates registration / transformation, management, query, analysis, modelling, cartographic composition and production of cartography and maps within these projects. GIS does not contain maps or images: it contains a database.

The concept of database becomes central in all processing and is the main difference between a GIS / remote sensing and a simple study in air pollution mapping system, which can only produce a good graphic output. These projects therefore incorporate a database management file system and benefit from the geographic information system in data management and inference.

6.1 Mixed Satellite/site data based application

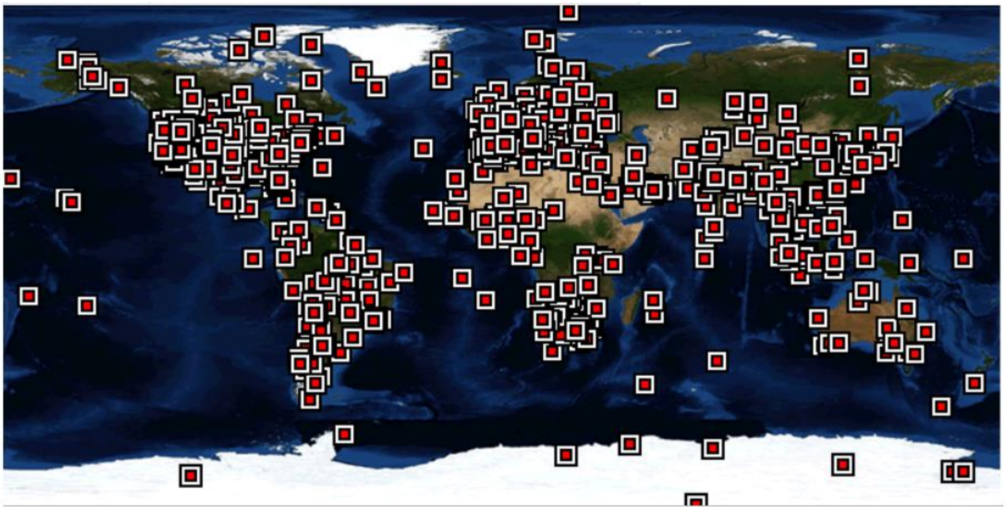
NASA Aeronet

The AERONET (AErosol RObotic NETwork) project consists of a federation of aerosol ground remote sensing networks established by NASA and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalization Satellitaire; Univ. Of Lille 1, CNES and CNRS-INSU) and is remarkably expanded by networks (e.g. RIMA, AeroSpan, AEROCAN and CARSNET) and collaborators of national agencies, institutes, universities, individual scientists and partners. Within the AERONET project it is possible to find the first operational recovery algorithm for the microphysical properties of the aerosol which was introduced by Nakajima in 1996 [159], when the multiband automatic solar and sky scanning radiometer was used in the AErosol RObotic NETwork, or AERONET [160]. All the methods mentioned above treated the aerosol particles as homogeneous. The current AERONET operational inversion algorithm was developed by Dubovik [161], which is inherited from algorithms developed by King [162] and Nakajima [163] but they were implemented for the simultaneous recovery of particle size distribution and complex refractive index with sophisticated inclusion of multiple a priori constraints. This project is essential for those who work with air pollution data. It represents the past, present and future of such monitoring.

NASA Aeronet methods and effect

For more than 25 years, the project has provided long-term, continuous and easily accessible public domain databases of the optical, microphysical and radiative properties of aerosols for aerosol research and characterization, validation of satellite recoveries and synergism with other databases. The network enforces instrument standardization, calibration, processing and distribution.

The collaboration with AERONET provides globally distributed observations of the optical depth of the spectral aerosol (AOD), inversion products and precipitable water in different aerosol regimes. Version 3 AOD data is calculated for three levels of data quality: Level 1.0 (unshielded), Level 1.5 (cloud-shielded and quality-checked), and Level 2.0 (quality assured). Inversions, precipitable water, and other AOD-dependent products result from these levels and can implement additional quality controls.



9 Control Points of the Auronet project located on the world map **[164]**

The AERONET collaboration provides globally distributed observations of aerosol spectral optical depth (AOD), inversion products and precipitable water in different aerosol regimes. Aerosol optical depth data is calculated for three levels of data quality:

- Level 1.0 unshielded
- Level 1.5 cloud shielded
- Level 2.0 shielded on the cloud and guaranteed quality.

Inversions, precipitable water, and other AOD-dependent products result from these levels and can implement additional quality controls.

ESA Aurora project

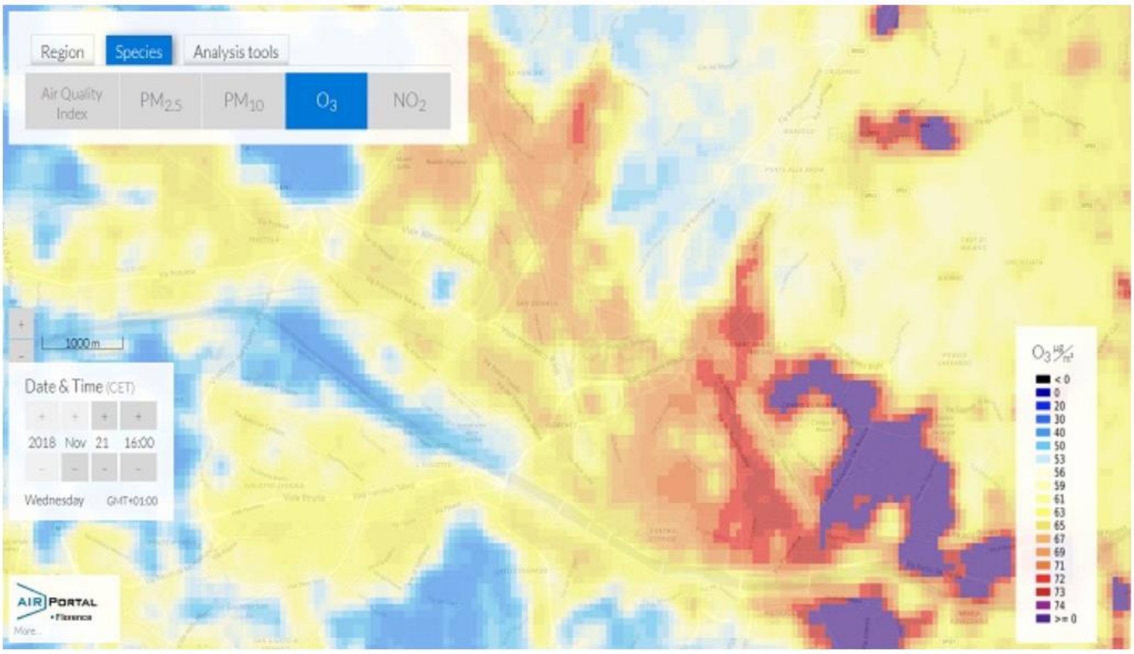
The AURORA project officially started on 1 February 2016 with a duration of 36 months. Aurora is a space research project funded by H2020, whose general objective is to use the satellites of the Copernicus Sentinel 5P, Sentinel 4 (not yet in orbit) and Sentinel 5 (not yet in orbit) missions that are equipped with atmospheric instruments to monitor the profile of the ozone concentration in the earth's atmosphere. The project aims to demonstrate that the synergistic use of geostationary satellite sensor (GEO) and low earth orbit (LEO) data in different frequency ranges is a viable strategy for full vertical ozone profiling, used to calculate tropospheric columns and surface radiation layers of the lower atmosphere. In particular, it covers the lower layers of the atmosphere in Europe, North Africa and the Middle East, where the action of ozone acts as a pollutant and as a greenhouse gas. The project will use innovative methods to combine the information measured by the various tools, short-term forecast models, a web-GIS that will allow access to data and a database with cutting-edge techniques for managing big data. This combination will stimulate the development of innovative downstream applications with high commercial potential. The project will develop two examples of commercial applications in the field of preventive health care, based on near-real-time monitoring and short-term forecasts of ozone pollution. The first relates to ozone pollution in the lower layers of the atmosphere and the second to the dosimetry of UV radiation.

The project includes the creation of a technological infrastructure to implement the data processing chain, including a geo-database and web services for data access, which is the basis for a market analysis of pre-market and diffusion in commercial communities. Advanced Ultraviolet Radiation and Ozone Retrieval for Applications - is a space research project funded by the European Commission's H2020 program in the field of Earth observation.

Aurora methods and effect

The quality assessment and validation of the observations on the atmospheric state in this project are mainly based largely on making comparisons with measurements of the observable itself. On the other hand, data merging or fusion schemes involve the combination of observations from different sources, weighted by functions that mix uncertainties, aspects of information content and space-time representativeness. The remote sensing of the atmosphere by means of space and terrestrial instruments also consists of under-constrained inverse problems that mix the necessary preliminary information in the recovered atmospheric state profiles [165].

AURORA is particularly interesting as a project because it deals with ground level ozone as one of the most important short-lived greenhouse gases (GHG). Tropospheric ozone is highly variable and strongly oxidizing. This means that it directly affects other greenhouse gases that affect the global climate. Such monitoring has a significant impact on the measurement of air quality in our cities and, consequently, on our health. AURORA is making scientific and technological advances in this field. The project is carried out before the launch of the atmospheric Sentinels, AURORA will simulate, merge and assimilate the synthetic data of Sentinel L2. This will help provide accurate analyses and forecasts on ozone and cities in the coming years.



70 Aurora project portal **[166]**

AURORA is planning a tailor-made application to inform users in major cities (citizens and public employees) about air quality. It will provide awareness of actual air quality at high spatial resolution (neighbourhood to street level) in near real time and transform data into practical recommendations. Watch this space for more information as the product develops.

6.2 Site data based application

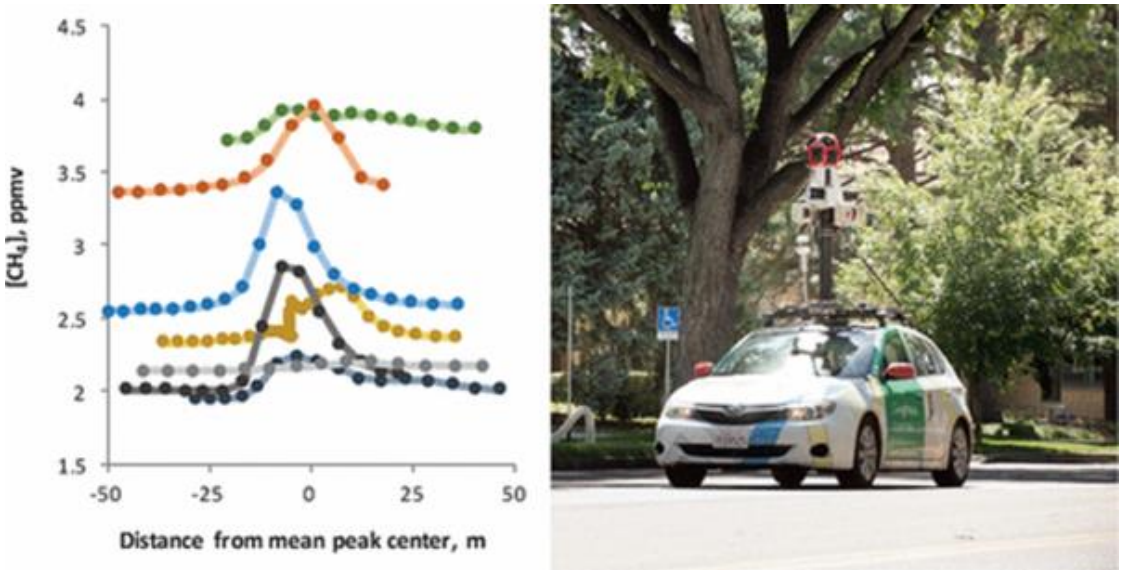
6.2.1 Project Air View: Tracking Pollution in Your Area

Among the most interesting projects for the mapping of city pollution there is Air View, a Google project which, in addition to creating accurate maps of the world, also helps us to map information on air quality. Air View was launched by Google in some experimental cities in 2015, it used Google Street View cars to travel in many American cities by taking air samples. In this way, they were able to obtain complete data on the air quality in the city using GPS and it was also possible to calculate the fluctuation over time. This research could potentially allow users to examine the average air quality in their local area or in other areas of the world in the future. Accessibility of information such as this would ensure more effective targeting of anti-pollution initiatives and give people a warning about the most dangerous areas nearby when it comes to poor air quality.

Air View methods and effect

Street View cars make at least 2 trips in a certain area to acquire good air quality data. Google technicians used the cars to install an intake pipe on the front bumper to collect air samples, which are then processed by a methane analyser in the trunk. Finally, the data is sent to Google Cloud for analysis and integration into a map showing the size and location of the methane leaks. Since the trial began in 2012, google has built methane maps for 11 cities and helped the Environmental Defense Fund (EDF)[63] to find more than 5.500 gaps.

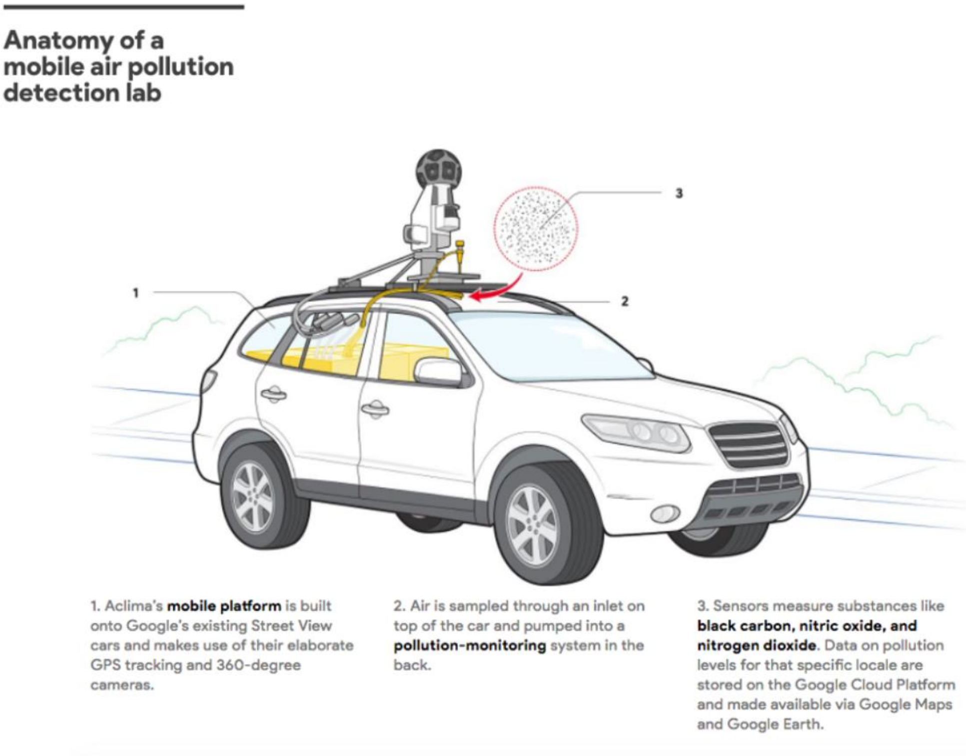
The methane maps have not only helped government agencies but have helped utilities allocate resources more efficiently for long-term repairs and improvements. This project inspired the Google team to explore the use of Street View cars to measure overall air quality. For years, Google has worked on measuring indoor environmental quality in corporate offices with Aclima, which builds networks of environmental sensors. In 2014, it extended the partnership to the outside world, equipping many other Street View cars with its mobile "Environmental Intelligence" (Ei) platform, including science-grade analyzers and low-cost, small-scale sensor arrays to measure pollutants, including particulates, NO2, carbon black CO^2 and more. The new project was planned as a pilot study in Denver and will finish mapping cities in 3 California regions by the end of 2016. And today the system provides reliable data that matches the fixed metering network of the United States Environmental Protection Agency .



71 A Google Street View car equipped with equipment for measuring air pollution

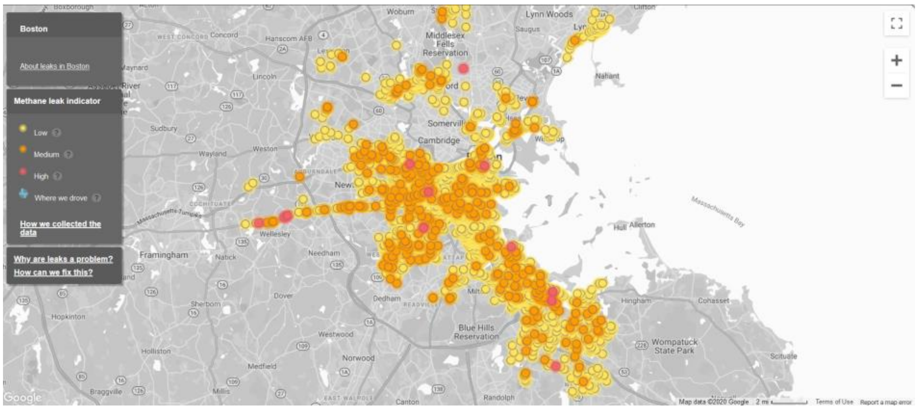
[63] works to solve the world's major environmental problems through innovative public policies, solid science and cross-cutting partnerships with prominent voices from the business community.

The project started with a few cars, but Aclima's mobile platform, which has already produced one of the world's largest air quality datasets, could also be expanded through deployment to vehicles such as buses and postal trucks, on the road to create a road map of the pollution level. This hyper-local data could help people make more informed choices about things like when to let their children play outdoors and what changes to support to make their communities healthier [167].



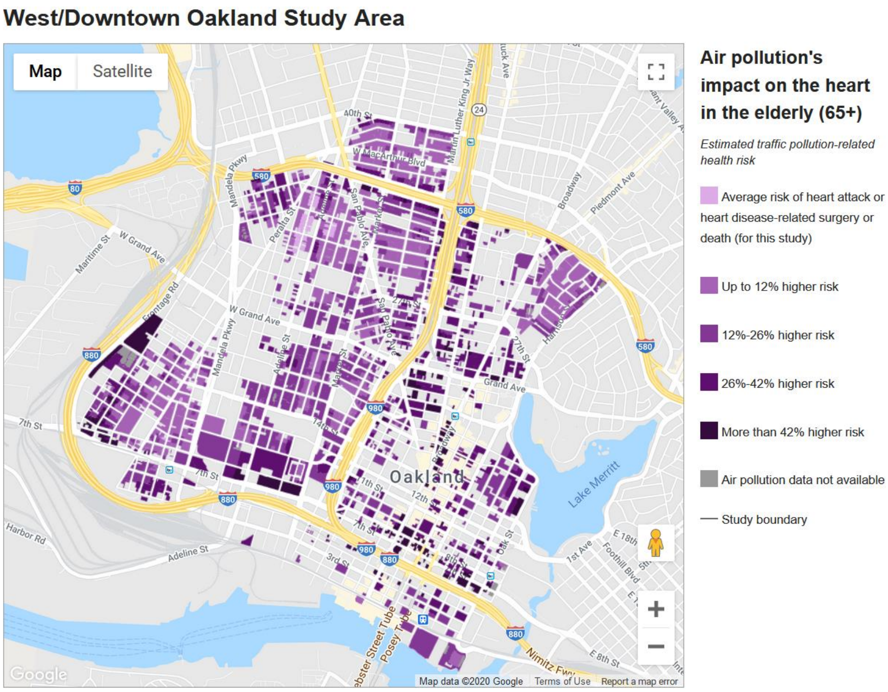
72 Detail of the equipment mounted on a Google Street View car equipped with equipment for measuring air pollution **[168]** © Google

In addition to normal air detection and monitoring, these data can help us to study the impact of pollution on human health. Just Google and EDF have combined traffic air pollution data block by block with electronic health records showing the impact of the position on health.



73 Detail of the surveys monitored by the Google Street View car in the city of Boston **[169]** © Google

The study pointed out new ways big data can be used to ultimately improve human health and calculate risk. Although air pollution has long been associated with an increased health risk, the study showed that for the elderly, the differences in pollution between neighbours, even those living on the same street or just blocks from each other, they can increase the risk of heart attack and death from heart disease.



74 The map shows NO2 pollution-associated increases in the risk of heart attacks, heart surgery and / or death from coronary heart disease among the elderly (age 65+) for residential plots in West, Downtown and East Oakland. Air pollution (NO2) levels were measured in the period May 2015-June 2016. The health risk estimates used to generate the map are based on the average effects of the published empirical study on air pollution and cardiovascular disease. The map does not represent a) Individual heart disease risk, because many factors that influence individual risk are not used to create

this map. b) Real-time exposure or risk levels, as air pollution levels can change over time. c) The addresses of the study participants. The data from the study and used to generate this map are anonymized. EDF assumes no responsibility for the use of this map or data, including medical advice **[170]**

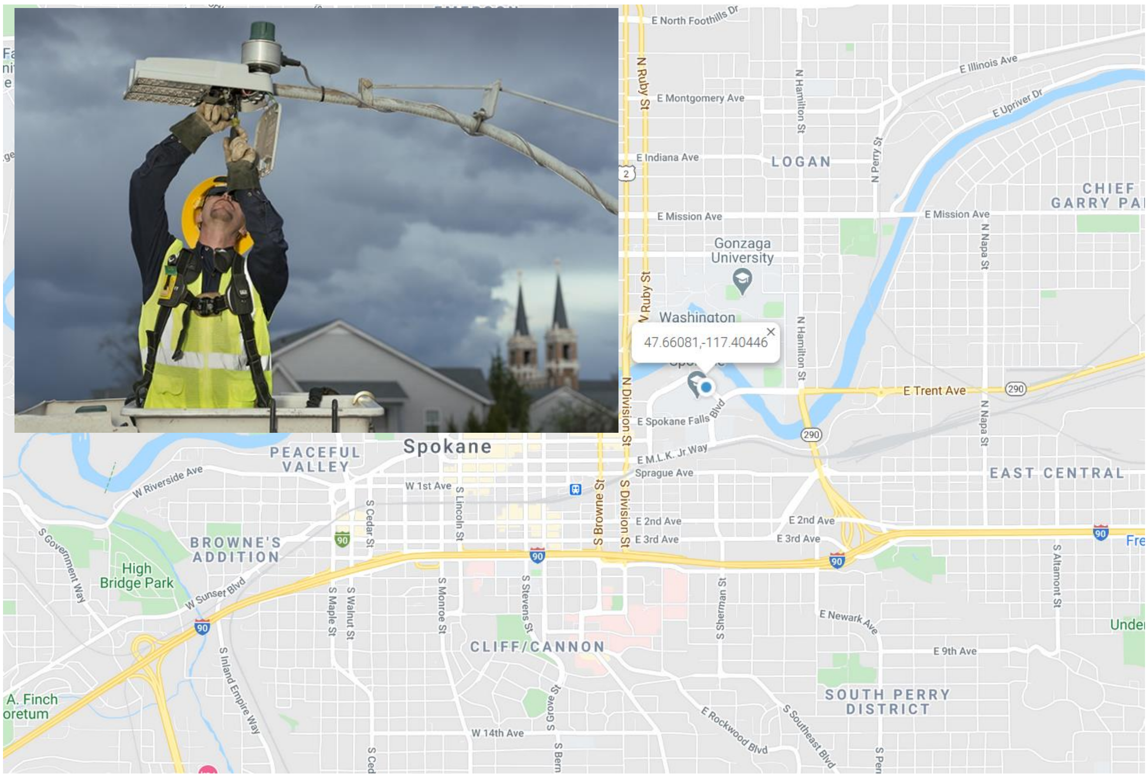
Specifically, it found that for people aged 65 and over, higher concentrations of nitrogen dioxide (NO2) and black carbon (BC) in the streets outside their homes were associated with an increase in the rate of heart attack, heart surgery and / or dying from coronary heart disease. The analysis took into account other established risk factors (including age, race, gender, obesity, poverty, smoking, basic health, and drug use). Effects among adults of all ages (> 18 years) were weaker and inconclusive. Due to the damage accumulated over time, environmental exposures are more likely to trigger heart attacks among the elderly. Older people and other vulnerable populations, such as children and pregnant women, are more likely to suffer the health impacts of exposure to air pollution [171].

Pollution in the city, as seen previously, can vary from area to area, depending on the time of day and location. And this can have a significant impact on human health. The new sensor technology allows EDF scientists and Google to collect data in innovative ways using Google Street View cars and dense fixed networks. Cars have made it clear that air pollution is not evenly distributed and can in fact be up to eight times worse at one end of a block than the other. This project, if extended to scale the globe, could become a fundamental source of data for studying air pollution in the city.

Smart Streetlights and Sensors methods and effect

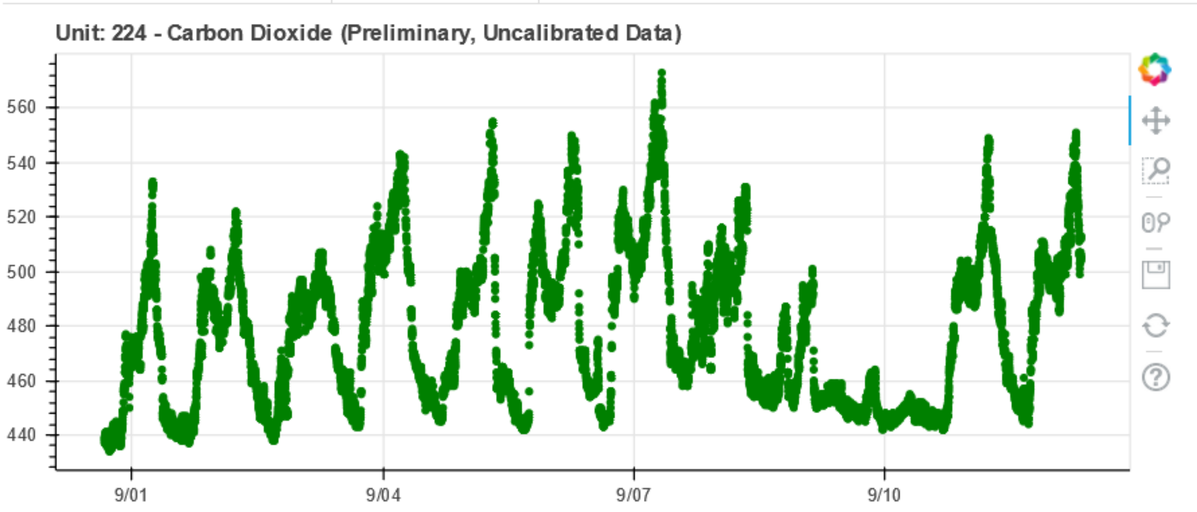
The project sees the installation of atmospheric quality sensors inside urban equipment such as street lamps. As part of the project, the researchers installed sensors, located in strategic locations, that will capture air quality conditions.

The sensors collect data on weather conditions, carbon dioxide levels and particulate matter. Particulate matter levels are of particular concern because they impact on human health, including heart and lung disease.

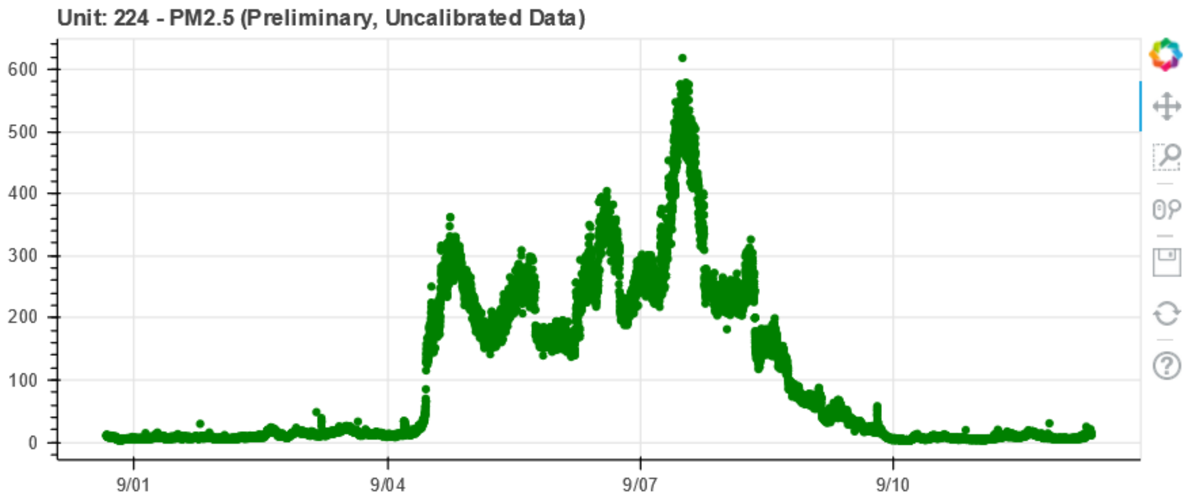


75 Urbanova project detail with relative map for viewing by users **[172]**

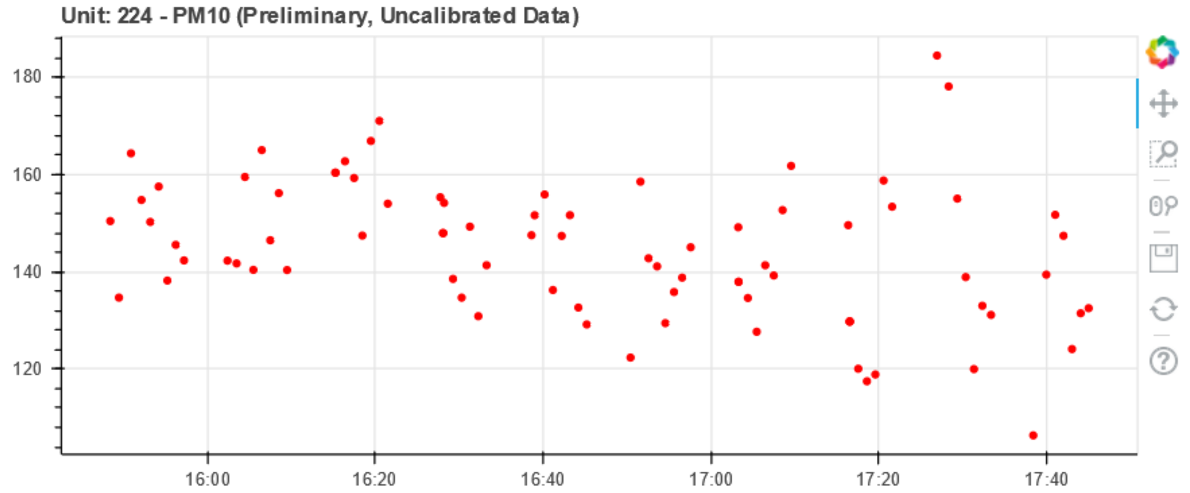
This project is an example of a technological application to monitor even similar medium-sized cities rarely studied for air pollution. Street furniture will ensure a thin spatial grid that will be used by advanced weather and air quality models to improve the understanding of microclimates in urban areas.



76 Urbanova Data CO2 **[172]**



77 Urbanova data PM2.5 **[172]**



78 Urbanova Data PM10 **[172]**

Researchers have also installed many other sensors and developed a software platform to integrate, store and analyse air quality data, as well as data from the power grid, making real-time data on pollution levels available to the public.

6.2.2 AirCasting

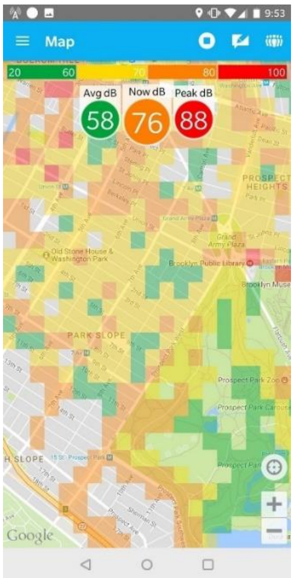
AirCasting is an open source end-to-end solution for collecting, viewing and sharing environmental data that is collected using smartphone. The platform is made up of sensors that detect atmospheric change in our cities, including a palm-sized air quality monitor called AirBeam, the AirCasting app for Android, the AirCasting website, and wearable LED accessories. By documenting and leveraging health and environmental data to inform personal decision making and public policy, the AirCasting platform empowers citizens, scientists and change makers. [173].

AirCasting methods and effect

The AirBeam device uses a light scattering method to measure PM10 or PM2.5 particulate matter. Air is drawn in through a sensing chamber where the light from laser scatters particles in the air stream.

79 Airbeam

When recording a mobile AirBeam session, the measurements are communicated on average once per second to the AirCasting app for Android via Bluetooth. AirBeam uses a fixed scan, these measurements are communicated approximately once a minute to the AirCasting website via WiFi or smartphone. At the end of each mobile AirCasting session, the collected data is sent to the AirCasting website, where the data is crowdsourced with data from other AirCasters to generate heat maps indicating where particulate concentrations are highest or lowest.



80 AirCasting for Android via Bluetooth

81 AirCasting for Android via Bluetooth

The same project also developed AirCasting luminescent accessories that connect to the AirCasting app via Bluetooth to illuminate the LEDs in response to sensor measurements received from the AirCasting app: green for low intensity, yellow, orange and red for higher intensities. AirCasting Luminescence was developed to communicate sensor measurements without the normally required reference to a screen interface and to stimulate direct interaction between AirCasters and the people in their immediate vicinity.

82 Luminous accessories that communicate atmospheric pollution through light **[174]**

The advantage of this object is to interact with the user. The information is automatically stored within the AirCasting platform. Lastly, the advantage of this project is to have the open-source code. Users can connect their devices to the AirCasting platform for Android to record health and environmental data, and transmit them to everyone in real time.

83 AirCasting for Android via Bluetooth

In this way the project becomes interactive and participatory.

7 Design of a EO-based pollutant and climate monitoring system

The general objective of this thesis is to bring clarity on the question of the definition, classification, collection and dissemination of data on atmospheric pollution on urban areas, on the use of roofs and on the possible economic value. In this chapter I will present the methodology applied and the possible variables to take into account. A project for the city of Munich is the application of moss and mats on the roofs of abandoned buildings

Urban regeneration, known as the installation of different forms of vegetation within the city, including street trees, roof gardens, green roofs, green walls, etc. It represents a strategic approach if supported by enabling technologies. Green infrastructures, in fact, can considerably reduce the concentration level of particulate matter and CO^2 through the sequestration capacity of the soil and plants linked to photosynthesis and the regulation of the urban microclimate, contrasting the increase in temperature with the evapotranspiration of the leaves. Since the 90s, green infrastructures and their different applications (green roofs, green walls, vertical gardens) have become very popular elements to counterbalance the effects of urban pollution and regenerate certain areas [175] through some species in the city. A crucial role in the sequestration of CO^2 and particulate matter is played in particular by moss which is usually applied to cover roofs and walls of buildings through the creation of a "mat[64]".

Our case study refers to the city of Munich (Germany) taking as reference period the period from February 2019 to August 2019 with the processing of satellite images classified on a monthly average. Munich is the third largest city in Germany with the highest population density and the capital of Bavaria, one of the most competitive industrial regions in Europe. Within the project, we processed information from the sentinel 5P satellite, the first mission dedicated to monitoring atmosphere. Operating in synchronous orbit with the sun, the satellite maps a multitude of air pollutants around the world. The latter, in combination with the auxiliary input data, made it possible to process the concentration of each atmospheric gas and model it on the basis of its absorption characteristics at specific wavelengths of light. The data we have analysed refer to the air column and not to specific points in the city, this allows us to analyse the problem of atmospheric pollution with a different view from the normal ground control units. In this study I do not consider winds and possible variables that could interfere with our results.

Therefore, the preliminary phase of the study was to identify the surfaces and buildings suitable for hosting garden covers and green areas. I understood that all buildings cannot accommodate garden roofs or walkable green areas. In particular, the city of Munich has a building architecture characterized mainly by pitched roofs or roofs not suitable for additional weights. To solve this problem, I have identified the solution in

[64] Directive 2000/60 / EC

absorbent moss panels. These panels solve numerous problems: first of all the moss does not grow like a classic vertical plant but remains flat and can be installed both on pitched roofs and on all roofs that already host solar panels or external bodies. Moss is an inexpensive material for insulating homes. It is characterized by environmental friendliness, antiseptic properties, resistance to deformation. Furthermore, moss is characterized by being adaptable to almost all temperatures, in fact it requires little water due to its ability to capture it from the humidity of the air and natural rainfall. This is why it manages to remain dry for long periods, changing colour and then greening as soon as it absorbs water. This ensures a wider scalability of the solution as the moss carpet can be used in both southern and northern Europe.

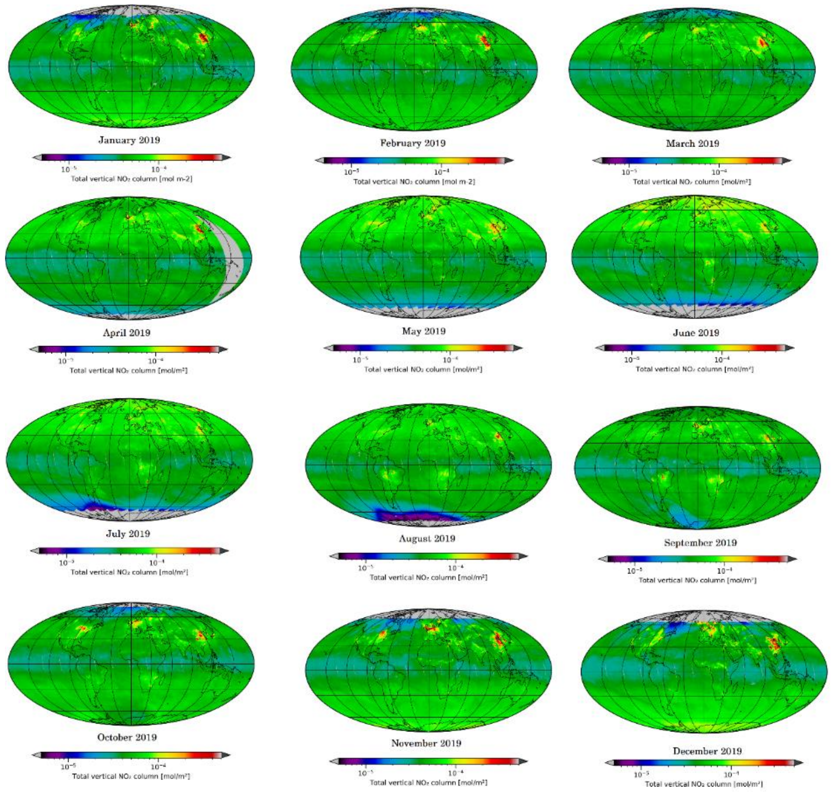
84 Moss installations in Stockholm, Sweden. 2017 © by Anselmo Lepore.

Due to the low maintenance needs of the musk carpet, I have studied the effects of its installation on public and abandoned buildings and industrial areas. I have chosen this type of buildings because, on the one hand their large size guarantees a greater surface available to plant the moss. On the other hand, being public buildings, the interlocutor is in most cases a public administration, so it should be simpler finding agreements addressing community benefits. Furthermore, public and industrial buildings are homogeneously located throughout the city. Authors of many studies from North America and Europe have made strong economic arguments in favour of adaptive reuse of old public buildings, claiming that rehabilitation projects cost around 30 % less than comparable new construction, with possibility to access to tax credits and incentives to offset the high cost of rehabilitation [176]. Abandoned buildings are often catalogued as a problem, but with the installation of mosses and green areas they play a double function. The first one is purely aesthetic, the second one is tied to the environment: abandoned buildings may turn into "sponge" buildings, literally buildings with the qualities of absorption of polluting substances.

7.1 Targets

Currently, four out of five Europeans live in urban areas and their quality of life directly depends on the state of the environment in cities. Cities are highly artificial and man-made places and, inside them, the air quality is extremely altered. Even the alteration of the level of light and noise are forms of urban pollution, the main chemical pollutants of the air, due to their impact on human health, are ozone (O3), sulphur dioxide or sulphur dioxide (SO2), nitrogen oxides (NOx), fine dust (PM10), carbon monoxide (CO) and carbon dioxide (CO^2). As a goal, this chapter aims to demonstrate how much urban vegetation can influence the quality of the environment and of life in the city: in addition to the well-known aesthetic and recreational functions, I want to demonstrate that urban green by mitigating the pollution of various environmental matrices (air, water, soil), improves the microclimate of cities and has achieved the conservation of biodiversity.

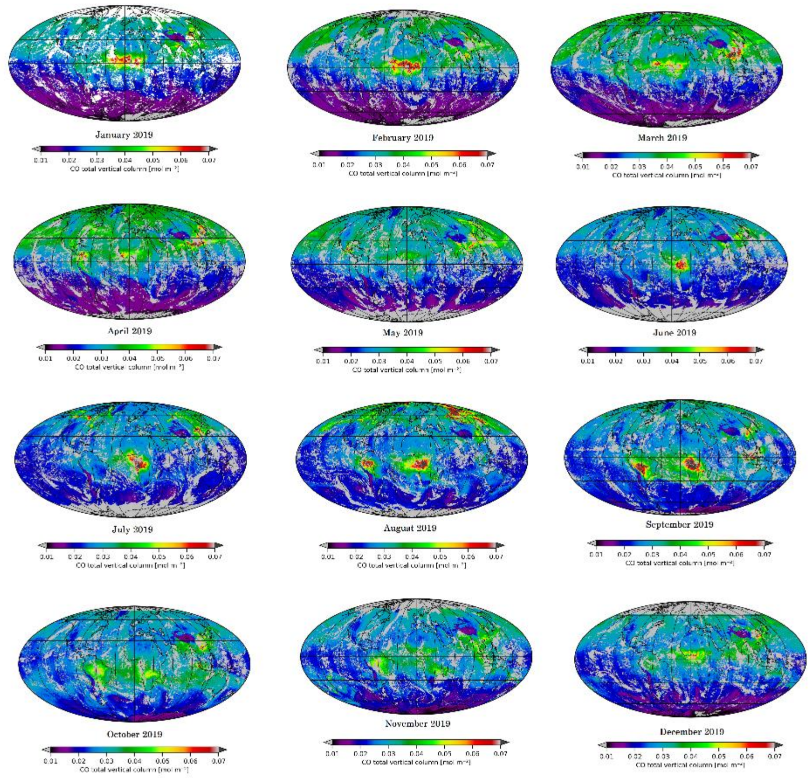
To achieve the objective, the CO, SO2, NO2, O3 gases, monitored directly by the satellite, highlight the significant changes between the time frames of the period from 1 January to 31 December 2019. Comparative cartographic representations of the average mosaics at 5, 6 and 10 days of the number of tropospheric columns of NO2, CO, SO2, O3 density, extracted from the high resolution images, were drawn for a better understanding of the spatial and temporal changes that occurred in the world during the selected time intervals. The high resolution representation of the images is not shown for graphics and text space questions. It should be remembered that at the poles in the winter months the satellite data are absent due to the absence of light. The data is downloaded and resampled, on count of geographical position and shooting time.



91 Comparative cartographic representations of the average density of the number of tropospheric NO2 columns at 10 or 5 days in the world between January and the end of December 2019

Analyses of maps and data from mid-January to the second decade of February reveal that there were no significant changes in the level of NO2 pollution in 2019, as it maintains high values over large areas around the world. Of course, it should be noted that the areas with the highest values are in South Asia, Northern Europe and North America. The spatial distribution of NO2 values indicates two categories of NO2 pollution patterns in Europe, with an intense contrast between them. The first category refers to large areas facing NO2 pollution problems, such as the notable regions of central and northern Europe, including Germany, the Netherlands, Belgium, northern France, southern regions of Great Britain, Poland and

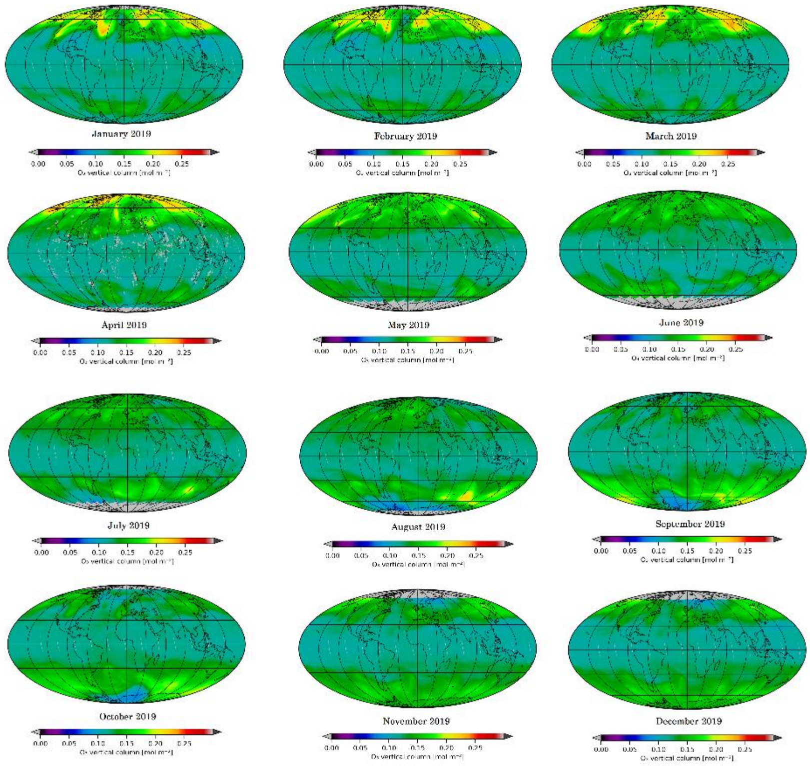
Northern part of the Czech Republic. This can be explained by the intense industrial activities and car traffic which overlap a dense network of transport infrastructures (mainly highways). Another large area affected by NO2 pollution covers the territory of the Lombardy region in Northern Italy, where the density of the number of tropospheric NO2 columns maintains high values during the revision periods and their adjacent areas, following the same causes of above. The second category comes from developing countries or countries with strong industrial traction, such as China and India.



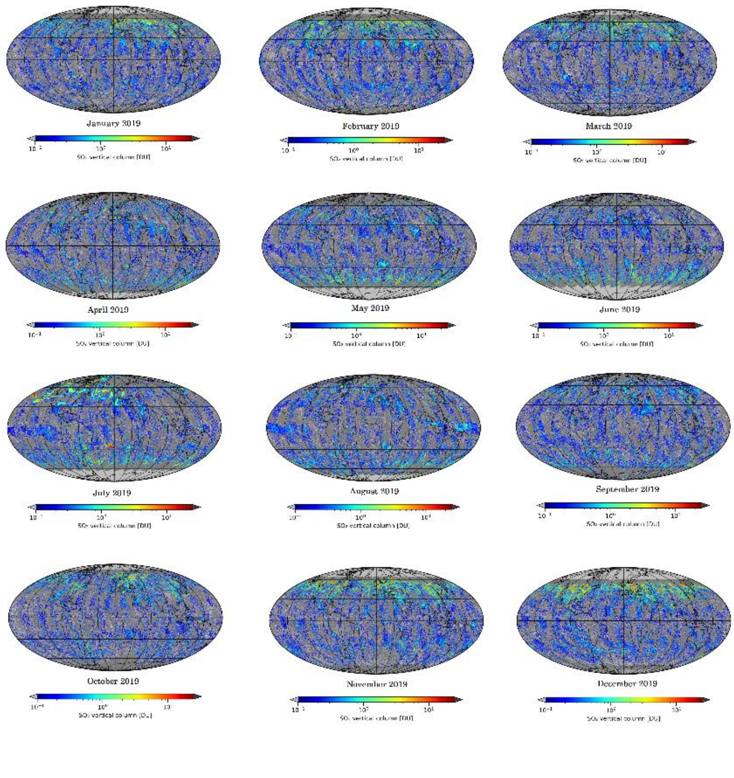
92 Comparative cartographic representations of the average density of the number of tropospheric CO columns at 10 or 5 days in the world between January and the end of December 2019

The CO data is influenced by the devastating fires that burned vast swathes of Siberia, the Amazon and Central Africa that not only caused a terrible loss in forest area and biodiversity, but also left a mark on the atmosphere, affecting the world climate and air quality. From the data, it emerges that in the month of August 2019 79 thousand fires broke out in the world, an incredibly higher number than in the same period of the year 2018, when there were about 16,500 fires. The satellite data provides an answer by reporting the values especially in the equatorial areas. In addition, even in the winter months there are high values in the northern hemisphere that can be attributed to combustion or emissions from our apartments.

Both the ozone (O3) and the sulphur dioxide (SO2) shown on the next page have no anomalous or decisive values to report. But it should be remembered that they too have a significant impact on the atmosphere and human health.



93 Comparative cartographic representations of the average density of the number of tropospheric Ozone columns at 10 or 5 days in the world between January and the end of December 2019



94 Comparative cartographic representations of the average density of the number of tropospheric SO2 columns at 10 or 5 days in the world between January and the end of December 2019

7.2 Pre-processing

The first fundamental process for creating a reliable data set is the one called Data Cleaning. In this phase of the analysis I proceeded with a sort of filtering of the features, in such a way as to keep only those strictly necessary for the analysis to be carried out. Sentinel and Landsat data. For each single product it was deemed necessary to save the following information:

- reference latitude and longitude of the patch, centroid
- latitudes and longitudes of the bounding box that defines the patch
- value of the pollutant
- product quality indicator.

A further filtering step was applied to the data obtained from the Sentinel-5P satellite, thanks to the use of an indicator, which certifies its accuracy and reliability. This reliability value, represented within the metadata with the identifier qa_value, is represented by a number included in the range [0, 1], where the value 1 represents the precision of the associated data equal to 100% and the 0 indicates the lack of data. As recommended by the manual, only data with qa_value> 0.5 were considered.

Weather data

The following features were taken into consideration: CloudCover, dewPoint, humidity, latitude, longitude, ozone, PrecipIntensity, PrecipProbability, pressure, temperature, time, uvIndex, visibility, windBearing, windGust, windSpeed. Some of these have been modified in such a way as to be easily manipulated. The attribute 'Time', represented by timestamp, was converted obtaining the information: 'Date' in the format 'dd / mm / yyyy' and Hour in the format 'hh'; the temperature attribute has been converted to Celsius.

Data interpolation

While the service guarantees global daily coverage, Sentinel data has some shortcomings. Sometimes there are missing data or poorly quality data that cannot be taken into account. Consequently, the time series representing the trend of individual pollutants present interruptions. This also occurs for time windows larger than a single day. In order to limit the incidence of these shortcomings in the final analysis, an interpolation method was applied. Interpolation is a process that tries to estimate a missing value of a series between two given values of the same. The interpolation methods involve the insertion of an intrinsic error in the estimated data. To limit this, some special attention has been made: it was decided to use a cubic interpolation function in such a way that the interpolating function could follow the curve of the original data in the best possible way; furthermore, the interpolation function was only applied if the time window of missing data had a maximum duration of three days.

Creating Maps

For the creation of the map on the case study the images were divided into sectors equal to the size of the smallest sentinel patch, equal to: 3.5x3.5 Km2. The Haversine formula was used for the calculation of distances, since all the quantities, in the sentinel data, are given in degrees and in this case a conversion to km was necessary. At the end of this processing, the product has a number of different sectors depending on the size of the area considered. Since the Sentinel coverage is not uniform, that is, there are sectors that intersect with multiple sentinel patches and sectors that are not intersected by the latter, and this coverage varies according to the pollutant considered, I have acted as follows:

(i) the sectors that intersect with more sentinel products, for a given pollutant, have been assigned the average value of the same;

(ii) the sectors with no intersection have been assigned the value of the closest patch for each pollutant.

As regards the values of the auxiliary data, a daily aggregation of the data belonging to each sector was carried out. The maximum, minimum and average value of each feature was calculated through a zonal statistic.

Database

After applying the Mapping function that allows to create a geographical link between the pollutant data and those of the weather conditions, the database was created, which houses the datasets used in the modelling process, consisting of the following information:

- Date: reference day
- Sector
- Pollutants (t)
- Auxiliary data information (t).

The database and the different datasets allow to analyse the different data sources and correlate them through the machine learning methodologies.

7.3 Collected data and data collection methods

Data from the S5P satellite and data from the EEA air quality database were used. All files contain hourly data, separated by the pollutant or the measured parameter: CO, SO2, NO2, O3. Hourly events were collected between January 1, 2019 and January 1, 2020.

Sentinel 5P offers a wide range of products that characterize the atmospheric composition. Among these it was chosen to use the following components:

● Sulphur dioxide (SO_2);

● ozone (O_3);

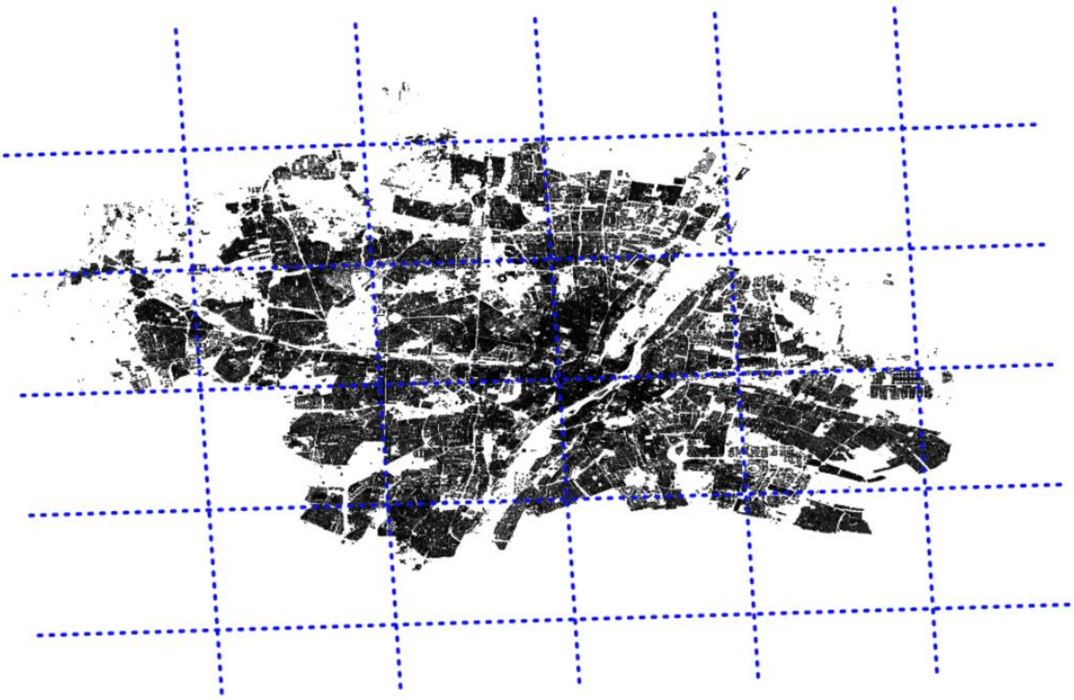
● carbon monoxide (CO);

● Nitrogen dioxide (NO_2).

All are downloaded at level 2 of data processing, and processed at level 3 as described in chapter 4.2 of this thesis. In addition, the possibility of enriching the entire data set by adding additional functionality from the data reported in chapter 5.3 is considered,

Having the data on a global scale it is very easy to obtain the information of all the cities of the world. The S5P product processing workflow was conducted, using Python languages together with HARP, Panoply and QGIS software. The column density of all data is taken from the total columns of the different products. This conversion is based on a series of parameters, referring at the same time to dimensions (time, latitude and longitude), variables (names and data types), attributes and coordinates. The main steps are 3.

The first step involves the creation of a spatial grid, which covers the European region of each individual test city, with a spatial resolution of 5 Km × 5 Km resulting from the resampling of the original product. Below I show the grid used for the case study of the city of Munich:

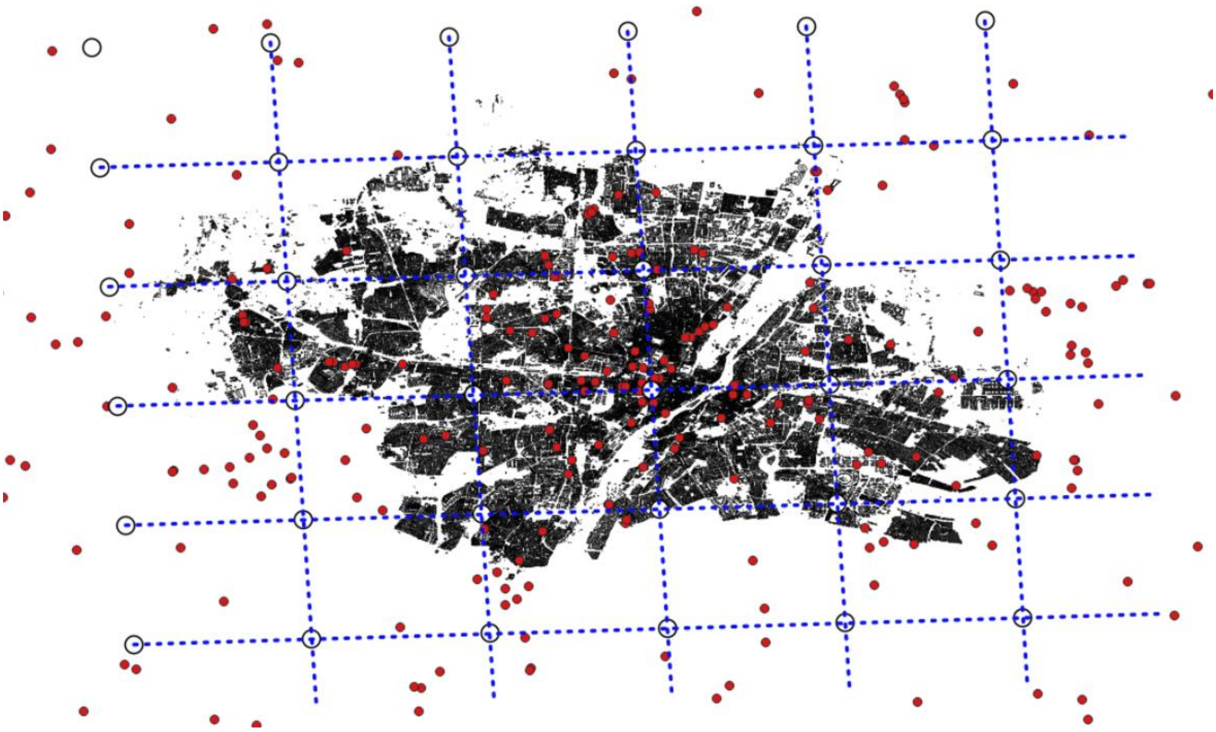


85 Regular grid city of Munich, builder on the footprint of sentinel-5p

The second step processes the data by filtering it with a numerical density value of higher quality than 75, in order to remove cloud-induced errors.

The third and last step is to derive the density of the number of tropospheric columns per day in international units of molecules / cm2 or in Dobson 'DU' depending on the index, combining the products by time dimension, in order to obtain a single raster that covers the entire study area.

For the column density mosaic, the different indices at 5 and 10 days were derived also using the time dimension parameter, using an arithmetic mean of the cell values from overlapping layers. After the image processing phases and the derivation of the pollution parameters for the density of the number of tropospheric columns of the various indices, a GIS analysis was used in order to extract data from essential points such as the main industrial and urban centres from the city. The time series values were extracted from the satellite and measurements on the ground and in different locations for the 12-month period.



86 Regular grid city of Munich, builder on the footprint of sentinel-5p, with attached ground station (atmospheric survey)

The statistical data have been reported in graphs, in order to analyse the correspondence of the trendline dynamics over time through visual comparison. Best-fit lines or trend lines have been created as straight lines to show the overall direction of the data. Statistics representing the variability of the daily tropospheric column values of each data compared to the average value of the semester were plotted, based on the data of the days with clear skies collected by the TROPOMI sensor in 2019, in order to show the seasonal characteristics, as well as the differences between the different periods of the year.

The possible identification and installation of a sponge building was carried out through a cross-correlation analysis to validate the results and statistically explain the correspondence between the calibrated measurement of the TROPOMI spectrometric sensor and the corresponding average from the ground station measurements.

Analysed cities

The 1-year timeframe was considered as the reference period, from January 2019 to January 2020. The data after January 2020 were not used because, due to the Covid-2019 pandemic, they could be distorted compared to the normal activities in the cities. As already mentioned in chapter 4.2, the Sentinel-5P mission is a recent mission, and the available data provide complete coverage of all products only starting from December 5th, 2018. The data are all downloaded from the ESA portal and use a common naming which can be read by following the table presented below.

For example, the image with the Name: S5P_OFFL_L2__O3_____20191202T070058_20191202T084228_11065_01_010107_20191208T093203.nc

Character number	Meaning	Example	Definition
3	Mission name	S5P	Sentinel-5P
4	Data processing type	OFFL	Offline
10	Product identifier	L2	Level 2
2	Product sensor	O3	Ozone
15	Acquisition start time (UTC)	20191202T070058	Time
15	Acquisition end time (UTC)	20191202T084228	Time
5	Orbit number 2	11065	
2	Collection number	01	
6	Processor version number	010107	
15	Product processing time (UTC)	20191208T093203	
2	File extension (.nc)	.nc	

9 Sentinel 5p Product Naming Convention

All the images and all the orbits present in this year have been downloaded. Before processing them, the orbits were classified by inclination and geographic location to avoid overlapping. Using the temporal and spatial extremes of the study areas, requests were carried out for analogous auxiliary data with the smallest possible granularity. After a domain analysis of the individual features and a correlation study between them, a process of spatial aggregation of the features and a consequent study of statistical quantities have been performed. The use of a 1/6 degree step allowed to create, on the study area, a grid with 3500 acquisition points. The data were divided, first of all, into smaller partitions to correct processing and greater speed. Of each partition created the following was calculated:

The standard deviation which is a statistical dispersion index of a distribution of values. It is also called standard deviation or root average square deviation and is indicated with the Greek letter sigma (σ). The standard deviation formula is:

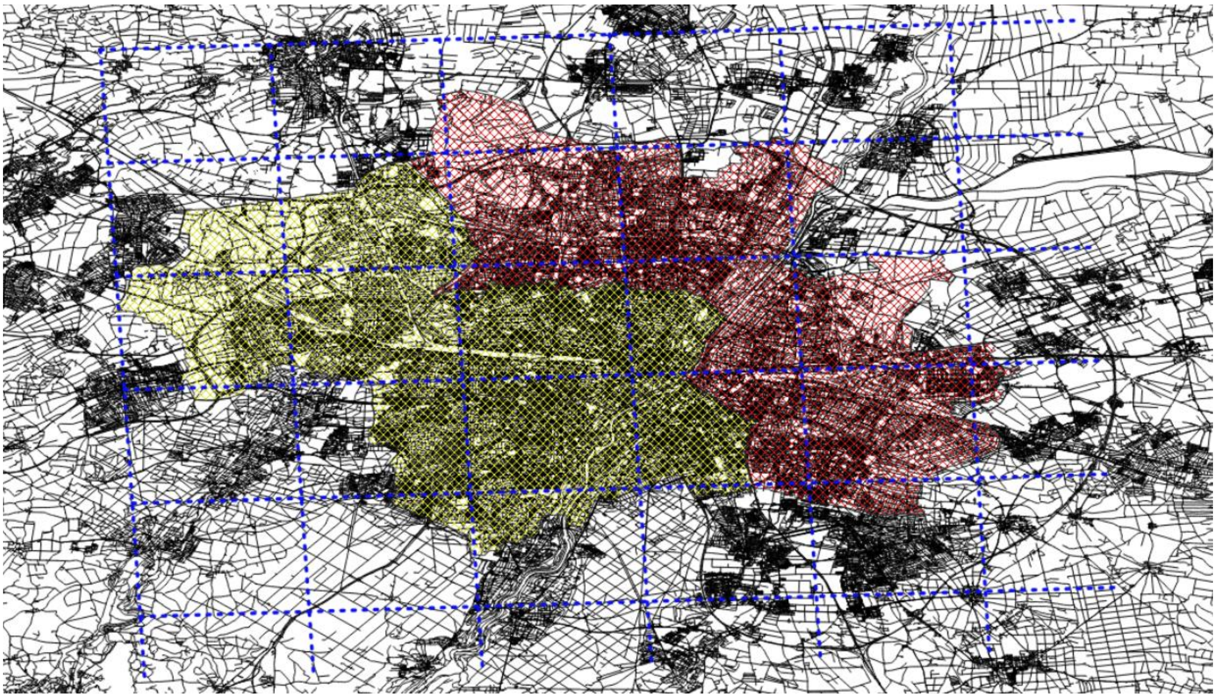
$$\sigma = \sqrt[2]{\left(\frac{\sum_{i=1}^{N}(x_i-\mu)^2}{N}\right)}$$

8 Standard deviation

The standard deviation was intended to reduce the:

- Standard error of the avarage
- Variability of the data

The grid of points was created in combination with a 30-meter resolution DEM that made it possible to have a regular and univocal grid on all the cities analysed. The method can be replicated on a world scale since both the DEM and the sentinel data are globally available. Below are the illustrations of the first partitions created, in order to make the criterion used clearer, and of the final grid.



87 Regular grid city of Munich, builder on the footprint of sentinel-5p, and peripheral control areas.

The matrix correlation analysis was performed which is a method to statistically evaluate the mutual relationship between two or more variables. An indicator is used to calculate the correlation. In statistics there are various coefficients, in this analysis the Pearson correlation index was used. Pearson's correlation coefficient is a measure that represents the correlation between two variables X and Y. It can assume a value between -1 and 1, where: 1 indicates a positive linear correlation; -1 a negative linear correlation; 0 lack of correlation.

$$\rho_{XY} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}.$$

9 Formula coefficient Pearson

where σXY is the covariance between X and Y and σX, σY are the two standard deviations.

The coefficient always assumes values between - 1 and 1:

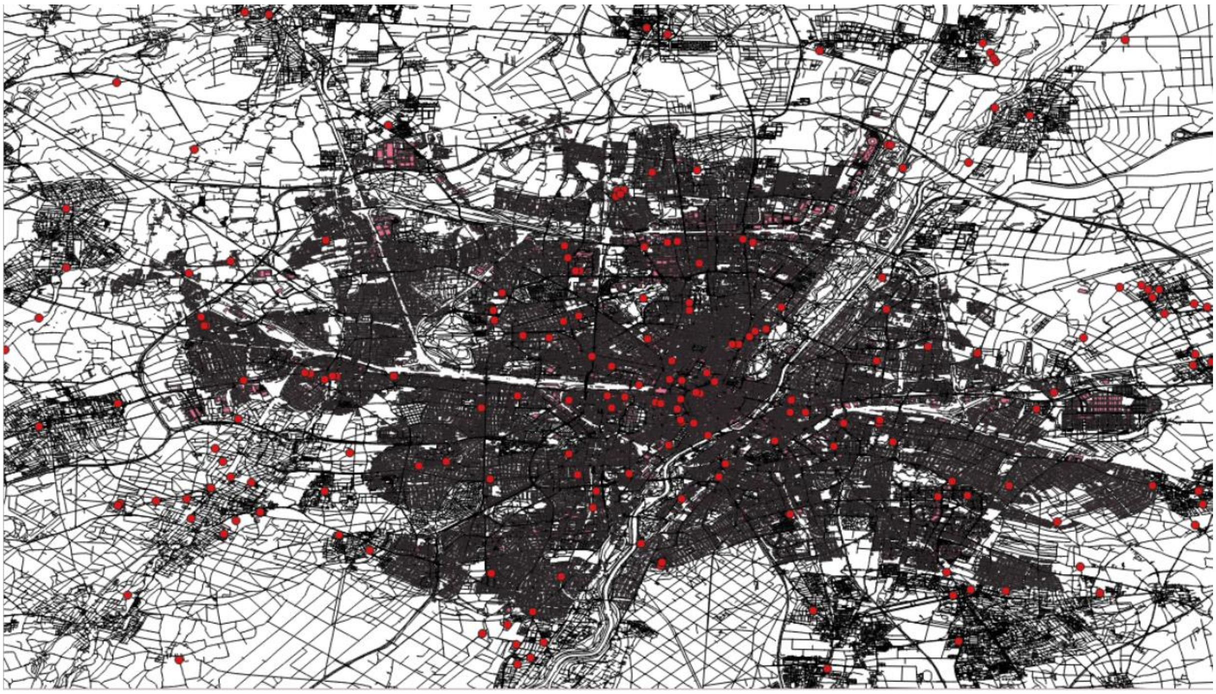
$$-1 \leq \rho_{XY} \leq 1.$$

10 Pearson coefficient value range

A correlation matrix was created. It is a symmetric matrix that presents on both axes the data whose correlation is to be studied. Each cell represents the correlation index between the attribute.

Local Scale Pollution Mapping and Assessment

The Munich case study is also useful for local-scale analyses in order to better understand the role of pollution sources on the definition of air quality parameters. For this reason, Munich has been selected as a case study, and because it is one of the cities in the center of Europe and has been fighting for years to convert its buildings to garden roofs.



88 Atmospheric monitoring station (represented by the red dot)

A limit presented by the Sentinel-5P mission is to provide information regarding the entire atmospheric column that encompasses both the tropospheric and stratospheric layers, which makes the data provided not comparable with data obtained from ground sensors.

However, 130 air quality ground stations were selected in the research. The ground stations had the task of validating and confirming the reliability of the data and of the methodology used on pollution monitoring. But it was not possible to correlate the results on a single result. Thus, satellite-based TROPOMI products in terms of tropospheric column number density are statistically correlated with independent data sets of soil-based measurements of the same index concentrations, from selected hot spots across Europe on clear sky days. The positions of the points correspond mainly to urban and suburban air quality monitoring stations, but is carried out directly by the agency providing the data.

7.4 Data Validation

The EPA, the EU and many other national environmental agencies have established air quality standards and guidelines regarding allowable levels for these pollutants. The Air Quality Index (AQI) is an indicator created to report air quality, measuring how clean or unhealthy the air is and what associated health effects could be of concern, especially for at-risk groups. It focuses on the health effects that can be experienced within hours or days of being exposed to polluted air. It is calculated on the basis of the maximum individual AQI recorded for the pollution criteria mentioned above.

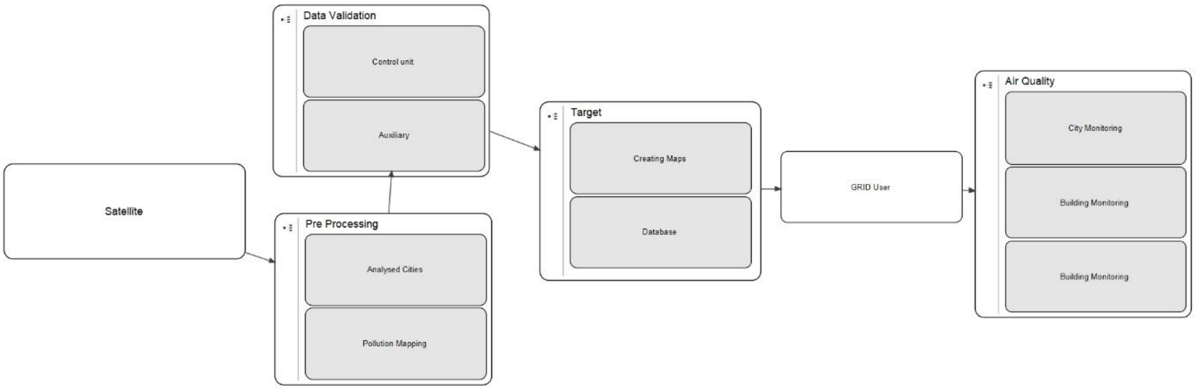
Building a forecasting system, based on the concentration levels of individual pollutants, capable of predicting air quality every hour, will make the AQI more flexible and useful for the health of the population. Systems capable of generating alarms based on air quality are therefore necessary and important for populations. They can play an important role in health alerts when air pollution levels exceed specified levels; in addition, they can complement existing emission control programs, for example by giving environmental regulators the option of 'on demand' emission reductions, operational planning or even emergency response.

For the validation of the models the ML technique was used as explained in chapter 5.3.5. the subdivision of the total dataset into N parts of equal size was envisaged. In a cyclical manner, using a master subset as validation of the secondary set, the model was trained. The model is trained N times, in order to overcome the problem of overfitting. Furthermore, it should be remembered that the data present in this thesis present a spatial difference as well as a temporal difference. For this reason, a master grid is recreated that allows the algorithm to divide the outgoing dataset. In this way, during the split Train there are no temporal overlaps of the datasets. Since each instance of the starting dataset goes to consider a time window lasting 1 day, to make sure that there is no overlap.

In conclusion, to validate S5P data, ancillary data from other satellites such as OMI (in the case of Ozone data) and ground stations were also used. The data was literally divided into 10 samples. For each fold of samples, learning was carried out for only nine folds, while the remaining fold was used for validation. However, within the cross-validation cycle, the characteristics with the best score (in training) were selected based on univariate statistical tests.

For each set of important characteristics, the machine learning model established with the training folds was used to predict physiognomic classes with the validation fold. The minimum number of features with the best score that gave the highest N coefficient was noted as the optimal number of features. The standard deviations of the overall accuracy and the N coefficient across the 10-fold cross-validation cycle in the case of the optimal number of features were also calculated. The overall accuracy, expressed by the sum of the true positives and true negatives divided by the number of validation points, measures the correctness of the classification. The coefficient N measures the agreement between the parties by counting the proportion of cases where the predictions agreed with the validation data (observed agreement) after adjusting for the proportion of agreements that occurred by chance (expected agreement).

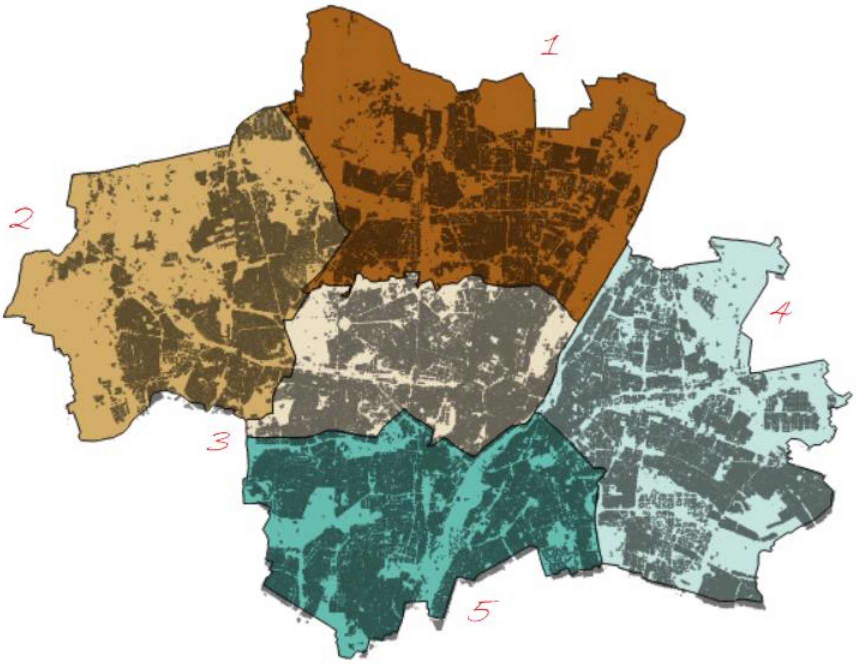
A diagram is shown below in graphic form that attempts to summarize and illustrate all the phases of the Methodology.



89 Flow chart of the methodology used

7.5 Processing model

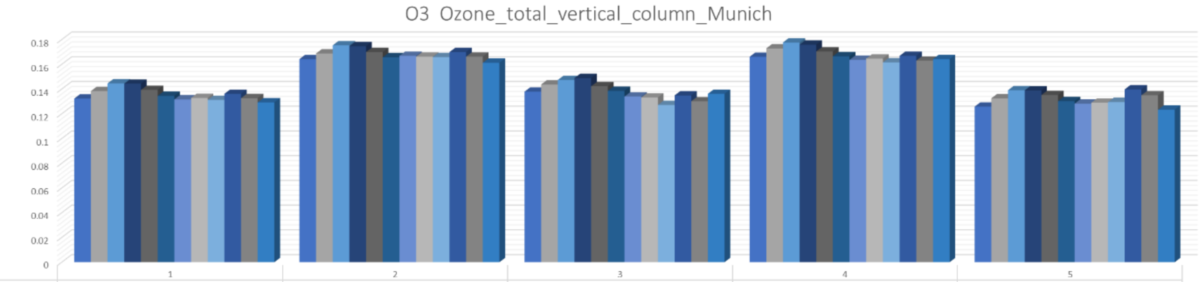
To better define and locate the areas with the highest pollution, Munich has been divided into 5 areas used as a classification tool for statistical surveys. The 5 areas are very different from each other. For example, area 3 is the historic centre, area 1 is mainly industrial, area 4 and 5 are residential and industrial, finally area 2 is a residential area with a strong presence of greenery.



97 Portioning of Munich in five study areas.

For each zone the satellite data were downloaded, reprojected on the ground and cleaned of the wrong pixel data and those with clouds. The predictive models assigned to each area a continuous output value. RMSEMean Squared Error (MSE), the mean square difference between the expected values and the estimated values, was applied. It is calculated as the sum of the variance and the square of the estimator's bias.

The result is shown accordingly with the value listed by index, zone and month.

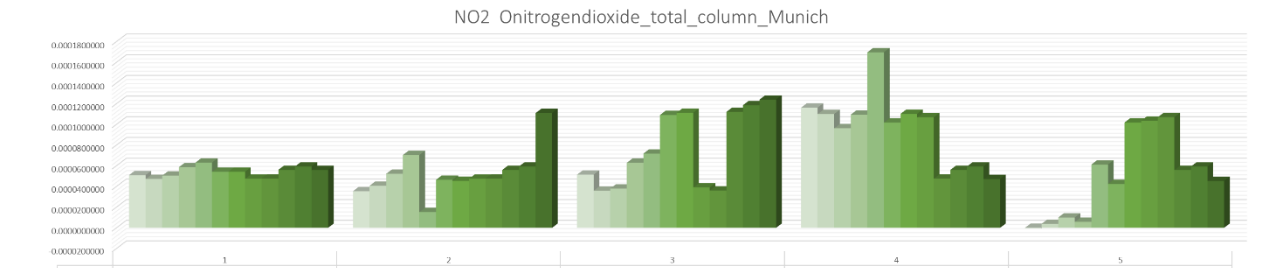


	1	2	3	4	5
Febrary	0.132311046	0.1641437032	0.1378316135	0.1660317731	0.1257487268
March	0.1383837461	0.1687425296	0.1436697420	0.1728205470	0.1324727610
April	0.1446065903	0.1753409199	0.1472873163	0.1776011855	0.1390156378
May	0.1442748308	0.1746227311	0.1488943501	0.1758717233	0.1388222032
June	0.1392713785	0.1698974023	0.1422577759	0.1703743728	0.1351167789
July	0.1344473362	0.1656716578	0.1385362367	0.1665170102	0.1302033630
August	0.1315846890	0.1668070033	0.1339532605	0.1635839780	0.1282118624
September	0.1327833980	0.1661618687	0.1331559689	0.1646160552	0.1289726210
October	0.1312318891	0.1657884990	0.1271125691	0.1615906726	0.1294616155
November	0.1360859722	0.1698184833	0.1347771755	0.1668203018	0.1397113940
December	0.1326420307	0.1661975216	0.1300847098	0.1629899310	0.1349175071
January	0.129234061	0.1612333496	0.1361117255	0.1642123635	0.1232748294

10 Distribution of Carbon Monoxide within the 5 study areas in Munich expressed in mol/m2 (at variable temperature and pressure) – Monthly Average

The table above shows the density values of the vertically integrated CO column. The most favorable conditions for the stagnation of this pollutant occur in winter. The main anthropogenic source of CO is represented by vehicle exhaust gases, especially when operating at low speeds such as in situations of intense and slowed-down traffic. Even in the case of Munich, the highest values are found in the winter period. But it must also be said that the summer data were influenced by favorable weather and climatic conditions that helped to slightly clean up the atmosphere.

Furthermore, the same table highlights the values of the monthly averages, which show the highest values and therefore a greater concentration of CO in two areas (2 and 4) compared to the others. It should be remembered that the values are very similar to each other. After calculating the air columns of the entire city for a period of 15 months, for the purpose of this work it was necessary to detect with certainty the available buildings and their conformation. The carbon monoxide (CO) data is calculated using the measurement of the terrestrial radiance of the clear sky and the cloudy sky in the 2.3 µm spectral range of the short wave infrared part (SWIR) of the solar spectrum. Clear sky observations from TROPOMI provide total CO columns with sensitivity to the tropospheric boundary layer. For cloudy atmospheres, the sensitivity of the column changes with the path of the light.

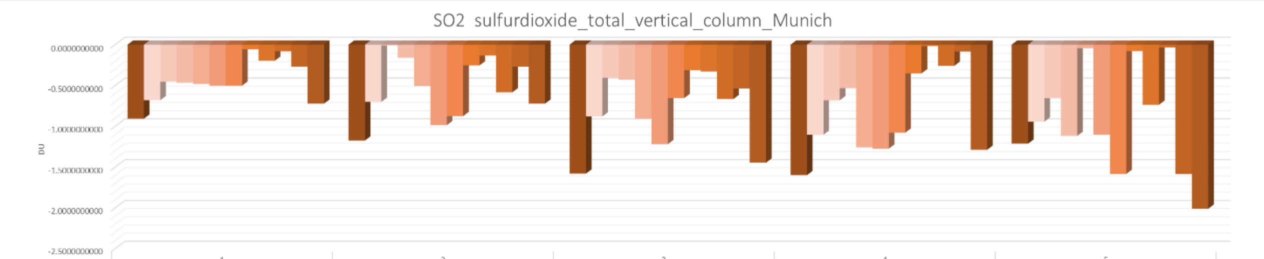


	1	2	3	4	5
Febrary	0.0000508550	0.0000353779	0.0000513165	0.0001160523	-0.0000003655
March	0.0000471519	0.0000406347	0.0000358107	0.0001098971	0.0000038440
April	0.0000503936	0.0000522083	0.0000378550	0.0000962208	0.0000098969
May	0.0000584931	0.0000702738	0.0000628271	0.0001093905	0.0000057747
June	0.0000629321	0.0000152902	0.0000717051	0.0001696227	0.0000611174
July	0.0000541591	0.0000463462	0.0001090242	0.0001018010	0.0000423785
August	0.0000541591	0.0000453171	0.0001110700	0.0001101330	0.0001018010
September	0.0000474550	0.0000474550	0.0000389361	0.0001066906	0.0001034288
October	0.0000476419	0.0000476419	0.0000360482	0.0000476419	0.0001068775
November	0.0000559738	0.0000559738	0.0001119476	0.0000559738	0.0000559738
December	0.0000592356	0.0000592356	0.0001184712	0.0000592356	0.0000592356
January	0.0000559163	0.0001108180	0.0001239164	0.0000470743	0.0000452126

11 Distribution of Carbon Monoxide within the 5 study areas in Munich expressed in mol/m2 (at variable temperature and pressure) – Monthly Average

Nitrogen dioxide is also linked to the role it plays in the formation of photochemical smog. In weather conditions of stability and strong insolation (spring-summer), ultraviolet radiation can cause the dissociation of nitrogen dioxide and the formation of ozone, which can recombine with nitrogen monoxide and re-establish a situation of equilibrium.

In the case of Munich all periods are normal and there are no particular differences between the different areas.

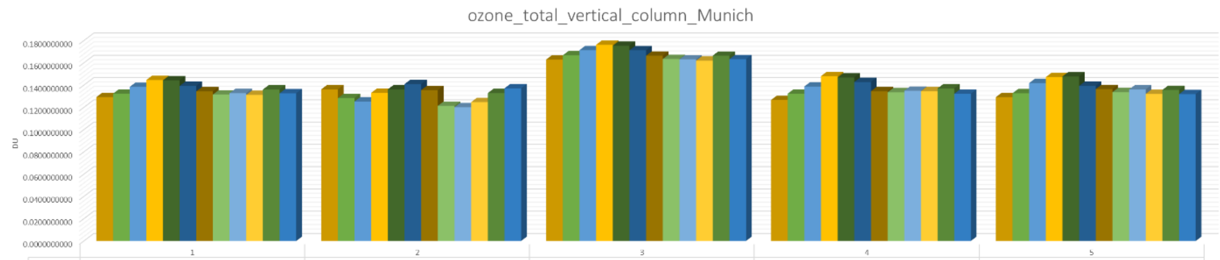


	1	2	3	4	5
January	-0.9075681039	-1.1753878123	-1.5803491365	-1.5990324085	-1.2136935187
Febrary	-0.6808882071	-0.7015570676	-0.8798384950	-1.1044002710	-0.9431217004
March	-0.4551474727	-0.0099086187	-0.4076881656	-0.6821414906	-0.6565300025
April	-0.4670866729	-0.1610854783	-0.4315665661	-0.5335196763	-1.1191751481
May	-0.4819379193	-0.5068805002	-0.9065079128	-1.2588781991	-0.0431224427
June	-0.5026067798	-0.9868894017	-1.2200294767	-1.2741072069	-1.1033064844
July	-0.5026067798	-0.8754437458	-0.6550833445	-1.0789336112	-1.5846536116
August	-0.0573679258	-0.2549878939	-0.3123558197	-0.3511754562	-0.0790944291
September	-0.1966055852	-0.1338577507	-0.3304633358	-0.0176252609	-0.7364002980
October	-0.0823105067	-0.5849172865	-0.6672277932	-0.2597111938	-0.0362283659
November	-0.2694667048	-0.2694667048	-0.5389334096	-0.0854329333	-1.5847473193
December	-0.7229671811	-0.7229671811	-1.4459343622	-1.2890630483	-2.0120302294

12 Distribution of SO2 within the 5 study areas in Munich expressed in DU (at variable temperature and pressure) – Monthly Average

Table 12 shows the concentration of SO2 which shows a very evident seasonal variation, with the maximum values in the winter season, this is due to the fact that domestic heating systems fed with solid fuels are in operation. Up to about 30 years ago, sulphur dioxide was considered one of the main air pollutants while today, the progressive improvement of the quality of fuels (lower sulfur content in refinery products) and the increasingly widespread use of methane gas they markedly decreased their concentration in the atmosphere.

SO2 is the main cause of "acid rain" as it tends to turn into sulphuric anhydride and, in the presence of humidity, into sulphuric acid. Sulphur dioxide at low concentrations causes a slowdown in the growth of plants, while at high concentrations it causes their death by altering their physiology in an irreparable way. In the leaves, the sulphur dioxide is transformed into sulphurous acid and sulphites, from these, by oxidation, sulphates are generated. When the level of sulphur dioxide in the air becomes unsustainable, unused sulphites accumulate in the leaves which, at high concentrations, cause the destruction of chlorophyll, cell collapse and tissue necrosis.



	1	2	3	4	5
January	0.1292340606	0.1361943930	0.1629547876	0.1266010057	0.1291999430
Febrary	0.1323110461	0.1283746362	0.1667478470	0.1322769285	0.1326910750
March	0.1383837461	0.1253618449	0.1713783414	0.1387637750	0.1418510222
April	0.1446065903	0.1331151575	0.1762034828	0.1480738663	0.1472185289
May	0.1442748308	0.1362353414	0.1753778251	0.1468867694	0.1478393886
June	0.1392713785	0.1409100145	0.1713410526	0.1428359363	0.1393479608
July	0.1344473362	0.1355046779	0.1664466252	0.1345239185	0.1364310437
August	0.1315846890	0.1214254349	0.1634173461	0.1335683966	0.1337085234
September	0.1327833980	0.1200932562	0.1631421815	0.1349072325	0.1361172046
October	0.1312318891	0.1247439086	0.1619662187	0.1345656957	0.1321568103
November	0.1360859722	0.1328705251	0.1664338725	0.1370108934	0.1356835758
December	0.1326420307	0.1371433139	0.1632680545	0.1322396343	0.1319123679

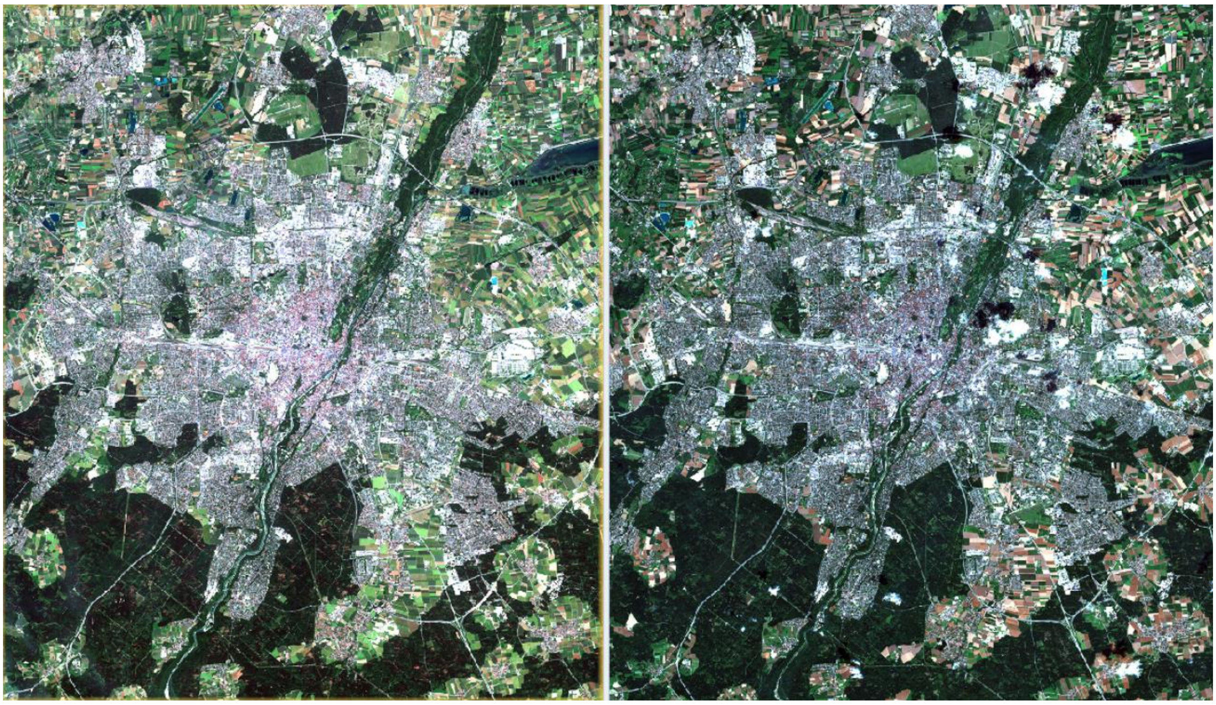
13 Distribution of Ozone within the 5 study areas in Munich expressed in DU (at variable temperature and pressure) – Monthly Average

Environmental O3 concentrations tend to increase during the warm and sunny periods of the year. During the day, the levels are low in the morning (the trigger phase of the photochemical process), reach their maximum in the early afternoon and progressively decrease in the evening as the solar radiation decreases. Ozone is a secondary pollutant, e.g. it is not directly generated by anthropogenic activities and is formed in the atmosphere following a cycle of complex photochemical reactions involving in particular nitrogen oxides and some of the volatile organic compounds (VOCs), called precursors. Ozone causes a reduction in plant growth and, at higher concentration, chlorosis and necrosis of the leaves. The first visible effect occurs on chloroplasts which, after exposure, take on a light green colour and break easily, dispersing the chlorophyll in the cell cytoplasm. Zone 3 has higher values than the other areas, but being the historic centre I presume it is due to the scarce presence of urban greenery, which is more present in the remaining 4 areas. Urban greenery emitting volatile organic compounds (VOCs), mitigates and contributes to problems inherent in air quality, including the formation of O3 [177].

7.6 Economic values and building identification

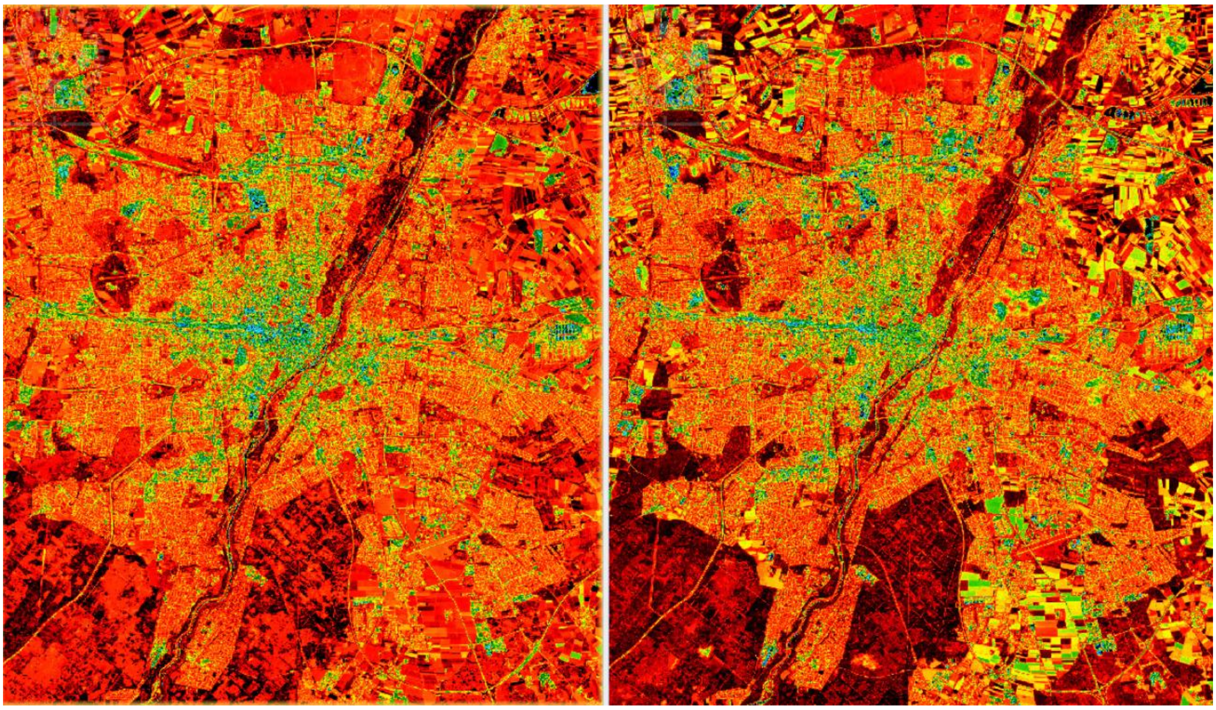
As seen above, climate change is expected to increase environmental risks to people, goods, economies and ecosystems, including the risks of heat stress, extreme storms and rainfall, inland and coastal flooding, landslides, pollution, drought, water scarcity, sea level rise and storm surges. Increasing urban green spaces is a proposed method to mitigate these problems through urban planning.

Green space in urban areas reduces many pollutants presented previously: in particular, atmospheric CO_2 is reduced through sequestration, shading and evapotranspiration, making it the direct target of this thesis work. Shading and evapotranspiration indirectly reduce atmospheric CO_2 by reducing the need for air conditioning, which decreases CO_2 emissions from power generation. CO_2 sequestration is the direct removal of CO_2 from the atmosphere through photosynthesis and carbon fixation in plant litter and root exudates. CO_2 sequestration in plants and soil has already been quantified, showing that an ecosystem can act as a carbon sink for a sufficient period of time. However, urban areas are mainly covered by impermeable surfaces (e.g. roads, parking lots and buildings), which makes it difficult to plant trees and increase urban green. Consequently, a green roof, which replaces an impermeable surface with a green space, is a key solution to this problem. The total area of green roofs in the city of Munich has increased by about 12 times between 2015 (358.74 m^2) and 2020 (4,304.88 m^2). The data was obtained by processing sentinel-2 data: 24 images were downloaded, two for each month of the year. The vegetation indices (NDVI) and the foliage area index (LAI) have been processed from the images. The NDVI index had the purpose of controlling the vegetation throughout the phenological year that allowed to distinguish plant areas from anthropogenic areas. Instead, to distinguish green areas from garden roofs, the LAI index intertwined with the layout of the buildings in the city of Munich was used. The Leaf Area Index helps to obtain a measure of the leaf area per unit of soil surface and is an essential parameter for the study of agricultural coverings on the roofs of our cities. Once all the images were analysed, a unique stamp was created, which gave life to the masking of the green buildings. Below is an RGB image on the left year 2015 on the right year 2020. The 2015 images were downloaded at level 1 and resampled at level 2 with the Sen2COR software. For the 2020 images, I was able to take advantage of the corrected atmospheric data at level 2 (available on the ESA website).



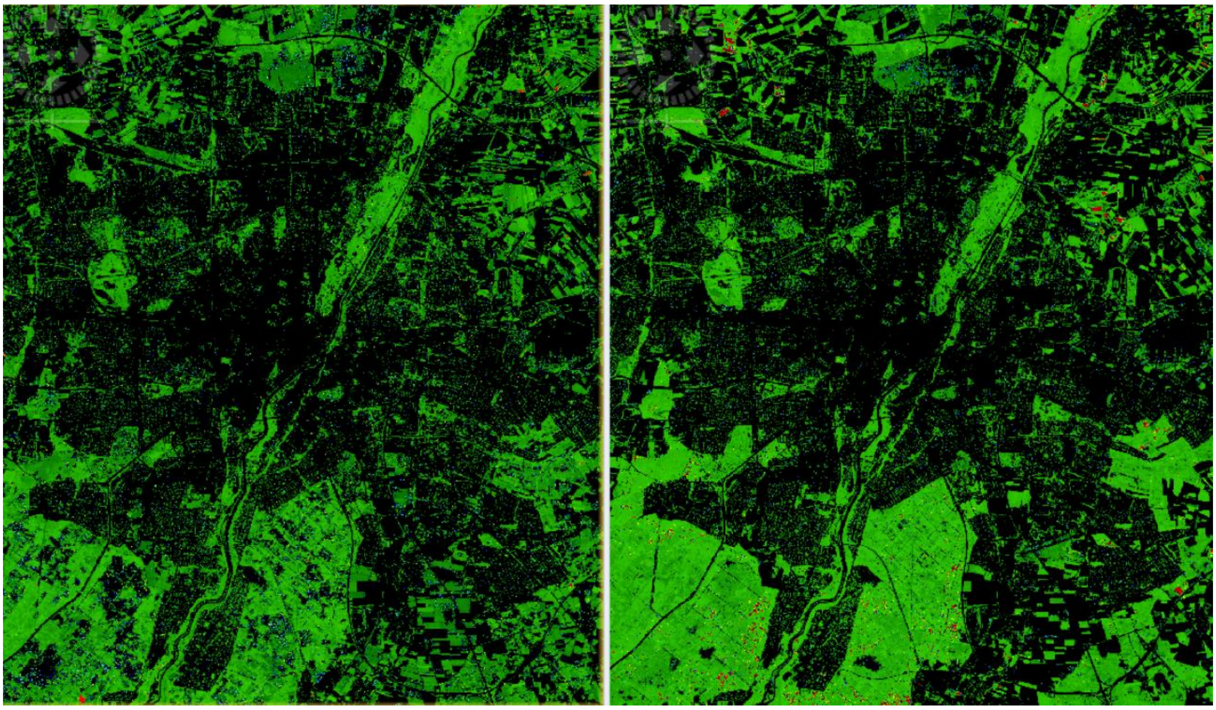
83 Pair of RGB images level 2 Sentinel-2 On the left year 2015 and on the right year 2020 represent the city of Munich

The different elaborations produced a single image for the entire year 2015 and 2020. The images show differences even with the only eyes. You can see the profound changes in the urban fabric of the city of Monaco. The 2015 images on the left and 2020 on the right are shown below. The buildings are highlighted in blue, with a resolution of 10m * 10m. On the other hand, the red shows the vegetated areas.



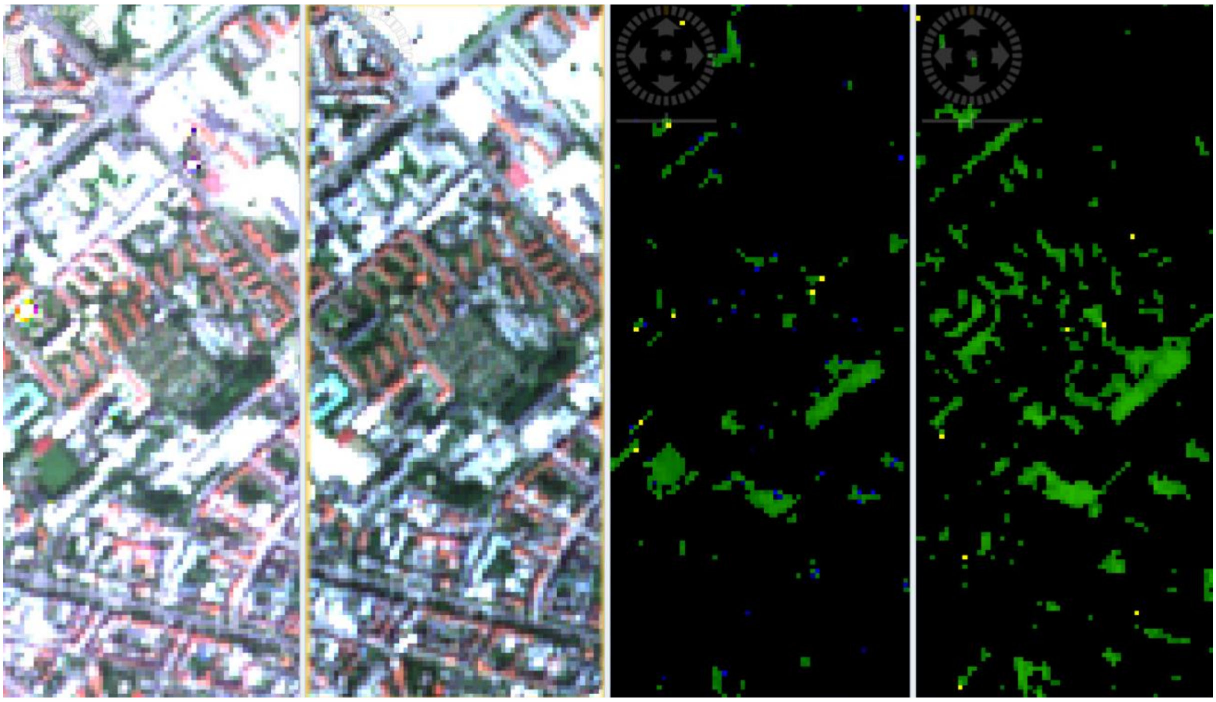
84 Pair of classified images of the Sentinel-2 satellite In the year on the left 2015 and in the year on the right 2020 they represent the city of Munich

Through a supervised neural network it was possible to create a detailed map of the city's green areas.



85 Pair of images representing the environmental mask In the year on the left 2015 and in the year on the right 2020 they represent the city of Munich.

After the neural network, the superimposition of the anthropogenic input masking (OSM buildings) made it possible to interpolate the green areas on the sentinel-2 grid with the real polygons of the buildings. The interpolation made it possible to create the difference between the map of green roofs for the year 2015 and the year 2020.



86 Detail Building with green roof in the city of Munich RGB and Mask Green Buildings. Respectively for both images on the left 2015 and in the year on the right 2020.

Once the green roofs were identified, it was possible to create a T0 value for the city of Munich which allows any city to understand how much green space it has, but above all how much more surface it will need to have to reach zero impact. (T1). Knowing that green roofs therefore also contribute to the indirect reduction of atmospheric CO^2 through the reduction of the energy consumption of buildings and the sequestration of carbon in plants and substrates, the energy saving potential of green roofs could be extensively studied also using pre-existing software such as the Green Roof Energy Calculator[65], which allows to readily estimate the annual energy savings for buildings with a green roof.

[65] The Green Roof Energy Calculator is an online tool that allows users to compare the annual energy performance of a building with a vegetative green roof to the same building with either a dark roof or a white roof. Simulations are available for new construction (ASHRAE 90.1-2004) and old construction (pre-ASHRAE 90.1-2004) office and residential buildings driven by typical precipitation and weather data. Representation of an irrigation schedule is optional. The Green Roof Energy Calculator was developed through a collaboration led by Dr. David Sailor (while he was on the faculty of Portland State University), along with researchers at the University of Toronto, and Green Roofs for Healthy Cities. The effort was funded by the US Green Building Council with additional financial and in-kind support from University of Toronto, Portland State University, Green Roofs for Healthy Cities, and Environment Canada.

87 Green Roof Calculator calculation example [175]

On the contrary, there are no software that allows to measure the ability of green roofs to sequester carbon in plants and substrates, there are no software capable of interpolating sequestration data with pollutant monitoring data in the city. Also it should be remembered that green roof systems are designed to facilitate installation and alteration and generally consist of vegetation mats, substrate, substrate containers. These green roof system components also have their potential environmental impacts during their life cycle (raw material extraction, production, distribution, use, repair and maintenance, and disposal or recycling). Several studies have used the Life Cycle Assessment (LCA) methodology to determine the environmental impacts of green roofs [176]. These studies compared the environmental burden and possible benefits of green roofs and assessed their overall environmental impact. In particular, a study [177] indicated that the annual reduction of air pollution from a green roof offsets the emissions associated with its production after 13-32 years. For this reason, the installation and maintenance of the garden roof will also be taken into account in this thesis product. However, there have been few studies on the CO^2 offset of modular green roofs and the carbon balance of a modular green roof system, e.g. whether it acts as a well or a source, will not be covered in this thesis.

In addition to the environmental impact, there is also economic gain as a secondary objective. The only study that addressed this issue was that drawn up by a team of Japanese researchers in 2018: [178] the study quantified the CO2 emitted during the production and maintenance of a hypothetical modular green roof and estimated the reduction of CO2 from energy saving and CO2 sequestration. The study results show that CO2 emissions are offset through CO2 sequestration and energy savings after 5-9 years, indicating that green roofs contribute to the reduction of atmospheric CO2 and the mitigation of global warming during their cycle. of life. Furthermore, the same study provided in detail the quantity of pollutants per component of the garden roof and allowed to identify that the greatest quantity of pollutants is produced for the substrate, for the gutters, for fertilizers and for irrigation. The images below are taken from the same study:

System Components and Maintenance	Main Raw Material	Required (for 200 m^2)
Substrate	Perlite	1572 kg
Substrate container	Polypropylene	800 kg
Water reservoir tray	Polyvinyl chloride	174 kg
Water proofing membrane	Polyvinyl chloride	55 kg
Edge divider	Aluminum	75 kg
Irrigation pipe	Polyvinyl chloride	5 kg
Irrigation tube	Special polyethylene	208 m (142 $)
Automatic watering device	-	1 machine (231 $)
Irrigation	Water	161.6 $t \cdot year^{-1}$
Fertilizer	Compound fertilizer	8 $Kg \cdot year^{-1}$

88 The main raw material and the quantity of each component used for the hypothetical green roof in the practice of production and maintenance the chart is present in the CO2 study Payoff of Extensive Green Roofs with Different Vegetation Species Page 4 [176]

System Components	CO_2 Emission Factor	CO_2 Emission ($kg\text{-}CO_2 \cdot 200\ m^{-2}$)	CO_2 Emission ($kg\text{-}CO_2 \cdot m^{-2}$)
Substrate	1.15 $kg\text{-}CO_2 \cdot kg^{-1}$	1809	9.04
Substrate container	1.89 $kg\text{-}CO_2 \cdot kg^{-1}$	1512	7.56
Water reservoir tray	3.70 $kg\text{-}CO_2 \cdot kg^{-1}$	644	3.22
Water proofing membrane	3.29 $kg\text{-}CO_2 \cdot kg^{-1}$	182	0.91
Edge divider	10.26 $kg\text{-}CO_2 \cdot kg^{-1}$	769	3.85
Irrigation pipe	3.56 $kg\text{-}CO_2 \cdot kg^{-1}$	16	0.08
Irrigation tube	0.55 $kg\text{-}CO_2 \cdot \$^{-1}$	78	0.39
Automatic watering device	0.13 $kg\text{-}CO_2 \cdot \$^{-1}$	30	0.15
Total	–	5040	25.2

89 CO2 emission factors and CO2emissions for each modular green roof system component in this experimen the chart is present in the study CO2 Payoff of Extensive Green Roofs with Different Vegetation Species Page 7 [176]

Maintenances	CO_2 Emission Factor	CO_2 Emission ($kg\text{-}CO_2 \cdot 200\ m^{-2} \cdot yr^{-1}$)	CO_2 Emission ($kg\text{-}CO_2 \cdot m^{-2} \cdot yr^{-1}$)
Water	0.36 $kg\text{-}CO_2 \cdot t^{-1}$	58.8	0.29
Compound fertilizer	0.90 $kg\text{-}CO_2 \cdot kg^{-1}$	7.2	0.04
Total	–	66.0	0.33

90 CO2 emission factors and annual CO2 emissions for each maintenance practice in the hypothetical modular green roof the chart is present in the CO2 Payoff of Extensive Green Roofs with Different Vegetation Species study Page 7 [176]

It emerges that the total CO^2 emissions from the production of a modular green roof were 25.2 kg-CO^2 / m^2 and can be reduced to 24.6 kg-CO^2 / m^2 by removing the irrigation system only. By the same principle, using moss it is possible also to remove emissions due to fertilizers and edge divide reducing emissions by another 11.16 kg-CO^2 / m^2.

Identifying part of the pollutants allows to create a business strategy and continuous monitoring of the city. The pollutants presented in the previous paragraph are only a part of those present in our cities. But identifying them on a global scale allows us to have a tool to fight them locally. The possible additional weapon is to use urban vegetation as a "bioindicator" or as a "remouver" of pollutants from the atmosphere. The pollutants visible from satellite are the ones that cause the greatest health problems. Satellite processing allowed us to identify a greater presence of pollutants in zones 1 and 4 among all indices.

Once the areas with the greatest air pollution were identified, the roofs with the greatest absorption potential had to be identified.

Identifying the buildings was not difficult, the shapefile of the buildings was downloaded from the OSM database and compared it with a Sentinel-2 3 images from August 2019. Although Sentinel-2 data have a resolution of 10 m * 10 m and are not very useful for the urban center, it was preferred to use them anyway to make a comparison with the available OSM DATA, and validate the effective goodness of the geometries. Therefore, Sentinel-2 images were classified into one to remove the clouds and any shadows, after which a Pixel and object segmentation was carried out which determined the final vector of the buildings.

Once the buildings of the entire city of Munich were identified, with the help of Google API it was possible to identify the major public buildings in areas 1 and 4. The choice of public buildings is not random, there are at least three reasons that lead to privilege them over private buildings. The first is that they are buildings located in all areas of the city, a second reason is their size, the third and last reason is linked to a business aspect. Such buildings should be the first to adopt green policies and set an example for private individuals. In areas 1 and 4, 65 public buildings have been identified with a total area of 175,156 m². Below we show a table that highlights the dimensions of each individual building, the area in which it is located and its type. Having used Google geocoding I would also have the intended use of the same, but I preferred not to mention it. In the next image I show the buildings in question with a red x.

90 Selected "sponge" buildings located in area 1 and 4 of Munich

Summary table of buildings:

Type	Reason	Area [m2]	zone
building	public	2941	1
building	public	897	4
building	public	1460	1
building	public	6143	1
building	public	872	4
building	public	23591	1
building	public	504	1
building	public	2791	1
building	public	5637	1
building	public	460	1
building	public	6096	4
building	public	29	4
building	public	50	4
building	public	5668	4
building	public	640	1
building	public	1269	1
building	public	381	1
building	public	4308	4
building	public	2828	4
building	public	6996	1
building	public	1697	1
building	public	8881	1
building	public	948	1
building	public	385	4
building	public	9409	4
building	public	4196	4
building	public	2718	4
building	public	257	4
building	public	1117	4
building	public	786	4
building	public	479	4
building	public	619	4
building	public	2237	4
building	public	156	1

building	public	3140	1
building	public	2021	1
building	public	951	1
building	public	1040	1
building	public	2895	4
building	public	2237	4
building	public	969	4
building	public	888	1
building	public	770	4
building	public	538	1
building	public	301	1
building	public	1531	1
building	public	677	1
building	public	1855	1
building	public	4569	4
building	public	5561	4
building	public	2193	1
building	public	799	4
building	public	6451	1
building	public	3858	1
building	public	3170	4
building	public	793	4
building	public	745	4
building	public	1260	4
building	public	780	1
building	public	1122	1
building	public	731	1
building	public	719	1
building	public	14409	1
building	public	737	1
		175156	

10 List of 65 public buildings in munich, with their size, type and area to which they belong.

Now it remains to define the pollutant seizure potential of the extended green roofs in the city of Munich to define the exchanges between urban green and urban atmosphere. During the day the moss like all plants, through microscopic openings (stomata), in addition to emitting oxygen and absorbing carbon dioxide, can also absorb, with a similar mechanism, polluting gases such as ozone (O3), carbon monoxide (CO), dioxide nitrogen (NO2) and sulfur dioxide (SO2). The absorption of pollutants by the leaves depends on their water solubility and the ability to penetrate the cell membrane. By installing moss on 65 public buildings they could reduce the presence of pollutants by 15% per month in the two selected areas. The data were calculated taking into account that moss has a storage capacity of 2,500 μg / m^2 per hour of carbon monoxide [179]. Regarding SO2 and NO2 there is no real seizures of the substance, but it is possible to speak of stomatal absorption and / or deposition on tree tissues. On the other hand, for ozone, since moss is a "low emission" species of VOC, it can be a valid strategy to help reduce O3 levels in the city. Finally, in addition to the storage of pollutants, the moss itself could capture 3.5 kg m^2 of carbon per year, which can be sold on the Voluntary Emission Reductions - VER) through a blockchain-based system.

Using the surface area of the 65 buildings simulated by GIS and the values obtained from the literature review on moss. The specific carbon sequestration value (measured in kg C / m2) of the plant species was multiplied by the total area (measured in m2) of the green roofs. The carbon sequestration potential of moss was analysed to determine both the minimum and maximum sequestration rate. The calculations considered a minimum roof coverage of 50% and a maximum roof coverage of 100%. A carbon sequestration potential was calculated for four different scenarios. The calculations performed to analyze these four different scenarios have been summarized in the next table

Scenario	Type	Specific Carbon Sequestration Rate	Roof coverage	Installation carbon used
1	Minimum Sequestration Potent	Minimum sequestration rate	50%	100%
2	Low sequestration Potential	Minimum sequestration rate	100%	50%
3	High Sequestration Potential	Minimum sequestration rate	50%	100%
4	Maximum Sequestration Potential	Minimum sequestration rate	100%	50%

11 Introduction to the different project scenarios

The calculations were performed on four different scenarios using the two moss sequestration results obtained from the S2 satellites for the city of Munich, both a best case and a worst case scenario for the usable roof area. These calculations are simply a linear relationship, and therefore linear interpolation can be used to determine the carbon sequestration of any percentage of roof coverage between 50% and 100%, for the respective specific sequestration rate. At best, 100% of the roof area approved in the building selection would be converted into a green roof area. In the worst case scenario, 50% of the roof area approved would be converted into a green roof. For example, if some buildings that might contain green roofs actually cannot, or if some buildings cannot fill 100% of their roof with greenery, the 50% scenario would explain this. The results of the four scenario calculations are shown in the next table:

Scenario	Specific Sequestration Rate [1 years]	Roof Coverage	Total Roof Surface Area	Total carbon (C) Sequestration [1 years]	Total CO2 emitted for installation [forfait]
1	5.5 kg/m2	100%	175156 m2	963.358 kg C	23540.9664 kg CO2
2		50%	87578 m2	481.679 kg C	11770.4832 kg CO2
3	2.1 Kg/m2	100%	175156 m2	367.827 kg C	23540.9664 kg CO2
4		50%	87578 m2	183.913 kg C	1581.952942 kg CO2

12 the building surface (measured in square meters [m2]) and the carbon sequestration potential of moss (measured in kilograms of carbon dioxide per square meter [kg CO2 / m2]) to determine the total amount of carbon (measured in kilograms of carbon dioxid

As mentioned, the installation of sponge roofs has a profound initial impact that can be absorbed over the years and create gains and added value for the owner of the building in subsequent years. Before talking about any gains it is fair to talk about costs, installing a green moss roof has an average cost of 200 euros per m^2, instead a kg of carbon costs between € 0.011 and € 0.070, in the simulation I will use a price average of 0.035 €. Of course, all the data placed in the simulation are the result of research, but there may be differences depending on the place of installation. In the next table I will present how the 65 buildings in the city of Munich could help improve air quality and the respective earnings or costs for a 20-year simulation. The tables show the simulation on the four scenarios shown above. Scenarios 1 and 2 manage to reduce installation costs in the first 10 years, from the eleventh, they start to receive direct earnings (Table 15). The third and fourth scenarios cuts installation costs in 20 years and can give profit in the last 20/30 years of life. The costs are net, without specifying any financing or any tax reductions that could be deducted for projects of this type. Table 16 instead shows that in all scenarios there could be economic gains of between 40 and 8 thousand euros per year. The same table also estimates the CO^2 emissions and energy savings of modular green roofs that could be installed in the city of Munich, a hypothetical average has been set for the city's green roofs, starting from the same dimensions as the study shown above 200 m^2 and a substrate depth of a possible moss is 5 cm, I will use these parameters in this emission model. Starting from the data obtained from sentinel-2 in Germany the roofs have a LAI index between 0.10 and 0.30, multiplying this value by the average storage values we can define the reduction of CO^2 in the atmosphere which is added to around 5.5-2.1 kg -CO^2 / m^2 / yr − 1. Both results will become our in put for the scenarios.

The results for Munich's hypothetical green roofs indicate that CO^2 reduction from the combination of CO^2 sequestration and energy saving by a green roof can offset the CO^2 emitted during its production and maintenance after 2/6 years (see table 16). It is generally believed that the lifespan of moss green roof components is between 40 and 50 years [180], so it is clear that the CO^2 reduction of the useful life of modular green roofs offsets the CO^2 emitted during their production and maintenance. Consequently, they suggest that modular green roofs are an effective way to reduce atmospheric CO^2 and mitigate global warming. Finally, other studies identify [181] the CO^2 payback time of solar photovoltaic systems which is between 1.3 and 4.1 years. Therefore, the CO^2 payback time will be one of the indices that could compare the carbon balance of green roofs with that of rooftop solar photovoltaic systems already funded by many member states' campaigns [182].

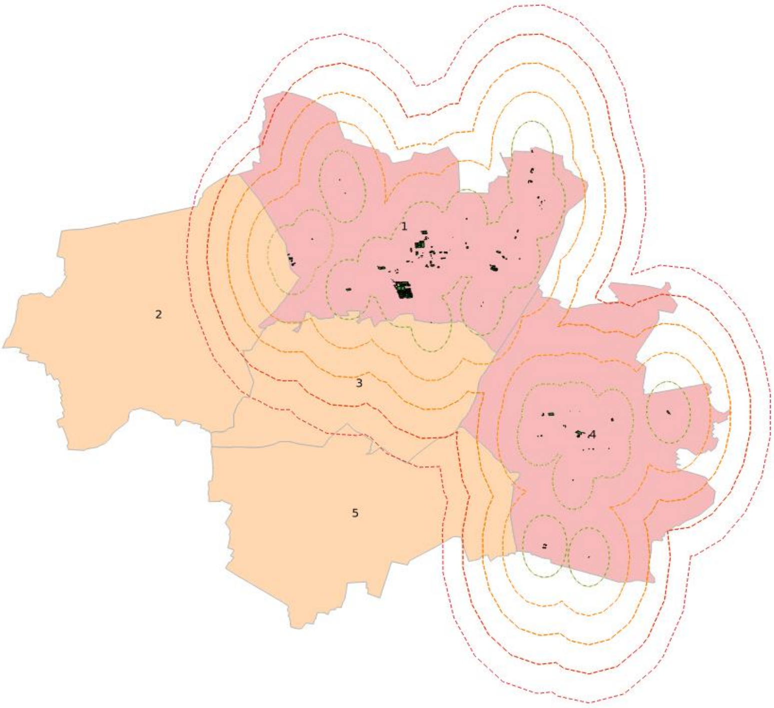
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Public buildings [m²]	Public buildings [m²]	Public buildings [m²]	Public buildings [m²]
2019		175156	87578	175156	87578
Moss Installation Cost [m²]		200 €	200 €	200 €	200 €
Total CO2 emitted for installation [forfait]	0.1344	23540.9664	11770.4832	23540.9664	1581.952942
Carbon Volunteer Market [Average price 2019]	0.04 €				
TOTAL Installation Cost		-350,312.00 €	-175,156.00 €	-350,312.00 €	-175,156.00 €
Carbon sequestration revenue [1-Year]	0.04 €	-311,777.68 €	-155,888.84 €	-335,598.92 €	-167,799.48 €
Carbon sequestration revenue [2-Year]	0.04 €	-273,243.36 €	-136,621.68 €	-320,885.84 €	-160,442.96 €
Carbon sequestration revenue [3-Year]	0.04 €	-234,709.04 €	-117,354.52 €	-306,172.76 €	-153,086.44 €
Carbon sequestration revenue [4-Year]	0.04 €	-196,174.72 €	-98,087.36 €	-291,459.68 €	-145,729.92 €
Carbon sequestration revenue [5-Year]	0.045 €	-152,823.61 €	-76,411.81 €	-274,907.47 €	-137,453.84 €
Carbon sequestration revenue [6-Year]	0.045 €	-109,472.50 €	-54,736.25 €	-258,355.25 €	-129,177.75 €
Carbon sequestration revenue [7-Year]	0.045 €	-66,121.39 €	-33,060.70 €	-241,803.04 €	-120,901.67 €
Carbon sequestration revenue [8-Year]	0.045 €	-22,770.28 €	-11,385.14 €	-225,250.82 €	-112,625.58 €
Carbon sequestration revenue [9-Year]	0.045 €	20,580.83 €	10,290.42 €	-208,698.61 €	-104,349.50 €
Carbon sequestration revenue [10-Year]	0.05 €	68,748.73 €	34,374.37 €	-190,307.26 €	-95,153.85 €
Carbon sequestration revenue [11-Year]	0.05 €	116,916.63 €	58,458.32 €	-171,915.91 €	-85,958.20 €
Carbon sequestration revenue [12-Year]	0.05 €	165,084.53 €	82,542.27 €	-153,524.56 €	-76,762.55 €
Carbon sequestration revenue [13-Year]	0.05 €	213,252.43 €	106,626.22 €	-135,133.21 €	-67,566.90 €
Carbon sequestration revenue [14-Year]	0.05 €	261,420.33 €	130,710.17 €	-116,741.86 €	-58,371.25 €
Carbon sequestration revenue [15-Year]	0.05 €	309,588.23 €	154,794.12 €	-98,350.50 €	-49,175.60 €
Carbon sequestration revenue [16-Year]	0.06 €	367,389.71 €	183,694.86 €	-76,280.88 €	-38,140.82 €
Carbon sequestration revenue [17-Year]	0.06 €	425,191.19 €	212,595.60 €	-54,211.26 €	-27,106.04 €
Carbon sequestration revenue [18-Year]	0.06 €	482,992.67 €	241,496.34 €	-32,141.64 €	-16,071.26 €
Carbon sequestration revenue [19-Year]	0.06 €	540,794.15 €	270,397.08 €	-10,072.02 €	-5,036.48 €
Carbon sequestration revenue [20-Year]	0.06 €	598,595.63 €	299,297.82 €	11,997.60 €	5,998.30 €

13 The table shows the amortization of the installation costs on the 4 scenarios of the thesis. The sequenced carbon is multiplied by a non-constant but dynamic carbon value that could follow the real market values over the years

. Carbon Sequestration	Scenario 1 [kg/m^2* Year]		Scenario 2 [kg/m^2* Year]		Scenario 3 [kg/m^2* Year]		Scenario 4 [kg/m^2* Year]	
2019	963358		481679		367827		183913	
C to CO2	3612.5925		1806.29625	1806.29625	1379.35125	1379.35125	689.67375	689.67375
TOTAL Installation Cost	kg-C/m2 Euro	kg-CO2/m2	kg-C/m2 Euro	kg-CO2/m2	kg-C/m2 Euro	kg-CO2/m2	kg-C/m2 Euro	kg-CO2/m2
Carbon sequestration revenue [1-Year]	38,534.32 €	-19928.3739	19,267.16 €	-9964.18695	14,713.08 €	- 202.6016921	7,356.52 €	-892.2791921
CSR [2-Year]	38,534.32 €	-16315.7814	19,267.16 €	-8157.8907	14,713.08 €	1176.749558	7,356.52 €	-202.6054421
CSR [3-Year]	38,534.32 €	-12703.1889	19,267.16 €	-6351.59445	14,713.08 €	2556.100808	7,356.52 €	487.0683079
CSR [4-Year]	38,534.32 €	-9090.5964	19,267.16 €	-4545.2982	14,713.08 €	3935.452058	7,356.52 €	1176.742058
CSR [5-Year]	43,351.11 €	-5478.0039	21,675.56 €	-2739.00195	16,552.22 €	5314.803308	8,276.09 €	1866.415808
CSR [6-Year]	43,351.11 €	-1865.4114	21,675.56 €	-932.7057	16,552.22 €	6694.154558	8,276.09 €	2556.089558
CSR [7-Year]	43,351.11 €	1747.1811	21,675.56 €	873.59055	16,552.22 €	8073.505808	8,276.09 €	3245.763308
CSR [8-Year]	43,351.11 €	5359.7736	21,675.56 €	2679.8868	16,552.22 €	9452.857058	8,276.09 €	3935.437058
CSR [9-Year]	43,351.11 €	8972.3661	21,675.56 €	4486.18305	16,552.22 €	10832.20831	8,276.09 €	4625.110808
CSR [10-Year]	48,167.90 €	12584.9586	24,083.95 €	6292.4793	18,391.35 €	12211.55956	9,195.65 €	5314.784558
CSR [11-Year]	48,167.90 €	16197.5511	24,083.95 €	8098.77555	18,391.35 €	13590.91081	9,195.65 €	6004.458308
CSR [12-Year]	48,167.90 €	19810.1436	24,083.95 €	9905.0718	18,391.35 €	14970.26206	9,195.65 €	6694.132058
CSR [13-Year]	48,167.90 €	23422.7361	24,083.95 €	11711.36805	18,391.35 €	16349.61331	9,195.65 €	7383.805808
CSR [14-Year]	48,167.90 €	27035.3286	24,083.95 €	13517.6643	18,391.35 €	17728.96456	9,195.65 €	8073.479558
CSR [15-Year]	48,167.90 €	30647.9211	24,083.95 €	15323.96055	18,391.35 €	19108.31581	9,195.65 €	8763.153308
CSR [16-Year]	57,801.48 €	34260.5136	28,900.74 €	17130.2568	22,069.62 €	20487.66706	11,034.78 €	9452.827058
CSR [17-Year]	57,801.48 €	37873.1061	28,900.74 €	18936.55305	22,069.62 €	21867.01831	11,034.78 €	10142.50081
CSR [18-Year]	57,801.48 €	41485.6986	28,900.74 €	20742.8493	22,069.62 €	23246.36956	11,034.78 €	10832.17456
CSR [19-Year]	57,801.48 €	45098.2911	28,900.74 €	22549.14555	22,069.62 €	24625.72081	11,034.78 €	11521.84831
CSR [20-Year]	57,801.48 €	48710.8836	28,900.74 €	24355.4418	22,069.62 €	26005.07206	11,034.78 €	12211.52206

14 The table shows the economic gains of the 65 roofs of the city of Munich and the return of the CO2 emitted for the installation. The difference in the amount of carbon in the soil, C sequestered. it is converted into sequestered CO2 to be able to subtra

Below is an estimate of the advantages of the 65 buildings for the two polluted areas of Munich: proximity to these green infrastructures is a non-trivial condition to ensure the highest level of pollutant abatement. With a buffer of 1 km, a projection of the potential benefits of these sponge buildings on the city can be created. The areas within the green line will benefit most from the presence of green roofs and walls in terms of the mitigation effect of air pollution.



15 Mitigation effects of sponge buildings in the area 1 and 4 of Munich

8 Comparison case study

Rapid urbanization in China and rapid economic growth have caused severe environmental problems in recent years. To solve the problems, the Chinese state launched a spongy city building program in 2015-2016, mainly the program was aimed at absorbing rainwater in Chinese cities. I will refer to those cities to understand if the Chinese model can help to understand if the project presented in this thesis can be sufficient to improve the environmental impact. While the spongy city building initiative is attracting attention and rapidly spreading nationwide, some challenges and risks remain. In China, the spongy city model was tested on 30 pilot cities and a wide range of challenges were identified, from technical, physical, regulatory and financial ones to community and institutional ones.

The most dominant challenges involve uncertainties and risks. The problems, the various opportunities and the atmospheric improvement of those cities will be identified. Based on the results, solutions will be proposed to improve the idea supported by the whole thesis work. These cities provide an opportunity to urge local governments to eventually adopt regulations and permits for sponge cities to alleviate water quality problems related to urban flooding. Of course, it will also address economic and environmental benefits, embracing regional flexibility and results-oriented approaches and focusing on a wider range of funding resources to fund the Sponge City program.

Chinese sponge cities

More and more cities in China as in the rest of the world in the early 2000s faced the challenge associated with urban sustainability and deteriorating water quality. China has decided to tackle the problem by investing in sponge cities. A sponge city addresses sustainable urban development, including flood control, water conservation, water quality improvement, and natural ecosystem protection [183]. Imagine a city with a water system that works like a sponge to absorb, store, infiltrate and purify rainwater and release it for reuse when needed [184]. Sponge City's policies are inspired by various excellences and projects of the past, for example the 1997 low impact development (LID[66]), to green infrastructure in 1983 from the United States (bmP SbeSt[67]) , (IUWM[68]) in 1990-1992 from Europe and (WSUS[69]) in 1992 from Canada,

[66] Vision to multiple areas of environmental management, with the aim of low-cost solutions and respect for ecological conditions (design with nature by McHarg).

[67] Guide to specific practices for water planning in cities, through the integration of non-structural solutions and green infrastructures

[68] Specific application in the urban context of integrated water treatment, with interrelationships between several research areas in the hydrological cycle

[69] Strategies to minimize the hydrological impacts of cities on the environment, through the control of floods, collection and water quality.

to sustainable drainage systems (SUDS[70]) in 1980-1992 from UK and other countries, to water-sensitive urban design (WSUD[71]) in Australia and New Zealand.

The Sponge City program was launched in late 2014, under the direct guidance and support of the Ministry of Housing and Rural Urban Development (UHURD) [185], of the Ministry of Finance (MOF) and the Ministry of Water Resources (MWR). In April 2015, the first group of 16 cities was selected as the pilot sponge city; a year later, in April 2016, the pilot program was extended to another 14 cities. Figure 2 illustrates the locations of these pilot cities. The central government has awarded each pilot city between 400 and 600 million Chinese Yuan (CNY) each year for three consecutive years, and pilot cities are encouraged to raise matching funds through public-private partnerships[72](PPP) and other funding initiatives. With strong support from central government and enthusiastic participation from local governments and private sectors, the Sponge City program has gained strong momentum; however, it should be remembered that numerous obstacles and challenges documented by local newspapers and scientists have emerged over the past five years. The inadequate strategies that have emerged most are attributable to a lack of knowledge and guidance, design standards and codes, as well as adequate education and training that can lead to poor planning and implementation of some spongy city measures. Other frequent problems involve the excessive use of green measures or building green measures in inappropriate or unnecessary places. For example, some sponge parks are largely found in underdeveloped natural areas with over 75% of the land covered by trees, plants and greens, away from the most polluted and industrialized areas. Finally, the designed green roofs were built in arid areas without worrying about water scarcity: rain gardens and depressed green spaces were designed in coastal areas with high aquifers and seawater intrusion problems with no knowledge of plant suitability.

State of the art pilot city

Due to the nature and potential benefits of green infrastructure, most of the pilot cities are located in the central and south-eastern regions of China, where annual rainfall ranges from 410 to 1830 mm and the average annual temperature from 4.6 to 25.5 ° C. In order to acquire diversified experiences, the Chinese government has also selected cities in the north-eastern cold zone and in the arid zones near north-central China. The cities in these first 5 years are actively seeking solutions; most are exposed or engaged in the early stages of green infrastructure planning and LID practices. Most LID measures are planned within the designated pilot areas, and other green

[70] Urban runoff management through the use in cities of sequences of tools that favor natural cycles as much as possible.

[71] The terminology adopted by the various currents of water treatment planning in the city differs mainly for the geographical area in which they are widespread and presents approaches: LID, WSUD, IUWM and SUDS Each of these has contributed to the evolution of urban management towards a holistic approach and environmental integration in a different way

[72] Public-private partnership (PPP abbreviated) is a form of cooperation between public and private authorities, with the aim of financing, building and managing infrastructures or providing services of public interest. This form of cooperation with private entities allows the public administration to attract more investment resources and skills not available internally. The PPP currently represents neither a legal category nor an institution, but rather a descriptive notion of a model of organization and administrative action, expressed in both typical and atypical figures and institutions. On the other hand, there are no exact regulatory definitions of PPPs at Community level.

infrastructure planning and grey infrastructure improvements can expand outside the pilot areas. The aim is to watch the changes to the environment brought about by these public policies from satellite. To do this, we need to start from the classification of sponge cities. The general information on the pilot cities is mainly based on climatic characteristics such as average annual rainfall (mm), average annual evaporations. (mm) Temperature (° C), the perimeter of the pilot area (km2) and the average high / low annual average.

No	Pilot Cities	Goals of Sponge City Construction					
		Annual Average Rainfall (mm)	Annual Average Evapor. (mm)	Temperature (°C)		Pilot Area (km2)	Investment (Billion-RMB)
				Annual Average	Average High/Low		
1	Qian'an	672	1100	11.5	26/−5	21	4.493
2	Baicheng	410	1840	4.6	38/−32	21	4.230
3	Zhenjiang	1063	1277	16.1	29/3	22.0	3.060
4	Jiaxing	1194	1313	17.2	29/5	18.4	1.948
5	Chizhou	1483	1444	12.7	24/1	18.5	4.045
6	Xiamen	1530	1651	21.3	29/14	45.5	6.474
7	Pingxiang	1600	--	18.1	30/6	28.8	4.600
8	Jinan	665	1526	14.8	28/−1	39	7.600
9	Hebi	665	2016	14.1	28/−1	29.8	3.476
10	Wuhan	1257	950	17.2	30/4	38.0	10.278
11	Changde	1366	--	17.5	29/5	41.2	17.350
12	Nanning	1298	1367	22.6	29/14	60.2	9.519
13	Chongqing	1107	1193	18.0	7/35	18.7	7.047
14	Suining	928	950	17.8	28/7	25.0	5.760
15	Gui'an	1158	1200	15.3	24/5	19.1	4.760

16	Xixian	520	1481	14.3	27/1	17.8	3.123
17	Fuzhou	1360	970	19.7	28.8/10.6	36.9	7.800
18	Zhuhai	1766	1469	23.0	32.2/−3	52.0	10.656
19	Ningbo	1517	830	17.2	29/6	31.0	6.042
20	Yuxi	909	1801	19.2	22/10	20.9	4.873
21	Dalian	736	1551	9.1	22/−8.1	21.8	2.898
22	Shenzhen	1837	1675	22.4	29/16	24.9	3.529
23	Shanghai	1191	1420	15.7	29/5	79.0	8.560
24	Qingyang	510	1425	9.5	23/−8.4	29.6	4.735
25	Xining	460	1364	6.2	14.9/−0.3	21.6	6.375
26	Sanya	1392	2361	25.5	28.8/21.6	20.3	4.040
27	Qingdao	776	1401	12.2	25.1/−1.2	25.2	4.870
28	Guyuan	458	1099	6.1	24.7/−14.3	23.0	3.654
29	Tianjin	511	1639	13.5	27.2/−2.4	39.5	7.490
30	Beijing	573	1164	11.7	26/−4.7	19.4	3.937

16 the regional characteristics and general information of the first group of pilot sponge cities and No. 17–30 are those of the second group of In bold those that will be selected for the case study [162]

The table presents the regional characteristics and general information on the 30 pilot cities, including rainfall and climate, the size of the designated pilot areas. Monitoring by satellite the major cities included in the table, they help us to monitor implementation efforts and clarify the real potential of this thesis project to the reader. In particular we take into consideration the city of Shenzhen which will become our case study.

Shenzhen is a coastal city located in southern China, and one of the striking examples of rapid urbanization. In just 40 years, Shenzhen has transformed from a fishing village to a bustling megalopolis. Today known as the technology capital of the world. But it should be noted that today, around 50% of Shenzhen's 13 million residents live in its urban villages. Within the villages there are very few green spaces, such as parks or gardens. Poor vegetation coupled with a limited underground sewage system, during the city's six months of the rainy season, transformed urban villages into areas particularly vulnerable to flooding.

To solve this problem, the Nature Conservancy (TNC), together with other key partners, launched an innovative pilot project called Green Cloud in 2010, transforming the roofs of urban villages into a "living sponge" space.

The Green Cloud project started in Shenzhen in 2010, after 9 (We will use satellite data from 2019) years it should allow us to evaluate the actual carbon storage and understand the real gain it could have generated if it had followed the idea presented in this thesis project.

It should be noted that the green roofs built in the Chinese city are not made of moss but are often real urban green areas (walkable) composed of either small plants or sedum. Here are some examples:

Vista aerea del progetto Green Cloud. Credito fotografico: The Nature Conservancy

The project uses three-dimensional lightweight steel structures that are simple to build and have the capacity to hold over 420 plant containers filled with plants mostly native to southern China. The original concrete roof is transformed by the vegetation, which is able to absorb and preserve rainwater and air pollution, the project has become an important example of the "Sponge City" initiative mainly by creating a rainwater management system nature-based for the residential building, achieving a 65% runoff control rate. Consequently, a "green cloud" as it is called by the authors in addition to storing water cleans the air of Shenzhen.

Data	Shenzhen
Annual Temp. (°C)	22.4
Annual Rainfall (mm)	1837
Annual Evap. (mm)	1675
Runoff Control (%)	70
Runoff Control (mm)	31.3
Rain Resourcing (%)	≥8
Green Roof (%)	≥30
Depressed Green (%)	≥10
Permeable Paver (%)	≥70

Satellite results on Chinese city sponges

In order to create a true simulation, I looked for a single building that participated in the Sponge-City initiative. The selected building was built in the Futian district of Shenzhen and occupies 3,000 m2. It has a plot ratio of 4, a coverage rate of 38.5 percent, and a total construction area of 18,170 m2. The main structure of the building consists of 12 floors above ground and 2 underground floors. The building was completed and put into operation in March 2009, has been part of the Sponge City program since 2012 and has met its original goals and met the requirements of the three-star level of the national green building assessment standards and LEED gold, with a total project cost of 4,000 yuan / m2 (Approximately 30 Euro / m2). The building created significant social benefits. According to the preliminary calculation and analysis, the whole building has a construction area of 18,000 m2 and can save 1.5 million yuan in operating expenses per year. Compared to conventional buildings, it can save 1.45 million yuan of electricity, 54,000 yuan of water, 610 tons of standard coal, and reduce 1,600 tons of CO_2 emissions. From the Sentinel-2 data the same building has a LAI value that is around 0.10-0.15 by multiplying this value by the average storage values it is possible to define the reduction of CO_2 in the atmosphere of 1.3-1.5 kg-CO_2 / m2 / yr^{-1}. I used this rate and multiplied by the m2 of the Sedum garden roof. As mentioned in the previous chapter, the costs of installing garden roofs involve CO_2 imbalances, buildings in China have provided all the criteria and materials suitable for a standard extensive garden roof. Therefore, an average consumption of 25.4 kg-CO_2 / m2 / was calculated.

The total costs of the garden roof were searched on-line, but there is no information about it: to remedy the problem, the cost of the loans disbursed in 2012 by the Chinese government for the square footage of the building was divided in question. The initial costs were 36K. As already done previously, the same costs have been scaled in a 20-year simulation. In the same work, a project was simulated that respected the canons presented in chapter 7 and compared with the real project. The carbon price was adjusted to the reference period.

The results are shown below, the simulated columns in blue, the real columns in orange:

Carbon Volunteer Market [Average price 2019]		Shenzhen Green cloud	Shenzhen Green cloud (NOW)		Shenzhen Green cloud (With thesis project)	
		Urban and Rural Community Affair	Public buildings	Carbon Sequestration [kg/m^2* Year]	Public buildings	Carbon Sequestration [kg/m^2* Year]
2012		* [Government Fund]		24750	18000	99000
Cost Installation Government Fund		1,998,352.00 €				
Total CO2 emitted for installation [forfeit] Idea thesis	0.1344				13305.6	
Total CO2 emitted for installation [forfeit] Shenzhen	0.254		6286.5			
Specific Sequestration Rate (Idea thesis Scenario 1)	5.5					
Specific Sequestration Rate (Shenzhen)	1.375					
C to CO2			92.8125		371.25	

Table 17 (1 Part) Simulation Thesis project on the real case of Chinese sponge cities *Source: Shenzhen Website and Municipal Report

TOTAL Installation Project Cost		36,000.00 €		kg-C/m2 Euro [m²]	kg-CO2/m2	kg-C/m2 Euro [m²]	kg-CO2/m2
Carbon sequestration revenue [1-Year]	0.02	-36,000.00 €	-36,000.00 €	495.00 €	-6193.6875	1,980.00 €	-12934.35
CSR [2-Year]	0.02	-35,505.00 €	-34,020.00 €	495.00 €	-6100.875	1,980.00 €	-12563.1
CSR [3-Year]	0.02	-35,010.00 €	-32,040.00 €	495.00 €	-6008.0625	1,980.00 €	-8838.1
CSR [4-Year]	0.02	-34,515.00 €	-30,060.00 €	495.00 €	-5915.25	1,980.00 €	-5113.1
CSR [5-Year]	0.045	-33,401.25 €	-25,605.00 €	1,113.75 €	-5822.4375	4,455.00 €	-1388.1
CSR [6-Year]	0.045	-32,287.50 €	-21,150.00 €	1,113.75 €	-5729.625	4,455.00 €	2336.9
CSR [2019 7-Year]	0.045	-31,173.75 €	-16,695.00 €	1,113.75 €	-5636.8125	4,455.00 €	6061.9
CSR [8 -Year]	0.045	-30,060.00 €	-12,240.00 €	1,113.75 €	-5544	4,455.00 €	9786.9
CSR [9-Year]	0.045	-28,946.25 €	-7,785.00 €	1,113.75 €	-5451.1875	4,455.00 €	13511.9
CSR [10-Year]	0.05	-27,708.75 €	-2,835.00 €	1,237.50 €	-5358.375	4,950.00 €	17236.9
CSR [11-Year]	0.05	-26,471.25 €	2,115.00 €	1,237.50 €	-5265.5625	4,950.00 €	20961.9
CSR [12-Year]	0.05	-25,233.75 €	7,065.00 €	1,237.50 €	-5172.75	4,950.00 €	24686.9
CSR [13-Year]	0.05	-23,996.25 €	12,015.00 €	1,237.50 €	-5079.9375	4,950.00 €	28411.9
CSR [14-Year]	0.05	-22,758.75 €	16,965.00 €	1,237.50 €	-4987.125	4,950.00 €	32136.9
CSR [15-Year]	0.05	-21,521.25 €	21,915.00 €	1,237.50 €	-4894.3125	4,950.00 €	35861.9
CSR [16-Year]	0.06	-20,036.25 €	27,855.00 €	1,485.00 €	-4801.5	5,940.00 €	39586.9
CSR [17-Year]	0.06	-18,551.25 €	33,795.00 €	1,485.00 €	-4708.6875	5,940.00 €	43311.9
CSR [18-Year]	0.06	-17,066.25 €	39,735.00 €	1,485.00 €	-4615.875	5,940.00 €	47036.9
CSR [19-Year]	0.06	-15,581.25 €	45,675.00 €	1,485.00 €	-4523.0625	5,940.00 €	50761.9
CSR [20-Year]	0.06	-14,096.25 €	51,615.00 €	1,485.00 €	-4430.25	5,940.00 €	54486.9

17 (2 Part) Simulation Thesis project on the real case of Chinese sponge cities *Source: Shenzhen Website and Municipal Report

The results are evident but leave some perplexities that we will address later. Reading the table, it is clear that Chinese spongy cities will have an excellent impact on rainfall, but they are very expensive in carbon during construction. The carbon produced during installation is not absorbed even after 20 years. The choice of installing Sedum will certainly have social and aesthetic benefits, but it has a slower carbon storage capacity. The simulation of the thesis work in comparison gave excellent results, in the eleventh year the project would have returned from the state investment and would have started to produce profits. Instead, the extensive roof would have reabsorbed the installation carbon in just 5 years.

The biggest perplexities are about the uncertainty about costs and benefits that come after 8 years from the start of the Chinese project. Although the design, financing, and construction costs for spongy city projects are fairly clear, the life cycle costs, including operation and maintenance, are unknown. Furthermore, there are currently no economic projects on the market similar to the project presented in this research work. In some cases, the duration of some spongy urban projects is also uncertain. In current practices in China, sufficient funds are allocated for initial construction, however, the financing needs for future operation and maintenance are not addressed. Furthermore, due to the uncertainty of life cycle duration and performance, life cycle benefits, including environmental, ecological and social benefits, cannot be adequately assessed. For an investment without a clear picture of future benefits, the financial risk is quite high for both public and private entities.

Summarizing the results, I believe that currently the vision of green cities to be undertaken is very far from the work done in China. The funding was excellent to start an ambitious project like that of the sponge city, but they had to be followed more and a constant economic return had to be created. Financing long-term projects is very important but maintenance must be taken into account. The Chinese project invested heavily in the early years, but will force new investments. The idea presented in this thesis, on the other hand, would have optimized funding and at the same time would have been self-sustainable over time and would have involved the end user more.

9 Issues and future evolution

Delimitations and limitations of the thesis

Given more time, much more information could have been taken and better work done. If I were to self-criticize this thesis work, I believe that the following information should be reported, which I hope to be able to enrich in future works:

- The thesis work had to be done in tandem with an IOT tool and a real case study. But for reasons of time and costs of implementation, this hypothesis was discarded, giving more space to the satellite data.
- The thesis project had to respond more to information related to moss and substances detected by satellite. Due to the little material on the net and the very little information received from the Moss production companies, it was not possible to receive more detailed results on CO, O3, NO2 and SO2. On the contrary, numerous data on CO2 emerged.
- Few satellite images have been included to avoid misunderstandings to the reader, giving priority to the final data.
- The mechanism of carbon credits and the economic scab of the same needed to be explained more. But for a matter of technicalities and priorities, it was preferred to omit it.
- Regarding the carbon sequestration potential, only two scenarios have been described. But given the large difference in carbon sequestration numbers, more documentation could potentially have meant more accurate project results
- Forecasts on carbon sequestration and moss disposal, the available literature lacks detail on this topic. The availability of information would have allowed the results of this project to give a better idea of the effectiveness of the green roof and its disposal costs.

Critical issues

The risks that this thesis can hold are many. The main ones are:

- avoid that technology replaces the classic design
- technology must avoid masking the problem (technology, by creating income, can distort the citizen's interest in limiting air pollutants).
- projects that remain abstract, not integrated and involved in the city context must be avoided.
- Avoid that the advantage for all does not become the prerogative of all.

Future hypothesis

The satellite acquisition of data on pollution allows us to overcome the problem of the local installation of sensors, which imposes major physical limits mainly due to the conformation of the territory. Furthermore, the analysis of this information provides an important tool for the study of the phenomenon and the implementation of possible policies that allow to limit the problem of pollution and more.The study carried out in this thesis demonstrates that the Sentinel-5P mission it has great potential as it provides an overview of the entire terrestrial globe. The future aspects to be addressed will certainly concern the business aspects. For example, the integration of this project into participatory policies and financing of bursars would be the first objective.

Or make city policies related to traffic dialogue with sponge buildings. In this way, those who pollute in the city could compensate for the co-thrust of a fellow citizen.

10 Conclusions

Climate change is a threat and at the same time a new challenge for the cities of the future. This paper is aimed at exploring potential benefits of the extensive use of interconnected technologies combined with urban greening in terms of climate change mitigation.

This research intends to provide a fundamental contribution for the smart and reactive monitoring and management of cities in terms of:

- monitoring and diagnosis of pollutants
- detection of anomalous or inefficient polluting conditions
- ability to remotely manage climate change related problems
- possibility of enabling services / added-values (e.g. income for families, city design, lowering of temperatures, management of heat island effect, environmental monitoring)

Main results from the case study unveil the high sequestration capacity of moss even in a small reference area, expecting therefore a higher mitigation effect in case of extension to the entire city of Munich. Moreover, differently from other “living” infrastructure, its poor management and requirements makes it a low-cost and scalable project. In addition to direct impact, there are several indirect benefits that should be also taken into consideration.

First of all, it will positively affect the quality of life with a subsequent improvement of health conditions and a reduced burdening on local economy: not only the health expenses will decrease but this solution may even create socio-economic value. Besides from being the new city lungs, moss walls can also become a net carbon sink whose tokenization of carbon credits through blockchain technology may lead to a full self-funding project. Furthermore, urban vegetation also contributes to requalification. Most of the selected sponge buildings in Munich are currently abandoned resulting in a dual benefit: beautification of city natural landscape and inclusion of low-income communities. On the one hand, cities reduce their exposition to diseases and on the other rehabilitate poorest area. The installation of green infrastructure, then, plays also a key role in sensitizing citizenship. These imponent green spaces, in fact, raise public awareness and stimulate active participation.

The application of open data from satellite drives city stakeholders to the adoption of an open, transparent and more participative governance where the openness of environmental data collection and analysis creates a shared knowledge about climate change and its effects that can shape a community consciousness and ethics and therefore, a more comprehensive and equal form of planning.

The great advantage of the presented integrated approach is that not only it mitigates climate change effect by monitoring and absorbing carbon emissions, but it also enhances adaptative actions related to the creation of green infrastructures and, in a future, a community-scale business model.
Environmental degradation increases everyone’s vulnerability to climate change recalling on choral effort in order to empower resilience capacity. Making effects of climate change visible, however, helps integrate this variable into urban planning decisions: the integration of several technologies can therefore trigger experiential

learning and participatory planning within communities. Based on City Sensing approach, in fact, our solution gives back decision-making power, especially to most vulnerable groups, allowing the development of shared goals and coordinated actions [178].

In conclusion, the solution here presented has an evident empowerment potential in terms of health, environment, landscape and governance which are all drivers of a sustainable resilient path. The comparison with the Chinese project of spongy cities also rises up the crucial issue of the high "cost" that the community has to pay, both a material cost for the massive maintenance such a project requires but also environmental as the pollution generated by its creation and its maintenance does not offset, unless on a very long period, the pollution sequestration effect.

As a result, in the view of circular economy, the introduction of blockchain system identified as economy catalyser, represents an innovative aspect to be taken into account in order to face at the same time management and maintenance costs but also and especially socio-economic costs of these sponge cities.

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List Figures

List Table

List of abbreviations and notations

AATSR	Advanced Along Track Scanning Radiometer
AOCS	Attitude an Orbit Control System
AOD	Aerosol Optical Depth
AOD	Aerosol Optical Depth
AOT	Thickness of aerosol
AP	Aerosol Particles
AQI	Air quality index
ATBD	Algorithm Theoretical Basis Document
BAT	Best Available Techniques
BOT	Bottom-Of-Atmosphere
C3S	Copernicus Climate Change Service
CAMS	Copernicus Atmospheric Monitoring Service
CDM	Clean Development Mechanism
CDM	Clean Development Mechanism
CDRs	Climate Data Records
CEMS	Copernicus Emergency Management Service
CEOS	Committee for Earth Observation Satellites
CER	United Nations Certified Emission Reduction Projects
CGLS	Copernicus Global Land Service
CH4	Methane CH4
CLMS	Copernicus Land Monitoring Service
CMC	Canadian Meteorological Center
CMEMS	Copernicus Marine Environmental Monitoring Service
CNN	ConvNet
CO	Carbon monoxide
COMM	Communication Subsystem
COP	Conference of the Parties
CRN	Climate Reference Network
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSOC	Cybersecurity Space Operations Centre
DFS	Digital Fantasy Sports
EC	European Commission
EC	Circular economy
ECMWF	European Centre for Medium-Range Weather Forecasts ECVs Essential Climate Variables
EDF	Environmental Defense Fund
EEA	European Economic Area

EI	Ambient Intelligence
EIB	European Investment Bank
ENISA	European Union Agency for Network and Information Security
ENVISAT	Environmental Satellite
EO	Earth Observation
EOO	Earth Orbiter
EPC	Energy Performance Contracting
EPS	Electrical Power Subsystems
EPSG	Geodetic Parameter Dataset
ESA	European Space Agency
ESEC	European space Security and Education Centre (REDU)
ESRIN	European Space Research Institute
EUMETSAT	European Or. for the Exploitation of Meteorological Satellites
FDS	Flight Dynamics System
FOS	Flight Operation Segment
GAW	Global Atmosphere Watch
GCOS	TOPC Terrestrial Observation Panel for Climate
GCOS	Global Climate Observing System GHGs Greenhouse gas
GCS	Ground Control Segment
GDP	Gross domestic product
GEO	Geostationary Earth Orbits
GEOSS	Global Earth Observation System of Systems
GMES	Global Monitoring for Environmental Security
GMES	Global Monitoring for Environment and Security (ESA)
GMS	Ground Mission Management
GPP	Green Public Procurement
GUM	Guide to the Expression of Uncertainty in Measurement
HEO	High Elliptical Orbits
HFCs	Hydrofluorocarbons
HW	Hardware
ICT	Technology Information and Communication
IGRA	Integrated Global Radiosonde Archive
IoT	Internet of things
IPFS	Inter Planetary Name System
IPNS	Inter Planetary Name System
IWV	Integrated Water Vapour
JAXA	Japan Aerospace Exploration Agency
JCGM	Joint Committee for Guides in Metrology
JPEG	Joint Photographic Experts Group
JPL	Jet Propulsion Laboratory
K	kelvin
KO	Kick-Off
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LSA–SAF	Land Surface Analysis – Satellite Application Facility
LST	Land Surface Temperature
LT	Lower Troposphere
MCS	Mission Control System
MEO	Medium Earth Orbits
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-Angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOMO	Matrix Operator Model
MOOC	Massive Open Online Courses
MPC	Mission Performance Centre
MR	Monthly Report
MSI	Multispectral Instrument
MTR	Mid-Term Review
MTRR	Mid-Term Review Report
MWR	Microwave Radiometer
N2O	Nitrous oxide
NASA	National Aeronautics and Space Administration
NASA	National Aeronautics and Space Administration
NCSS	National Cyber Security Strategies
NDVI	Normalized Difference Vegetation Index
Near-InfraredNIR	near infrared band
NIR	Near Infrared
NO2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production
NRT	Near real time
NRT	Near Real Time OBJ Objective
NTC	Non Time Critical
O3	Ozone
OBDH	On-Board Data Handling subsystem
OFFL	OFFline
OLCI	Ocean and Land Colour Instrument

PDF	Portable Document Format
PDGS	Payload Data Ground Segment
PFCs	Perfluorocarbons
PM	Progress meeting
PM10	Particulate matter
PM2.5	Fine particulate matter
PP	Particulate pollution
PTS	Suspended particulate
QWG	Quality Working Group
RD	Reference Document
ROI	Return Of Investment
S3	Sentinel-3
S3A	Sentinel -3A
S3B	Sentinel-3B
S5P	Sentinel-5P
S3VT	Sentinel-3 Validation Team
SAR	Synthetic Aparture RADAR (in technical aspect as instrument)
SBU	Swift Broadband Unit
SDGs	The Sustainable Development Goals
SDU	Service Data Unit
SF6	Sulfur hexafluoride
SI	System International
SiSTeR	Sea and Ice Surface Temperature Radiometer
SLSTR	Sea and Land Surface Temperature Radiometer
SMEs	Small and Medium Businesses
SO2	Sulfur dioxide
SR	Scientific Roadmap
SST	Sea Surface Temperature
STR	Structural Substems
SURFRAD	Surface Radiation Budget Network
SYN	Synergy SoW Statement of Work
TCP	Transmission Control Protocol
TCS	Thermal Control Subsystem
TIR	Thermal Infrared
TNC	The Nature Conservancy
TOA	Top Of Atmosphere
TT&C	Telemetry Tracking and Control
UHI	Urban heat island
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
URL	Universal Resource Locator
USB	Universal Serial Bus
UT	Upper Troposphere
UVN	Ultraviolet-Visible-Near-Infrared
VINR	Visible and Near Infra Red (part of the electromagnetic spectrum)
VIS	Visible (part of the electromagnetic spectrum)
VIS	visible bands
WFR	Water Full Resolution
WGCV	Working Group for Calibration and Validation (of CEOS)
WHO	World Health Organization
WMO	World Meteorological Organization
WP	Work Package
WRR	Water Reduced Resolution
WV	Water Vapour
WWW	World Wide Web

Cities represent more than 50% of global population and are the main responsible of energy consumption in the world, accounting for more than 70% of CO^2 emissions deriving especially from energy and transportation sectors (Global Covenant of Mayors, 018). At the same time, also cities are negatively affected by Climate Change in terms of infrastructure, economy (e.g. agriculture), public services, urban planning and food security, all crucial dimensions for sustainable development.

In this scenario, urban planners and policy makers are called to identify innovative solution against crucial challenges related to the evolution of city and environment planning and management. Based on the City Sensing [1, pp. 10-13] approach, the aim of this thesis is to identify innovative technological approach that can support citizens to monitor the level the air pollutants and carbon emissions through the interrelation of Copernicus satellites, big data and cognitive techniques, in order to improve inclusive and sustainable urbanization and management of human settlements.

Satellites can help cities to become more resilient to climate change in terms of :

- prevention of climate change through the development of risk management plans based on satellite data series
- adaptation to climate change thanks to the issue of ad hoc policies and interventions for each city
- communication of climate change in order to develop an informed decision making which foresees in climate change an opportunity rather than a risk.

The project will present how the combination of different technologies such as satellites, sensors, the internet drives the development of a new model of knowledge based on distributed acquisition of information whose combination with other already available data, provide a detailed, real time, dynamic and accessible framework for planning the future of a city. Moreover, the crystallization of these information within recorded blocks of blockchain can even create 'shared value' where certified data related to emissions and pollutants are associated with an economic value and resold on the market, in line with the carbon crediting system. In this way the pollutants stop being a problem to become for the cities and start being a solution