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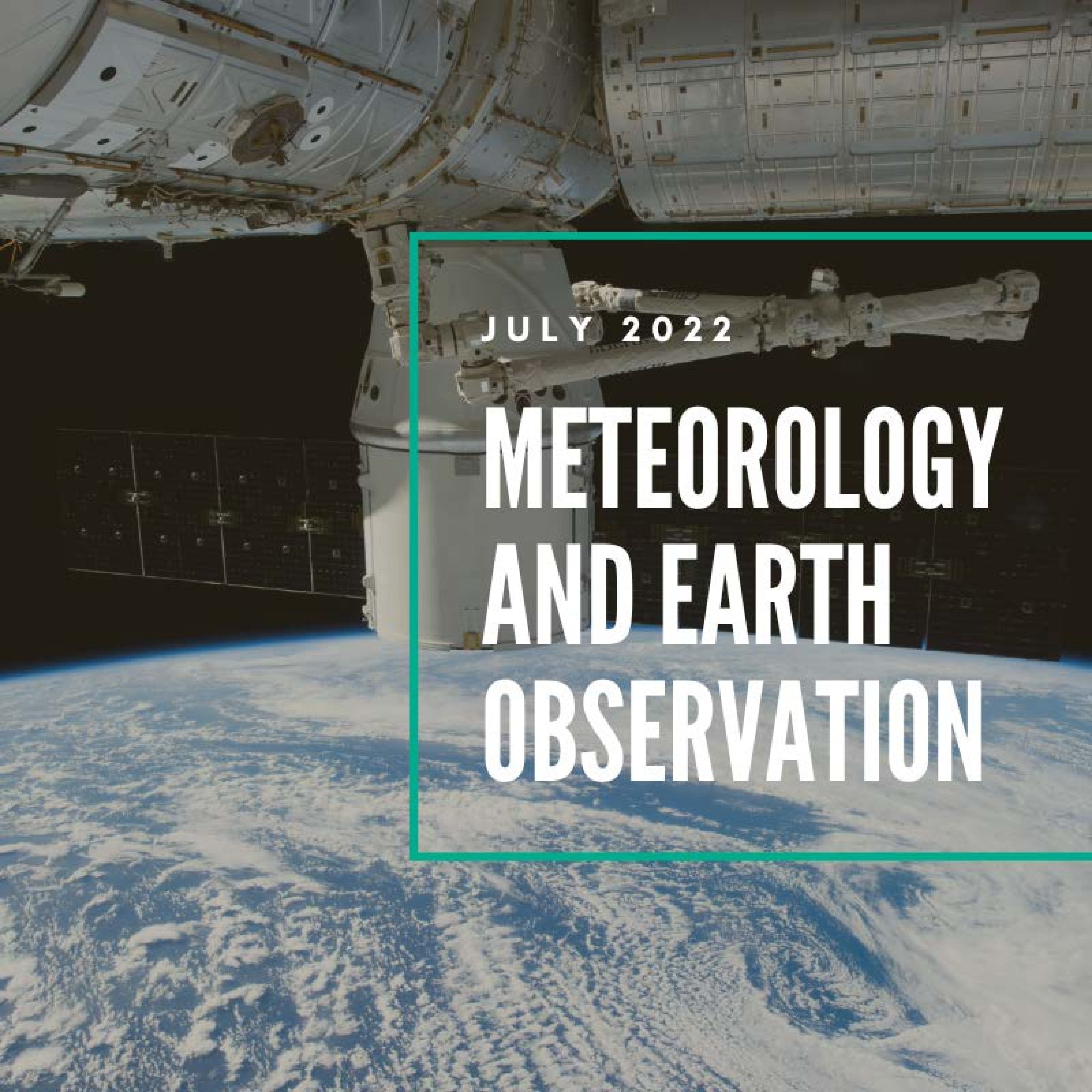
METEOROLOGY AND EARTH OBSERVATION



Green OAT

Public Subsidies to Weather Forecast and Earth Observation Activities

Final Report

Evaluation team

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CITIZING

With the contribution of Michel Jarraud, former Secretary-General of the World Meteorological Organization

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List of acronyms

CNES	Centre national d'Etudes Spatiales (National Center for Space Studies)
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDF	Electricité de France
EEA	European Environment Agency
EO	Earth observation
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GHG	Greenhouse Gas
INRAE	Institut national de recherche pour l'agriculture, l'alimentation et l'environnement
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NMS	National Meteorological Service
NOAA	National Oceanic and Atmospheric Administration
OAT	Obligation Assimilable du Trésor (Treasury Bond)
PPP	Plant Protection Products
RTE	Réseau de Transport d'Electricité
WMO	World Meteorological Organization

Executive summary

Context

This report assesses the environmental impact of meteorological and Earth observation activities carried out by Météo-France, the European Centre for Medium-Range Weather Forecasts (ECMWF), European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the European Space Agency (ESA) and the French national center for space studies (CNES). These five organizations are partly financed by French public expenditures eligible for the Green OAT of France launched in 2017 by *Agence France Trésor*. The evaluation is based on the four environmental objectives defined in the Green OAT framework document: climate change mitigation, climate change adaptation, biodiversity protection and pollution reduction.

The counterfactual scenario is based on the following rationale: at the national level, public subsidies given to Météo-France and the CNES are the main sources of these two organizations' budgets. If such subsidies had not been given for decades, the two organizations could not have run their activities. At the European level, public subsidies of France finance the annual contributions of the country to ESA, EUMETSAT and the ECMWF. In the absence of those contributions for decades, implying the absence of technological and scientific knowledge of France as well, the quality of service provided by European meteorological organizations would be lower and Earth observation development would not be at its current level. Hence, the counterfactual scenario relies on two assumptions: 1) we suppose the absence of weather and climate forecasting activities provided by France and the use, instead, of the American service provided by the NOAA and 2) we assume that Earth observation is still at its beginning in Europe with some exploratory missions but without the Copernicus program that has operational use.

The methodology consists of identifying environmental impacts through interviews with the organizations, the academic literature, and the expertise of Michel Jarraud[1] on weather forecasting. Given the important number of impacts, we elaborate a strategy for prioritizing the impacts to be studied to guarantee a high level of analysis for each one of them. When possible, impacts are quantified using models relying on assumptions to provide orders of magnitude, whose sensitivity is shown by estimating a range of values rather than a single value. When uncertainty is too important, as it is for Earth observation that is a very indirect contributor to environmental impacts, qualitative analyses are presented. Finally, we specify that the scope of the study for weather forecasting activities is limited to areas overseen by Météo-France (i.e. France and some international areas such as Western Indian Ocean) while Earth observation is studied over a larger extent, in Europe and beyond.

Main results

We are able to conclude that meteorological and Earth observation activities analyzed in this evaluation have a positive effect on:

- **climate change mitigation**
  - weather forecasts, as:
    - these are widely used by farmers to optimize the timing of phytosanitary products and fertilizers. This optimization results in limiting the amount of such products to be wasted in the nature because of unanticipated rain or wind and to avoid an increase in products use to maintain a constant effectiveness that would lead to higher levels of greenhouse gas (GHG) emissions due to plant protection products (PPP) and fertilizers production and consumption. Based on assumptions, **weather forecasts provided by Météo-France (with**

[1] Michel Jarraud was Secretary-General of the WMO from 2004 to 2015. He is a specialist in numerical weather prediction and had high-level operational responsibilities at Météo-France and ECMWF before joining WMO.

the support of ECMWF and EUMETSAT) might have enabled to avoid between 746 and 3,672 ktCO2-eq per year in the low scenario and between 3,706 and 18,307 ktCO2-eq per year in the high scenario (that also relies on a conservative assumption) compared to the counterfactual scenario.
    - meteorological conditions are essential to the Civil Security in the prevention and control of forest fires that highly contribute to CO2 emissions into the atmosphere. We estimate that **weather forecasting services provided by Météo-France may have prevented between 23,000 and 41,000 hectares per year of forest to burn, resulting in CO2 emissions mitigation ranged between 1,084 and 1,952 ktCO2 per year** compared to the counterfactual scenario.
    - renewable wind and solar energies rely on weather and could not have developed as much as they have without weather forecasting services offered by Météo-France and the ECMWF, which would have reduced their market penetration in favor of more GHG-emitting energy sources. Moreover, the absence of data from Météo-France and ECMWF would have caused more errors in anticipating the production of solar and wind farms leading to more upward adjustments in energy supply (to match demand) with domestic and foreign fossil fuels. **The quality of weather forecasts provided to predict wind energy production enabled to limit such situations and thus additional GHG emissions compared to the counterfactual scenario, estimated to range between 18,000 and 40,000 tCO2-eq in 2019**.
    - weather forecasting contributes to optimize ship routing by providing meteorological conditions at sea, leading to consequent time and heavy fuel oil savings for ships and thus GHG emissions reduction compared to non-optimized routes. **As a minimum boundary and to provide an order of magnitude, we estimate Météo-France to have contributed to avoid between 1.5 and 3 million tons of CO2-eq in 2018 (0.2 to 0.4% of total maritime transport emissions) by supporting ships to optimize their routes on maritime areas overseen by the French institution**.
  - Earth observation, as:
    - Earth observation produced within the European Copernicus program (Sentinel missions) also contributes to the optimization of farming treatments by providing data for precision farming services. Such services help farmers to spread treatments only in parcels of the field that need them, reducing products consumption.
    - Earth observation shows promising results for the provision of rapid fire detection and mapping to reduce burned areas and CO2 emissions.
    - it acts as a crucial informative support to authorities for more efficient wetland management and conservation, that requires monitoring over large areas of wetlands, sometimes difficult to access. Such observation is more and more used by authorities and environmental agencies to implement appropriate measures to protect or restore wetlands that are particularly important for carbon sequestration.

- **climate change adaptation**
  - weather forecasts, as:
    - Météo-France provides predictions on the future evolution of climate at local levels and specific climate services such as the provision of predictions on forest fire risk evolution in France and evaluations of local projects' effectiveness to face urban heat islands. These are determinant for managing authorities to undertake appropriate climate change risks mitigation measures and make territories more resilient against global warming and increasing heat waves.

- Earth observation, as:
  - the detection and monitoring of coastal erosion through time is an essential information to policy and decision-makers on local, regional and national levels for optimal climate change adaptation measures, specifically to make territories more resilient against sea rise and increasing flood risks. Earth observation through the Copernicus program is a significant contributor to the improvement of coastal erosion monitoring.

- **biodiversity protection**
  - weather forecasts, as:
    - weather forecasts at the field-scale provided by Météo-France enable to limit wasted amounts of farming fertilizers loss in the nature (because of unanticipated rain or wind before the spreading), reducing water eutrophication risks and thus protecting aquatic biodiversity from asphyxia. We estimate that each year, **weather forecasts provided by Météo-France avoid for 11 to 54 km³ of water (freshwater, coastal water, ground water) to lose all its species for a year** compared to the counterfactual.
    - services provided by Météo-France contribute to reduce the consequences of forest fires and oil spills on biodiversity by providing forecasts helping authorities for optimized and rapid actions.
    - the forecast of local and reliable meteorological conditions provided by Météo-France are determinant to guarantee the safety of dams and nuclear power plants to prevent accidents that would have disastrous impacts on the biodiversity around.
  - Earth observation, as:
    - As mentioned above, Earth observation also contributes to the optimization of farming treatments for the development of precision farming services, limiting the overuse of products and reducing eutrophication risks.
    - The Copernicus program provides data for rapid fire detection as well as for developing fire damage assessment maps that are essential to foresters to identify affected areas and undertake optimal measures for ecological restoration.
    - Earth observation shows promising results for monitoring land use and status of forests, wetlands, and coastal areas. Such monitoring is essential to detect and map human and natural stresses on ecosystems and on the biodiversity with a high degree of precision enabled by the Copernicus satellites, so that appropriate protective and restoration measures can be undertaken by environmental agencies and relevant authorities.

- **pollution reduction**
  - weather forecasts, as:
    - the optimization of farming treatments, fires control, and oil spills countermeasures, as well as the monitoring of atmospheric pollution enabled by Météo-France with ECMWF and EUMETSAT contribute to the reduction in air, soil and water pollution compared to the counterfactual scenario.
  - Earth observation, as:
    - Earth observation is also a contributor to the optimization of farming treatments and fires control as described above, reducing air, soil and water pollution. Satellite data are used for oil spills detection and monitoring and for atmospheric pollution monitoring. However, the evaluation does not investigate further the role of Earth observation regarding these two topics.

Moreover, the added value of Earth observation lies in its capacity to produce data to enhance the scientific knowledge on environmental fields, especially on climate change. Meteorological organizations, including Météo-France, are also important contributors to the research in climate fields, aiming to improve our understanding of the climate and its evolution. The scientific knowledge is then an essential tool to political actors to implement relevant measures for climate change mitigation, climate change adaptation, biodiversity protection and pollution reduction.

Activities carried out by the studied organizations have direct impacts on the environment, through energy consumption required for their infrastructures and technological resources. Earth observation also contributes to the space pollution with an increasing number of unused objects floating through space. However, we can reasonably argue that such impacts are more than compensated by all the indirect environmental benefits generated by those activities.

Finally, the weather forecasting activity and the Earth observation activity are not eligible[2] to the criteria of the delegated act of the European Taxonomy for climate change, as it is not specifically dedicated to solving an environmental problem (e.g. reducing emissions) for the former and given the very indirect contribution to climate change mitigation and adaptation for the latter. However, operational climate services provided by Météo-France could meet both eligibility and alignment criteria, provided that sufficient information is collected to prove it.

[2] Eligibility of activities implies that an activity is included/covered in the delegated act on climate change. Alignment of an activity goes beyond eligibility and implies that an activity complies with the technical criteria designed specifically for this activity in the Taxonomy.

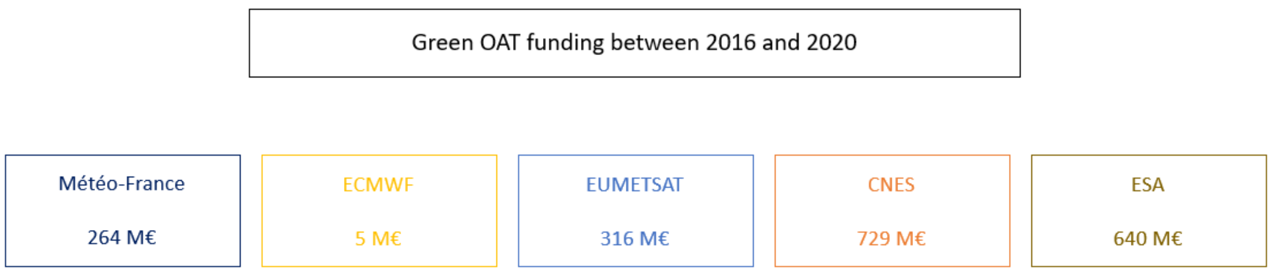
Introduction

In January 2017, the Agence France Tresor announced the creation of the Green OAT 1.75% 25 Juin 2039 issued by the French government for an initial total amount of 7 billion euros, raising up to 30,94 billion euros today. In 2021, a second Green OAT has been launched (Green OAT 0,50% 25 Juin 2044) for an amount of 7 billion euros, and has now reached 14,18 billion euros, bringing the total amount of green OATs issued to 45,12 billion euros in early 2022. **These Green OATs aim at financing expenditures foreseen in the state budget that play a role in addressing environmental concerns of our society**. Specifically, France's Green OATs sets out its ambitions in terms of climate change mitigation, climate change adaptation, biodiversity protection and pollution reduction.

Among Green OAT-eligible public expenditures, the French government includes expenditures for weather forecasting activities as well as Earth observation activities, which are the subject of this report and represented 7.1% of the total amount of Green OAT issued between 2017 and 2020. This report discusses past expenditure matched with the Green OAT, and as such does not cover green eligible expenditure matching with the second Green OAT. In particular, Green OAT funds allocated to those activities cover in the 2021 budget nomenclature the following programs:

- State subsidy to **Météo-France** (program 159, action 13; 27% of the subsidy is eligible, as it corresponds to system and organisation expenditure, plus 10% of the subsidy for applied research and innovation expenditure)
- Share of the state subsidy to **Centre National d'Etudes Spatiales** (CNES) dedicated to Earth observation at national level (program 193, action 2, title 3)
- France contribution to the **European Organisation for the Exploitation of Meteorological Satellites** (EUMETSAT) (program 193, action 7)
- France contribution to the European **Centre for Medium Range Weather Forecast** (ECMWF) (a part of program 172, action 18, title 6)
- France contribution to Earth observation activities of the **European Space Agency** (ESA) (program 193, action 2, title 6)

Figure 1: Green OAT funding



Source: French budgetary documents

As those activities are partly funded by the Green-OAT, it is important to assess the extent to which they contribute somehow to environmental objectives set by France. In addition to the yearly publication of the Green OAT allocation and performance reports, France has also undertaken to disclose the environmental impact of French public expenditure associated with Green OAT issuances. In line with this commitment, ex-post evaluations of the environmental impact of eligible green expenditure financed by Green OAT issuance are conducted with oversight by the Green OAT Evaluation Council. In this perspective, **the objective of the study is to provide the main qualitative and quantitative environmental impact data of weather- and Earth observation-related expenditure financed by Green OAT.**

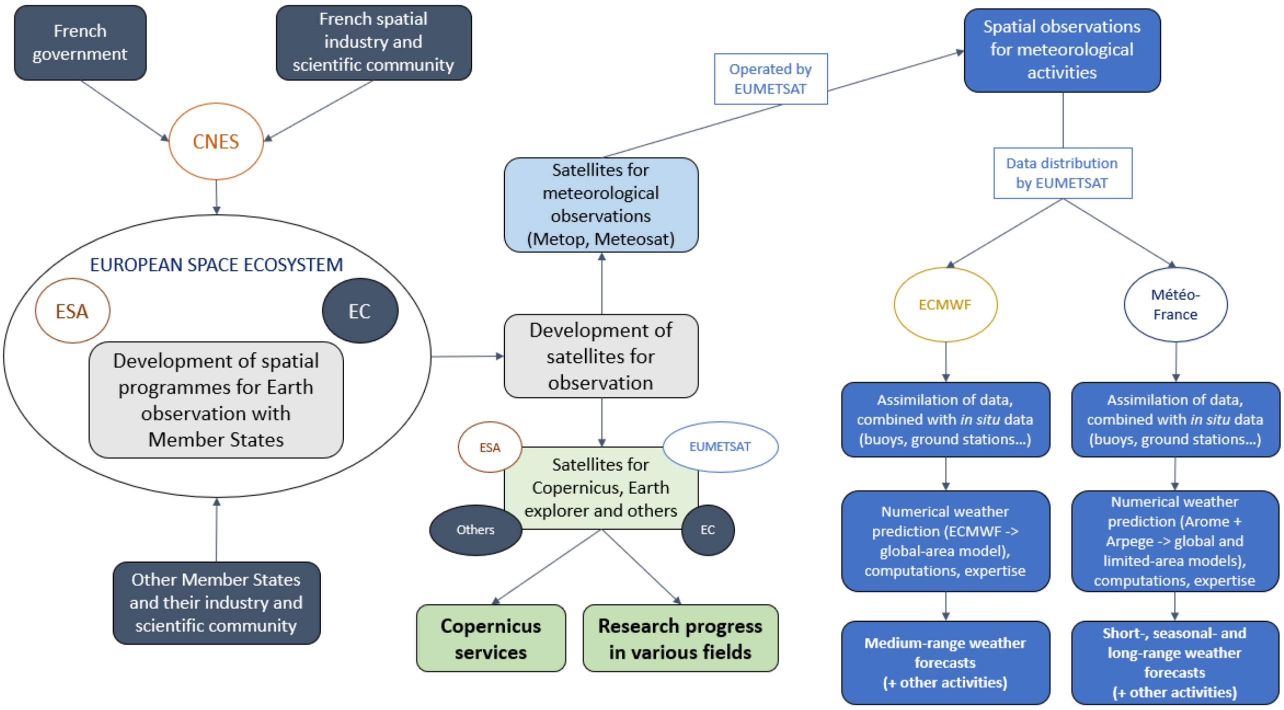
The evaluation will also attempt to answer in **what extent activities carried out by Météo-France, the ECMWF, EUMETSAT, the CNES and ESA comply with the criteria of the European Green Taxonomy**.

The first part of the following evaluation describes the activities of the Green OAT-funded organisations (Météo-France, the ECMWF, EUMETSAT the CNES and the ESA) and explains specifically the process in chain to provide weather forecasts. After having discussed our counterfactual scenario, we enlighten the general methodology that was followed. Then, we present quantitative and/or qualitative analyses of environmental impacts arising from those activities. Finally, we describe the extent to which organisations' activities may comply with the European Taxonomy.

Organizations and their activities

This section aims at presenting the five organizations studied (i.e. ESA, the CNES, EUMETSAT, the ECMWF and Météo-France) and their activities.
Before describing each organization into details, one should note that interactions between those are very complex and make their activities highly interdependent, as described in the figure below.

Figure 2: interactions between the five organizations



Note: CNES = Centre National d'Etudes Spatiales ; ESA = European Space Agency ; EUMETSAT = European Organization for the Exploitation of Meteorological Satellites ; ECMWF = European Centre for Medium-Range Weather Forecasts ; EC = European Commission. (Source: authors' own elaboration)

Meteorological services such as Météo-France and the ECMWF use both ground observations of various atmospheric and oceanic variables and spatial observations to run their weather prediction models (see below for more details). Spatial observations have been crucial to reach the current level of accuracy of weather forecasts. Such observations are provided in particular by EUMETSAT that operates meteorological satellites, disseminates data, and contributes to the development of those satellites in cooperation with ESA. EUMETSAT also contributes to the Copernicus program as some of its Sentinels satellites (see box in section European Space Agency (ESA) below) are carried on EUMETSAT's meteorological satellites (Sentinel-4 and Sentinel-5) and two others are operated by EUMETSAT (Sentinel-3 and Sentinel-6). The figure above offers a simple presentation of these complex interactions between the organizations studied in this evaluation. However, numerous actors intervene in Earth observation and meteorological activities, particularly outside Europe such as the NASA, the NOAA, Japan, China, India… that exchange various spatial and *in situ* observations with Europe. The World Meteorological Organization (WMO) is also a crucial actor managing cooperation between worldwide national meteorological services. For instance, the mission Jason-CS, also called as Sentinel-6 of the Copernicus program, will be the next radar altimetry reference mission for sea-surface height measurements. This mission is involving the CNES, the NOAA, the NASA, the European Union, ESA and EUMETSAT, at different stage and scale.

European Space Agency (ESA)

ESA is a supranational agency created in 1975 to coordinate the space projects carried out jointly by its 22 Member States. It aims at promoting cooperation between those countries in the field of space and develops and implements long-term European space policy, activities and programs. Among those programs, we distinguish mandatory and optional programs. Member States must contribute to mandatory programs, dedicated to basic activities (studies on future projects, technology research, shared technical investments, information systems, training programs), but decide whether they want to subscribe or not to optional programs. Those latter concern launchers, navigation, telecommunications, space exploration and Earth observation.

The scope of this evaluation is limited to Earth observation programs, containing **3 types of missions** pursued by ESA:

- Science: named Earth explorer missions, those are designed to improve our understanding of Earth. They use cutting-edge space technologies to learn about interactions between the atmosphere, biosphere, hydrosphere, cryosphere and Earth's interior. Importantly, they address scientific questions that help predict the effects of climate change and address scientific questions that have a direct bearing on societal issues that humankind is likely to face in the future. Some missions can develop operational uses once the technology used gains in maturity (ex: Eolus now used by the ECMWF for weather forecasts).

- Copernicus: largest environmental monitoring program in the world, Copernicus has replaced the Global Monitoring for Environment and Security program (GMES) in 2014. It aims at continuously collecting and disseminating reliable data on Earth state. It is coordinated and managed by the European Commission in partnership with the European Space Agency, EU members and EU agencies such as the European Environment Agency. As Earth explorer missions, Copernicus contributes to improvements in research and climate change knowledge. However, its data are also used operationally to manage maritime safety, monitor disasters (fires, earthquakes, etc.), anticipate harvests, improve management of our environment, etc. Through Copernicus Sentinel missions (see box next page), the EC and ESA provide Copernicus services for a wide range of practical applications. Data from Copernicus are free of charge and open to users worldwide, which not only eases the essential task of monitoring the environment, but also helps stimulate enterprise, creating new jobs and business opportunities to develop operational services.

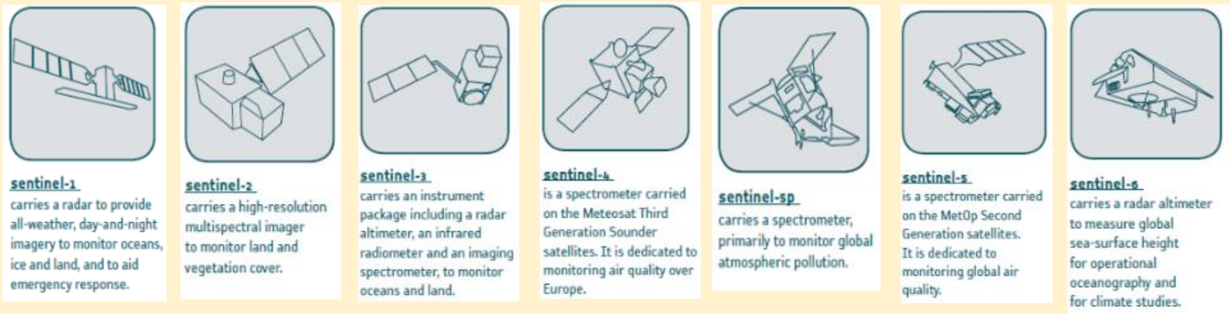
- Meteorology: in cooperation with EUMETSAT, ESA develops a fleet of meteorological satellites, in both geostationary and polar orbits, to provide essential information for weather forecasts. Information from these satellites operated by EUMETSAT is also used to understand and monitor climate change.

ESA's Earth observation program also forges new scientific discoveries and pioneers' new services through its Science for Society activities, stimulating downstream industrial and economic growth. These activities drive the development of a network of Earth observation exploitation platforms in Europe to foster easier and more comprehensive exploitation of the data.

Focus on the Copernicus program

The program provides various services in different fields: atmosphere monitoring, marine environmental monitoring, land monitoring, climate change monitoring, security applications, emergency management. Those services use observational data provided by several satellites. Such satellites all have different functions and observe specific characteristics of the Earth (atmosphere, land, oceans…). Six missions have been launched or are planned to be launched, namely Sentinel missions, and each of them uses one or two satellites. Each Sentinel mission carries state-of-the-art technology to deliver a stream of complementary imagery and data tailored to the needs of Copernicus and its services. This data also results in services offered by various actors (public authorities, private companies…) across Europe, independently of Copernicus services.

Figure 3: Sentinel missions



Source: ESA

Sentinel-5p is temporary until Sentinel-5 is launched with the next generation of EUMETSAT's satellites, and complements Sentinel-1, -2 and -3 to provide services and feed research community.
The table below describes the stage of the development process for each of Sentinel missions.

Programme	Mission	Objectives	Satellite	Status
Copernicus	Sentinel-1	Ocean and land services	Sentinel-1A Sentinel-1B	Launched on 3 April 2014 Launched on 25 April 2016
	Sentinel-2	Land services	Sentinel-2A Sentinel-2B	Launched on 23 June 2015 Launched on 7 March 2017
	Sentinel-3	Land and maritime services	Sentinel-3A Sentinel-3B	Launched on 16 February 2016 Launched on 25 April 2018
	Sentinel-4	Atmospheric services	Meteosat Third Generation Sounder: MTG-S	Planned launch date early 2024
	Sentinel-5	Atmospheric services	Polar System Second Generation: MetOp-SG A	Planned launch date early 2024
	Sentinel-5P	Atmospheric services	Sentinel-5P	Launched on 13 October 2017 until Sentinel-5 is launched
	Sentinel 6	Ocean services	Sentinel-6A Sentinel-6B	Launched on 21 November 2020 Planned launch date for 2025

It is important to note that Sentinel-4, -5 and -6 are not yet operational so did not generate any benefits yet. However, Sentinel-6 is the next series of the Jason mission already in orbit for several years, which means that we already have measurement data of sea levels.

Centre Nationale d'Etudes Spatiales (CNES)

The CNES was created in 1961 to coordinate and lead French space activities. Today, the institution works in collaboration with Arianespace (Evry) and the European Space Agency (ESA) in five areas of activity: access to space (launchers); Earth, environment and climate (observation); consumer applications (telecoms and navigation); science and innovation (for astronomy and fundamental physics); security and defense. The CNES is at the origin of many space projects, even though it no longer manufactures launchers or satellites. It also acts as an assistant to the contracting authority (the European Space Agency) for new developments, notably for Copernicus.

In the field of Earth observation, the CNES is involved in many missions, from research to design, development and operation. In particular, it provides instruments and is involved in the scientific exploitation of the results. ESA issues calls for tender and French industry builds the satellites. However, the CNES can sometimes manufacture some of them, which are very specialized (e.g. microcarb).

The core of the CNES's activity is to communicate with the scientific community on their needs (in particular with the IPCC and the Global Climate Observing System-GCOS) and promote those needs to the ESA to launch and develop spatial missions enabling to provide such needs (data/observations) and develop research. In other words, the CNES is in charge of leading the French spatial policy by participating to project decisions and their design in Europe. It acts as a link with the scientific community, monitors calls for tender of research projects and manages a research laboratory with the CNRS (leader in climate change). Numerous technological innovations have been made by the CNES as a result of its support to and involvement with the scientific community. The agency initiated the very first European project for Earth observation, namely Meteosat, dedicated to meteorology, whose first satellite was launched in 1977. Then, the CNES developed its program SPOT for Earth observation (the first program in Europe) to monitor the Earth and its environment. It also developed precious technologies and instruments (e.g. optical imagery that has been essential to Earth observation development and which is used on Sentinel-2 of Copernicus, solar panel on satellite…).

Moreover, the CNES also developed projects on its own or through international partnerships, as it was the case for the Jason mission aiming at measuring sea topography. This mission (Jason 1, Jason 2 and then Jason 3) was developed with the NASA for research purposes, independently of the European spatial policy. However, the mission became such a success that EUMETSAT found an interest in cooperating on this mission for its activity. The Jason mission entered the Copernicus program and now involves ESA, EUMETSAT, the NOAA and NASA.

The CNES can also operate some satellites. For the Merlin project[3], for example, the CNES will be responsible for the satellite control center and the ground segment for data distribution during the operational phase.

The French institution offers commercial services ("Connect by Cnes") and has an Earth observation laboratory (Lab'OT) created in 2018 to support the promotion of space solutions and help users develop applications with a satellite component. The Earth Observation laboratory is also involved in the so-called "downstream" programs of future space projects: it informs and trains potential users in the use of future data; in return, it contributes to the identification of user needs in order to include them in the definition of future projects.

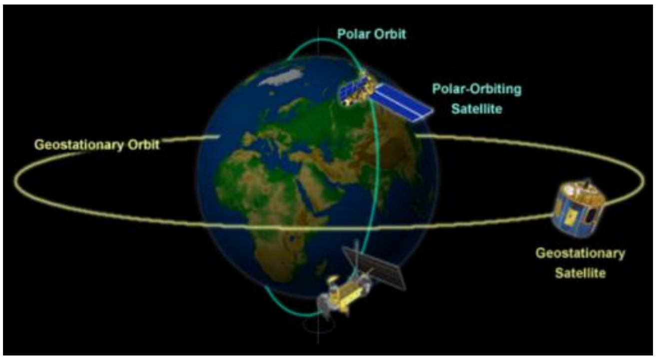
[3] MERLIN, which stands for Methane Remote Sensing Lidar Mission, is a scientific minisatellite developed by the German and French space agencies to measure with unprecedented accuracy the spatial and temporal distribution of methane emissions for the entire planet.

European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)

Created in 1986, EUMETSAT is an intergovernmental organization dedicated to the monitoring of weather, climate and the environment from space. Its activities represent the highest part of the chain to produce weather forecasts as represented in the figure above.

The organization operates a constellation of satellites, which means that it is responsible for the safe operation of those satellites, provides the necessary monitoring and control of them as well as of the ground infrastructure, and collect all the data. Its role is essential for meteorological services in Europe that are very dependent on spatial observations to provide reliable forecasts and need continuous provision of such data. EUMETSAT also ensures that data generated by partners (USA, Japan, Russia, India, China…) are distributed to European users.

Figure 4: geostationary and polar orbit



Source: NASA

Two families of satellites are operated by EUMETSAT:

- **Geostationary satellites** Meteosat -9, -10 and -11 over Europe and Africa and Meteosat-8 over the Indian Ocean: those satellites have an altitude of about 36,000 kilometers and move at a speed corresponding to that of the Earth, thus giving the feeling that they are stationary. This enables to get observations from a distant point of view but with a high frequency (e.g. every 5 minutes over Europe on the same point of view) which is particularly useful for immediate weather forecasts (allows to characterize the atmosphere and to anticipate natural hazards to warn the population).
- **Polar-orbiting satellites** Metop -A, -B and -C: those satellites circle the globe via the poles and continuously collect data from an altitude of 817 km. Although more precise than geostationary satellites as they are closer to Earth, they observe a same place of the Earth twice a day only. This is particularly useful for short-range (up to 3 days) and medium-range weather forecasts (from 3 days to about 2 weeks ahead).

Moreover, the European Union has entrusted EUMETSAT with exploiting the four Sentinel missions of the Copernicus space component dedicated to the monitoring of atmosphere, ocean and climate on its behalf (Sentinel-3, -4, -5 and -6). EUMETSAT carries out these tasks in cooperation with ESA and already exploits the Sentinel-3 marine mission. Hence, EUMETSAT not only monitor the weather but also oceans, land, and the atmosphere. Through the delivery of those data to its Member States, the Copernicus services, and users worldwide:

- it supports the development of operational oceanography
- it monitors fires, vegetation cover, land surface temperature, snow cover, soil moisture…
- it supports the operational monitoring and forecasting of atmospheric composition (aerosol, volcanic ash, dust storms, Ozone, NO_2, CO, CH_4…)

To exploit the full potential of its satellite data, EUMETSAT's ground segment includes a network of eight Satellite Application Facilities (SAFs) that each specialize in the delivery of products in one application area. Using specialist expertise from Member States, SAFs are dedicated centers of excellence for processing satellite data (each one of them led by a national meteorological service). The set of data and products generated across its ground segment are then delivered to users in real time and offline.

As an operational agency, EUMETSAT also needs to plan and develop the future satellite systems required to deliver and further improve observational inputs to forecasting and climate monitoring. Hence, EUMETSAT develops new satellite systems in cooperation with ESA. Specifically, ESA is responsible for the development of satellites which fulfil the user and system requirements defined by EUMETSAT, and for the procurement of recurrent satellites on its behalf. EUMETSAT develops all ground systems required to deliver products and services to users and to respond to their evolving needs, procures launch services, and operates the full system for the benefit of users.

Finally, EUMETSAT also performs various tasks on its data archives, required by meteorological services to run climate predictions. Those tasks include recalibration, cross-calibration, reprocessing, quality control and ultimately delivery of data to climate community. As progress is made in spatial observations, climate data can be difficult to compare from one year to another, for example because an observation one year has been captured in digital format while the same observation later has been captured in HD digital. Climate analyses require long-run data that need to be consistent, comparable, and exploitable, which is ensured by EUMETSAT. Then, some advanced meteorological services will run re-analyses, i.e. new assimilation of all data with the latest and most sophisticated data assimilation systems.

European Centre for Medium-Range Weather Forecasts (ECMWF)

The ECMWF is an intergovernmental organization supported by 22 European countries and 12 other countries that are either associated with or in the process of becoming members. The Centre was established by a convention signed in 1975.

ECMWF is both a research institute and a 24/7 operational service, producing and disseminating numerical weather predictions to its Member States. This data is fully available to the national meteorological services (NMSs) of Member States. The Centre also offers a catalogue of forecast data that can be purchased by businesses worldwide.

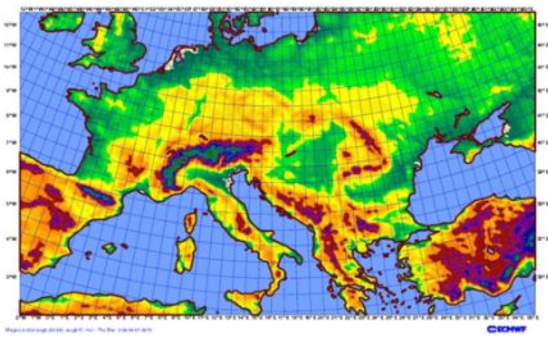
How to make a weather forecast?

Producing weather forecasts can be divided into 4 stages:

- observation of the state of the atmosphere using satellites (EUMETSAT), radars, ground stations, buoys…
- assimilation of the observation data, i.e. the processing to make them usable by the model
- simulation of meteorological parameters evolution with models based on the fundamental laws of fluid mechanics, thermodynamics, and changes of state of water
- supercomputers are essential to carry out the considerable amounts of computation required for assimilation and simulation in a limited time (so that simulation results can be made available to forecasters and relevant users very quickly)

ECMWF produces weather forecasts at medium-range (from 3 days up to about 2 weeks ahead). Extended-range forecasts are also produced for monthly and seasonal timescales, but not for short-range. Forecasting for all these time ranges requires forecast models that cover the global domain (global-area models). Production of short-range forecasts of up to 3 days ahead is primarily a task for the national meteorological services (NMSs), using limited-area models, with a finer resolution than the ECMWF one, or for some of them their own global-area model. ECMWF has one of the best global-area models worldwide with a resolution of 14 km.

Figure 5: ECMWF global-area model



Source: ECMWF

High resolution creates a detailed picture of the atmosphere, which means that when the picture is reliable, very accurate and localized forecasts can be produced. The ECMWF model (on the left) is a global-area model and provides forecasts with a lower resolution than limited-area models. However, such models are particularly useful to observe large-area trends and the evolution of weather over longer time periods (from several days to weeks). Moreover, global-area models enable to set boundary conditions for limited-area models run by NMSs. France has both a limited- and a global-area model but still uses the ECMWF model to set boundary conditions of its limited-area model. The ECMWF model is also determinant for weather forecasts over the Indian Ocean and thus over Reunion island, as well as for the Caribbean, French Guiana and the French Pacific territories.

ECMWF uses advanced computer modelling techniques with its model and human expertise to analyze observations and predict future weather for the entire global atmosphere. ECMWF's assimilation system uses 40 million observations a day from more than 50 different instruments on satellites, and from many ground-based and airborne measurement systems. It also produces climate re-analyses using the latest data assimilation system to produce improved climate datasets for past decades, essential for climate research.

In addition, the organization carries out research on all aspects of global weather prediction up to one year ahead through international collaboration with Member States and Co-operating States, as well as space agencies and research institutes around the world. It also provides training programs to assist Member States and Co-operating States in training scientists in numerical weather forecasting and maintain an archive of meteorological data to use them for climate and weather forecasting.

Finally, ECMWF operates two Copernicus services on behalf of the European Union: the Copernicus Atmosphere Monitoring Service and the Copernicus Climate Change Service. It also contributes to the Copernicus Emergency Management Service and collaborates with the Copernicus Marine Environment Management Service.

Météo-France

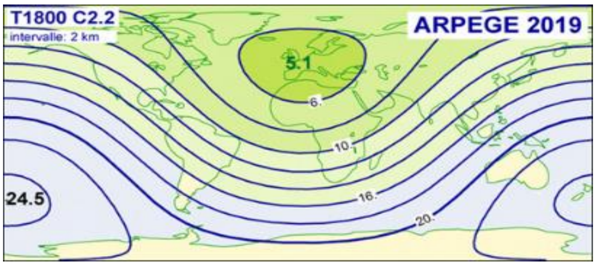
Météo-France is a French public administrative institution since 1993, placed under the supervision of the Ministry of Ecological Transition. It is the French national meteorological service, covering mainland France and the overseas territories, responsible for forecasting meteorology and knowledge of climate change. Météo-France has a special regional responsibility within WMO for the prediction of tropical cyclones in the South-West Indian Ocean.

The institution's scientific and technical skills enable to cover all stages of the forecasting chain:

- observation: It ensures the collection, transfer, dissemination and use of data from satellites, networks of ground measurement stations, buoys, radiosondes, sensors on airliners or ships and hydrometeorological radars. Météo-France also coordinates at the national level the meteorological observation networks in partnership with the flood forecasting services, the research institute INRAE, EDF and many other structures that need meteorological data, and exchanges observations with the World Weather Watch network managed by the WMO. Its "Centre de météorologie spatiale" (Space Weather Center) receives, processes and disseminates data from meteorological satellites (assimilation).

- modelling: Once data have been assimilated, they can be implemented into numerical weather prediction models. As the ECMWF, Météo-France uses a global-area model but also a limited-area model. Forecasters start to simulate the major atmospheric phenomena around the Earth using global models, and then zoom in on smaller and smaller parts of the territory using limited-area models, which are more accurate in the area they cover. The global-area model of Météo-France, namely Arpege, enables to simulate and forecast large-scale phenomena such as lows, highs or frontal systems up to three days ahead. Its resolution is 5 km over Europe and 16 km across the globe (as represented on the right). This model is complemented by the ECMWF model but also by the Aladin model developed by Météo-France to refine the forecasts for Antilles, French Guiana, French Polynesia and New Caledonia (around 7 km resolution over these places) and for cyclone forecast in the Indian Ocean (including Reunion island). Météo-France has developed a limited-area model at a high resolution (1.3 km in 2015) over mainland France and neighboring countries (Germany, Belgium, Switzerland, the Netherlands). This latter makes it possible to improve the consideration of local phenomena and the forecasting of dangerous phenomena for time frames between 3 and 36 hours. It needs the ECMWF global model to set boundary conditions. Running these models requires extremely powerful computers, known as supercomputers. Between 2016 and 2020, Météo-France had 2 supercomputers, with a total theoretical computing power of 5 Petaflops, or 5 million billion operations per second. In 2020, new supercomputers replaced the previous ones to reach a computing power of 20 Petaflops.

Figure 6: resolution of Météo-France global-area model



Source: Météo-France

- analysis by forecasters: Météo-France forecasters assess the uncertainty associated with forecasts coming from models, characterize the risks of dangerous phenomena and take decisions on vigilance. They ensure direct contact with certain categories of users, such as the services in charge of civil security in France.

Moreover, Météo-France carries out longer-term forecasts (seasonal forecasts and climate projections). It produces regionalized climate scenarios with operational purposes in various sectors. It provides different products and climate services dedicated to energy management, sustainable farming, sustainable transport modes, adaptation to climate change, etc. Operational actors may directly access to regionalized climate projections through free climate datasets made available by Météo-France on the “Climathèque”, or benefit from a specific support service of Météo-France. Since the evolution of the climate can also be anticipated a few months ahead, Météo-France issues seasonal forecasts for the coming quarter. However, such seasonal forecasts remain uncertain and difficult to accurately assess, particularly in Europe. Such forecasts are more general trends with uncertain probabilities, still at the research stage, but are more and more used at an operational level in the tropical belt where predictability is more directly influenced by interactions with oceanic conditions.

The institution is also highly involved in research to improve our understanding of climate change. Consequent amounts of research work have been accomplished in the CNRM (National Center for Meteorological Research managed by Météo-France) to understand climate mechanisms, to model them and to model their impacts on local territories and worldwide. The institution is a major contributor to the IPCC work. More generally, the research center studies the various components of the Earth (atmosphere, soil, snow cover, oceans, vegetation) to better understand natural processes and their evolution and thus, improve weather and climate forecasting.

Counterfactual scenario

The chosen counterfactual scenario relies on the following hypothesis: **no public subsidies are given to Météo-France and the CNES and France has never contributed to the ECMWF, nor to EUMETSAT, nor the ESA**.

Absence of public subsidies for meteorological organisations

Météo-France heavily relies on the public subsidy that represented in 2019 46.3% of its total budget[4]. The rest of the budget comes from the public subsidy dedicated to the French contribution to EUMETSAT (19.3% in 2019), aeronautical charges from the French Directorate General of Civil Aviation (21.8%), commercial revenues (8%) and other revenues (4.7%). Without public subsidies to Météo-France and EUMETSAT, not only Météo-France would lose almost 2 thirds of its total budget, but it could lose part of its access to spatial observations provided by EUMETSAT. As a result, the French infrastructure would mainly have access to *in situ* observations (radars, radiosondes, sensors…). Moreover, the absence of the French contribution to the ECMWF would deprive Météo-France from access to high resolution medium-range forecasts of the ECMWF and to data of its global area model enabling to give the boundary conditions for the limited area model of Météo-France. From the combination of all those consequences, **we can reasonably deduce that Météo-France would not have enough financial and technological resources to operate and could not provide any reliable service**. Hence, **we set the assumption that Météo-France does not exist in our counterfactual scenario and has never existed**. Concretely, there is no limited area model of Météo-France capable of providing short-range and precise weather forecast in metropolitan France. The absence of its global area model and access to the global area model of the ECMWF prevents France access to less precise short-range weather forecasts on its territories (including domains) and to the most reliable medium-range weather forecasts on Europe provided by the ECMWF (that is essential of weather forecasts in French domains). One should add that other French competitive weather forecast services that use Météo-France models' output such as La Chaine Météo or Météociel, and that provide forecast for non-institutional services, would not exist either.

Beyond the border of France, **the other European countries would also have a degraded situation** compared to the real one. As France's annual contribution represents around 14%[5] of the ECMWF's total budget and since Météo-France closely cooperates with the ECMWF for developing the ECMWF's global model, we could easily think that **the European service provided would have been less efficient** than it is today. Moreover, contributions of Member States are the main revenue sources of EUMETSAT to operate and are proportionate to the gross national income (GNI) of individual states for mandatory activities. France's contribution is relatively important given the weight of its economy in Europe. For instance, the French contribution for mandatory activities represented 13.9% of the total contributions in 2019[6]. Therefore, we can think that in the counterfactual scenario, weather forecasting of the ECMWF and of foreign national meteorological services are degraded compared to the real situation. It is difficult to state the level of weather forecasts of other European national meteorological services, in particular of the United Kingdom and Germany that are the only other European countries (apart from France and the ECMWF) to have a global area model capable of providing forecasts that cover the Europe and thus France (with a grid resolution of 10km over Europe for the British model and of 7km for the German one).

[4] Source: meteofrance.fr
[5] Information collected during an interview with the ECMWF
[6] Source: French budget annexes: https://www.performance-publique.budget.gouv.fr/sites/performance_publique/files/farandole/ressources/2019/pap/html/DBGPGMJPEPGM193.htm

Considering all those consequences, the most likely scenario that we choose is the following: **France would rely on American weather forecasts provided by the National Oceanic and Atmospheric Administration (NOAA) through the Global Forecast System (GFS).** This weather forecast model generates data for dozens of atmospheric and land-soil variables, including temperatures, winds, precipitation, soil moisture, and atmospheric ozone concentration. It is a global model that has a vision over the whole globe with a base horizontal resolution of 18 miles (28 kilometres) between grid points for forecasts of less than a week. Horizontal resolution drops to 44 miles (70 kilometres) between grid points for forecasts between one week and two weeks. This model does not provide analysis and forecasts beyond 16 days. Since the NOAA operates its own meteorological satellites, cooperating with the NASA, **we can assume that the American administration would remain able to provide a service relatively reliable to Americans and to other countries**.

Absence of public subsidies for Earth observation activities

The CNES and the ESA do not have a fixed budget that will determine what spatial programs they will develop. Instead, they propose different programs to European governments (the CNES to France, the ESA to European Member States). Then, governments decide which spatial programs they want to implement and in which of them they will invest in. If a country financially contributes to 10% of the funding of a programme, then 10% of the activity related to this program (development of satellites, research…) will be carried out by the industry of the country.

In a situation where the French government had never funded any program for Earth observation, the CNES could not have developed any project in this domain, neither providing instruments and scientific exploitation of Earth observations. **Hence, we can reasonably assume in our counterfactual the absence of the CNES for Earth observation and thus all the projects it has contributed to**.

The absence of the CNES for Earth observation in the counterfactual scenario deeply affect Earth observation as we know it today for several reasons:

- Earth observation in Europe was born in France through the CNES that developed its first satellite for ESA (Meteosat for weather forecasting), by a team of the CNES who brought their technical skills from the French industry and was launched in 1977.
- Then, the French government started its program SPOT with another satellite (SPOT-1 launched in 1986), way before the ESA started its own Earth observation program. To do so, the CNES developed optical imagery for this satellite, that is used today for the satellites of Sentinel-2 (Copernicus).
- The CNES has also been fundamental for developing numerous instruments of satellites, such as solar panel to feed them with energy.
- Projects from the CNES are mainly dedicated to research purposes but some of them became or may become operational and enter the Copernicus program. For instance, the CNES has developed, with the NASA, the Jason mission (measuring oceans' heights), at first for research purposes but as it appeared promising and useful, the ESA and EUMETSAT jointly cooperated to include it in the Copernicus program within Sentinel-6. Hence, **the CNES's contribution is considerable to develop technologies and missions, mainly for research but that can show promising operational uses**.

The absence of France's contribution to European Earth observation programs through contributions given to the ESA would also have affected Earth observation progresses. As explained above, the amount of participation of a country represents the extent to which the country will technically and scientifically contribute to the program, through its national industry. For a long time, France was the main contributor to Copernicus (today third contributor) and to other missions and had the highest level of technical and scientific skills in the space area with its industry. Without the involvement of France in Earth observation programs, the ESA could not have placed contracts in French industry that has been determinant to make progress (solar panel, optical imagery, satellite platform…).

Hence, we can reasonably assume in our counterfactual that Europe would not have developed yet the level of technologies available today for Earth observation. Although the Copernicus program and the other missions may come up eventually, this would take more time as technical skills that have been developed in France should be developed somewhere else. This confirms the idea that EUMETSAT activities would be deteriorated in our counterfactual, when considering the importance of France for European spatial development, including for EUMETSAT's satellites.

Consequently, **we can assume for our counterfactual the absence of the CNES for Earth observation (and thus of research missions it has contributed into), as well as the absence of the Copernicus program, because of the delay in terms of technological and scientific skills, compared to the situation as we know it**. Programs provided by the ESA would thus be limited to exploration projects (i.e. at research level) as it was several decades ago, with important improvements to make to achieve operational services and to provide rich and reliable data to the scientific community.

The American Landsat program, also offering free-of-charge and open data, would probably have developed in a similar way as it happened. However, the image resolution of its satellites has been much lower than images provided by Sentinels' satellites. Hence, we assume that no other international program could have provided free data with the quality level provided by Copernicus, which means that services that developed using Copernicus data in various sectors in Europe would probably not exist either.

A theoretical counterfactual scenario

We remind that the counterfactual scenario is fictive, and uncertainty remains. For example, relationships and cooperation partnerships are very common in the meteorological sector, particularly through the World Meteorological Organisation who facilitates the exchange of weather information across national borders. Moreover, spatial organisations such as the CNES and the ESA participate in developing satellites for EUMETSAT but also in partnerships with the NASA and the NOAA (e.g. with the Jason-CS mission). Hence, **it is likely that degraded services of the ESA and EUMETSAT and the absence of the CNES for Earth observation would also have consequences on non-EU national meteorological services such as the NOAA**. For simplicity's sake in this evaluation, **we suppose that the American weather forecasting service would not be affected and would be the essential resources in France to obtain weather forecasts**.

The absence of Copernicus is also very uncertain. Although the role of France has been considerable, through its financial but also scientific and technological contribution, it is possible that Germany and Italy would have invested more in Earth observation development and made breakthroughs or that the EU would have cooperated with international agencies to develop Copernicus. **As it is impossible to know for sure what would have happened without the French contribution, we decide to assume the absence of the Copernicus program as the reference scenario**.

From this counterfactual scenario, **we will analyse the implications for each sector and each impact that we will investigate**. Thereby, the degraded weather forecasting service may have different consequences according to the sector. For instance, we can think that unlocalised forecasts would be useless for farmers and would be equivalent as no forecasts at all. On the other hand, the absence of precise forecasts might have lighter consequences for the long-run adaptation of cities to global warming.

General methodology

We approached the evaluation process by distinguishing as far as possible between weather forecasting and Earth observation activities. Although complementarities exist between these two types of activity, it was easier to approach them separately when identifying and analyzing their impacts, and then to bring their synergies together. The reason behind this choice relies on the fact that the chain of impacts from the organizations' activities to the environmental effects is not quite the same between Earth observation and weather forecasting (see next section). EUMETSAT is a particular case as it produces spatial observations but in order to carry out weather forecasts. Therefore, it represents the first link in the impact chain of weather activities and was thus treated with them.

Regarding the methodology for weather forecasting activities (Météo-France, ECMWF, EUMETSAT) and their impacts analysis, four main steps were carried out. **First, we identified all the main sectors whose activities rely on weather and climate forecasting**, so that we could have a full vision of the study's scope. A review of the socioeconomic evaluations that have been made on weather subjects (*e.g. Citizing, 2016; Citizing, 2017; France Stratégie, 2018; Citizing, 2021; London Economics, 2015; Leviäkangas et al., 2007; Leviäkangas et Hautala, 2009*) enabled to establish a list of the most important sectors. **Second, we needed to identify environmental impacts through the sectors found in the previous step**. To do so, we reviewed the aforementioned socioeconomic evaluations of meteorological activities, we ran interviews with Météo-France and the ECMWF, and we received the expertise of Michel Jarraud[7], a specialist in numerical weather prediction, to validate the impacts and adjust them. The final list contained 44 positive environmental impacts[8] distributed over 5 sectors and 3 negative environmental impacts directly related to meteorological activities (see Annex A *table A1* and *A2* for all the impacts and their rationale). **Third, the important number of impacts and the limited time to carry out the evaluation made necessary to establish a pragmatic selection of those**. Hence, we offered a simple and readable decision support tool based on common sense to determine as objectively as possible a classification of the environmental impacts. This tool is based on a scoring approach presented in detail in Annex B. The short-list contains 10 environmental impacts distributed over 5 activities using weather or climate forecasts that we deeply investigated (impacts considered to be the most important ones according to our scoring approach). However, we decided to qualitatively present some additional impacts (considered as important but less important than the others chosen) in order to cover other interesting topics for which meteorological activities can play a role. Moreover, we also included a section dedicated to research (for both meteorological and Earth observation) as we have made considerable advances in climate and environmental fields thanks to those activities. Such advances have enabled to obtain a better knowledge of climate change, crucial to undertake political decisions to intend to mitigate it and to adapt to it. **Finally, we intended to quantify as much impacts as possible** by:

- investigating what are the technological means in terms of weather and climate forecasting provided by the studies organisations
- figuring out the consequences within our counterfactual scenario for the activities we are interested in (agriculture, energy…)
- setting a strategy of quantification according to available environmental metrics, available data and the literature to estimate the magnitude of the impact of weather forecasting activities
- using assumptions to provide scale of magnitude of the impacts or providing qualitative analyses.

Regarding the last point, some qualitative elements (particularly to describe the different sectors, their relationships with weather forecasts, or some case studies) were taken from the work done by *Citizing* during

[7] Michel Jarraud was Secretary-General of the WMO from 2004 to 2015. He is a specialist in numerical weather prediction and had high-level operational responsibilities at Météo-France and ECMWF before joining WMO.
[8] distributed over 30 activities using weather forecasts to implement actions that have one or several potential environmental impacts

previous missions. This concerns in particular parts on maritime transport and marine pollution, for which substantial work had been carried out as part of the socio-economic evaluation of the ECMWF supercomputer (*Citizing*, 2017).

Two additional important points must be specified:

- It has been decided to favor quantification of some impacts using assumptions on their magnitude, over a simple qualitative analysis. The objective is to provide an idea of the potential order of scale of an impact, based on a range of magnitude values relying on a qualitative rationale (e.g. are we talking about thousands or millions of avoided tons of CO2 thanks to weather forecasting…). Sensitivity tests are carried out on fragile assumptions.
- The scope of the study for weather forecasting impacts is limited to impacts in France (however we will see that sometimes it goes way beyond, particularly for maritime activities) and from 2016, year of the implementation of the French green OAT. However, as environmental impacts and meteorological activities have longer temporal scope, we may sometimes look further into the past with the aim of smoothing heterogeneous variables from one year to the next and identifying trends instead.

Regarding the methodology for Earth observation activities (CNES and ESA) and their impacts analysis, **we first identified all the missions for which the ESA or the CNES have been involved into**. Then, **we investigated, through the literature and interviews with organisations, potential environmental impacts of Earth observation data provided by Copernicus, by looking for operational services offered in Europe that are based on spatial data (at least partly) and that provide support to users enabling to avoid environmental damages**. As such data are open and free to all, we cannot guarantee that all existing services using spatial data have been identified in this evaluation. However, we identified the main sectors and types of services using Earth observation according to interviews and the review of Copernicus services (see Annex A *table A3* for a non-exhaustive list). **Given the limited time to carry out this evaluation, we decided to focus on services in sectors that we do not already cover in the analysis of weather forecasting activities.** However, we also study impacts of Earth observation for forest fire management and farming treatment (also considered for weather forecasting analyses) as they were highly scored in our scoring approach to prioritize impacts of weather forecasting and since they involve the higher number of environmental impacts.
Finally, we identified all the spatial missions dedicated to research in environmental and climate fields.
As the quantification of environmental impacts of Earth observation is too challenging (see next section), we decided to provide qualitative analyses and case studies in Europe that show the potential of spatial data in addressing environmental issues.
The scope of the study for Earth observation will not limit itself to France as the ESA operates at the EU level (sometimes even further). Although the public subsidies to weather forecast and Earth observation activities started matching with the Green OAT in 2016, we went a little further into the past as spatial missions are usually carried out over years from the development of the satellite until the end of the operation in space.

This evaluation unavoidably omits environmental impacts of meteorological and Earth observation that cover a considerable number of different topics. However, choices we made regarding which impacts to study enable to present a list containing very diversified activities, all the main sectors using meteorological and/or Earth observations, and with a particular care given to activities for which those observations have important environmental impacts (in terms of magnitude or number).

Challenges of the evaluation

In the meteorological sector, one of the first methodological difficulties concerns the weak link between weather forecasting (produced by Météo-France and the ECMWF) and its environmental benefit. Indeed, the value chain from forecasting to environmental impacts, shown below, highlights several filters potentially reducing the final impact. The chain is even longer for EUMETSAT that provides Earth observations to produce weather forecasts.

Figure 7: value chain for weather forecasting

Météo-France, like all other national meteorological services (NMS), is therefore not a "direct provider" of environmental benefits but a lever for environmental benefits. This multi-stage chain largely explains the difficulty in accurately quantifying the environmental return attributable to weather forecasting and meteorological and climatological infrastructure.

Earth observation activities carried out by spatial agencies also generate environmental impacts through an indirect mechanism represented below. The operational program Copernicus provides free open data that can be used by the population, public authorities, and companies that will use those data to develop operational services in various sectors. Then, users of the service will implement actions with this support, which can lead to environmental benefits.

Figure 8: value chain for Earth observation

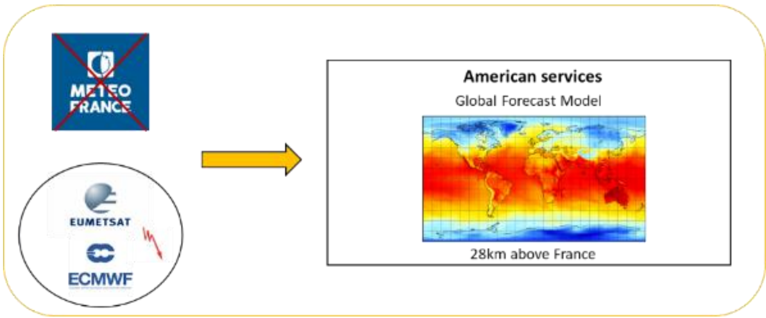
Hence, the magnitude of the impact may depend on the quality and the content of the service using Earth observation data, which probably vary from one company to another and between regions in Europe. Moreover, contribution of spatial data is only partial to develop those services that also require in-situ data, artificial intelligence, machine learning algorithms, models, etc.

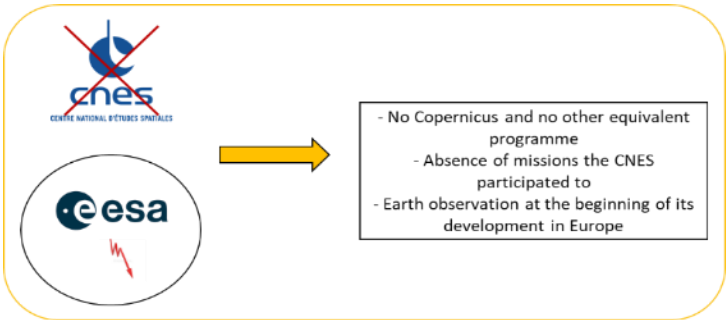
In addition to this difficulty, we encountered a considerable lack of literature that studied environmental impacts of weather and Earth observation activities. This is not surprising as environmental fields remain challenging to study and to quantify and as impacts of weather and Earth observation activities are very indirect through mechanisms above described. We also have little step back on Copernicus that has been implemented in 2014 as an operational program.

Finally, attributing the share of the impacts due to the French subsidy is also challenging since meteorological and Earth observation activities depend on a very interconnected ecosystem where international partnerships are regularly made to run those activities, even beyond Europe.

Global view

The counterfactual scenario described before is represented in the following figures and will be used all along the report to compare environmental impacts.





Environmental impacts are categorized within sectors and will be presented through quantitative and/or qualitative analyses.

Table 1: List of environmental impacts and overview of quantitative and qualitative analyses

Sector	Impact	Weather		Earth observation	
		Quanti	Quali	Quanti	Quali
Agriculture and forestry	Optimisation of agricultural treatments	✓	✓		✓
	Prevention and control of forest fires and their consequences	✓	✓		✓
	Management of forests and their ecosystems				✓
	Management of land use and habitat decline				✓
Energy production	Development of solar and wind energies		✓		
	Reduction in forecast errors of wind and solar power production reducing compensation with fossil to maintain energy market equilibrium	✓	✓		
	Management of hydraulic dams		✓		
	Management of nuclear power plant during heat waves		✓		
Aquatic and maritime areas	Optimisation of ship routing for maritime transport	✓	✓		
	Management of oil spills		✓		
	Monitoring wetlands				✓
	Monitoring coastal ecosystems and erosion trends				✓
Urban areas	Adapting to heat islands		✓		
	Mitigating atmospheric pollution		✓		
Research	Improving knowledge on climate		✓		✓
	Improving research in environment				✓
Meteorological and Earth observation activities	Direct environmental impacts from organisations' activities	✓	✓		✓

Source: authors' own elaboration.

Notes:

- *In grey: not concerned by the impact; in brown: concerned but not studied in this evaluation; otherwise colored in yellow*
- *"Quanti" box checked: impact has been quantified for at least one environmental objective (climate change mitigation, climate change adaptation, biodiversity, pollution)*
- *"Quali" box checked: a qualitative analysis is provided for the impact (additionally to a quantification or not)*

Environmental impacts of meteorological and Earth observation

1. Agriculture and forestry

A. Optimisation of agricultural treatments

Cultivated areas cover approximately 173 million hectares in Europe (39% of total land area of the EU), of which 26.9 million hectares in metropolitan France, i.e. almost 50% of the territory[9]. Four main categories of crops can be distinguished:

- Extensive field crops, including cereals and oilseeds
- Permanent crops other than grassland, such as vines and other fruit
- Fodder and grassland
- Other crops such as vegetables, flowers and seeds

i. Role of weather forecasts

Weather plays a crucial role in agriculture, as crop growth depends on weather conditions. Although knowledge of the weather or climate does not guarantee that it is possible to react or adapt, weather forecasting and climate projections are useful at all time frames. The most frequent forecasts used by farmers are short- and medium-term weather forecasts that can inform farmers' decisions such as:

- Timing and intensity of fertilizer application
- Timing and intensity of crop protection treatments
- Time of sowing
- Timing of harvesting
- The implementation of weather protection measures (hail nets, canopies, and heating systems)
- The choice to graze livestock, etc.

This section aims at analysing the 2 first farmers' decisions of the list. Indeed, weather forecasting is one of the parameters for optimising phytosanitary and fertiliser treatments. Fertilisers are grouped under the name NPK. NPK refers to nitrogen, phosphorus and potassium, which are used to promote crop growth. Plant protection products, i.e. herbicides, fungicides and insecticides, are used to protect crops from pests.

For plant protection products (PPP) to be effective, treatments must be carried out in the right place at the right time, depending on soil moisture, temperature, hygrometry, soil characteristics and wind speed on the day of application and the following days. Hygrometry and temperature conditions are essential for the absorption of products by the plants and therefore the effectiveness of the treatment. According to Bayer, a manufacturer of phytosanitary products, the reliability of 5-day temperature and humidity forecasts is a determining factor in improving the effectiveness of treatments. Plant protection products can also be carried away by the wind (volatilization). It is even forbidden to spray when winds exceed 19 km/h[10]. However, the effect of dispersion is present from 12 km/h. Regarding fertilizers, they can be washed away by heavy rain (leaching) or by the wind. The effectiveness on the crops is then reduced, the water and the soil are polluted, and the environment is at risk of eutrophication (nitrate pollution). The technical agricultural institute Arvalis estimates that rainfall of about 15mm in the three days following the treatment constitutes the ideal conditions for spreading fertilizer[11].

[9] Source : Agreste.
[10] French order of 4 May 2017 governing the conditions of use of plant protection products
[11] https://www.arvalis-infos.fr/oui-il-faut-15-mm-de-pluie-pour-valoriser-un-apport-d-engrais-azote-@/view-18372-arvarticle.html

All those conditions show the importance of reliable and very local weather forecasts to avoid failed treatments. Exchanges with experts in meteorological services for agriculture at Météo-France during previous *Citizing* missions confirmed that weather forecasts are increasingly integrated into decision support tools designed for farmers (e.g. GPN from Total and FARMSTARR from Arvalis). The causal relationship between better weather forecasting and farmer decision-driven impacts thus appears robust.

Counterfactual scenario
Farmers would have access to American forecasts which means that they would have short-range forecasts with **a 28km resolution** and medium-range forecasts with a 70km resolution. Given the importance of very local meteorological conditions to anticipate precipitations, temperatures and wind, farmers could not use American forecasts as a support. In this case, **the counterfactual scenario is equivalent to assuming no weather forecasts to support farmers' actions**.

By developing a strategy and setting assumptions **(described in Annex C.1: GHG emissions reduction arising from optimal farmers' treatments using weather forecasts and Annex C.2: biodiversity harm reduction arising from optimal farmers' treatments using weather forecasts)**, we intend to provide an order of magnitude on the impacts of weather forecasting as regard greenhouse gas emission mitigation and biodiversity preservation through reduced consumption of fertilizers and PPP by farmers in France. As justified in the annex, we consider that despite the current quality of weather forecasting services provided by Météo-France, **5% of treatments (expressed in mass) fail**. In the counterfactual scenario, i.e. in **the absence of localized weather forecasts,** we assume that **between 10% and 30% of treatments would fail.**

- **Impact on GHG emissions (see details of the quantification in Annex C.1: GHG emissions reduction arising from optimal farmers' treatments using weather forecasts)**

We find that, based on our assumptions, weather forecast services provided by Météo-France (supported by EUMETSAT) might **enable to avoid between 3.35 kilotons** (counterfactual = 10% failed treatments) **and 16.75 kilotons** (counterfactual = 30%) **per year on average of wasted PPP** (in the sense that the treatment failed, and PPP are released into the environment). It may also **enable to avoid each year on average between 110 kt and 546 kt of wasted nitrogen-based products and between 9 kt and 47 kt of wasted phosphate-based products**.

Failed treatments have consequences on crop productivity which impacts economic performance of farmers. To maintain an equivalent level of effectiveness, they should increase the number of treatments to compensate losses. Hence, diminished amount of wasted fertilisers and PPP enable, at constant efficiency, savings on fertilisers and PPP consumption and thus on their production and their use, reducing the carbon footprint of agricultural activities. Indeed, production of PPP and fertilisers products implies relatively important emissions for manufacturing and after spreading[12]. For nitrogen, the emission factor of nitrous oxide (N2O) after spreading has important uncertainty (from -80% to +400%) as it depends on various natural phenomena. Still, we show the range of values between this uncertainty interval to quantify it, because N2O emissions from spreading (through fertilisers decomposition in fields) is usually the main factor for fertiliser. The results are the following (depending on the counterfactual's assumption – 10% or 30% of failed treatments):

- **Avoided emissions from PPP (whole life-cycle)**:

[12] Emissions of CO2, N2O and CH4. Nitrogen-based products' production leads to NH3 emissions (ammonia) expressed in CO2-eq here and nitrogen-based products' spread leads to N2O emissions (nitrous oxide) expressed in this unit and converted into CO2-eq.

- between 31 and 155 kt of CO2 per year
- between 0.09 and 0.45 kt of CH4 per year (3 to 13.5 ktCO2-eq[13])
- between 0.0008 and 0.004 kt of N2O per year (0.21 to 1.06 ktCO2-eq)

- **Avoided emissions from fertilisers (manufacturing)**:
  - between 584 and 2,900 kt of CO2-eq /year for nitrogen-based products (ammonia)
  - between 5.3 and 26.8 kt of CO2-eq /year for phosphorus-based products
  - no data for potassium-based products
- **Avoided emissions from nitrous oxide (after spreading):**
  - *with low value of emission factor:* between 0.46 and 2.3 kt of N2O per year (122 to 610 ktCO2-eq)
  - *with high value of emission factor:* between 11.5 and 57.4 kt of N2O per year (3,048 to 15,211 ktCO2-eq)

Table 2: Summary of impacts on mitigation

Impact of weather forecasting activities on mitigation (/year)		
Share of failed treatments		
Project option	5%	
Counterfactual	low scenario 10%	high scenario 30%
Wasted amount (in kt)		
PPP	3.35	16.75
nitrogen-based products	110	546
phosphorus-based products	9	47
Emissions (in ktCO2eq)		
PPP (whole life-cycle)	34.21	169.56
nitrogen ammonia (production)	584	2900
nitrous oxide (spread - low factor)	122	610
nitrous oxide (spread - high factor)	3048	15211
phosphorus (production)	5.3	26.8
Total avoided emissions (ktCO2eq)	**[746 ; 3672]**	**[3706 ; 18307]**
Total emissions from treatments France	*[14890 ; 73268]*	

Notes: values represent differences in corresponding variables between the counterfactual (low or high scenario) and the project option.
The last row shows total emissions in France arising from PPP and fertilizer treatments, computed based on the same data and emission factors used in this section.
The last two rows depends on the emission factor of nitrous oxide spread. We provide results between the range of uncertainty of this factor (defined as "low" and "high" factor here)

Source: authors' own elaboration

Although ranges can be quite large, it provides an idea of the potential scale of the avoided environmental impact on air allowed by weather forecasts.

❖ Impact on pollution

[13] Conversion in GWP 100 years with Ademe database: https://www.bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?prg.htm

Failed treatments also have consequences on soils, water quality and biodiversity. Through run-off, leaching or drainage, PPP and fertilisers can be swept away and pollute soils, other farms' crops, rivers, lakes, wetlands, aquifers, and eventually coastal waters. **This pollution issue negatively impacts biodiversity (fauna and flora), crops productivity and human health** (traces of PPPs, which are toxic to humans, can be found in the water and the crops we consume). Moreover, part of PPPs, during the spray application, may be carried away by wind and increase air pollution. Fertilisers can also be toxic for human when the nitrate concentration in drinking water exceeds $50 mgNO_3^-/l$.

- **Impact on biodiversity (see details of the quantification in Annex C.2: biodiversity harm reduction arising from optimal farmers' treatments using weather forecasts)**

One of the most important negative effects of intensive fertiliser use is water eutrophication. Eutrophication is defined as the process by which an entire body of water, or parts of it, becomes progressively enriched with minerals and nutrients. Excess nutrients, usually nitrogen (especially for coastal waters) or phosphorus (particularly for freshwaters), stimulate algal and aquatic plant growth, which leads to overcrowding competition for sunlight, space, and oxygen. Increased competition can cause potential loss of habitats and biodiversity of species.

We assume that 70% of nitrogen fertilisers ends up in water bodies when treatments fail. Based on this assumption, a precise weather forecasting service that allows to decrease the number of failed treatments could enable to avoid between 76.5 and 382 kt of nitrogen to end up in water bodies. In ecological terms, this means that **they enable to prevent around 11 to 54 (PDF)km³.year from eutrophication**[14]. There are several possible interpretations from this result. Knowing which one would occur is too complex and unpredictable. We thus decide to stick to assessing three of the possibilities:

- **weather forecasts avoid for between 11 and 54 km³ of water (freshwater, coastal water, ground water) to lose all its species for a year**
- **weather forecasts avoid for between 110 and 540 km³ of water to lose 10% of its species for a year**
- **weather forecasts avoid for between 11 and 54 km³ of water to lose 10% of its species for 10 years**

Table 3: Summary of impacts on biodiversity

Share of failed treatments		Impact of weather forecasting activities on biodiversity (/year)		
Project option	Counterfactual	difference in wasted nitrogen-based products (kt)	difference in nitrogen ending up in water (kt)	difference in PDF (PDF.km³.year)
5%	low scenario 10%	110	76.5	11
	high scenario 30%	546	382	54
		Note: the columns represent differences in corresponding variables between the counterfactual (low or high scenario according to the line) and the project option		

Source: authors' own elaboration

[14] We use the PDF indicator ("potentially disappeared fraction of species") which represents the rate of species loss (or in ecological terms the extinction rate) in a particular area of land or volume of water during a particular time due to unfavorable conditions associated with land conversion, land occupation, toxicity, increase in average global temperature, or eutrophication

ii. Role of Earth observation

Earth observation is determinant to provide data to meteorological services so that they can produce weather forecasts. The previous section showed that those forecasts are very important to farmers and can enhance their anticipation to better optimise fertilizer and phytosanitary treatments. However, **Earth observation has also contributed to the support of farmers through the emergence of dedicated services using Copernicus data across Europe and even further away**. Copernicus is a European space programme managed by the European Union and ESA, with the technical and scientific support of EUMETSAT, the CNES and the other ESA's member states. This programme allows to give a free and open access to a large variety of data used to develop operational services. As explained in the Counterfactual scenario section, we assume that the Copernicus programme would not exist yet in the absence of the French public subsidy, which means that services provided to farmers that use Copernicus data would not exist either. We thus study environmental impacts of Copernicus in absolute terms.

Copernicus led to the emergence of a new generation of high spatial and temporal resolution satellite sensors and has been a major step forward to develop services for precision farming such as services providing recommendation maps for various crop inputs (fertilizers, growth regulator, etc.) from satellite images. Some of those services already existed before the implementation of Copernicus but used unfree data from the French SPOT mission or open images but with lower resolutions from the US Landsat missions (15-120m vs 10-20m for Sentinel-2) that was complemented with airborne acquisitions. Launched in 2015 and 2017, Sentinel-2A and -2B have brought an innovative wide swath high-resolution multispectral imager with 13 spectral bands, giving a new perspective of our land and vegetation[15]. With its multispectral imager and a swath width of 290 km, the Sentinel-2 mission not only offers continuity, but also expands on the French Spot and US Landsat missions. In other words, Copernicus has brought an increased precision and a higher reliability of land data, at a high frequency (every 5 days).

Sentinel-2 satellites can monitor the vegetation cover, the level of biomass as well as the sunlight reflected by vegetation (process of remote sensing[16]). Once spatial data have been processed down to individual plots and coupled with agronomic models (crop characteristics, weather forecasts, etc.), it becomes possible to characterize the biophysical parameters of a field and then to generate vegetation maps and indices such as Leaf Area Index or Chlorophyll[17]. **This latter is particularly useful to indicate whether the plant within an individual plot needs nitrogen**. Indeed, since nitrogen is a part of chlorophyll, measuring chlorophyll is indirectly a way of measuring the amount of nitrogen in the plant. This allows for more efficient programming of fertilizer applications. **Monitoring the level of biomass on the field is also of particular use to apply fertilizers where and when it is needed, but also pesticides as this index can enable to identify disease infected parts of the parcels**.

Although services using Copernicus data are different from weather forecasting services, **they lead to similar environmental impacts as they contribute to optimize farming treatments**. **By applying fertilizers and pesticides over specific areas identified with spatial information instead of applying them over the whole field, farmers can reduce the volume of their treatments**. For example, field trials conducted by Yara (a large distributor of plant nutrients) showed that when comparing sensor-controlled fertilization with uniform

[15] Success Stories of ESA: https://sentinel.esa.int/web/success-stories/-/copernicus-sentinel-2-leads-precision-farming-into-new-era

[16] Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft).

[17] Chlorophyll is the green pigment that enables plants to photosynthesize. This process uses sunlight to convert carbon dioxide and water into basic plant components.

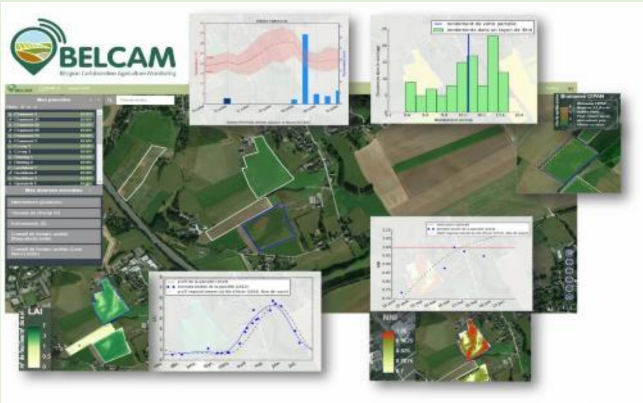
application on large scale field trials in Germany over 5 years, sensor-controlled fertilization reduced nitrogen application by 12% on average[18].

As in the analysis of weather forecasting activities, **this reduction in fertilizer and pesticide volumes enabled by the contribution of Copernicus likely benefited to the climate, soils and rivers quality and the biodiversity,** as the production and spreading of fertilizers and pesticides lead to GHG emissions, pollution of rivers and soil and water eutrophication.

Given the complexity and the very indirect contribution of Copernicus data in such environmental impacts (explained in the Challenges of the evaluation section), a quantification would be too uncertain. However, **we present an example of service using Copernicus data to support farmers in their farming treatments**.

Case study: BELCAM platform for a smart nitrogen management (Belgium)

Figure 9: BELCAM platform for farmers



Source: ESA

BELCAM is an Earth observation-based collaborative platform designed for public authorities and farmers for crop monitoring based on the joint use of field observations and Copernicus satellite data. Funded by the STEREO program, the Belgian Collaborative Agriculture Monitoring (BELCAM) platform has been developed to make the wealth of satellite information available, relevant and usable to all Belgian farmers to help them meet society's expectations. **Applying the right amount of nitrogen fertilizer, at the right time and in the right place, contributes to its full absorption by the plants and considerably minimizes its impact on the environment** and its associated carbon footprint, while improving farmers' incomes.

The BELCAM platform, represented above, contributes to smart nitrogen management of wheat, potato and maize in Belgium by providing to users satellite-based nitrogen recommendations at parcel level. Recommendations include information such as the crop nitrogen status, the Nitrogen Nutrition Index (NNI) that determines the nutrition level of a crop, and the amount of fertilizers to apply[19]. These products are built from surface reflectance and vegetation indices derived from Sentinel-2 (available every 5 days) that enable to estimate the nitrogen absorbed by the crops, the level of biomass and the leaf area index (LAI).

Figure 10: illustration of Nitrogen Nutrition index map

Source: ESA

The picture at the right describes the crop nitrogen status of some winter wheat fields in Belgium in May 2017 using the NNI. White areas are areas where fertilization is required (NNI < 0.7) whereas red areas are areas with an excess fertilization (NNI > 1).
Such a service has an important potential to reduce the consumption of fertilizers and thus their associated environmental damages. However, Sentinel data has not been the only contributor to the development of this service (weather forecasts, field data, crop characteristics modelling, users' feedbacks, etc.) and this platform first started as a pilot for 4 years until 2019. Still, this service is gradually becoming more and more operationally used and **this case study shows the contribution that Copernicus can have to enhance farming practices and the environment**.

[18] "Precision farming for sustainable agriculture", Yara factsheet (Online) : https://www.yaraagri.cz/globalassets/country-websites/campaign-assets/nbs-campaign/sub-pages/profit-page/crop-performance/pure-nutrient-fact-3-precision-farming.pdf/
[19] The Ever-Growing Use of Copernicus Across Europe's Regions (2018). Report of the EC and ESA

Services aiming at bringing precision farming using Copernicus data have already been developed in several European countries but also outside Europe, and some of them have already showed promising results. For instance, the Gaiasense project (in Greece) supported the provision of smart farming services and showed after two years that fertilizers and pesticides consumption decreased by an average of 19%[20]. Other similar projects of applications using Copernicus data have been developed such as FARMSTAR[21] (France), EUGENIUS (Italy), CropSAT (Denmark), FruitLook (South-Africa), etc.

This section showed that Earth observation and meteorological observations have been complementary support tools to improve farming treatment management. Although EO-based services for precision farming are still developing, we can already observe promising results in various places to reduce negative environmental impacts arising from fertilizer and pesticide use in agricultural activities.

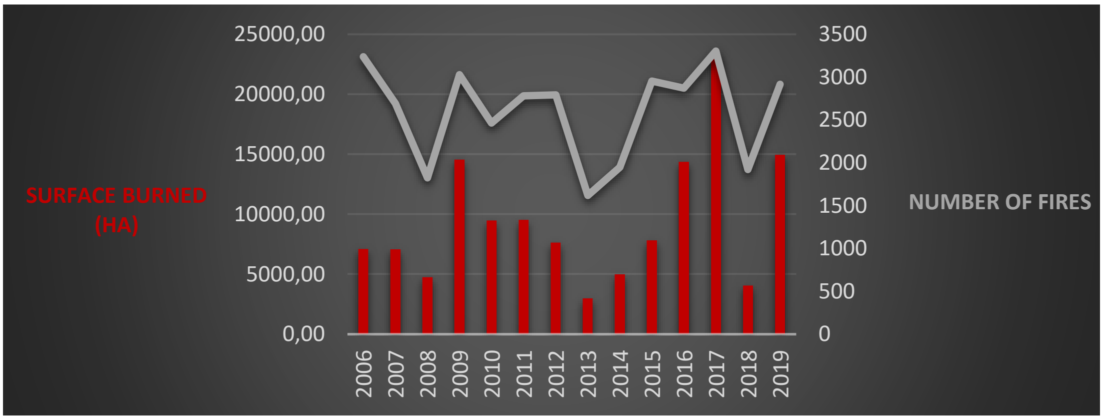
B. Prevention and control of forest fires and their consequences

i. Role of weather forecasts

One of the phenomena that concerns the safety of people and property for Météo-France is vegetation fires. France is the fourth most forested country in Europe with 16.9 million hectares of forest in its metropolitan area. The size of its wooded areas makes it vulnerable to the risk of forest fires, particularly during summer. Fires have a major impact on natural areas, destroying all or part of the animals and plants in their path, but also leading to important CO2 release into the atmosphere. In 2019, around 6,735 million tons of CO2 have been released into the atmosphere as a result of worldwide forest fires, according to the Atmospheric Monitoring Service of the European Copernicus program, which is more than the United States' total emissions this year (5,100 million tons).

For the last 40 years, **we observe that the burned surface of fires has been decreasing**. Over the period 1976-1990 in France, the annual average burned surface was around 45,000 hectares (*Chatry et al*., 2010). Over the period 2006-2019, there was an annual average of 2,593 fires that destroyed on average 9,485 hectares of forest per year (source: BDIFF database in mainland France and Reunion island).

Figure 11: Evolution of forest fires in France for 15 years



Source: BDIFF France

Note: the red histogram represents the surface burned reported on the left axis while the grey curve represents the number of fires on the right axis

[20] The Ever-Growing Use of Copernicus Across Europe's Regions (2018). Report of the EC and ESA

[21] https://sentinel.esa.int/web/success-stories/-/copernicus-sentinel-2-leads-precision-farming-into-new-era

During this latter period, most of these fires occurred in the Mediterranean area (annual average of 1720 fires destroying 6748 hectares per year, according to the Promethee database) that represents more than 71% of the annual average burned surface. Although the risk highly depends on vegetation characteristics, **meteorological conditions** (drought, temperature and wind) **also have a strong influence on the sensitivity of vegetation to fire and on the propagation** once a fire has started. Whether they are of natural origin (lightning, for example) or man-made (as is the case for 90% of fire starts[22], whether due to an economic activity - construction sites, agricultural activities - or an everyday activity - cigarette, barbecues, etc.), the extent of the fire depends to a large extent on weather conditions.

Over the last decade (2010-2019), Météo-France gained in accuracy with its two new supercomputers implemented in 2014 and improved in 2016. Their deployment in January 2014 initially increased the real power of the computing system by a factor of 12 compared to the previous configuration, with a total peak power of 1 Petaflops, i.e. one million billion operations per second. Since 2016, new developments have enabled the peak computing power to be increased to more than 5 Petaflops. Beyond the technological progress made in forecasting, Météo-France actively participates to "The national forest fire monitoring and forecasting system" under the responsibility of the Directorate General for Civil Protection and Crisis Management (DGSCGC in French). It provides civil security services with expert fire weather hazard maps, meteorological data and specific indexes, including Fire Weather Index (FWI) maps. This index is calculated according to a Canadian method from meteorological data: rain, temperature, air humidity, wind, etc. Weather forecasts are very localized as they are provided by Météo-France with the AROME model that has a high resolution for very short-range forecasts (1.3km). In addition, each summer, Météo-France forecasters are transferred with the authorities who coordinate the fight against forest fires from the operational centers in Marseille and Bordeaux. Their support is crucial for both short-range and medium-range time scales. **Weather forecasts of the next 72 hours are key information to implement fire management action plans** (e.g. transfers of helicopters, of fixed-wing air tankers, of fire fighters and equipment) and to better control new and on-going fires. **Forecasts of 1 to 2 weeks ahead are also determinant as they enable to better anticipate the evolution of fire risks so that the civil security can implement strategic decision-making** such as pre-positioning human and material resources in the most critical and risky areas to better control on-going fires and better anticipate new fires.

However, although the civil security relies on weather forecasting, their services have improved as well over the last decades and their actions have become more and more efficient. Moreover, preventive actions supplement control actions and have likely contributed to the reduction in forest fires for the past 40 years. In particular, we distinguish three complementary preventive actions[23]:

- Information and awareness-raising campaigns for citizens
- Defense of the forest against fire, managed by the Office National des Forêts (ONF), which is based in a global policy of development and maintenance of the rural and forest areas
- Control of land use and the use of forest fire risk prevention plans (introduced in 1995, they aim to control the habitat-forest interface and to avoid settlements that can cause fires and are difficult to protect in the event of a fire)

[22] Source: Feux de forêt. Les prévenir et s'en protéger (2020). Ministère de la transition écologique. Basé sur les statistiques de la sécurité civile
[23] Source: https://www.georisques.gouv.fr/articles-risques/prevention-du-risque-1

Counterfactual scenario

The civil security would have access to American forecasts which means that they would have short-range forecasts with **a 28km resolution** and medium-range forecasts with a 70km resolution. Given the importance of meteorological conditions to anticipate locations at risk, usually communicated through risk maps, the civil security could not use American forecasts as a support. In this case, **the counterfactual scenario is equivalent to assuming no weather forecasts to support civil security's actions**.

We intend to provide a scale of magnitude on the impact of weather forecasting as regard greenhouse gas emission mitigation. This strategy **(described in Annex C.3: GHG emissions reduction arising from optimal forest fires management using weather forecasts)** consists in comparing burned areas between the project option (over period 2010-2019) and our counterfactual (over period 1976-1990 – adjusted to forest cover increase, climate risk increase and improvements in forest management and civil security's equipment). However, the analysis relies on assuming that the difference in burned areas is moderated by 30% due to improvements in forest management and civil security's equipment. Although we cannot be certain about this hypothesis as there is not such data, **this analysis will enable to get an interesting idea of the order of scale of the impact of weather forecast activities**. However, **the results should be taken with caution** as they rely on this uncertain assumption. In order to assess the sensitivity of this latter, we carry some sensitivity tests below and choose to present a range of magnitude.

Over the period 2010-2019 the annual mean of burned forest was 11,805 ha (data given by the DGSCGC according to a report from the Senate[24]). Therefore, using our strategy (see annex), we estimate that public subsidies of weather forecasting activities might enable to avoid on average each year around **32,000 hectares**[25] of burned forests, compared to a situation in which France does not have Météo-France and only has access to the American global area model.

- **Impact on GHG emissions (see details of the quantification in Annex C.3: GHG emissions reduction arising from optimal forest fires management using weather forecasts)**

Forest areas saved from fires benefit to the society in terms of avoided economic and lives costs. From an environmental point of view, fewer burned areas allowed by weather forecasting also means **less CO2 emissions released in the atmosphere**. Based on the literature and on our assumptions, we conclude that weather activities over the last decade could enable to avoid the release of around **1,518 kt CO2/year** in the atmosphere compared to a situation with a level of forecasting degraded and almost equivalent to the level of the period 1976-1990.

However, we observe that this result is quite sensitive to the assumption set on the decrease in burned ha in the counterfactual scenario enabled by forest management and civil security's resources improvements:

[24] Source : http://www.senat.fr/rap/r18-739/r18-739_mono.html

[25] (58,000 ha – 11,805 ha) x 70% (70% being the share of the decrease explained by weather forecasting)

Table 4: Sensitivity test and assessment of a range of values of the impact on forest fire emissions

Share independent from weather forecasting (scenario)	Impact explained by weather forecasting		
	difference in annual burned ha	difference in ktCO2	difference in % tCO2
30% (reference value)	32229	1518	0%
low: 10%	41437	1952	29%
high: 50%	23020	1084	-29%
extreme: 90%	4604	217	-86%

Notes: the first column represents the share of the decrease in burned area between 1976-1990 and 2010-2019 explained by a better forest management and improvement of resources for civil security. We test four scenarios with different shares. The 2nd and 3rd columns represent the difference between the counterfactual and the project option. The last column is the variation in avoided CO2 emissions compared to the reference value (e.g. 29% means that there is +29% of avoided emissions when 90% of the decrease in burned area is attributed to weather forecasting instead of 70% (reference value)).

Source: authors' own elaboration

The extreme scenario is very unlikely as weather forecast quality improvement has been crucial to decrease the number of fires for 40 years and to support forest management (through climate projections) and civil security's actions. The low and high scenarios are both more reliable as extreme values of the parameter accounting for the forest management and civil security's contributions. **Hence, we can conclude that avoided CO2 emissions allowed by weather forecast services as we know them today might be ranged between 1,084 and 1,952 kilotons of CO2 per year.**

In the long run, as burned trees regrow, the released carbon is being sequestrated back. However, this process is very long, and it can take decades before the released carbon is sequestrated. Besides, the increasing number of forest fires will slow down the regrowth process. Current research indicates that even in environment where significant regrowth is able to occur, some 10% of CO2 is remaining in the atmosphere after sequestration (Johns, 2020). In other words, even after sequestration of one year of emitted carbon arising from wildfires (which could take several decades), some 152 ktCO2 could remain into the atmosphere and worsen global warming. But this share of sequestrated carbon can be challenged as it heavily depends on forest characteristics and the speed of regrowth.

❖ Impact on adaptation to climate change

If the impact cannot be fully attributed to weather forecasting as the ONF has also improved forest management regarding fire prevention, we must keep in mind that prevention in the long run such as forest management and raise-awareness campaigns rely on the knowledge that we have on global warming and on the risk evolution in certain areas in terms of fires. In other words, climate predictions support diverse decision-makers such as the ONF to better understand which areas are at risk and where measures are necessary, and more importantly which areas will be at risk in the future[26]. Hence, climate forecasting is crucial to adapt forests and people's behaviors. In the counterfactual, we would know about the increasing risk of fires but not on specific location of French territories that are increasingly exposed to fires, which would make preventive measures less effective.

[26] For example, a risk map produced by Météo-France shows that in the future, forests in northern France will be increasingly exposed to fires because of climate change.

❖ Impact on pollution

Saving areas from fires bring additional environmental impacts that we cannot quantify. First, it enables to **reduce air pollution from the smoke**. Estimating such a reduction is difficult as it depends on meteorological conditions and types of vegetation. Some studies intended to measure emissions of particles and other pollutant (CO, CO2, SO2, NOx, COVT, HCl, HAP, PCB, PCDD/DF, I.TEQ) with trials or from case studies (Ineris, 2004; Anses, 2012) in g per kg of biomass burned but those are still highly context-dependent (influenced by meteorology, topography, type of fuel…) and data about amount of different specific types of biomass that burned does not exist in France[27]. Nonetheless, it is likely that a reduction of burned areas could reduce the impact of pollution on air quality and on health, sometimes really affected by wildfires. For instance, a vegetation fire in 2009 located south-east of Marseille led to a punctual increase of the air pollution brought by the wind. We noticed an increase in PM10 and PM2.5. On the station "Timone", PM10 increased from an average of 52 µg/m³ before the fire to 158 µg/m³ during the fire, reaching a maximum hourly concentration of 302 µg/m³ [28], while the WHO recommended level of 24-hour mean PM10 concentrations is 45 µg/m³ [29].

❖ Impact on biodiversity

Weather forecasting can also allow to avoid some damages on biodiversity in saved areas: killed animals (particularly reptiles and animals that cannot easily flee); destroyed habitats and food leading animals to death; degradation of vegetation coverage that can lead to increased runoff and a rising erosion risk; increased erosion risks caused by the accumulation of ashes on soils preventing the rain to penetrate (in slopping paths, runoff then increases which lead to erosion and further to landslides) and loss in mineral components such as nitrogen which may affect soils.

ii. Role of Earth observation

While weather forecasting is particularly useful to assess risks of wildfires and their potential evolution according to the meteorological conditions, Earth observations provided by the **Copernicus Sentinels are becoming precious supporting tools to deliver detection and delineation of fires to firefighters and damage assessments to forest managers after the fire**.

The arrival of high-resolution satellites has made it possible to develop support tools in the fight against forest fires and their consequences. In particular, Sentinel-2 provides very high spectral and resolution data (up to 10m) at a high revisit frequency (around 5 days and even less according to the latitude) to detect forest fires (by capturing the light they produce) and the degree of severity of fires (by perceiving the absence of light reflection of chlorophyll in vegetation to identify burned areas). The Sentinel-1 mission can also be useful to compensate for the difficulty of satellites of Sentinel-2 (cloud perturbations) with its SAR (Synthetic Aperture Radar) device. On the other hand, Sentinel-2 compensates for the difficulty encountered by Sentinel-1 (sensitivity to ground moisture). Based on data from Sentinel-1 and -2, combined with other spatial data (notably from the American Terra and Aqua satellites[30]), in-situ data and algorithms, the European Commission has developed a free-of-access Copernicus service specifically dedicated to forest fires included in its Copernicus Emergency Management Services. This category of service (CEMS) contains two items:

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[27] This is important because for instance, a leaf or grass fire (smouldering fire) leads to higher emissions of organic pollutants and particles than a branch fire (live fire).

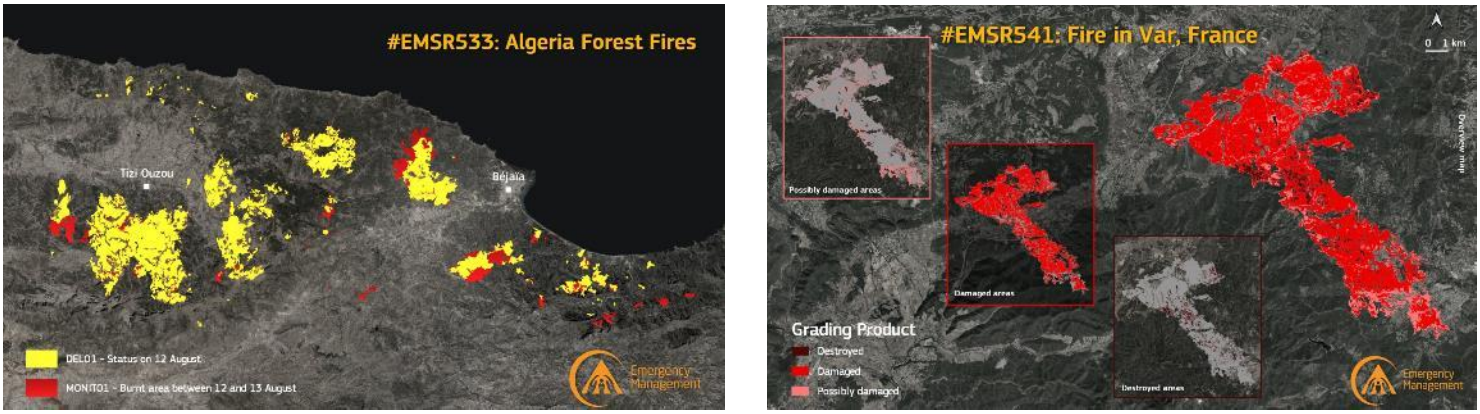
[28] See https://www.anses.fr/fr/system/files/AIR2010sa0183Ra.pdf: unpublished data, transmitted by Atmo PACA (Association agréée de surveillance de la qualité de l'air de la région PACA) to the Anses.

[29] https://www.c40knowledgehub.org/s/article/WHO-Air-Quality-Guidelines?language=en_US#:~:text=The%20updated%20recommended%20guideline%20levels,m3%208%2Dhour%20mean.

[30] Terra and Aqua satellites carry a MODIS instrument (Moderate Resolution Imaging Spectroradiometer) capable of detecting heat anomalies, but those satellites have a lower resolution than Sentinel-2 with a resolution of 250m at most.

- A cartography content, namely the Copernicus Emergency Mapping Service (EMS)
- An early warning content composed of three different systems for the prevention of floods, droughts, and fires. **The latter system is The European Forest Fire Information System (EFFIS) that provides information and maps of several products including delineation products and damage products** as illustrated in the two figures below. The Global Wildfire Information System (GWIS), that is a joint initiative of the GEO[31] and the Copernicus Programs, completes the EFFIS but at the world scale level.

Figure 12: illustration of Delineation and Damage products delivered by the Copernicus Emergency Management Service



Overview of a wildfire evolution from August 12th to August 13th in Algeria (left picture) and map of damages after a fire in France (right picture)[32]

The left picture shows the evolution of a fire in Algeria with in yellow the burned area on August 12th and in red burned area between August 12th and 13th. This map can be particularly useful to firefighters to detect starting fires using near real-time information provided by Copernicus and then to observe the evolution of a fire to undertake appropriate actions to face it. Data that satellites collect can supplement the often-dangerous work traditionally mapped with special sensors on aircraft that fly at night above the flames. The right picture shows damages of a fire in France with a distinction between destroyed areas, damaged areas and possibly damaged areas. This information can be exploited by public administrations in charge of restoring the burned-out spaces to prioritize the most urgent actions.

Environmental impacts of Copernicus data to detect and monitor the evolution of fires are similar to the ones presented in the above section resulting from weather forecasting activities. Indeed, **spatial data can provide very helpful information to enhance the effectiveness of firefighters' actions which undoubtedly led to reducing burned hectares of forest compared to a situation in which no Earth observation data would have been given**. Avoiding hectares of forest to burn by stopping the fire sooner is crucial to reduce GHG emissions, air pollution from smoke and important damages caused to the biodiversity. Of course, Copernicus could not avoid the drastic and huge consequences of forest fires, especially during summers, but it appeared to become **a promising supporting tool that provides information to detect and monitor fires evolution much faster than it is collected on-the-field, especially on difficult terrain**. As fires can propagate at very high speed, obtaining rapid information can be determinant to save areas from the flames. In addition, **Sentinel-2 data can help identify and learn the extent of the burned areas and define the degree of severity produced by the forest fire on a very detailed scale. Such information enables to get accurate and timely burned area mapping that is essential for designing both short-term ecosystem restoration measures and direct pre-emptive measures that can mitigate the possible impacts of the fire**. Those measures to be carried out by foresters (such as afforestation or putting foliage and other vegetation covers on soils) improve the filtration

[31] GEO (Group on Earth Observations) is an intergovernmental partnership (more than 100 national governments) working to improve the availability, access and use of open Earth observations.
[32] Source: https://www.copernicus.eu/en/news/news/observer-unprecedented-mobilisation-copernicus-ems-during-2021-mediterranean-wildfire

level of runoff water which reduces soil losses and fertility, improving water quality, the biodiversity and the habitat of the species.

The extent to which Copernicus data can contribute to fire detection and fire severity assessment is too uncertain to provide a quantification as it may depend on the quality of the operational service and because this data is not the only contributor to support firefighters and foresters. The contribution of Earth observation for fire detection started to be recognized and studied before Copernicus became operational with its Sentinels, for example with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument developed by the NASA (*Giglio et al.*, 2003). The American instrument "Visible Infrared Imaging Radiometer Suite" (VIIRS) carried by the Suomi satellite with a 375m resolution also showed to be effective for fire detection with an average commission error of 1.2% (*Schroeder et al.*, 2014). Although Sentinel-2 cannot detect hot spots, it brings a higher spectral resolution to get more precisions on areas where fires are starting (up to 10m against 250m for MODIS and 375m for VIIRS). In the post-fire stage, remotely sensed imagery effectiveness appeared ambiguous with varying degrees of reliability depending on satellites' resolutions and algorithms using spatial data (*Barbosa et al.*, 1999; *Giglio et al.*, 2009; *Roy et al.*, 2005) as well as on the complexity of the observed area. For instance, the heterogeneity of savanna results in heterogeneity of fire-induced spectral changes (*Pereira*, 2003). **Images generated from Sentinel-2 have been shown to be useful to map burned areas** (*Weirather et al.*, 2018). Colson et al. (2018) studied the Sierra del Gata wildfire that occurred in Spain during the summer of 2015 and found that Sentinel-2 data generated into a Support Vector Machine (SVM) classifier (algorithm) obtained a very accurate burned area mapping, with a derived accuracy of 99.38%. Regarding fire severity assessment, the same authors found that a SVM classification using as input both optical (Sentinel-2) and radar (Sentinel-1) data was a very effective approach of delineating burn severity of fires, achieving an overall accuracy of 92.97%.

In addition to Copernicus services offered by the European Commission, **other actors developed their own services based on Sentinel data to provide support in detecting fires and monitoring their damages**, particularly in Mediterranean countries that face the highest risks in Europe. This is the case in Norway with the Silvisense service proposed by a company to quickly identify forest disturbance outbreaks (pests, storms, fires, land use). The Rheticus Wildfire service provided in Italy offers weekly information about burned areas and fire severity in the Alta Murgia National Park and has helped the local public administration to "oversee and report fire activity and to support fire management and recovery planning through actionable knowledge on burned areas"[33]. In Greece, the National Observatory of Forest Fires (NOFFi) has developed a Sentinel-2 data-based mapping service of burned areas shortly after the fire, at first on a pre-operational basis in 2016 but that has become rapidly widely used in 2017 mapping burned areas from 97 wildfires in Greece (more than 20,000 ha) and two between Albania and Greece[34]. This same year, the arrival of Sentinel-2B enabled the Greek service to produce mappings 6 to 7 days after the start of the fire on average and became highly useful to the Ministry of Environment and Energy as confirmed by Antonios Kapetanios[35]: *"The Sentinel-2 based NOFFi service constitutes a new invaluable tool in post-fire management"*. Other similar services have also been developed in Spain (Forest fire Yeste) and in Croatia (Wildfire management on the Croatian territory).

This section showed that the quality of weather forecasts provided by Météo-France has been determinant for the Civil Security to anticipate and to better control forest fires that have major environmental consequences. As for Earth observations provided by the Copernicus program, the Sentinel missions already showed promising insights in Europe, especially in Mediterranean countries highly affected by forest fires, for rapid detection and mapping of fires, but also to monitor damages and undertake the optimal measures

[33] Fabio Modesti, Alta Murgia National Park (source: The ever-growing use of Copernicus across Europe's regions (2018))
[34] Source: The ever-growing use of Copernicus across Europe's regions (2018). EC
[35] Antonios Kapetanios is the Directorate General of Forests and Forest Environment in Greece who participated to the study "The ever-growing use of Copernicus across Europe's regions" (2018)

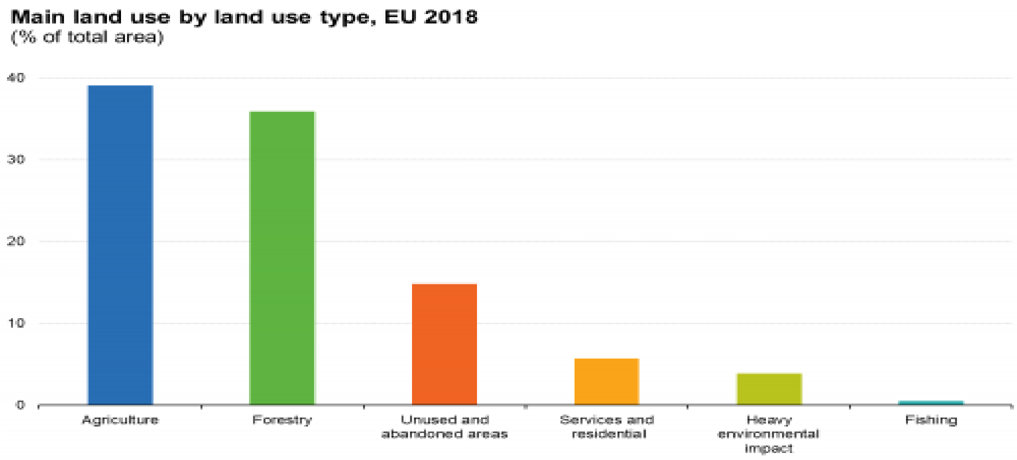
for ecological restoration. Given the effectiveness of Sentinel data claimed by the different users in Europe to develop such services, it is very likely that new similar services will appear in the next years.

C. Management of forests, lands and mountains and their ecosystems

i. Role of Earth observation for monitoring land use and land cover change

Europe is one of the regions in the world that uses the largest share of its land, especially for settlement, production systems and infrastructure (up to 80% of European land according to EEA[36]). **Land being a finite resource, its use constitutes one of the main drivers for environmental change, with significant impacts on ecosystems**. Hence, it is crucial to better manage the use of land and its impact.

Figure 13: Main land use by land use type in Europe (2018)



Source: Eurostat

Based on the LUCAS survey (land use/cover area frame survey)[37] carried out between March and November 2018 in Europe, Eurostat distinguished the categories of land use in Europe and their relative importance in term of land area. We thus observe that the major share of the European area was dedicated to agriculture (39.1% of total area distributed over arable lands, grasslands, etc.) and forestry (35.9%)[38]. Around 15% of total area was unused or abandoned and 5.7% served for services and residential purposes (commerce, finance and business, community services, recreation, leisure and sport, residential, nature reserves) while 3.9% was for activities having direct environmental impacts[39] (mining and quarrying, energy production, industry, water and waste treatment, construction). Finally, a little share of the area (0.5%) has been used for fishing.

Although land use and land cover are often interchangeably used, the two concepts have different meaning: land use indicates the socioeconomic use of land (for example agriculture, forestry, residential use as seen above) whereas land cover refers to the biophysical coverage of land (for example crops, grass, broad-leaved woods, built-up areas). Land cover is a good indicator to identify land use though it may require investigating further to really understand the use of an area (for example are identified built-up areas dedicated to residential use or to industry?).

[36] See https://www.eea.europa.eu/themes/landuse/intro#:~:text=Europe%20is%20one%20of%20the,that%20involve%20hard%20trade%2Doffs.
[37] The LUCAS survey is the largest harmonized land field survey implemented in the EU based on field visits
[38] Source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics#Land_use
[39] Defined as "heavy environmental impact" on the graph but it depends on how those activities are managed.

Human activities have led to an excessive use of land which exerts important pressures on ecosystems, the biodiversity, and habitats. Between 2013 and 2018, only 14.7% of habitat assessments in the EU had a good conservation status. 35.8% of habitats was in a bad conservation status and 44.9% in a poor conservation status[40]. **Agricultural activities, when intensive, can be major sources of pressures on habitats** through extensions of cultivated areas (particularly with conversion to arable lands at the expense of grasslands that are semi-natural habitats for livestock, plants, and animals), overgrazing, etc. **Forestry is also a sector whose activities can exert an important pressure to the ecosystem**: deforestation for wood production, grazing or construction, branch cutting for fuel and fodder (affecting tree growth), tourism, etc.

The raising awareness and concern of EU Member States regarding the fragilization of ecosystems and the decline of the biodiversity led the European Union to implement legislative measures of which the most known are ***the Birds Directive***[41] to protect all the 500 wild bird species threatened by human activities (intensive agriculture, forestry, transport, fisheries, hunting, etc.) and ***the Habitats Directive***[42] to ensure the conservation of a wide range of rare, threatened or endemic animal and plant species as well as 200 rare habitat types. The latter aims to promote the maintenance of biodiversity and establishes the EU wide ***Natura 2000***[43] ecological network of protected areas, safeguarded against potentially damaging developments. In particular, Article 17 of the Habitats Directive requires from EU Member States a report to be sent to the European Commission every 6 years assessing the conservation status of the habitats and species targeted by the directive.

Combined with *in-situ* investigations, **spatial observations have proved very useful to map and monitor land cover changes to better detect and control pressures on fragile ecosystems and to undertake appropriate measures to comply with European Directives**. Regarding land use in forests, inventories of forest resources appeared as precious monitoring tools and **improved with the emergence of spatial observations to complete on-the-field inspections**.

Monitoring of land cover from space was already well developed before the implementation of the operational Copernicus program in 2014 thanks to the American Landsat-8 and other satellites such as Deimos-1 and satellites of the previous generation of Copernicus (GMES). The European Environmental Agency initiated in 1985 as part of the European program GMES the Corine Land Cover inventory, a European database of biophysical land cover including 39 countries. However, the past six years have shown great potential of Sentinel-2 in land cover mapping and analysis. The major factors driving the success of the Sentinel-2 data are the free access to the data, the high spatial resolution (10-20 m), the short revisit time, and the presence of an instrument[44] able to detect leaf reflectance with precision (used to obtain key information on the vegetation state and to derive vegetation indices). In other words, Sentinel-2 has brought a more precise (higher resolution) and complete view of land cover than Landsat and the other previous programs and offered opportunities for detailed land cover/use mapping at a fine scale. Kussul, et al. (2017) compared the land cover classification results between Landsat OLI-8 which has no red-edge band and Sentinel-2 images. The results showed that the red-edge bands improved classification accuracy by 4–5% (*Phiri et al*., 2020).

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[40] Source: https://www.eea.europa.eu/ims/conservation-status-of-habitats-under

[41] Directive 79/409/EEC adopted in 1979 and amended in 2009 as Directive 2009/147/EC: https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=celex%3A32009L0147

[42] Council Directive 92/43/EEC adopted in 1992: https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=celex%3A31992L0043

[43] *Natura 2000* is the largest coordinated network of protected areas in the world completed in 2010. It offers a haven to Europe's most valuable and threatened species and habitats.

[44] Namely red-edge bands that are spectral bands.
-> More on J.G.P.W. Clevers' paper (https://www.researchgate.net/publication/283419755_Using_the_red-edge_bands_on_Sentinel-2_for_retrieving_canopy_chlorophyll_and_nitrogen_content)

Figure 14: Land cover map from Sentinel-2 data

Source: European Space Agency

While the Copernicus Sentinel-2 mission delivers ideal images to map land cover, producing maps means that huge amounts of time-series data must be processed. To make this possible, the ESA-funded Sentinel-2 for Science Land Cover project[45] explored novel ways of capitalizing on the latest cloud-computing technologies and machine learning to perform automated mapping. While still in the experimental stage, the results demonstrate that fully automated mapping is just around the corner. For example, Europe's land-cover has been mapped using 13 land cover classifications (see Figure 14 at the left).

This figure shows that Copernicus has the potential to map land cover at a very detailed scale and for detailed land cover types. The accuracy of this mapping also appeared as promising. For instance, Helber et al. (2019) find an overall accuracy of 98.57% for a land cover classification using images from Sentinel-2 satellites (compared to aerial photographs establishing precise land cover). **Sentinel-1 satellites can also be used to support land cover classification**, for example by detecting forest clear- and partial-cut and by helping identifying forest and farming types.

In the forest sector, Sentinel-2 data have been a powerful tool for mapping of forest area, establishing boundaries of specific forest types, discrimination of forest types, etc. (Phiri et al., 2020). **The development of a forest management approach strongly supported by an effective assessment of current resources, by the detection and monitoring of the most relevant forest changes and land-use trade-offs has contributed to mitigate the main negative ecological impacts** (e.g. loss or degradation of native vegetation areas and habitats)[46] and thus to better conserve vulnerable natural areas.

The agricultural sector has also seen the development of Copernicus data-based land cover mapping services. In Spain for instance, Sentinel-1 and -2 provide useful tools for assessing land cover, detailed crop and natural land maps every year in Castile and Leon. **Such maps have allowed the government to control the protected areas included in the Habitats Directive**[47]. **Sentinel-1 and -2, in addition to on-the-field inspections, have also enabled to monitor the deterioration of grasslands**. As the deterioration of grassland quality reduces the quality of ecosystem services and functions that it provides, leading to a loss of biodiversity, **land use information** is crucial to local authorities to implement optimal measures to better manage those areas (for example, a monitoring of biologically valuable grasslands that should be mowed or grazed but cannot be ploughed in order to maintain biodiversity).

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[45] https://www.esa.int/ESA_Multimedia/Images/2020/03/Europe_land-cover_mapped_in_10_m_resolution

[46] The Azores Regional Forest (Portugal) is a good example as it combined Landsat-8, Sentinel-1 and Sentinel-2 data to complement on-the-field surveys to improve classification accuracy in forest inventories → see "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 53.

[47] "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 33

Moreover, **Sentinel-2 has shown to be useful to monitor natural mountain grassland**. For instance, in the Gran Paradiso National Park (Italy)[48], **plant productivity, snow cover, surface temperature, as well as changes in land cover were derived from MODIS, Landsat, and Sentinel-2 data**. Such observations contributed to the monitoring of the park's biodiversity and herbivores' survival that have been useful to competent authorities to take better-informed decisions and thus to improve the conservation of the natural landscape, habitats, and animal populations.

Finally, the Habitat Directive requires habitat assessment within the *Natura 2000* network that includes remote areas such as the alpine zone. In-field mapping of habitat types in such areas can be cost- and time-intensive because they are difficult to access given their environmental characteristics. Mountainous areas are a good illustration as they present large areas, a steep topography, fast changing weather conditions, and short snow-free period. **High resolution images brought by Sentinel-2 have enhanced habitat mapping in those areas.** For instance, the Austrian government implemented a project to support alpine habitat assessment – using Sentinel-2 data that helps indicating land cover changes in sensitive areas (vegetation, rocks, glacier, snow, etc.) – and as a planning tool for designing difficult in-field mapping. **This project has been a precious support to monitor decline in biodiversity (through detecting ecosystem quality deterioration) and for authorities to implement specific nature protection practices to halt or slow down this decline[49]**.

The first years of Copernicus showed promising potential as a complement to in-field studies for land cover mapping. We have seen that the use of recent Sentinel Earth observations fosters a more reliable and economically viable solution for land cover- and habitat-mapping, which is less biased towards human perception and time-consuming than traditional in-field mapping, and more precise than other Earth observation programs. Moreover, the high temporal and spatial resolution of Sentinel-2 facilitates regular updating of habitat changes and continuous monitoring, which is required every six years by the European Habitat Directive.

ii. Role of Earth observation for monitoring tree disease

Tree disease control belongs to the major activities in forestry since forests suffer from multiple pathogens, nutrient deficiencies, and pest invasions. A tree disease suggests any deviation or malfunctioning due to a persistent agent. There exist about a hundred diseases for each of thousands of plant species, with different triggers. Pathogens that may prompt tree diseases include fungi, bacteria, viruses, parasitic plants, nematodes and other microorganisms. The identification of a type of tree disease thus depends on the cause, the host tree, the affected tree part, and the tree age. The most common symptoms associated to diseases are early discoloration and defoliation, but bark abnormalities, decay, dead branches, or uneven growth can also be indicators that a tree is suffering from stress caused by a disease.

European forests are essential resources and habitats for biodiversity with 178 million hectares representing 40% of the total area of the EU. Those forests are often exposed to important stresses such as fires but also tree diseases. For instance, Southern Europe has been exposed to a deadly bacterium, *xylella fastidiosa*, affecting olive trees since 2013. In seven years, the disease has killed millions of olive trees in Italy and is now threatening Spain and Greece[50] while scientists are still looking for a cure. It is therefore crucial to better prepare to tree diseases, particularly within a changing climate that will lead to an increase in occurrence and intensity of those[51].

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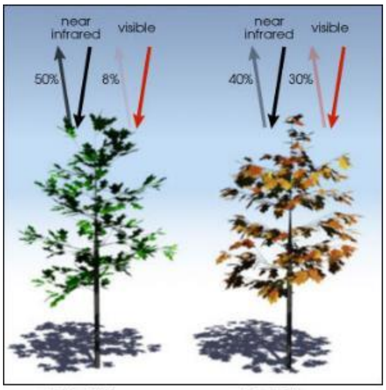
[48] Project ECOPOTENTIAL carried out by the park managers and the scientific staff that is being developed with 24 other protected areas across Europe → source: "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 69
[49] More on this project in "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 63
[50] Source: https://www.npr.org/2020/05/03/849551027/southern-europe-could-lose-22-billion-fighting-deadly-olive-tree-disease
[51] Indeed, warmer winters will contribute to greater overwintering success of pathogens, leading to increasing disease occurrence and severity.

One critical goal in the management of the disease is to identify and remove affected trees from site before the disease spreads to other healthy trees. Trees with visible symptoms can be identified by a human observer due to specific symptoms such as discoloration and defoliation. **However, the symptoms of the disease usually appear first on top branches, which are harder to observe from the ground** (Iordache et al., 2020). Moreover, although the presence of a bacteria can be confirmed by laboratory analysis after collecting woody samples from trees, it is impossible to collect samples from all trees over relatively large areas. Therefore, **remote sensing has come naturally into play as a viable tool to complete this important management task**. **Early detection of tree diseases allowed by images from space can increase the potential for successful disease management, particularly when combined to drones and in-field inspections**.

Figure 15: The NDV index for tree canopy



$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72$ $\frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$

Source: NASA

In particular, the arrival of high temporal and spatial resolution images provided by Sentinel-2 every 5 days has brought a significant potential for improving tree disease detection and control. From data collected by Sentinel-2, it is possible to represent a forest with indices such as the Normalized Difference of Vegetalization Index (NDVI) and then to classify the trees between healthy and infected ones based on their canopy[52]. The NDVI is a dimensionless index that quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs)[53]. This index is thus widely used to estimate the density of green on an area and to monitor if the area contains living green vegetation. Specifically, this index shows whether a tree canopy is green or brown – the latter being a symptom for tree stress – for an early disease detection. As shown in the figure at the left, the higher is the NDVI value, the healthier is the vegetation. On the other hand, a low NDVI means less or no green vegetation that can be associated to a disease. **Such information at the tree level is determinant as it can be used to guide foresters for in-field inspections** in case some areas appear as suspect. **First research has shown promising results regarding the contribution of Copernicus for early tree disease detection**. For example, Hornero et al. (2018) showed that Sentinel-2 imagery can provide useful spatio-temporal indicators to track and map canopy alterations produced by the *Xylella fastidiosa* infection in olive orchards over large areas. Haghighian et al. (2020) studied the performance of Sentinel-2 images to detect infected oaks trees by one of the most important pests in forests of Iran, namely the *Tortrix viridana*. Several indices were extracted from Sentinel-2 satellite images such as the NDVI but also the SAVI (soil-adjusted vegetation index), the IPVI (infrared percentage vegetation index) and the IRECI (inverted red-edge chlorophyll index). **The results showed that those vegetation indices in affected and non-affected areas of the study site have significant differences at 99% confidence level (with low Spearman's correlation coefficient levels between affected and non-affected areas for all indices), highlighting that Sentinel-2 images can be used to detect pests in forest areas**. The Silvisense service, based on Sentinel-2 data and algorithms to map forests disturbances, has been so far tested in Portugal. According to a report from the European Commission, users of this service can be able to detect disturbance outbreak and clear-cut the declining trees at an earlier stage, resulting in a 60% reduction in corresponding disease outbreak during the following season[54].

Early and effective detection of tree diseases is of particular importance to better control them and prevent irreversible environmental damages. Indeed, preventing a disease to spread leads to a reduction in the

[52] The term canopy is used to refer to the extent of the outer layer of leaves of an individual tree or group of trees.

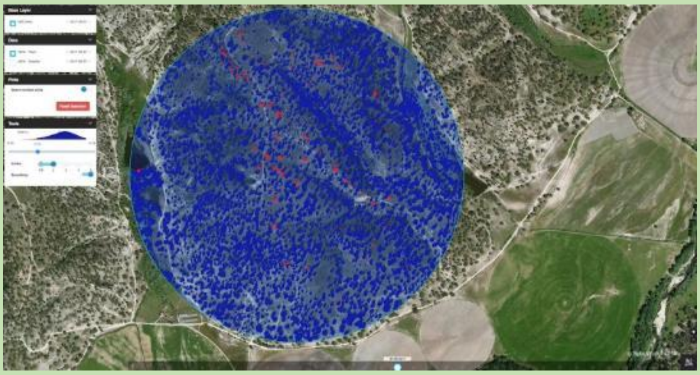
[53] Healthy vegetation (chlorophyll) reflects more near-infrared (NIR) and green light compared to other wavelengths, but it absorbs more red and blue light, explaining why we see vegetation in green. Satellite sensors like Landsat and Sentinel-2 both have the necessary bands with NIR and red.

[54] Source: "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 47

number of affected trees, the latter being essential for capturing carbon dioxide emissions and thus mitigate climate change. Ecological damages can also be reduced with access to early disturbance detections which result in improved water, soil and air quality[55] **as well as wildlife habitats preservation**.

Case studies

Figure 16: Disease detection in trees (Portugal)



Source: ESA

Mapp.it application[56] **(Portugal)**

Spin.Works (a Portuguese aerospace company dedicated to the development and deployment of space, unmanned and intelligent systems), launched in 2017 a map application that uses drones and Sentinel-2 satellites data to generate maps classifying healthy trees from the others. An illustration of this application is represented (in the map at the left) for disease detection in cork oak trees in the Alentejo region (southern-central part of Portugal), with healthy trees in blue and those affected by disease in red. From this map, foresters could carry out inspections and laboratory analyses of wood in relevant areas to identify the disease and to face it adequately and optimally (with appropriate measures such as breeding resistant trees, controlling insect populations, using chemical methods or biological methods, etc.).

Rezatec's interactive web GIS Portal for the Department for Environment, Food & Rural Affairs (UK)[57]

To support Defra in managing an outbreak of Sweet Chestnut blight, Rezatec (a satellite telecommunication service) was invited to develop an interactive map, using Sentinel-1 and -2 satellites data, capable of:

- identifying tree locations of sweet chestnut and oak trees: based on the unique spectral signature of these target species within the input Earth Observation datasets,
- detecting anomalies and change in vegetation: annual time-series were analyzed for all the detected pixels in the study area, to identify significant deviations (temporal and spatial) in phenological behavior, assumed to be an indicator of canopy stress. Locations where stresses on species are detected were then communicated to prioritize areas for ground inspections to determine the presence of pests and diseases.

The service appeared to be very effective and satisfying for Defra as confirmed by Willem Roelofs (Plant Health Team of Debra): *"Their ability to map a range of tree species at remarkably high-levels of accuracy has supported our response to outbreaks and could potentially revolutionize Defra's response to quarantine pests and diseases in the wider environment"*.

As highlighted before, **this section confirms the increasing usefulness of Copernicus data to support foresters in monitoring forests and their threats (human activities, fires, diseases…) to undertake the optimal restoration and conservation measures at an early stage**. **This is crucial as forests are essential carbon sinks, sheltering a large part of the biodiversity and guaranteeing a good quality of soils, water and air**.

[55] Trees and vegetation can help reduce water quality problems by decreasing stormwater runoff and soil erosion. Trees also absorb some of the nutrients in the soil that would otherwise be washed away. Finally, trees can also improve air quality by reducing temperature (leading to ozone reduction) and removing air pollutants.
[56] Source: ESA – Success Stories → https://sentinels.copernicus.eu/web/success-stories/-/disease-detection
[57] Source: "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p. 54

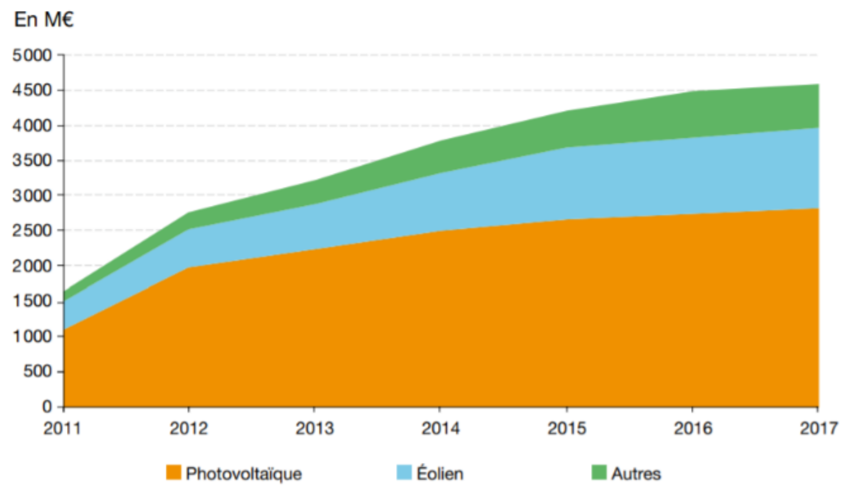
2. Energy production

A. Development of solar and wind energies

Electricity generation has seen the penetration of an increasing share of renewable sources since 2010 in France, including those most sensitive to short-term weather conditions, such as *onshore* and *offshore* wind, solar photovoltaic and solar thermal electricity. The production capacity of the installed wind farms has almost tripled between 2010 and 2019 (from 5,762 MW to 16,511 MW), while the capacity of solar farm has been multiplied by more than 10 over the same period (from 878 MW to 9,567 MW)[58].

Operational costs to implement wind and solar farms were particularly high when those energy sources emerged. Still, the French government has contributed to make renewables, including wind and solar generation, competitive in the market by subsidising intensively those sectors over the last decade[59], hoping for the costs to decrease through technological progress, the structuring of industrial sectors and scale effects.

Figure 17: Evolution of public subsidies for renewable energies in France (in million €)



Source: CRE, computations from SDES (Ministry of Ecological Transition)
Note: "photovoltaique" = photovoltaic; "éolien" = wind; "autres" = others

We observe that the largest share of subsidies has been used to support solar power producers, rising up to more than 2.5 billion euros in 2017 (2.5 times more than in 2011), and almost 1.2 billion euros were devoted to wind power producers (25% of total subsidies). Those subsidies have been allocated to producers under purchase obligations and additional remunerations.

Although public financial support has facilitated the emergence of wind and solar energies in France**, precise weather forecasts have also proven crucial for their integration as those energies heavily rely on meteorological conditions**. Moreover, new support tools based on Earth observations have been developed for producers to undertake optimal decisions, particularly regarding the choice of sites to build wind or solar farms.

[58] Source: RTE – Bilan Electrique 2020
[59] See https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2019-05/datalab-53-chiffres-cles-des-energies-renouvelables-edition-2019-mai2019.pdf

i. Predictability of renewable electricity production enabled by weather forecasting

To begin with, it is important to understand how the electricity market in France works. In order to promote the energy transition, France had committed to guaranteeing the purchase of 100% of renewable energy production[60]. The feed-in tariffs were then intended to ensure a normal return on investment of the production of electricity from renewable sources. The price level at which the energy supplier buys the electricity was fixed by decree at a level higher than the market price (corresponding to the rentability threshold of the producer).

However, in order to meet the dual European objective of energy transition and the principle of competitiveness, renewable energies are gradually entering the market, and the producers' need for a fixed price is gradually decreasing as their projects are becoming increasingly profitable (except for offshore wind which is on average still very costly). As they now do not need as much the feed-in tariffs, producers must now sell their electricity on the electricity market and review their production methods in order to adapt to market fluctuations. Their income now comes from their sells depending on a variable price market, and an additional remuneration introduced by the French government in 2015[61] when the support mechanisms for renewables were overhauled. The EPEX SPOT power exchange plays a central role in this new arrangement[62]. The first component of the remuneration allowed by the direct sales mechanism consists of the owner of a wind or solar farm selling his production at a negotiated price on the wholesale markets, either by his own means if he has a trading room, or through a third company (aggregator).

As producers must position themselves upstream on the quantities of electricity they will sell and make available to the grid, very short-term weather forecasting has become central for renewable energy producers. For example, if there is no wind, wind turbines will produce little electricity. If wind farm operators commit to selling a certain volume of electricity on Day +1 and cannot meet this commitment, they will be subject to penalties. This shows the financial impact that the accuracy of the weather forecast has on renewable energy producers. The more accurate, reliable, and localised the numerical weather forecast, the better the operational management for the whole sector, thus reducing the financial risk and providing a more robust incentive for this kind of sustainable investment.

Refined forecasts of the state of the atmosphere (wind, radiation), both at very-short range and short range, are thus essential for steering production and markets. For example, Pinson et al (2007) studied a 15-MW wind farm in Ireland and compared wind forecasts errors between an advanced forecasting method, namely Fuzzy-NN, whose performance is at the typical level that can be found in the state-of-the-art, and the simplest forecasting model, namely Persistence, that consists in using the last measured power value as a prediction for all look-ahead times. He found that using Persistence method (respectively Fuzzy-NN) leads to a 21% decrease in total revenue (respectively 13%) compared to an ideal situation with perfect forecasts.

This shows the importance of accurate weather forecasts for the profitability of producers. In the absence of Météo-France in the counterfactual, producers would have access to forecasts from the American GFS model providing since 2017 hourly forecasts with a 28x18km resolution of various variables such as wind or nebulosity (cloud cover) every 3h.

Wind power production depends on wind speed (which must be between 15 and 90km/h at the hub of the wind turbine) and direction. Such variables can heavily vary on a daily basis, even within small areas, particularly in regions with uneven reliefs or near oceans. Regarding solar power production, it is even more

[60] Article 10 of Law n°2000-108 of 10 February 2000
[61] Introduced by article 104 of the energy transition law adopted in France in July 2015
[62] See https://www.actu-environnement.com/ae/dossiers/eolien-fee-innovation/elies-lahmar-arnault-martin-epex-spot-integration-eolien-merche-gros-electricite.php

challenging to predict as cloud cover is more unpredictable than average temperatures, wind speed or rain. The genesis of a cloud involves a very large number of complex physical and chemical processes, and the forecast depends on what is happening over the whole planet, and within the whole atmosphere. **Having the resolution of the GFS model would thus likely lead to much larger errors in production prediction which would lead producers to pay more penalties. Although it is not the main decision factor for investors, we can think that they may have been less attracted in investing in this sector if wind speed were hard to predict, particularly now that prices are variable in the renewable energy market.**

Financial impacts of weather forecasting for renewable producers are important from an environmental point of view because investments in renewable energies have been determinant and will be determinant to achieve the energy transition and to reduce the use of fossil energies in the electricity grid. A study of RTE[63] assessed the emissions avoided by wind and solar generation. It has simulated what the current electricity system would be like without these installations. **This study estimates the avoided emissions at around 22 million tonnes of CO2 per year (5 million tonnes in France and 17 million tonnes in neighbouring countries through French imports).** In other words, if these capacities had not been developed, the fossil thermal means in France and Europe would have been more requested for the production, leading to additional emissions, in particular due to coal and gas power plants. Attributing a share of those avoided emissions to weather forecasting is too uncertain. However, **we have seen throughout this section that precise weather forecasts are crucial for financial revenues of wind and solar power producers and to ensure the development of those sectors. We can thus state that Météo-France, the ECMWF and EUMETSAT have been essential to develop the wind and solar generation entry into the market, thereby contributing to important avoided CO2 emissions**.

ii. Optimisation of the choice of production sites based on climate projections and spatial observation tools

Cros and Pinson (2018) state that a project developer of a wind or solar farm must know, before building the farm, the potential of a territory in order to optimize the choice of land, the capacity of the plant and its profitability. In order to estimate a forecast of the potential production in the long-run (around 20 years), time-series data over the past decades (from 10 to 30 years) can be used to obtain a statistical representative year of the territory (called Typical Meteorological Year, TMY). This indicator contains hourly means and quantiles of solar data and wind data, enabling to deduce the most likely production on the farm and to quantify future risks on profitability. **Such a climate projection based on historical data over a very localized area is proposed by Météo-France's services**. Whether American services provide such data is likely, but not at a farm scale. **This service encourages new renewable projects (by reducing the risk for potential investors) and increases the chance for a wind or solar farm to succeed and to enter the electricity grid on a long-term basis, at the expense of other sources, particularly carbon-intensive ones**.

This service can also be complemented by tools using Earth observations from the Copernicus program. For instance, satellite data – specifically meteorological (cloud, water vapor) and atmospheric (aerosol, ozone) – are used as key inputs into modelling systems which forecast the available ground-based solar irradiance over a given area to predict the potential of a site for solar energy production. Although not investigated in this evaluation, the role of Earth observation, provided by Copernicus, for estimating the most suitable renewable energy source for an area is gradually developing and will contribute to a more efficient energy transition.

[63] Notes sur les précisions sur les bilans CO2 établis dans le bilan prévisionnel et les études associées (RTE).

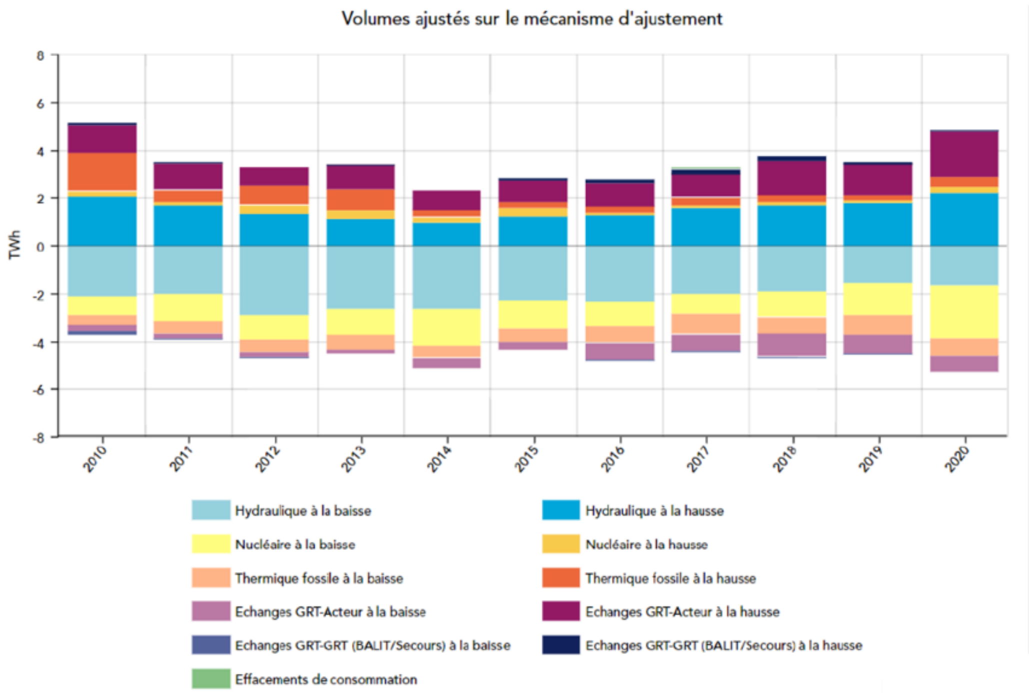
B. Reduction in production forecast errors of wind and solar power reducing supply-demand adjustments

Because of the thermal sensitivity of electricity consumption on the one hand, and the large margins of error in production forecasts on the other (particularly for photovoltaic production, which suffers from the lack of measurement systems on small farms[64]), it is very important to (1) provide for robust adjustment mechanisms, and (2) make progress on supply and demand forecasts. RTE (Reseau de Transport d'Electricité) is the French Transmission System that operates the electricity transport network in real time and ensures the security of supply (adjusting permanently the supply and the demand).

Since electricity cannot so far be massively stored, an excess of demand at a given moment cannot be compensated by an excess of supply a few hours earlier. Thus, production in excess over demand may result in costly exports or downward adjustments (for instance by shutting down a nuclear power plant). Conversely, peaks in consumption in winter and unexpected drops in production, for example in summer when high temperatures force power plants to shut down, cause excess demand over supply. **These imbalances can result in the activation of various reserve mechanisms and/or in imports**. Electricity imports are costly for the French economy, since they aggravate France's energy deficit, and come from countries with more carbon-intensive electricity generation methods (e.g. coal-fired power plants in Germany). **Unless renewable energy sources, such as hydroelectric dams or foreign wind farms, are used to fill the supply gap, upward adjustment situations lead to the mobilisation of the most expensive and polluting energy sources (coal, gas, etc.), whether they are in France or abroad**. Nuclear power is not often used as a source of upward adjustment, and more frequently as a source of downward adjustment.

The graph below, taken from RTE's 2020 electricity balance sheet, shows the adjustment volumes from 2010 to 2020 by source of electricity production. 2020 required the most adjustments in volume, with 10.1 TWh, or 2.3% of French consumption.

Figure 18: Upward and downward adjusted volumes on the French electricity grid



Source: Réseau de transport d'électricité (RTE)

[64] Source: interviews with RTE

As 2020 was a very particular year as a result of the worldwide COVID-19 pandemic, **we look at 2019 to illustrate the potential impact of weather forecasting in reducing necessary adjustments between supply and demand, that partly require mobilising polluting energy sources**. This concerns situations in which an upward adjustment is necessary to compensate the excess of demand over supply[65]. RTE leaves the market of electricity exchange works by itself up to 2 hours before real-time, with "Balance Responsible Entities" who predict energy consumption over their delimitated area and who buy energy from various producers to adapt to the evolving demand. Then, if still necessary, RTE operates in real time (up to 2-3 hours before) to quickly increase the level of energy production by boosting some energy sources production or by importing from neighbour countries (the UK, Germany, Switzerland, Italy, Spain). We observe in the graph above that in 2019 (similarly as the other years as well), half of the RTE's upward adjustments were made by boosting hydraulic production (as it is the easiest sources to mobilise quickly and in important amounts). Around 5% of the upward adjustments were made by boosting domestic fossil thermal production (i.e. coal, oil and natural gas) and 36% by importing from neighbour countries[66]. It represented respectively 0.18 TWh and 1.29 TWh of cumulated additional production to adjust the market over the year.

As wind and solar power production are intermittent and thus partly unpredictable, RTE makes its own prediction of production using its network IPES[67] fed by algorithms and weather forecast from meteorological services, of which Météo-France (Arpege) and the ECMWF. Data from French weather stations are also essential for RTE as they allow to get data at a higher frequency than global-area models (Arpege, ECMWF). This network enables to anticipate the expected production of the French wind and solar farms hour by hour for the current day and the next day and to better manage resources to put in place to ensure the balance of the market.

Although there may be numerous reasons explaining unbalanced situations with an excess of demand (cold waves leading to higher consumption of energy to heat houses, social contests on production parks, heat waves causing slowdown of nuclear power plants, environmental constraints…), we focus here on bad anticipation of solar and wind production arising from errors (overestimation) in predictions as those latter mainly rely on weather forecasts.

By using a model based on data from RTE and the IEA and assumptions **(presented in** **Annex C.4: GHG emissions reduction arising from less errors in wind production forecasts)**, **we offer a range of magnitude of CO2 emissions avoided in 2019 due to fewer adjustments related to the overestimation of wind power production**. This estimation accounts for adjustments made with both domestic and foreign fossil thermal sources and represents the share of avoided errors and CO2 emissions that we can attribute to the quality of weather forecasts provided by Météo-France, supported by the ECMWF and EUMETSAT (compared to our counterfactual scenario).

Counterfactual scenario

RTE would have access to American forecasts which means that they would have short-range forecasts with a 28km resolution and medium-range forecasts with a 70km resolution. **Given the necessity to predict meteorological conditions in very local areas (at farms level), and the likely heterogeneity in wind and nebulosity in certain areas (fields with uneven relief, close to the oceans…), RTE would have an inefficient**

[65] Downward adjustments (i.e. when there is an excess of supply, for example because of an underestimation of wind power production) do not lead to negative environmental consequences. In such a situation, either extra energy generation is exported, or other sources, mainly, hydraulic and nuclear power plants, are slow down, or pumped-storage hydro power plants are used. Issues arising from downward adjustments rely on financial costs.
[66] Imports represented in purple on the graph as "Echanges GRT-Acteur à la hausse". GRT-Acteur are European transmission system operators
[67] Insertion de la Production Eolienne et Photovoltaique sur le Système, implemented in 2009

model of prediction (with much more errors) and would need to adjust the balance more often, in part with fossil thermal sources.

The model developed in annex is based on assuming that the level of precision brought by current forecasting models allows to reduce errors in wind power production predictions by 10 to 20% compared to our counterfactual[68]. We find that precise weather forecasts of the studied organisations enabled to avoid **between 0.15 TWh and 0.3375 TWh of errors in wind prediction (that would need to be adjusted) per year, of which [0.008-0.017TWh] would have been adjusted with domestic fossil sources and [0.021-0.041TWh] with foreign fossil fuels. This represents between around 18,000 and 40,000 tons of CO2-eq avoided over 2019.**

Regarding solar power production, we cannot estimate such environmental impacts as available data on solar power production are not reliable. RTE encounters important difficulties to obtain precise production data[69], particularly for small farms and private houses that suffers from the lack of reliable measurement systems. However, as we stated above, predicting solar radiation and cloud cover is even more difficult and uncertain that wind. We can thus reasonably think that although the error rate is probably already quite high, having non-localised forecasts would worsen this rate and fossil sources would be more used to compensate such errors.

C. Other energy sources

The other renewable energy sources (hydropower, biomass, geothermal energy, tidal energy, wave energy, etc.,) are also weather sensitive. Hydropower depends on hydrological forecasts (availability of water resources) on average and seasonal timescales, while biomass certainly presents challenges in terms of climate projections. Moreover, non-renewable energy sources such as nuclear energy can also be weather-sensitive, though in a lower extent, as detailed below.

i. Role of weather forecasts to manage hydraulic production and dams

High precipitation in the mountains can cause significant flooding downstream, in the valley and even in the plains, especially in urban areas. In the valley, intense floods cause major environmental damages, particularly on fauna (wild and domestic), but also on soils and flora.

Électricité de France (EDF), which is a French company, producing and supplying electricity and owned at more than 80% by the French State, operates and manages hydroelectric dams, located in the valleys. In case of important precipitations, the development of a flood in a catchment area can take place in a few hours or few days on the main rivers. When it happens, EDF must ensure the safety of the dam by avoiding an overload that could submerge the dam or exert too much pressure and cause the dam to break. Such an event would be catastrophic for population living downstream as well as for biodiversity in the valley. To address this risk, dams are equipped with “spillways” that divert or discharge water held behind the dam in case the water level would exceed a certain limit. Moreover, dams with large reservoirs, such as the Cresent dam that contains more than 14 million m^3, which is responsible for protecting Paris, can also limit the effects of a flood. This work requires a strict monitoring of wind, thunderstorm, extreme precipitation and snow probabilities, river flows over a period of a few hours up to a few days and filling of reservoirs by rain and snowmelt. To do this, EDF has specialised teams for several decades that continuously collect and analyse measurements and issue

[68] This assumption relies on an interview with RTE that has confirmed that the error rate in wind power production forecasting would probably be higher if they used the GFS model. However, we could not have a precise error rate in such a situation, but we consider the GFS model as being a “medium to low fidelity model” as defined in Wang et al. (2019) (see annex C, box 4)
[69] Source: interviews with RTE

warnings to operators when flooding is forecast. **These teams use data provided by Météo-France and hydrometeorological stations located in the catchment areas where the dams are located. In other words, the absence of Météo-France's data would lead to less precise prediction of floods by EDF, which would increase the risks on dams' safety**.

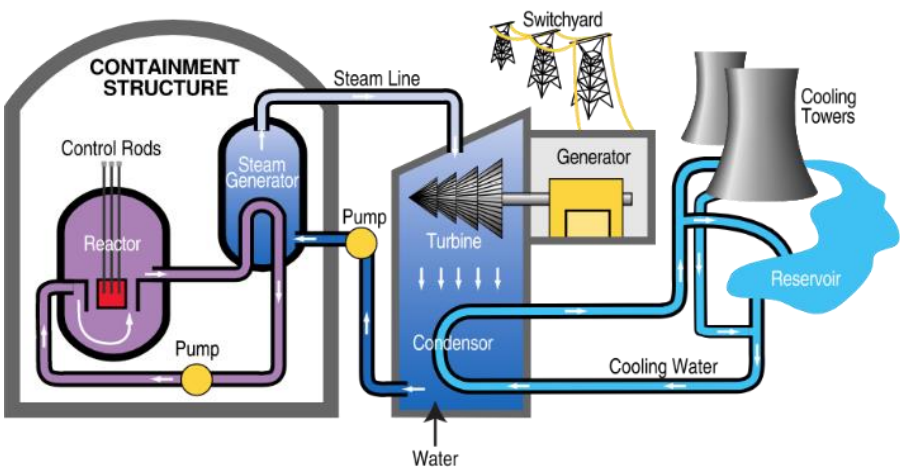
It is strongly likely that incidents such as dam breaks would occur, having devastating consequences on the environment (**drowned animals and plants, loss of wildlife habitats, loss of topsoil of vegetative cover, dispersion of debris and hazardous materials downstream that can damage local ecosystems, degraded wetland and farming fields, soil erosion, etc.**). Indeed, dam operators would anticipate water levels based on past observations or seasonal trends. For instance, they would probably store high levels of water by the end of spring, anticipating a dry climate in the summer[70]. However, if heavy rains occur after the dam lakes are full, a dangerous emergency release of waters would be necessary, and the dam could break due to too large pressure and cause additional heavy damage downstream.

ii. Role of weather forecasts to manage nuclear power plants during heat waves

Even the production of non-renewable electricity can be sensitive to the weather. **A nuclear power plant is largely dependent on water sources for cooling**. To provide water as a cooling source to nuclear power plants, the latter are usually built along a river or on the coast.

The reason why water from the environment is needed for nuclear power production is simple: steam allows the turbine to run and supply electricity to the network through the alternator. Once the quality of that steam has too much decreased, it cannot be used for electricity production anymore and must be cooled down until it turns back to water that will be reused to produce high quality steam. This cooling of the water in the secondary circuit takes place in the condenser and requires large quantities of cooling-water, in the tertiary circuit. After being used in the power plant, the cooling-water goes to a cooling tower before being reused or is directly returned to the river or the sea. **As it has been used as cooling-water, the water of the tertiary circuit has warmed up and thus contains less oxygen, which is harmful for the fish and other fauna**. When the water taken from the river is already warmer than usual (because of air temperature), the temperature of the water released into the environment can prove sensibly dangerous to the biodiversity.

Figure 19: Nuclear power plant circuit



Source: Wikipedia

Note: Water is heated through the splitting of uranium atoms in the reactor core. The water, held under high pressure to keep it from boiling, produces steam by transferring heat to a secondary source of water. The steam is used to generate electricity. Cooling water

[70] « Environment and self-endangered man ». J.V. Amin (2009). Page 29

from the river condenses the steam back into water. The river water is either discharged directly back to the river or cooled in the towers and reused in the plant.

Environmental regulations[71] exist regarding that matter and forbid a nuclear power plant to be active or reduce its activity when the cooling-water exceeds a temperature threshold when released (depending on regional decrees but usually between 25 and 28°C). Consequently, some nuclear power plants must stop their activity during heat waves when rivers' temperatures increase before even being used by the plant. Nuclear power plants located next to the sea are less affected by heat waves because their water discharges are diluted by powerful ocean currents and the 'warm' water discharged to the seabed rises rapidly to the surface by convection, reducing its impact on bottom-dwelling organisms.

Regulations are also defined during droughts when rivers are at minimum levels and their flow is lower (water withdrawal restrictions). When levels are too low, nuclear power plants must reduce or stop their activities, particularly if the drought period is planned to last, to avoid drying up rivers downstream, that would kill the aquatic species living there.

Météo-France provides early warning of heat waves and temperature forecasting, enabling EDF (operator of nuclear power plants in France) to anticipate the rising of rivers temperatures and droughts (leading to decreasing levels in water also dangerous for the biodiversity). As EDF must comply with environmental regulations, it regularly monitors rivers temperatures and flows as well as air temperature forecasts. **In case of heat waves forecasted to last days or weeks, certain power plants can be stopped** for some days during summers to comply with environmental regulations (depending on the length of the heat wave), **which avoids damages on the aquatic fauna and flora downstream the power plant**.

In 2019, Météo-France announced a period of high air temperatures that led to considerable increase in rivers temperatures in France. Consequently, EDF shut down the two reactors of the Golfech power plant (Tarn-et-Garonne) for more than a week[72]. At this moment, forecasts on the evolution of the heat wave were crucial for EDF to anticipate rising river temperature levels and to take decisions on whether other nuclear power plants needed to be shut down as well.

It is likely that the American GFS model could be useful in such situations as heat waves are usually global weather events extended in large areas. However, the GFS model is less reliable than Météo-France and the ECMWF models, which may lead to less precision in forecasts of temperatures and the duration of heat waves, thus affecting anticipations and decisions of EDF.

[71] See https://www.irsn.fr/FR/connaissances/Installations_nucleaires/Les-centrales-nucleaires/impact-secheresse-centrale/Pages/Impact-secheresse-fonctionnement-centrales.aspx#.YZPM3WCZM2w and Article 17 of French Order of November 26, 1999: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000762255/

[72] Source: Agence France Développement (AFD) and Le Figaro : https://www.lefigaro.fr/flash-eco/fin-de-la-canicule-la-centrale-nucleaire-de-golfech-redemarre-20200813?web=1&wdLOR=c8855CBA2-A8F7-44D5-AEB7-35A1066B1254

3. Aquatic and maritime areas

A. Optimisation of ship routing for maritime transport

Maritime transport is the transport of goods or passengers by ship. This transport mode is the backbone of world trade as it accounts for **almost 90% of global freight transport**[73]. Various types of goods are transported by sea: liquid bulk (oil, gas, chemicals), dry bulk (cereals, ores, semi-finished products) and all kind of manufactured goods packed in containers. Those latter are counted in TEUs: twenty-foot equivalent corresponds to 1 container. The transport of these different goods or passengers requires various types of specialized vessels (bulk carriers, oil tankers, roll-on/roll-off ships, container ships, ferries, etc.).

In 2017, the total number of registered vessels (bulk carriers, oil tankers, container ships, offshore supply, general cargo ships, liquefied gas carriers, chemical tankers, other ships including ferries) was **50,155 worldwide, of which 452 owned by French shipowners**[74]. French ports receive freight from French ships but also from ships coming from all over the world (a merchant ship berths a French port every 6 minutes according to "les armateurs de France").

Maritime routes are not materialised in the same way as roads on land, but are often mapped, at different scales. They emerge and evolve to meet various constraints: meteorology, coastal geography, sea relief, port infrastructure, security, or political factors. The maps below show the main marine routes followed by vessels and highlight the complexity and the international dimension of the maritime transport that presents various roads and itineraries.

Figure 21: Major shipping routes

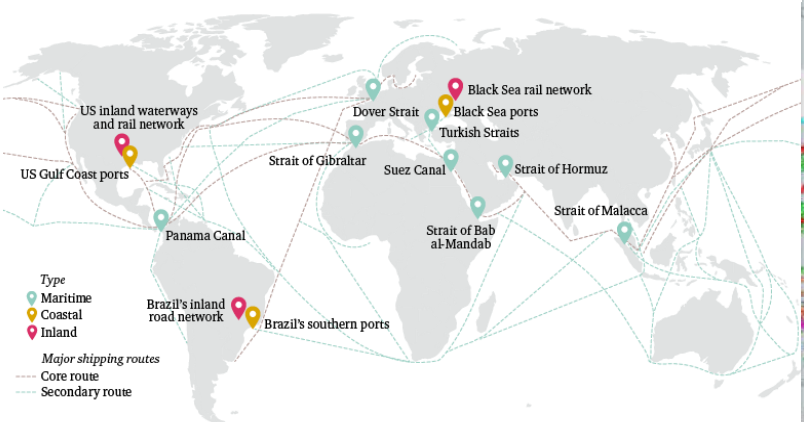


Figure 20: Position of vessels received via satellite on October 20th, 2021, at around 11am

Source: Chatham House Report[75] (left map) and marinetraffic.com[76] (right map)

Ship traffic has important consequences on the environment. GHG emissions from shipping account for 2.89% of total emissions worldwide (in equivalent CO_2). This includes international and national maritime transport as well as fishing, and represented 755 million of tons of CO_2-eq in 2018 (Armateurs de France[77]). The main sources of emissions come from the combustion of fossil fuels (from oil) during main propulsion, by auxiliary engines and by boilers. However, emissions from maritime transport have been decreasing over the last decade (794 million of tons of CO_2 in 2008, i.e. a 5% reduction in 10 years). Although there is still no mature technological solution for decarbonised propulsion of the vessels, progresses in **route optimisation**

[73] Source: Armateurs de France
[74] Source: https://unctad.org/system/files/official-document/rmt2017ch2_en.pdf
[75] Source: Chokepoints and Vulnerabilities in Global Food Trade, Chatham House Report (2017)
[76] Source: www.marinetraffic.com
[77] Source: https://www.armateursdefrance.org/sites/default/files/decryptages/emissions_des_ges_par_le_transport_maritimev2.pdf

have been made and have contributed to the decreasing emissions of the sector (reduction of speed, avoiding detours by choosing the best route, etc.).

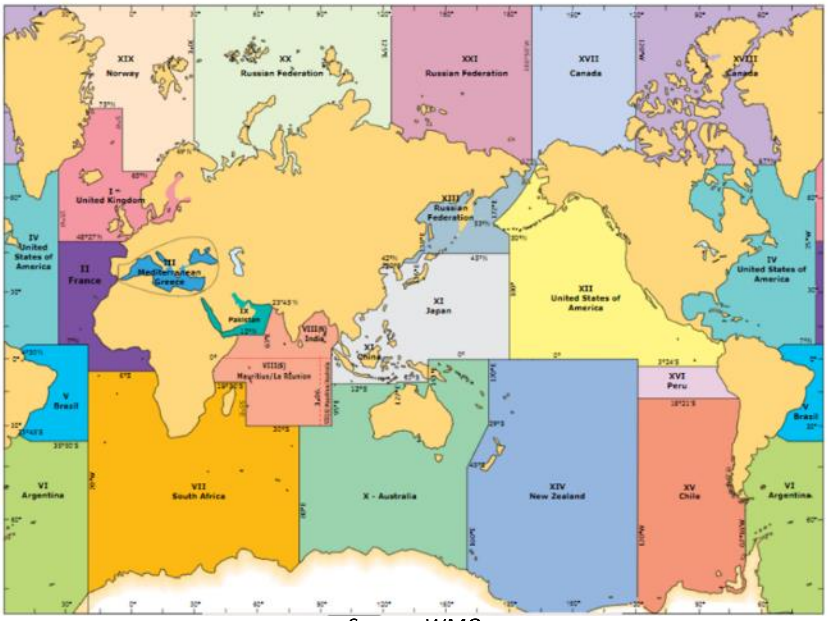
A socioeconomic evaluation of the ECMWF (*Citizing*, 2017) provides insights regarding optimal routing and states that optimizing the ship route is one of the most important tasks related to the operation of the vessel, its safety, and economic aspects of transport. When choosing the optimal route, several criteria are taken into account including minimum travel time, minimum fuel consumption for a given travel time, safety of the ship and cargo. Indeed, vessels encountering heavy weather will experience speed reduction due to increased resistance from wind and waves for instance. In addition, heavy weather increases the risk to crew safety as well as of damage from excessive ship motion, slamming or seas washing over the decks. When ships enter gale force winds or higher wind fields, the ability to handle the vessel becomes significantly affected, thus reducing route options. **Optimum ship routing is about developing the "best route" for a ship based on the existing weather forecasts**, ship characteristics, and cargo requirements. The goal is not to avoid all adverse weather but to find **the best balance to minimize time of transit and fuel consumption** without placing the vessel at risk to weather damage or crew injury. The routing goal may not always be to reduce the time of transit. Sometimes the goal will be to reduce fuel consumption or to keep a vessel on a regular schedule.

Medium range and short-range forecasts are regularly used for ship routing. Having accurate weather forecast is crucial for decision makers to decide whichever route to take and when (accurate vessel scheduling can help to curb emissions and reduce fuel costs) and to undertake real-time decisions to adapt the vessel speed to the actual conditions (wind, waves, severe weather conditions…) and therefore saving fuels and avoiding emissions.

Various studies (*Fearnleys*, 2002, *Bowditch*, 2002) have shown that **optimum ship routing savings in fuel range from 2-4% to as much as 8-10% depending on the type of vessel, season and ocean**. According to a report of the IMO (2000), **weather routing measures have the potential to reduce fuel oil consumption and CO2 emissions by 2 to 4%**. An article in the TradeWinds journal, dating back to July 2010, reports the thoughts of the leading chemical-tanker operator Odfjell, shortly after having signed up with US-based Applied Weather Technology (AWT) for 65 of its tankers. "**The company claims that over three months it has saved nearly $500,000 in fuel costs and reduced carbon-dioxide (CO2) emissions by 3,000 tonnes of CO2 through more efficient routing**".

These insights provide interesting orders of magnitude. However, due to missing data on global shipping fuel consumption and to the fact that the role of Météo-France is concentrated on very specific areas (see below) while the maritime transport is a globalized activity, we cannot provide an estimate of avoided fuel costs that could result from optimized ship routing enabled by weather forecasts.

Figure 22: Limits of METAREAS



Source: WMO

The World Meteorological Organization (WMO), that manages cooperation between national meteorological services all over the world, has divided the marine areas (oceans and seas) of the planet into 21 areas, called METAREAS (the map at the right shows the distribution of the ocean areas between different countries). In each one of them, the national meteorological service of the country is in charge of providing weather forecasts and other marine products to shipping. **Météo-France produces and coordinates the dissemination of marine forecast bulletins in the METAREA II area** on behalf of the World Maritime Distress and Rescue Service (GMDSS), and also produces weather bulletins in English in the western Mediterranean and the English Channel. Météo-France is a WMO Specialised Centre for marine meteorology and wave forecasting.

The establishment is also in charge of monitoring cyclonic activity in the south-western Indian Ocean: the Météo-France centre in Reunion island, located in Saint-Denis, has been the reference centre for the south-western Indian Ocean cyclonic zone since 1993, which includes East Africa and the Indian Ocean islands. Météo-France produces both regular bulletins (BMR) and special meteorological bulletins (BMS) issued in case of wind and sea conditions, starting from the "severe weather" warning. These bulletins are issued at sea by the Regional Operational Surveillance and Rescue Centres (CROSS) operated by the Directorate of Maritime Affairs.

Figure 23: Areas overseen by Météo-France

Source: authors' own elaboration

The map at the left highlights the areas covered by Météo-France[78]. As we can see, the role of France is concentrated on very specific areas of the world, which means that **Météo-France's forecasts can help vessels operators optimising their routes but only over those specific areas**. Estimating the number of vessels passing through these areas and the distance they make within the area is impossible considering the important number of vessels each year, but also the number of different possible trade routes a ship can take (and thus the distance it will make within an area covered by Météo-France). However, it appears quite clear that the French national weather service highly contributes to the worldwide objective of route optimisation as it provides over its area:

[78] The area VIII is shared with Mauritius. Météo-France is also responsible of forecasts over the western Mediterranean Sea (the rest is managed by Greece). The map in figure 23 has been made from precise GPS coordinates of the areas for which Météo-France is responsible.

- atmospheric forecasts: using its models Arome and Arpege, coupled with the ECMWF medium-range forecasts (particularly accurate on oceans, more than over the Mediterranean Sea)
- wave forecasts: using the MFWAM model, co-developed with the ECMWF with a resolution of 10km. Regional configurations of this model over France, West Indies, the Indian Ocean, French Polynesia and New Caledonia are available with high resolutions (from 2 to 10km), providing fine wave forecasting models for the coastal domain, with a resolution of 100 to 200m near the coasts (on the Atlantic and Mediterranean coasts of metropolitan France, on the West Indies, French Guiana and the Indian Ocean)

To illustrate the potential of weather forecasting provided by Météo-France to reduce CO2 emissions, we take the example of an average French container ship, that transports 7,695 twenty-foot equivalent unit (TEU), going from Le Havre (France) to the US. This corresponds to an average equivalent of around 75,000 tons of goods (source: French Ministry of Ecological Transition). From France to the US, the distance overseen by Météo-France is about 2,400 km. The French Ministry of Ecological Transition and Ademe, through a methodological guide[79], provide emission factors according to the distance travelled by the ship, its type and its capacity. This guide also estimates that a container ship transporting more than 7,500 TEU consumes around 210kg of heavy fuel oil by kilometre and emits 10gCO2/ton.km. As said before, the IMO found that weather routing measures may enable to decrease CO2 emissions by 2 to 4%. It means that **forecasts provided by Météo-France in the sea to optimise the route for this specific example could allow to decrease the fuel oil consumption of the ship and thus avoiding between 36 and 72 tons of CO2[80] for this part of the route**.

Although we cannot aggregate at the scale of all trips passing through these areas covered by Météo-France, **we provide a minor order of magnitude of the impact in terms of route optimisation**. The total surface area of the oceans and seas is 361 million km². We have estimated that areas covered by Météo-France represent about 37 million km², i.e. a little over 10% of the world's marine surface. As an example, total emissions from maritime transport in 2018 amounted to 755 million tonnes of CO2-eq. As a reminder, the literature estimates that optimising routing with weather forecasting reduces emissions by 2-4%, which would mean that without weather forecasting, global emissions could have been 770-785 million tCO2-eq. **We assume that the contribution of Météo-France to these avoided emissions is proportional to the coverage of the maritime surface it covers**, i.e. 10%. Thus, **we attribute 1.5 to 3 million tons of CO2-eq avoided in 2018 to the activity of Météo-France (i.e. the equivalent of 0.2 to 0.4% of total maritime transport emissions)**. This result must be taken with caution as 10% represents the share of oceans covered by Météo-France and not the share of maritime journeys. For instance, Météo-France oversees a part of the Mediterranean Sea, which is a relatively small but very strategic and used area. Hence, **this result shows a minimum boundary of the impact attributed to Météo-France as the institution probably oversees more than 10% of the maritime traffic**.

It is quite certain that without Météo-France, another national meteorological service would have been in charge of providing forecasts over those areas, because maritime transport is of international interest. However, it is impossible to know which country would have been in charge and it is less certain that the quality level of forecasts provided by this country would have been as high as what Météo-France provides. **What is important to keep in mind here, is that weather forecasting activities are crucial for ship operators and enable to avoid additional GHG emissions**. We have seen that Météo-France as well as the ECMWF have important contributions in that matter as they provide their support over several strategic maritime regions of the world.

Optimisation of aircraft routes through weather forecasting could also have been highlighted as it enables to reduce fuel consumption and therefore CO2 emissions. However, the forecasting activity provided by Météo-

[79] See https://www.ademe.fr/sites/default/files/assets/documents/86275_7715-guide-information-co2-transporteurs.pdf
[80] 2-4% x (2,400 km x 75,000 tons x 10gCO2 / 1,000,000) = 36-72 tons CO2

France to the aviation sector in France is not funded by public subsidies but by the aeronautical taxes and has therefore been excluded from the scope of this evaluation.

B. Management of oil spills

Weather forecasting and Earth observation data are also highly useful and used by competent authorities to undertake clean-up actions during hydrocarbon spills at sea (which can be caused, for example, by ship accidents, fires on oil platforms, etc.). Such actions cannot fully prevent ecological consequences of those maritime pollutions but **can mitigate them by removing as much as possible the toxic substance** (oil, gas, chemicals…), **and as quickly as possible** before it affects a large part of the biodiversity (both marine and terrestrial).

An oil spill is the release of a liquid petroleum hydrocarbon into the environment, especially marine areas, due to human activity, and is a form of pollution. The term is usually applied to marine oil spills, where oil is released into the ocean or coastal waters, but spills may also occur on land. Oil spills may be due to releases of crude oil from tankers, offshore platforms, drilling rigs and wells, as well as spills of refined petroleum products (such as gasoline, diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, or the spill of any oily refuse or waste oil. (*Citizing*, 2017)

Among maritime environmental disasters, oil spills in coastal waters seriously affect the ecological system, fisheries, and the economy. Although the number of large oil spills (>700 tons) has been decreasing, it is still a major problem for marine environments. Stranded oil tankers and collisions are the main causes of large oil spills, accounting for 64% of the total during the period of 1970–2010.[81] Weather conditions are not a cause of tanker's accidents at sea. However, they play an important role in the way the oil spills and its trajectory will develop, and more importantly in the clean-up methods to be used. Oil spill countermeasures are affected by weather such that, in some cases, these countermeasures cannot continue under adverse weather conditions. It is therefore crucial to be able to predict the movement of oil slicks as quickly as possible for appropriate actions to be taken to protect from and mitigate the damage.

As explained in detail in the study of *Citizing* in the socioeconomic evaluation of the ECMWF supercomputer (*Citizing*, 2017), oil spills affect water in a variety of ways and highly depend on weather. Indeed, "w*hen oil is released into water, it does not blend with the water. Oil floats on the surface of salt and fresh water. Over a very short period of time, the oil spreads out into a very thin layer across the surface of the water. This layer, called a slick, expands until the oil layer is extremely thin. […] Oil spills on the surface of the water are subjected to the whims of weather, waves and currents*[82]*. All these natural forces move slicks across the surface of the water. The temperature also directly affects the physical and chemical characteristics of oil. It can suddenly (on a daily basis) alter its viscosity and ultimately its content, reducing or increasing the potential physical and biological impact of oil. All those factors might facilitate or prevent the implementation of containment and clean-up operations.* ***Weather conditions will therefore affect heavily not only the oils slick in itself but also the performance of cleaning methods and crews****."*

Environmental consequences can be dramatic: pollution and contamination of natural areas (beaches, coasts, seas), destruction of habitats, killing of fish, birds and marine mammal (potentially endangered species), killing

[81] ITOPF (2011) ITOPF Handbook 2011/2012. London, England: ITOPF
[82] https://sciencing.com/oil-spill-affect-environment-4616883.html

of plankton, at the bottom of the food chain (suffering from water changes and lack of sunlight beneath the oil slick), which leads to the death of animals that usually feed themselves with plankton[83]…

As in maritime transport, Météo-France oversees the aforementioned areas of the planet (METAREAS) defined by the WMO, in which it produces its forecasts to provide ocean's products and to help in case of oil spills. In France, the fight against marine pollution is coordinated by the prefect of the maritime area concerned (Channel-North Sea, Atlantic or Mediterranean) who relies on the scientific and technical support of several organizations, including the CEDRE[84] (in charge of advising the authorities on the decisions to be taken) and Météo-France (which shares its results with the CEDRE). Météo-France also brings its support in the Indian Ocean as it did in 2020 when the Japanese ship Wakashio ran aground off the coast of Mauritius, with a leak of a significant amount of hydrocarbon spill. As Mauritius was not sufficiently equipped to deal with this problem, Météo-France intervened to predict the trajectory of the oil slick.

Météo-France can simulate the drift of pollutant slicks on the sea surface with MOTHY, its sea drift model. MOTHY takes into account a large amount of data, in particular the observed winds and wind forecasts produced by Météo-France, but also the deeper marine currents analyzed and forecast by the Mercator Océan oceanography system and the European Mediterranean Forecasting System program (part of Copernicus). The establishment also provides the authorities in charge of conducting response operations with valuable weather observations and forecasts for interventions at sea (by pollution response). **The MOTHY system is used by Météo-France on average about twenty times a week**, 3/4 of the time for human or object rescue and **1/4 for hydrocarbon spills**, of which 1/4 of the requests come from the DOM/TOM. Météo-France used its MOTHY model around 180 times for hydrocarbon spills in 2015 and 255 times in 2020[85]. In addition to those, the Wakashio accident, which occurred on 25 July 2020 south of Mauritius, resulted in 67 more uses of the model.

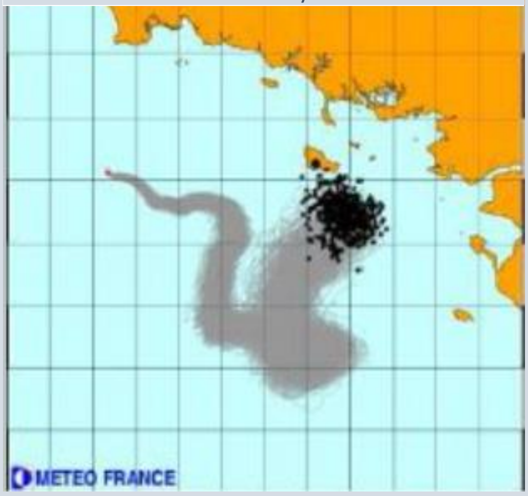
The literature did not provide any quantitative data for the performance of countermeasures under varying weather conditions. Moreover, it is difficult to predict what would have replaced Météo-France in our counterfactual scenario and what would have been the quality of the sea drift model compared to MOTHY. The international dimension of the activity makes the definition of the counterfactual challenging. Still, we know that over the areas overseen by Météo-France, the quality of its models for atmospheric forecasts are reliable and precise and the model MOTHY is of high quality. For instance, after the Erika incident in 1999 (see below), the MOTHY model appeared to provide the best prediction of the slick drift compared to two commercial models also used to predict this oil spill, namely OSIS (British model) and OILMAP (American model). Although the reasons of the difference between models is uncertain, the nature of the wind and current data needed for the models and how they are processed are likely explanations, considered by meteorologists[86]. Moreover, Météo-France also contributes to the Copernicus Marine Service by providing its data on ocean waves. Hence, although it is not relevant to define a counterfactual here and to make a quantitative analysis, we can reasonably argue that **Météo-France enables to bring a determinant contribution to mitigate environmental consequences of marine pollutions**.

[83] https://sciencing.com/remove-oil-sea-water-5649507.html
[84] Centre de documentation et d'expérimentation sur les pollutions accidentelles des eaux
[85] Source: http://www.meteorologie.eu.org/mothy/statistiques/lancements.html
[86] Marées noires et sols pollués par des hydrocarbures. Enjeux environnementaux et traitement des pollutions. C. Bocard (2006). p.108

Case study of an oil spill: Erika incident of 1999

The Erika is a Maltese-flagged oil tanker built in 1975 and chartered by Total, which sank on 12 December 1999 off the coast of Brittany while carrying 30,884 tons of heavy fuel oil from Dunkirk to Livorno.
While 11,200 tons stayed in the two pieces of the wreckage and have been pumped out, around 20,000 tons were released into the environment. Although weather forecasting could not enable to extract all of it from the ocean, it brought, in conjunction with flows predictions, considerable support to the authorities in charge of clean-up actions by providing crucial information and prediction on the trajectory of the slick. Eventually, 1,200 tons could be removed with this support and actions undertaken, which reduced environmental damages.
The picture at the right shows the simulation of the MOTHY model to predict the position and the trajectory of the oil spill up to 12 days ahead after the incident (represented in grey).

Figure 24: Simulation of slick drift from Erika with the Mothy model



Source: Météo-France

Sources: Météo-France website and Laurent Laubier (La marée noire de l'Erika : conséquences écologiques et écotoxicologiques, 2004)

Although the share of the volume of oil removed in the case study above seems quite low considering the volume released into the sea, one should note that the Erika incident resulted in a massive marine pollution leading to unavoidable massive consequences on the environment. Fortunately, an event of such magnitude is exceptional. Météo-France uses its MOTHY model every week for hydrocarbon spills (that correspond on average to 23% of all requests requiring the use of MOTHY[87], the rest being for rescue or other actions in the sea), but those are more manageable. **Weather forecasting allows to support the implementation of regular actions that will have a positive impact on the environment. As stated above, the MOTHY model supported authorities by being used 255 times in 2020 for hydrocarbon spills. In 2019, 237 marine pollutions were recorded in maritime areas overseen by Météo-France, of which 174 hydrocarbon spills that led to the activation of the MOTHY model almost 300 times[88]**.

Satellite data provided by the Copernicus program have also been determinant, first to provide observations to meteorological organizations to forecast the evolution of oil spills as explained in this section, but also for early detection of oil spills. Indeed, services are developing in Europe using SAR (Synthetic Aperture Radar) images to help authorities identify pollutant areas and the extent of the issue as soon as possible. Once the alert is received, the authorities carry out an on-site verification and implement the appropriate measures if the pollution is confirmed. In France, 605 reports of possible pollution were relayed in 2019 to the CROSS (responsible for monitoring of marine pollution), of which 48.7%[89] came from satellite detections from the European program "CleanSeaNet"[90]. Early detection is crucial to prevent an important spreading of pollutant and thus to limit environmental damages, particularly on biodiversity. **The potential of Earth observation for monitoring oil spills is not investigated further here, but one should remember that such observations are essential in this activity for early detection and for meteorological organizations to predict maritime meteorological conditions**.

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[87] Source: Météo-France
[88] Source: Météo-France and report « Surveillance des pollutions en mer, bilan annuel 2019 » from Directorate of Maritime Affairs (ministry of sea)
[89] The others coming from witness on ground or in the sea, or from aircraft. Source: « Bilan annuel 2019 de surveillance des pollutions en mer » → https://www.ecologie.gouv.fr/sites/default/files/Bilan%20annuel%20de%20surveillance%20des%20pollutions%202019.pdf
[90] This program is operated by the European Maritime Safety Agency (EMSA) and is a satellite-based pan-European oil spill and vessel monitoring service which processes images coming from Synthetic Aperture Radar (SAR) satellites - such as the Copernicus Sentinel-1A/B satellites - to identify and trace oil pollution on the sea surface and to monitor accidental pollution during emergencies.

C. Management of aquatic and maritime areas

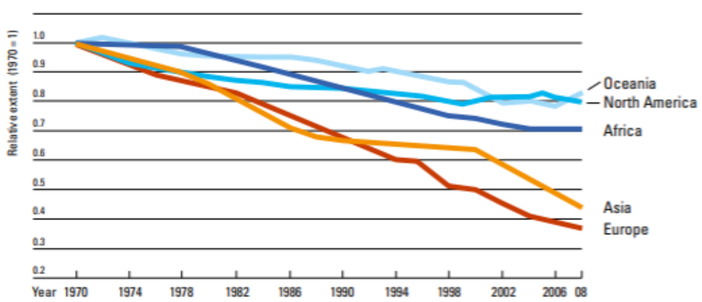
i. Role of Earth observation for wetland monitoring

There exist several types of wetlands that can be found in every country and all climatic zones, from polar regions to the tropics and from the highest mountains to the oceans. The term “wetland” groups a range of mostly aquatic habitats that usually have common features such as the presence of specific vegetation (adapted to anoxic hydric soils). The main wetland types are classified based on the dominant plants and/or the source of water. However, wetlands are among the most biologically diverse ecosystems and some of them have multiple types of plants and are fed by multiple sources of water, making them difficult to be classified. Among one the possible classifications[91], we can distinguish 5 main types of wetlands:

- Peatlands: wetlands with a thick water-logged soil layer made up of dead and decaying plant material, such as moors, bogs, mires, peat swamp forests, permafrost tundra, found everywhere on the planet
- Coasts and deltas: wetlands along coasts that are connectors between marine, freshwater, and terrestrial ecosystems such as mangrove forests, salt marshes… (developed in the next section Role of Earth observation for coastal areas monitoring dedicated to coastal areas)
- Rivers and lakes: natural watercourse, usually freshwater, flowing towards an ocean, a lake, a sea, or another river
- High altitude wetlands: glacial lakes, marshes, wet grasslands, peatlands, and rivers at high altitude
- Artic wetlands: peatlands, rivers, lakes, and shallow bays covering nearly 60% of the Artic

Wetlands are some of the most productive ecosystems on Earth, holding an important part of Europe’s biodiversity with diverse bird’s and mammal’s species depending on freshwater wetlands for breeding and feeding, and essential habitats for fish and amphibians. Moreover, **wetlands are particularly important for carbon sequestration.** For instance, peatland is formed by semi-decomposed plant material in a waterlogged. Due to the lack of normal decomposition processes, carbon from the atmosphere is locked up in these systems, estimated at more than 600 gigatons of carbon on a global scale[92] (which represents up to 44% of all soil carbon and twice as much as the world’s forests[93]). **Wetlands also provide a wide range of other services such as water provisioning, purification of water ensuring good quality levels and protection against floods**.

Figure 25: Evolution of wetlands extent index by region of the world



Source: https://www.ramsar.org

Note: the index measures the decrease in a global sampling of more than 1000 wetland sites with the basis being the year 1970

Wetlands have been facing various threats over the years leading to consequent losses in those areas as represented in the graph. **Scientific estimates show that 64% of the world’s wetlands have disappeared between 1900 and 2010**[94] and only 5 to 7% of the Earth’s surface is covered by wetlands today.

The main drivers of this loss are the increasing pressure of intensive agricultural activities, water diversion through dams, dikes and canalization, and infrastructure development. Moreover, in 2011, the European Commission published the results of the conservation status assessment of

[91] Being the classification made by the non-profit international organization Wetlands International dedicated to the protection of wetlands → https://www.wetlands.org/wetlands/types-of-wetlands-2/
[92] Source: IUCN → https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change
[93] Source: https://theconversation.com/peatlands-keep-a-lot-of-carbon-out-of-earths-atmosphere-but-that-could-end-with-warming-and-development-151364
[94] According to the Ramsar Convention

wetlands in EU member states, showing that only 10% of total areas in wetland ecosystems had a favorable conservation status of habitats whereas 45% were having a “bad” conservation status[95].

Many countries around the world have become aware of the importance of wetlands and are increasingly involved in the protection of these ecosystems. **The measures are varied and complementary: making policies that consider the ecosystem services that wetlands provide, and integrate them into land use planning; using all remaining wetland sites wisely (meeting human needs while sustaining biodiversity and other wetland services); restoring degraded wetlands; developing financing sources for wetlands conservation; educating others about the benefits of wetlands; etc.** Among the adopted policies and plans, we note the Convention on Wetlands of International Importance that was signed in Ramsar, Iran in 1971 (also called the Ramsar Convention). This convention has been the first international agreement specifically dedicated to the protection and the sustainable use of wetlands, bringing together 172 countries. **The main output has been the definition of wetland sites registered on the Ramsar List (254,685,425 ha worldwide today), meaning that these sites must be preserved and monitored by countries they are located into.** In particular, a set of criteria, such as the presence of sensitive fish and waterfowl species, must be met over those sites. **The Ramsar Convention is an international agreement, but at the EU level the Habitats and Birds directives** (described in the section Management of forests, lands and mountains and their ecosystems) **and the Water Framework Directive (WFD) are the key EU legislations ensuring the protection of Europe’s wetlands.** The EU wide *Natura 2000* network of protected sites has a major role together with the integration of wetlands into river basin management planning under the WFD in helping to guarantee their future conservation and sustainable use. Ramsar convention and *Natura 2000* have the same goals although the latter is not specifically dedicated to wetlands.

Earth observation as a support for wetland management and conservation is gradually being considered. Such observations, combined with in-field data, have the potential to provide key information to environmental authorities – that remains difficult to collect given the complexity, the size and the access of some wetland ecosystems – such as on:

- the wetland extent and how it has changed over time, through accurate wetlands mapping (delimitation) and its evolution (also a good indicator on the extent to which climate change affects wetlands)
- threats for the wetland through external pressures detection, for instance by detecting land use change around the ecosystem (urbanization, agriculture growth, aquaculture) or changes in hydrology caused by drainage, etc.
- signs of ecosystem and water quality deterioration (caused by eutrophication, large sediment loads, etc.) through status assessment (soil moisture index, vegetation cover, chlorophyll, etc.).
- the extent to which upstream water use affect the wetland ecosystem

All this information is crucial to implement appropriate measures to protect or restore wetlands and thus to guarantee the continuity of ecosystem services they provide. In particular, the arrival of free and open spatial data provided by Copernicus Sentinels has been and will be a considerable supporting tool to managing authorities for cost-effective and large-scale wetlands monitoring and to comply with the Ramsar convention (as well as with EU Directives for EU member states). While the American program Landsat provides high-quality data and observations over a long period (several decades), **Sentinels have brought considerable improvements regarding spatial resolution (from 60m to 10m for Sentinel-2 depending on the band) and revisit time over a same place on Earth (around 5 days for Sentinel-2).** Merging data from both American and European programs enables to guarantee high degrees of accuracy when monitoring and mapping wetlands. Although remote sensing can be limited to monitor wetlands where vegetation is

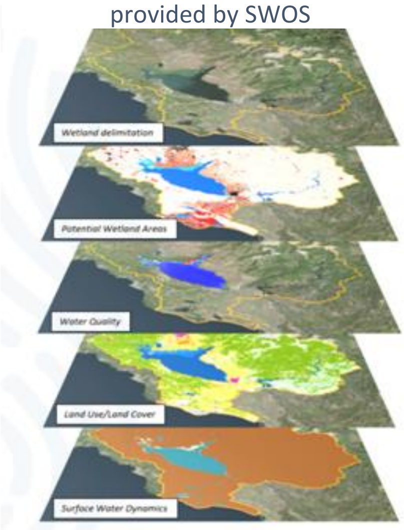
[95] Source: EEA → https://www.eea.europa.eu/data-and-maps/figures/conservation-status-of-habitat-types-4

important (for instance in mangrove forests where trees can hide the water basin when looking from space), **the literature has shown satellite data to be a reliable source to monitor these ecosystems, accompanied by in-field inspections, algorithms and other data sources (aerial photos…).** For instance, Ludwig et al. (2019) tested an algorithm using Sentinel-2 multispectral instrument imagery for water and wetness detection at three study sites with different wetland types in Kenya/Uganda, Algeria and Austria, and found an overall accuracy above 92% (>96% for water detection and >75% for wetness detection). Mahdianpari et al. (2018) shows that Copernicus Sentinels can be used for wetland inventory mapping. Their study focuses on five wetlands located in Canada (covering around 106,000 km^2) and uses Synthetic Aperture Radar (SAR) Sentinel-1 and optical Sentinel-2 data. Although the classification using Sentinel-2 optical imagery was more accurate than that of SAR, the inclusion of both types of data significantly improved their classification accuracy above 70%. The success of Sentinel-2 for wetland mapping and monitoring is also demonstrated by Kaplan and Avdan (2017), who studied wetlands in Turkey using Sentinel-2 data to estimate wetlands boundaries and indicators including Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI[96]) to classify contents within wetlands boundaries and showed successful mapping and monitoring of wetlands with a kappa coefficient of 0.95[97].

Given the potential of Copernicus data for wetland monitoring, the European Union and ESA, along with other partners, have launched two large projects relying on Copernicus and other satellite data, aiming at developing operational services to assist countries in decision-making for local conservation activities:

- **The Satellite-based Wetland Observation Service (SWOS)**: funded by the European Union and developed between 2015 and 2018 by 6 organizations/NGOs, 3 universities and 4 companies. **SWOS aims to provide a user-friendly wetland information and monitoring service**, including maps and indicators, a software toolkit and a community portal. A total of nine indicators, such as land use, land cover, water quality, and surface temperature, were developed with maps to monitor their variation over time and space. By taking into account the ecological and hydrological characteristics of a wetland, SWOS allows for an integrated assessment of the ecosystem and the threats it faces. The project provides an overview of the status of wetlands in more than ten countries and developed the service on fifty wetland locations across Europe, Africa and the Middle East (test-sites), using data provided by Sentinel-1, -2, -3, Landsat, Meris and other missions.

Figure 26: Examples of indicators provided by SWOS



Source: https://medwet.org/wp-content/uploads/2018/10/swos-en.pdf

- **GlobWetland Africa project[98]**: funded by ESA in partnership with the African Team of the Ramsar convention on wetlands and developed between 2015 and 2018, the project has been initiated **to facilitate the exploitation of satellite observations for the conservation, wise-use and effective management of wetlands in Africa and to help African stakeholders to better fulfil their commitments and obligations towards the Ramsar Convention on Wetlands**. It provides users with the necessary methods and tools to make the best use of the Copernicus satellite observations for wetlands inventory, assessment and monitoring. In particular, it uses data from Sentinel-1 and Sentinel-2 to map the extent and frequencies of water and moist soils, used as input for preparing national wetland inventories. Moreover, it uses data from Sentinel-3 for hydrographic indicators measures and for estimating some indicators of water quality.

[96] NDWI is a remote sensing derived index estimating the leaf water content at canopy level
[97] The kappa values range from -1 to +1. The higher the kappa value, the stronger the match. When the kappa = 1, a perfect match exists. If the kappa has a value of 0, the match is the same as that which could be expected at random. Here, 0.95 means that the mapping almost perfectly matches to reality.
[98] More on the project: https://www.ramsar.org/sites/default/files/documents/library/strp20_agenda_item5_globwetland_africa_mpaganini.pdf

However, the measure of the latter remains limited to water clarity, turbidity, watercolor and the concentrations of optically active constituents (such as algal pigments or suspended solids) and requires in-situ inspections for more precise water quality characteristics. The ESA's Cryosat mission is also used for hydrography.

Although still at their beginning, these two projects' outputs are already accessible to the public and will likely enhance the quality of wetland monitoring and the actions to protect and restore wetlands. Initial uses have already been demonstrated. For example, the application of the SWOS approach to map wetland ecosystems in Greece has enabled local authorities to understand changes in the extent of wetlands due to their conversion to agricultural land. In Tanzania, land use trends have helped wetland managers develop strategies that support economic development and natural resource sustainability[99].

Other operational services using Copernicus data to help wetland monitoring and restoration have also been developed in Europe. For instance, Yorkshire Peat Partnership (British organization funded by Department for Environment, Food & Rural Affairs and other agencies) developed a service using remote sensing data from Landsat and Copernicus programs and aiming to support environmental and other managing authorities for peatland restorations in a region of the UK[100]. By observing vegetation productivity and moisture through the calculation of vegetation indices, maps indicating the extent of peatland swelling (a characteristic of successfully restored peatlands) are created. Moreover, bare peat and burn scar maps are generated from image classification techniques (such as Maximum Likelihood and Support Vector Machine). These classifications use both Sentinel 1 and Sentinel 2 data and help to quantify the extent of damage across peatland sites.

In addition to the services developed under the initiative of the European Union, free and open Copernicus data has opened the opportunity for private companies and local and national agencies everywhere in Europe and beyond, to develop economic activities dedicated to support authorities in wetland monitoring and preservation. This has improved the management of those ecosystems resulting in various positive environmental impacts, including biodiversity protection and carbon emission reduction. However, wetlands are still highly threatened by human activities and will require more protective and restoration measures, for which Earth observation will undeniably bring considerable information.

ii. Role of Earth observation for coastal areas monitoring

The European Environment Agency (EEA) defines a coastal area as *"the part of the land affected by its proximity to the sea, and that part of the sea affected by its proximity to the land as the extent to which man's land-based activities have a measurable influence on water chemistry and marine ecology"*[101]. Coastal areas are significant in the European Union with a coastline of approximately 68,000 km long[102] (more than three times longer than that of the United States), and with coastal areas in Europe representing around 560,000 km² (aggregation of EEA coastal member countries). According to the EEA[103], almost half of the EU population lives less than 50 km from the sea. In 2011, 206 million people, or 41% of the EU population, lived in Europe's coastal regions (data for 2011 from Eurostat).

European seas include a wide range of marine and coastal ecosystems, ranging from the deep ocean to coastal waters, but also coastal lands such as beaches, forests, wetlands along coasts such as mangrove forests, salt marshes, seagrass beds, mudflats, etc. Those environments host an important part of the human population

[99] Source: https://cordis.europa.eu/article/id/254156-observing-wetlands-from-above/fr
[100] Source: "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p.82
[101] Source: https://www.eea.europa.eu/help/glossary/eea-glossary/coastal-area
[102] The length goes up to 185,000 km if Turkey, Iceland and Norway are included
[103] Source: https://www.eea.europa.eu/themes/water/europes-seas-and-coasts

as well as a rich biodiversity composed of a broad range of fish species, bird species, other animals such as insects and mammals, coral reefs, tree species, algae, and other plants. In addition, coastal ecosystems provide important services to the economy (provisioning services such as food through fishing, cultural services through tourism, etc.) and to the environment (supporting and regulating services such as natural defense against natural hazards, photosynthesis, climate regulation, etc.). However, **coastal ecosystems are more and more threatened by human activities and climate change, resulting in various environmental concerns such as biodiversity loss, sea level rise or coastal erosion**.

Monitoring ecosystems to prevent biodiversity loss

Biodiversity has been affected by numerous sources of stress such as the increasing population, fishing, intensive agriculture, industrial chemical pollution, tourism developments, shipping, energy infrastructures, other maritime activities, etc. In-field inspections are essential to detect such pressures on the biodiversity, particularly for chemical measures of water that cannot be carried out with satellite images. Nevertheless, remote sensing has proven to be effective to support in-field inspections for **early detection of changing patterns and altering ecosystems in coastal wetlands that can prevent irreversible biodiversity loss** and assist in the identification of problematic areas. The Copernicus Sentinel missions are now providing vital information to help visualize and explain trends to policy makers. For instance, satellites of Copernicus are able to detect areas with high mussel and cockle abundance or detect algae which some species (such as birds) feed upon[104]. Such information can be used to support or validate modelling works aiming at predicting bird population trends and dynamics with higher resolution (both in space and time) than traditional in-field investigations. **Those models help *in fine* to quantify ecosystem services, to provide information on species decrease such as decrease of birds and to optimize management strategies for biodiversity conservation in coastal wetlands**.

Moreover, **the Copernicus marine service provides observations to monitor the marine biodiversity**. The data offered allows decision-makers for a better understanding of this biodiversity and to adopt data-driven global strategies. Although it is not possible to detect and list the species from space, the Copernicus Sentinels (mainly Sentinel-3) give good marine health indicators such as chlorophyll-a and micronekton dispersion that can be used to track endangered species[105]. These variables represent the base of the marine food webs and shed light on animal behavior, including prey pathways. Physical data, such as marine temperature, salinity, or currents that can also be observed using spatial data, provide a larger picture of the marine environment and suitable habitat conditions for different species, although they require to be combined with in-situ data that are essential for measuring biochemical parameters (e.g. acidity). **Oceanographic data provided by satellites can thus be harnessed to complement in-situ data and to include an ecosystem-approach to policies related to environment and biodiversity protection such as the EU Marine Strategy Framework Directive, the EU Biodiversity Strategy, and the EU Habitat Directive**.

Monitoring coastal erosion to better adapt to climate change

Human activities and climate change have contributed to the accelerating coastal erosion. Coastal erosion is the loss or displacement of land, or the long-term removal of sediment and rocks along the coastline due to the action of waves, currents, tides, wind-driven water, waterborne ice, or other impacts of storms.

[104] Source: https://sentinels.copernicus.eu/web/sentinel/-/copernicus-sentinels-improve-monitoring-of-coastal-ecosystems
[105] Source: https://marine.copernicus.eu/services/public-policies/protecting-biodiversity

Figure 27: Beach erosion in New York, 2012

Source: Haddow et al. (2020) – photo by Andrea Booher, FEMA

Erosion leads to the destruction of animal habitats and of coastal features like dunes and mangroves that provide a natural defense against several hazards, including tsunamis and storm surges, making these areas more vulnerable to such hazards (*Haddow et al*., 2020). Indeed, although coastal areas have been changing with erosion for years, the increasing speed of erosion explained by climate change and the proximity of buildings and roads to the sea will lead to higher flooding and buildings collapse risks. **Monitoring of coastal environments and tracking their evolution with erosion through time is thus essential to provide information to policy and decision-makers on local, regional, and national levels for optimal climate change adaptation measures**. According to the IPCC, sea level rise caused by climate change will increase coastal erosion worldwide, significantly changing the shape of the coasts[106]. As sea level rise cannot be prevented but only limited, public authorities will have to adapt their territories to face the above-mentioned consequences of coastal erosion.

Sentinel missions from the Copernicus program have shown to be useful to monitor the evolution of shorelines and their erosion over time. In particular, **they provide repetitive and consistent view of coastal areas to complement other data (such as coastal maps, beach surveys, aerial photographs, etc.) and to improve the monitoring of hard-to-reach and large extent areas**. Sentinel-1 satellites provide Synthetic Aperture Radar (SAR) images and have been used to reproduce shorelines and highlight erosive trends. For instance, researchers at Deltares (an independent Dutch institute) developed an automatic method to retrieve the shoreline on the Torre Canne Apulian beach (Southern Italy), based on land-water separation, with Sentinel-1 data. The Torre Canne shoreline, derived from data of the Copernicus Sentinel-1 satellites, was compared to those generated using video imaging systems and was able to reproduce the shoreline, accounting for the resolution limitation of the satellite information. Local monitoring has shown that this beach faced an erosive trend over the past decades. **This shows the potential of Sentinel-1 that can be used to aid in the monitoring of similar beaches which do not currently have the benefit of video monitoring systems to track changes and inform policy makers**. **Optical imagery provided by Sentinel-2 has also proven to be reliable to detect erosional trends**. For instance, Gomes da Silva et al. (2020) combined Sentinel-2 data with Landsat images (from Landsat 5 and 8) to cover a wide time range (1994-2018) and analyzed the shoreline evolution in Tordera Delta (Spain). The authors find an average erosion tendency of -4.79 meters per year using satellite data and highlight that another study used high-resolution aerial photographs in the same region between 1995 and 2009 and found a quite similar value (-4.68 meters per year), showing that satellite images provide reliable results to monitor the shoreline evolution. Although Sentinel-2 appears to provide slightly better accuracy results to map shoreline changes than Landsat 8 images given its higher resolution performance (as shown for instance in Mitri et al. (2020)), the combined use of both image sources is expected to generate reliable and long-term data records for continuous monitoring of shoreline changes.

[106] Wong, P. P. et al. (2014). "Chapter 5: Coastal Systems and Low-Lying Areas". IPCC AR5 WG2 A 2014. pp. 361–409.

Figure 28: Products provided by the Coastal Erosion Project for an English coast

Source: GEO Business 2022

Given the potential of Copernicus for such an application, **ESA collaborated with an international Coastal Change from Space consortium to launch in 2019 the Coastal Erosion Project**, led by ARGANS Limited (experts from the UK and France) in partnership with AdwaisEO (Luxembourg) and IsardSAT (Spain)[107]. **This project intends to develop monitoring services on erosion, providing significant insights into determining where investments by governments should be focused and how corrective actions can be best targeted, in the framework of a climate adaptation strategy.** This group demonstrated how to derive 25 years of historic shoreline from both SAR and VNIR (Visible and Near-Infrared) imagery, using the Sentinel-1 and -2 constellations, along with ESA's catalogue of Landsat and ERS/Envisat data. Such applications are of key importance for the countries involved in the analysis to help them mitigate the negative socio-economic effects of coastal erosion. The development of the service and its products ended in 2021 and is now on its way to become operational and support managing authorities for the next years, extending over 2,800 km of coast analyzed across 4 nations and based on a 25 years' timescale of satellite imagery.

However, other services have also been developed to monitor coastline changes in Europe using Copernicus data and have already shown promising operational use. The following case study presents a concrete example.

Case study: satellite imagery for improved coastal management in the Nouvelle-Aquitaine region (France)[108]

Figure 29: Coastline detection and change analysis (2013-2015) in a French beach

Source: The ever-growing use of Copernicus across Europe' regions (2018)

The state of the sea surface and especially wave breaking in this region prevents easy and safe ground observations. On the other hand, frequent and synoptic observations acquired by multispectral optical satellite imagery enables a better monitoring of erosional trends that supports *in fine* adaptation of coastal observation strategies and management, both for scientist and end-users.

Based on ocean color and image processing tools combined with artificial intelligence and machine learning, Copernicus Sentinel-2 optical sensor allows accurate physical and biogeochemical parameters derivation (e.g. ocean temperature, salinity, chlorophyll, topography, etc.). Accuracy of coastal morphological features positioning and change analysis can reach high performance achieving accurate erosional trends such as coastline change, only limited by the resolution of the space borne sensors. The photo above illustrates the output of such analyses by showing the coastline on a beach located in the region with its evolution from 2013 (green line), to 2014 (red line) and then to 2015 (blue line), which highlights the erosion progressing at a high speed. In the very near future, remotely sensed coastal indicators such as Sentinel-2 derived bathymetric charts are to be compiled by the Aquitaine Coastal Observatory in order to derive more precisely the Aquitanian erosional trends. Such information will be crucial to distinguish local and short-term processes from long-term trends dedicated to forecasting the impact of future coastal hazard. Based on this, recommendations can be made to enhance coastal management and local strategies in order to undertake risk mitigation measures related to climate change, such as preserving natural areas that are determinant to reduce natural hazard's consequences (beaches, mangroves…).

Moreover, the next generation of Copernicus and Sentinel satellite missions such as Sentinel-6 will improve ocean products and observations that should enhance further the good monitoring of coastal areas.

[107] See more on the project here: https://coastalerosion.argans.co.uk/doc.html

[108] Source: "The ever-growing use of Copernicus across Europe's regions" (2018). EC. p.79

4. Supporting urban areas

A. Heat waves and urban heat islands

According to Météo-France projections, climate change will lead to extreme phenomena by 2100, with, for Paris:

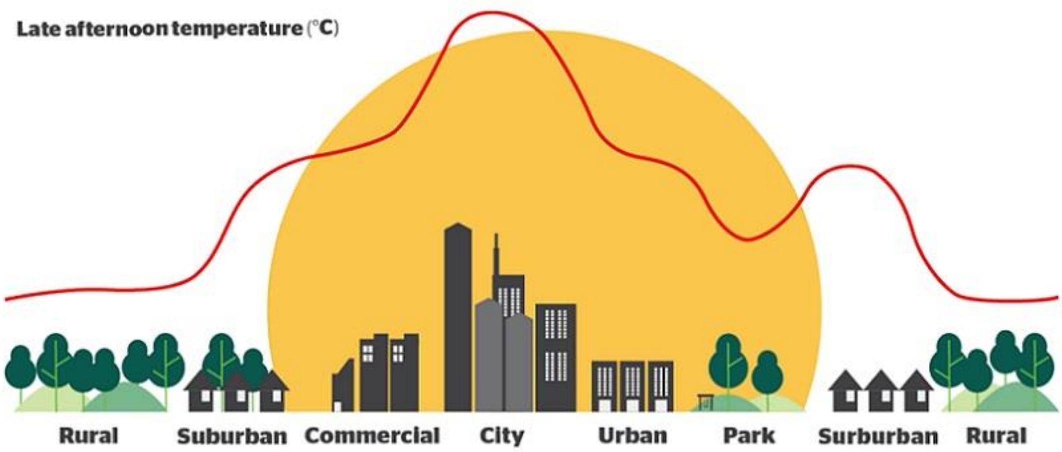
- 10 to 45 days of high heat per year (+30°C), compared to 10 days on average today
- 1 to 12 days of extreme heat/year (over 35°C), compared to 1 day today
- 3 to 26 days of heatwave/year, compared to 1 day/year on average today[109]

We are already seeing an increase in heatwave events and record temperatures rising year on year. In 2019, Paris was marked by an exceptionally intense heatwave, with a record of 42.6°C at the Parc Montsouris station. Extreme heat is more severe in urban areas than in rural areas, especially at night. This phenomenon is well-known as the urban heat island (UHI) effect, which makes it difficult for urban residents to live comfortably during heat waves. During the day in the countryside, plants and soils do not accumulate the solar energy they receive thanks to the evapotranspiration phenomenon. In cities, solar energy is instead stored in building materials and other impermeable surfaces such as road and pavement surfaces. Buildings and roads heat up, storing energy that they cannot dissipate. At night, impermeable surfaces return the energy accumulated during the day to the urban atmosphere. Hence, the air above the city cools down less quickly than in the countryside. In Paris, the UHI leads to a 2.5°C temperature difference with surrounding rural areas.

The UHI is largely dependent on climatic conditions. During the 2003 heat wave, for example, we observed a temperature variation of nearly 8°C between the heart of Paris and the rest of the agglomeration[110]. Urban heat islands are thus expected to become more widespread with climate change. Consequently, local public decision makers will have to adapt urban design and planning to address this issue.

Some solutions enable to reduce temperatures at night, while others aim to provide the population with islands of coolness during the day. The most common solution consists in greening public spaces and buildings because plants can humidify and cool the air through evapotranspiration.

Figure 30: Visual representation of an urban heat island



Source: World Meteorological Organization

Detailed knowledge of past climate change and the study of possible futures is an essential starting point for both mitigation and adaptation actions. In this perspective, Météo-France plays a key role in understanding

[109] Source: Agence Parisienne du Climat, Le changement climatique à Paris, Evolution du climat à Paris depuis 1900, quel Climat futur ?, Juillet 2015
[110] Source: Ville de Paris. https://cdn.paris.fr/paris/2021/05/12/92b8f55c368b25f126cd870d2343210b.pdf

the climate and its evolution. Researchers at Météo-France contribute in particular to the IPCC report (see research section below), which reports on scientific knowledge on the subject of climate change and builds predictive scenarios of its future evolution. **Météo-France also produces its own climate projections over France to help decision makers understand the evolution of natural hazards and undertake measures adapted to regional climate.** Such predictions are the first step for encouraging adaptation of territories to those irreversible changes as they raise public awareness about climate change. Indeed, few measures or non-adapted ones would be adopted if we did not have precise knowledge about the issue that we need to address.

In order for this knowledge to truly enable actions to be taken, it is essential to support the actors with real climate services. These services can take the form of portals and web applications, such as Climat HD, or the DRIAS portal, the future of the climate, which maps the evolution of numerous climate indicators between now and the end of the century. Other more targeted climate services, most often co-constructed with actors from different sectors and more accessible thanks to the "Resource Centre for adaptation to climate change", integrate climate data at the heart of the decision-making system.

In this sense, **Météo-France is participating in the development of urban projects with public institutions and urbanism agencies to make cities less exposed to the effects of heat islands**, and thus to anticipate global warming already felt. **Such projects are significant opportunities to experiment with innovative solutions that could later be developed on a larger scale and thus make cities more resilient to climate change** and increased heat waves. Météo-France acts as a climate forecaster (to help for decisions *ex-ante*), accompanier (through training and awareness-raising) and evaluator of the climate impacts (*ex-post*). The box below presents examples of urban projects Météo-France has been involved into, developed to mitigate UHI and adapt the territory to a warmer climate.

Case studies of Météo-France's contribution to projects aiming to adapt cities to increasing heat waves

« Oasis » project (Paris)

In the face of rising heat waves, the courtyards of schools and colleges have been identified as important levers as these spaces contribute massively to the urban heat island effect. 10 renovated courtyards will offer more natural spaces, more vegetation, better rainwater management and water points. Designed as real islands of freshness in the heart of the neighborhoods, these courtyards will also be able to welcome a wider public outside of educational time. Météo-France contributes to climate awareness-raising of pupils, formation of teachers, climate data collection *in-situ* and outside in the district (control group) to compare, and an evaluation of the reduction of the UHI and impacts on climate (through simulations).

« Lisière de Tierce Forêt » project (Aubervilliers)

In one of the cities with the greatest lack of green space, the project, supported by the Agence Parisienne du Climat and Météo-France, has enabled to transform a paved car park into a pedestrian and green living space. Before transformation, the car park absorbed 87% of the solar energy rejected at night (UHI). Météo-France set weather stations before the transformation on the car park and on a close roof (control group) to measure temperatures, humidity, wind, rainfall…

Before transformation

Those parameters enabled to estimate an indicator of thermal comfort indicator for the human body, called the Universal Thermal Climate Index (UTCI). The first results published by Météo-France demonstrate the effectiveness of the operation on the thermal comfort of users (*Parison S. et al*, 2020). During the days studied, there was a drop in the felt temperature (UTCI) of -2.5°C on average over 24 hours, going down to -6°C around 1pm, and -1°C in air temperature in the late afternoon recorded at the site.

After transformation

« Euromed » project (Marseille)

The Etablissement Public d'Aménagement EUROMEDITERRANEE, in charge of the urban rehabilitation of Marseille, commissioned a study to Météo-France, aimed at quantifying the climatic effects induced by the "Euromed 2" operation: impact of the park created for this purpose, use of an air-conditioning system using a seawater loop, modification of the reflective power of the walls. The study quantifies those impacts separately on Marseille during a heat wave. The temperatures obtained in the district with these hypotheses are compared to those obtained with the simulation of this heat wave for the current city, which makes it possible to quantify the relative contribution of each of these development actions. Results show that the presence of the park is the strongest lever (in term of temperature difference), the use of the seawater loop comes second. As for increasing the reflective power of the walls, in the context of Marseilles, it only provides a limited gain and may even prove to be counterproductive. This research project helped the planner to make the best decisions in view of the objective of adapting the city to climate change, particularly in terms of managing heat waves.

Sources:
https://www.paris.fr/pages/les-cours-oasis-7389 ; https://www.apc-paris.com/actualite/lisiere-tierce-foret-nouvel-ilot-fraicheur-a-aubervilliers ; https://www.adaptation-changement-climatique.fr/initiatives/euromed-etude-limpact-amenagement-urbain-sur-marseille-en-periode-canicule

Météo-France has only partially contributed to the level of knowledge we have today on climate change and the future increase in UHI. It is likely that public awareness of the issue would have been as high in our counterfactual scenario. However, **having a French national meteorological service enables to get more precise and regionalized climate projections in France with lower resolution grids, as well as dedicated climate services that are crucial to ensure effective measures to adapt territories at very local scales**. Although we enlightened the role of Météo-France to adapt to the future rise of heat waves, one should note that climate services provided by the institution can also help local authorities in adapting their territories to the likely increase of other natural hazards (e.g. extreme rainfall) that are not covered in this evaluation.

Moreover, the role of spatial data provided by Copernicus is not investigated either in this evaluation. **Using the Sentinel-2 satellites, all urban green spaces can be mapped, and vegetation indices can be computed in order to find specific places where green areas are lacking and should be vegetalized to mitigate heat waves and UHI.** Cities such as Valencia (Spain), Rennes (France) or Pilsen (Czech Republic) have already used Copernicus data to adjust their urban planning of green spaces and park renovations within a perspective of climate adaptation[111].

B. Urban atmospheric pollution

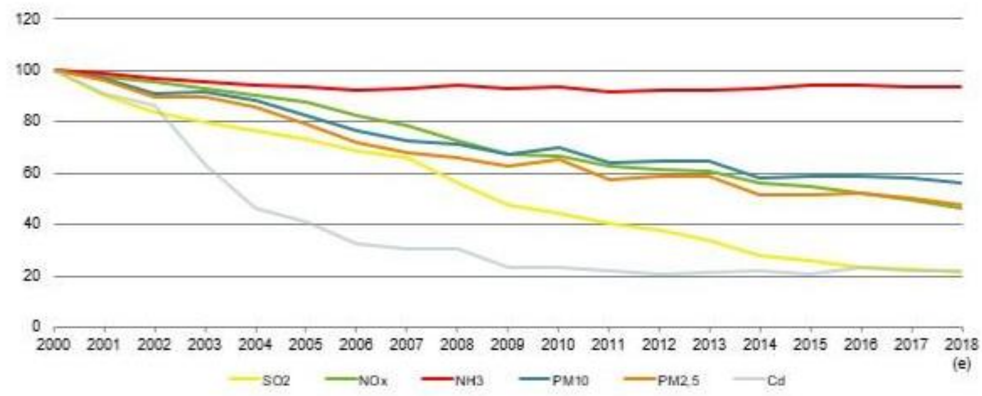
Air pollution is a deterioration of the quality of the air that can be quantified by measuring amounts of chemical, biological or physical pollutants. This phenomenon can have important consequences on human health and the environment (fauna, flora, soils, water basins, climate). We distinguish several types of pollutants having different causes and different impacts: Particulate Matter (PM_{10} and $PM_{2.5}$, i.e particles smaller than 10 micrometers in diameter and smaller than 2.5 micrometers), nitrogen oxides (NOx), Sulphur dioxide (SO2), Volatile organic compounds (VOCs), Ozone (O3), Ammonia (NH3), etc.

Atmospheric pollution peaks or episodes mainly occur in urban areas caused by human activities (industries, transport, residential heating…). However, rural areas can also be affected either through displacement or pollutants from urban areas or directly from agriculture activities or house chimneys. In France, pollutant

[111] Source: https://www.copernicus.eu/en/news/news/observer-copernicus-services-helping-cities-adapt-climate-change

emissions have been decreasing since 2000, enabled by the implementation of new regulations, the development of air quality monitoring and the increase and tightening of corrective and preventive measures (at both long and short term).

Figure 31: Evolution of pollutants emissions in mainland France (base 100 index)



Source: Citepa, MTE (April 2019)

The French Ministry of Ecological Transition reminds that air pollution causes around 48,000 premature deaths per year (of which 6,000 in Ile-de-France), i.e. 9% of mortality in France and a loss of life expectancy at age 30 that can exceed 2 years[112].

According to Météo-France[113], the institution "**contributes to the national air quality monitoring and forecasting system by providing its meteorological expertise to national and regional players**, in particular the LCSQA (Central Air Quality Monitoring Laboratory) and the Aasqa (Approved Air Quality Monitoring Associations), and by modelling pollutant concentrations with its chemistry transport model. In this context, **Météo France participates in the implementation of the national air quality forecasting and mapping platform Prév'Air** developed and managed by the National Institute for Industrial Environment and Risks (Ineris in French), with the support of Météo-France, the National Centre for Scientific Research and the LCSQA. Météo-France and Ineris have also been involved for several years in national and European programs for the assessment, forecasting and analysis of air quality in France and Europe. Since 2015, the two organizations have been co-leading the European air quality component of the Copernicus Atmosphere program."

Although the institution is not the only actor, its role is determinant to ensure reliable air quality forecasts. Air quality depends on various factors such as industries' activities, transports, residential heating… but also meteorological conditions. In particular, **weather highly influences the level of air pollution** through indirect effects (e.g. more car users and less biking during rainy and cold periods which will lead to higher level of emissions) and direct effects (e.g. transformation, dispersion of pollutants…). Those latter effects depend on four specific meteorological variables[114]:

- **Solar radiation**: transforms nitrogen oxides and volatile organic compounds into ozone
- **Wind**: disperses pollutants, which means that low wind speed increases risks for an area to accumulate pollutants. Wind may also displace them, which is not always conducive to good air quality, especially when wind direction is clearly defined toward a specific area that will be excessively polluted.

[112] Source: https://www.ecologie.gouv.fr/pollution-lair-origines-situation-et-impacts
[113] Source: https://meteofrance.com/actualites-et-dossiers/actualites/avec-meteo-france/journee-de-la-qualite-de-lair-pics-de-chaleur-et-pollution
[114] Source: https://www.atmo-auvergnerhonealpes.fr/article/influence-de-la-meteo

- **Temperatures**: when they are too high or too low, they have a negative impact on air quality. The volatility of some compounds increases with temperature, such as volatile organic compounds. Cold weather increases automobile emissions due to less efficient combustion. Finally, summer heat and sunshine favor photochemical processes, such as ozone formation.
- **Rainfalls**: generally beneficial to air quality because precipitation "leaches" the atmosphere by reducing concentrations in the atmosphere. However, there are perverse effects in this phenomenon. For example, in the case of nitrogen oxides, leaching is an effective way of reducing these concentrations, but the latter, through their chemical interaction with water, contribute to the formation of acid rain. The particles thus "leached" are found in the soil and contribute to soil and water pollution.

This shows the importance of very localized weather forecasts as air quality highly depends on meteorological conditions. Using weather forecasts hence contributes to forecasting air quality in the short term. Nowadays, the national air quality monitoring and forecasting system provides reliable predictions of air pollution episodes up to 2 days ahead. In the French region Auvergne-Rhône-Alpes, predictions in 2020 showed that the probability of good detection of a pollution episode in the region is 79% for the same day and 52% for the following day[115]. Errors in predictions come from several reasons such as the difficulty to directly quantify pollutant emissions, the absence of topography in the system for flow calculation or uncertainties in wind forecasts that can be important according to the model used and reliefs.

The air pollution episode management system in France is broken down into the following 5 stages.

Figure 32: air pollution episode management system

Source: Atmo Auvergne-Rhône-Alpes

Météo-France, together with European meteorological organizations that contribute to the chain of weather forecast production (i.e. EUMETSAT, ECMWF) and partners contributing to the national air quality monitoring and forecasting system Prév'Air, intervene at the second step of the process. **This step is crucial to inform local authorities so that they can undertake actions to reduce air pollution and its consequences on health and the environment**. **In the absence of Météo-France substituted by the American GFS model, it is likely that the system would be considerably affected as it requires very localized and reliable meteorological forecasts, particularly regarding wind whose speed and direction can vary even at small scales**.

The prefect of each department concerned implements the measures applicable within this perimeter by means of an order issued after consultation (stage 3) with the departmental council for the environment and health and technological risks. Emergency measures[116] can be related to transport (car speed reduction, differentiated or alternating traffic, immobilization of the most polluting government and public service vehicles, reduced or free public transport fares, free car parks…), to industry (slowing down or shutting down

[115] Source: https://www.atmo-auvergnerhonealpes.fr/actualite/comment-sont-evaluees-les-performances-de-prevision-de-la-qualite-de-lair
[116] See https://www.ecologie.gouv.fr/politiques-publiques-reduire-pollution-lair or http://www.driee.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/ppa_complet.pdf for more measures

certain polluting industrial installations), to agriculture around cities (ban on the burning of agricultural green waste, recommended to postpone fertilizer spraying operations…) to domestic heating or simply by raising awareness of local actors.

The continuation of measures over several days in the event of a prolonged episode applies without interruption as long as the meteorological conditions remain favorable to the continuation of the pollution episode. All these measures, along with monitoring improvement, new regulations and long-run measures (such as development of biking and public transport), have enabled to considerably enhance air quality over the last decade, which prevented more health and environmental damages.

Figure 34: Annual mean of PM2.5 concentration in France in 2009

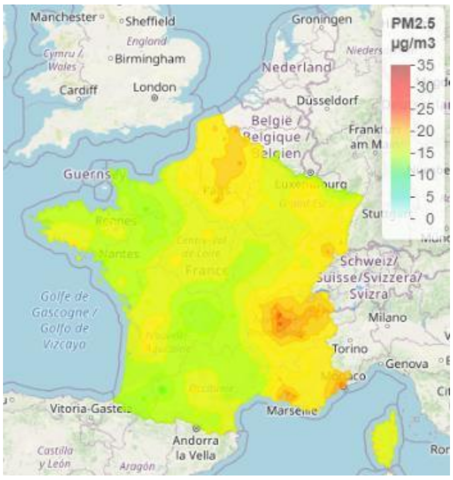
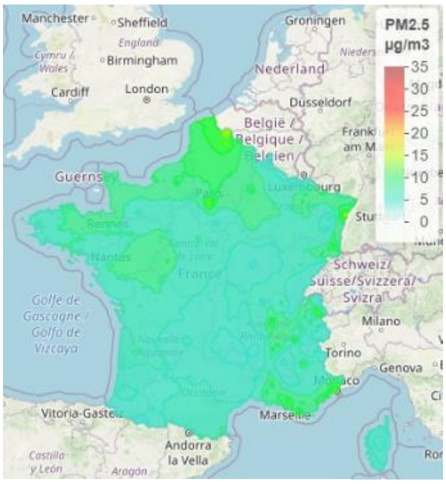


Figure 33: Annual mean of PM2.5 concentration in France in 2019



Source: Ineris

Maps above[117] show annual mean of PM2.5 concentration in France in 2009 (left map) and in 2019 (right map). The national annual mean had decreased by 50% between those two years, which show the effectiveness of the French air pollution management system. 28% of the population remained exposed to values higher than the WHO recommended threshold, which means that there is still progress in air quality to make. However, we observe an important improvement as the entire territory was exposed to levels above this threshold in 2009. Although we cannot assess the share of this effect to Météo-France, we argue that its role is determinant to monitor and inform local authorities of pollution episodes (for all types of pollutants) and their evolution, so that optimal measures are being undertaken.

The service provided by Météo-France is supported at the European scale by the Copernicus program with the Copernicus Atmosphere Monitoring Service (CAMS). This service has been implemented in 2014 by the ECMWF on behalf of the EC and in partnership with ESA and EUMETSAT. It became fully operational in 2015. Typical products provided by the service are:

- Maps and data for regional air quality forecasts
- Retrospective assessments of air quality
- Identification of pollutants and their source
- Pollen concentration levels in the atmosphere
- Resources for evaluating possible emission control measures
- Inputs to local air quality forecasts, health information and warnings[118]

The role of spatial data-based services is not investigated further in this evaluation, but one should note that the CAMS has appeared to be a very complete service to support the expertise provided by Météo-France and other national meteorological services in Europe to better monitor and predict air pollution. Moreover, the future arrival of Sentinel-4 and -5 in the next years, specifically elaborated to meet the needs of the CAMS, will bring a large number of additional data to monitor emission sources and air quality to provide a continuous monitoring system of air pollution.

[117] Source: https://www.ineris.fr/fr/recherche-appui/risques-chroniques/mesure-prevision-qualite-air/20-ans-evolution-qualite-air
[118] More on this service here: https://www.copernicus.eu/sites/default/files/documents/Copernicus_AtmosphereMonitoring_Feb2017.pdf

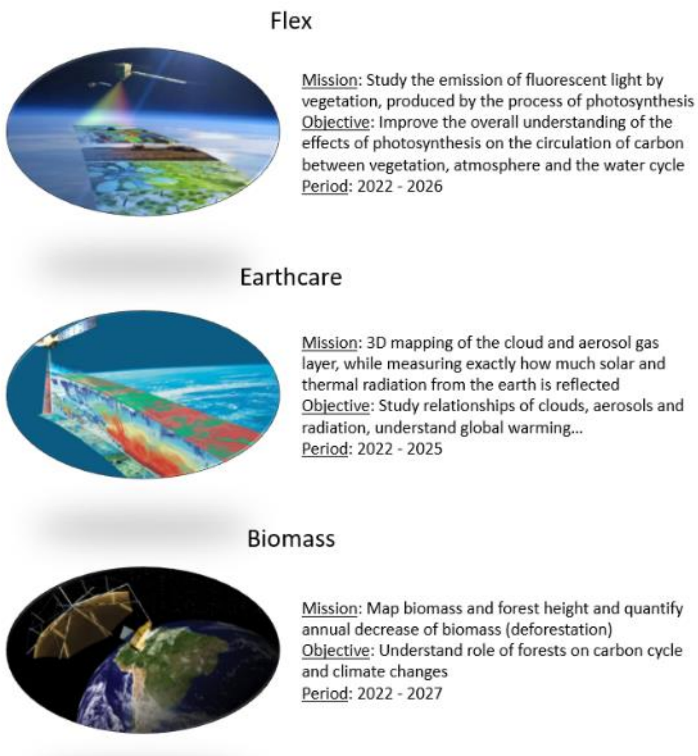
5. Research in climate and environmental fields

A. Research using Earth observation

The first and main output of Earth observation has been to support the scientific community for research in various fields[119]. Although Copernicus has brought the emergence of spatial data-based operational services, the program is also widely used for scientific research, making the distinction between operational use and research quite ambiguous. In addition, ESA implemented, in partnership with the CNES and other space agencies, Earth Explorer missions, since 2009, with new satellites to be launched in the next years. Earth Explorer missions focus on the atmosphere, biosphere, hydrosphere, cryosphere and the Earth's interior with the overall emphasis on **learning more about the interactions between these components and the impact that human activity is having on natural Earth processes**.

Figure 36: Examples of Earth Explorer missions

Figure 35: Future Earth Explorer missions



Source: authors' own elaboration

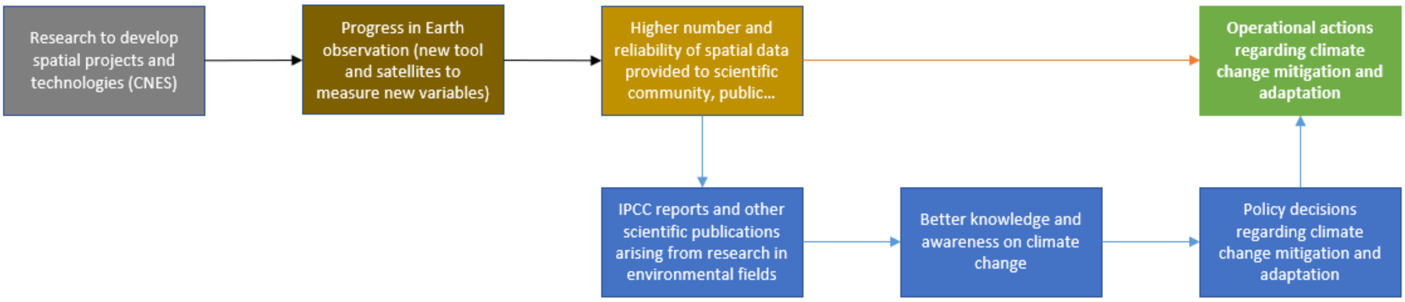
ESA and the CNES already started to work on the development of future Earth Explorer missions (development of technologies, manufacturing of satellites, etc.) such as Flex, Earthcare and Biomass missions. Moreover, the CNES has also developed scientific missions on its own, often with worldwide national space centers such as the NASA (American space agency), DLR (German space agency), ISRO (Indian space research organization), CNSA (China space agency), etc. The **Annex D** describes the recent projects (over the last 20 years) in which the CNES has been involved and that have been used for research in environmental fields.

Through all these missions, Earth observation has been a real support to develop research in environmental and climatic fields. Although contributing indirectly, research is indeed a fundamental step to achieve

[119] This statement has been confirmed during interviews run with stakeholders at ESA and the CNES.

objectives related to environmental issues, especially climate, but not only. In particular, environmental impacts obtained thanks to research can be explained by two mechanisms described below.

Figure 37: Chain of impacts through research



Source: authors' own elaboration

The first mechanism is represented by the orange arrow in the figure above. **Research is the very first step in space missions to achieve some day an operational stage, as Copernicus program did**. **The more reliable and complete spatial data obtained, the higher the number of operational services based on this data will be created to address environmental concerns**. The Jason mission is a good illustration of this mechanism: 30 years ago, the CNES and the NASA collaborated to develop an oceanographic research mission, namely TOPEX/Poseidon mission, that enables to measure sea topography and thus to observe sea level rise. This first mission generated a series of others (Jason 1 launched in 2001, Jason 2, Jason 3 and Jason-CS to come in the next years). As highlighted during interviews with space organizations, it is not possible to go from spatial data to operational management without a period of investment in research and development with the space industry. The first versions of the mission have been so successful that EUMETSAT collaborated to use this mission for meteorology observation. Eventually, this success encouraged ESA to implement this mission into the European Copernicus Program to support the development of numerous operational services such as meteorology, climate services and operational oceanography (coastal areas management, maritime transport, maritime pollutions, etc.). As explained before, **operational services will support various actors to optimize their actions, which *in fine* allows for positive diffuse environmental impacts**.

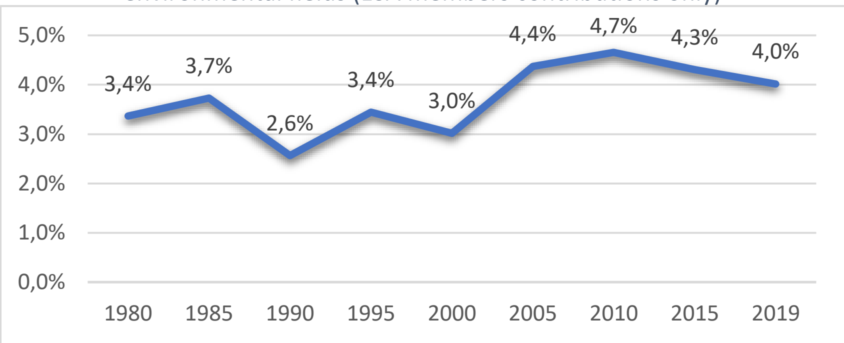
The second mechanism is represented by blue arrows in the figure above. The rationale is the following: the increasing number and reliability of spatial data has been determinant to improve research in climatology and other environmental fields. The importance of this mechanism relies on the fact that **research enables to improve our knowledge of climate and climate change, which is crucial to undertake optimal policies at optimal timing**. In particular, the last years have shown an increasing interest of populations and political actors regarding issues related to climate change. This increasing awareness has been made possible by increasing information and understanding of climate change, mostly obtained through research progresses. Such progresses have been more and more mediatized through reports published by the Intergovernmental Panel on Climate Change (IPCC). Those reports aim at providing policymakers with regular states of the art of scientific knowledge on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options. **Raising the awareness and understanding of climate risks of policy makers is crucial to undertake optimal actions in order to address climate change and to adapt to it.**

To illustrate this latter point, we intend to estimate the number of scientific publications in environmental fields that may have used Earth observations. In particular, we focus on research laboratories located in ESA's member states to reduce the scope to Earth observation from Europe. We use The Lens software[120], to carry

[120] The Lens is an aggregator of metadata aiming to discover, analyze, manage and share knowledge of scholarly works, patents, etc.

out this analysis and run an algorithm to identify **all the environmental-related papers**[121] **that mention in the abstract or the title at least one of the following specific space-related key words: “Earth observation”, “satellite”, or “Copernicus”.** Since 2000, we identify 146,132 papers worldwide responding to such criteria, of which **24,934 papers** with at least one author working in a laboratory located in an ESA member state. This represents on average 4.2% of all environmental-related papers for 20 years. The graph below describes the evolution of this share over the years.

Figure 38: Share of EO-based papers in environmental fields vs. all papers in environmental fields (ESA members contributions only)

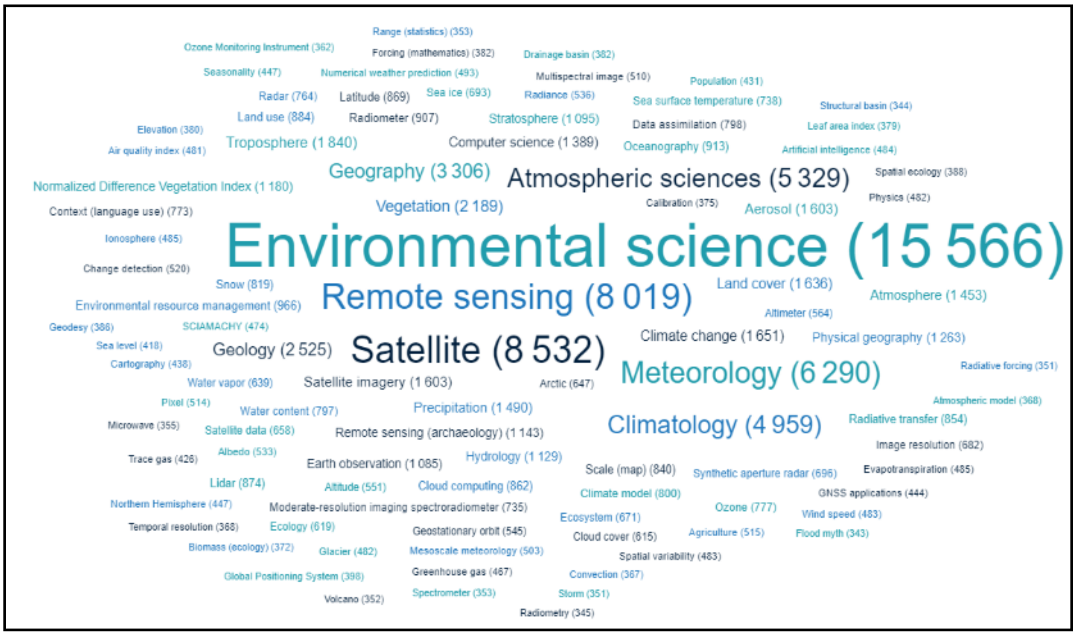


Source: estimation from the software The Lens

We observe that the share of environmental-related papers possibly using Earth observations (EO) compared to environmental-related papers, and to which ESA members have contributed, has been increasing for 2 decades, which points to the increasing use of Earth observation in research dealing with environmental topics.

Going further into the analysis, we observe on the figure at the right that the 24,934 publications identified covered a wide range of environmental topics such as meteorology, climatology, climate change, but also ecology, atmospheric science, vegetation, etc. **This illustrates the potential of Earth observation to support research in various environmental fields and not only for climate change**.

Figure 39: Fields covered by EO-based publications



Source: analysis carried out from the software The Lens

To conclude the analysis, the box below briefly presents two examples of scientific papers that used Earth observations to study climate and its evolution (among the most cited of the 24,934 identified publications).

[121] The Lens indicates fields of study covered in each paper. A paper can cover several fields. Here, papers with at least one field related somehow to the environment is considered, among the following list: Environmental science, Meteorology, Environmental resource management, Land cover, Vegetation, Land use, Cloud computing, Climate change, Normalized Difference Vegetation Index, Sustainable development, Environmental planning, Change detection, Hydrology, Climatology, Physical geography, Agriculture, Atmospheric sciences, Earth system science, Environmental monitoring.

Examples of scientific papers using Earth observation

"Recent decline in the global land evapotranspiration trend due to limited moisture supply". Jung et al. (2010)

- Cited at least 1424 times in scholar works
- Estimated evolution of annual global terrestrial evapotranspiration between 1982 and 1997
- Used earth observations among other things to estimate an average increase of 7.1mm in evapotranspiration per decade
- Increased evapotranspiration = one of the global warming indicators

→Useful to improve our knowledge of climate change

"Response of ocean ecosystems to climate warming". Sarmiento et al. (2004)

- Cited at least 757 times in scholar works
- Cited at least once in an IPCC report
- Determined biological response of oceans to global warming between Industrial Revolution and 2050: → predictions of chlorophyll in different regions depending on climate scenarios
- Used satellite data (based on colour variations) coupled with climate observations to develop empirical model
- Decreased chlorophyll = less absorption of CO2 by oceans
- Response to global warming depends on the region of the globe

→ Useful to better understand physical mechanisms and consequences of global warming

B. Meteorological organizations as actors for climate research and users of Earth observations

The climate research work carried out by Météo-France at the "Centre national de recherches météorologiques" (CNRM) results in particular in the production of climate projections for several decades or even centuries ahead. **These projections can benefit all sectors by informing climate change adaptation or mitigation strategies.** They can, for example, shed light on issues related to biodiversity and ecosystem services in the future, be used to design land-use planning policies, or even tourism development policies, etc.

Research at Météo-France also aims at improving our understanding of climate variables and their evolution to enhance the quality of weather forecasting models. In other words, all the impacts we highlighted along this report, that come from good quality levels of weather forecasts, also rely on research and development of the meteorological field that is at the top of the chain of added value.

Among the above-mentioned various fields using Earth observations to make research progresses, **meteorology is one of the most common users as meteorological organizations highly need observations of the atmosphere, lands and oceans for climate and weather forecasting research**.

Climate research carried out at Météo-France is determinant for policy makers to undertake the appropriate measures to mitigate or adapt to climate change. The chain of impact – from Earth observations provided by EUMETSAT through climate research at Météo-France to the action for the environment – is the one described in the previous section "Research using Earth observation" (blue arrows in the figure). **The CNRM contributes to important progresses on climate and climate change**, atmospheric physics, processes in the atmosphere, in the ocean, on continental surfaces, on the carbon cycle, etc., thus advancing science and feeding the expertise of the IPCC. In addition, some researchers at Météo-France are involved in writing the IPCC report. EUMETSAT and ESA[122] are also important contributors to IPCC reports as **around half of the 57 essential climate variables (ECVs), describing the Earth system and used to feed those reports, depend on spatial observations**. As an illustration, the last IPCC report (AR6) published in 2021 used 283 data products of which

[122] The Copernicus program is the main provider covering a large variety of data over the whole globe.

126 were collected with the contribution of space observation (45%). EUMETSAT contributed to the collection of 45 observations products, i.e. 36% of the 126 non-in situ datasets[123].

Information on climate change brought by research (including at Météo-France) and more and more mediatized through IPCC reports is determinant to accelerate political strategies in the right direction to mitigate climate change as soon as possible. Considering the irreversible and cumulative character of some effects of climate change, the sooner actions are taken, the less costly it will be in the future, when mitigation might be too late, and adaptation to the new climate becomes necessary. This reasoning is the basis of the Hope's model[124]. According to this economist, information on climate change, and particularly regarding global warming, is key to avoid heavy costs in the future. The model studies the transient climate response (TCR) to CO2 emissions, which describes the rise in global mean temperature that would be caused at the end of 70 years by a 1% per year increase in the concentration of CO2 in the atmosphere. It estimates that a better information on TCR received in time for 2020 is worth 9.29 trillion euros (in €2021[125]) in terms of the sum of abatement and adaptation costs avoided worldwide (in net present value over 70 years). A better TCR information received in time for 2030 is worth 8.76 trillion euros (in €2021[126]) "only" because the society waited too long beforehand (due to a lack of reliable information on TCR). In such a situation, the society would not be able to avoid some of the consequences of climate change and would incur adaptation costs that would not have been necessary if the society had had the information in 2020. In other words, **the average incremental value of receiving better TCR information in time to reoptimize emissions in 2020 rather than in 2030 is of the order of 530 billion euros**. This model illustrates the importance of refining our knowledge and predictions of climate change to set the right measures as soon as possible. Thus, **climate research, supported by Earth observation, has a key role to play in improving this knowledge to mitigate emissions today to avoid massive adaptation costs in the future**.

6. Direct impacts from organisations

Activities of Météo-France, the ECMWF, EUMETSAT, the CNES and the ESA are service activities. Hence, they do not directly impact ecosystems. However, such activities require consequent levels of energy consumption, particularly to run supercomputers and infrastructures (buildings, data centres, etc.), which contribute to GHG emissions and eventually climate change.

As we compare to a counterfactual scenario, impacts are not usually expressed in absolute terms. However, we assume the absence of Météo-France and the CNES without public subsidies given by the French government. Thus, we estimate the impacts of those two activities in absolute terms. Regarding the ECMWF, EUMETSAT and the ESA, the extent to which their energy consumption would be reduced in the scenario where their level of services is deteriorated is very uncertain. Hence, we decide to leave those organisations apart from the analysis here.

To our knowledge, GHG emissions of Météo-France are not publicly published, but the institution accepted to share with us the carbon footprint of the establishment over the year 2020, providing some information on that matter for 2019 as well. 2020 was a very atypical year considering the COVID-19 crisis. We thus present the impact for 2019, supposedly more representative of the usual emissions of Météo-France's activities. As any activity, Météo-France contributes to emissions through so-called scope 3 (indirect) emissions: home-work journeys of its employees, professional journeys, energy consumption of teleworking employees…

[123] Source: interview with EUMETSAT
[124] Hope C. (2015). "The $10 trillion value of better information about the transient climate response."
[125] $10.26 trillion in $2005 converted in euros (conversion rate of January 1st, 2005) and adjusted to inflation until 2021
[126] $9.67 trillion in $2005 converted in euros (conversion rate of January 1st, 2005) and adjusted to inflation until 2021

However, such impacts are not very relevant as they would happen even in the absence of Météo-France because employees would work somewhere else and would consume energy in the same way. Emissions directly related to meteorological activities (so-called scope 1 and scope 2 emissions) are more interesting for this study. Those come particularly from energy consumption of the infrastructures, as well as from radars and supercomputers used to produce weather and climate forecasts. Note that we could not estimate emissions of the whole life-cycle of supercomputers (particularly manufacturing of those that contributes to important emissions).

In 2019, Météo-France consumed around 24.36 GWh to power its buildings and its in-situ infrastructures (e.g. radars) and almost 20 GWh only for its supercomputers. Thereby, **the institution emitted around 6,600 tons of CO2-eq over 2019 (including 1,180 tons of CO2-eq for its supercomputers) that could have been avoided in the absence of the Météo-France**. Trends show that energy consumption for buildings at Météo-France has been decreasing (at least since 2018) and it follows this path as the objective of the institution is to reduce its consumption of final energy by 40% in 2030 compared to its 2019 consumption level. Regarding energy for computing, the implementation of new supercomputers always more powerful leads to increased levels of electricity consumption and thus of emissions (almost 2,000 tons of CO2-eq in 2020). However, **although computers and radars account for the majority of Météo France's energy consumption, they are responsible for one third of GHG emissions only**, because they are mainly powered by electricity and implemented in mainland France (lower carbon intensity of electricity compared to French oversea territories, with a large part produced from nuclear and hydraulic energies).

Although the activity of weather forecasting is not carbon neutral, we can reasonably argue that such an externality is more than compensated by all the environmental benefits this activity enables to bring. Quantitative analyses provided in this report show that **at least 3,348 kilotons of CO2-eq per year (i.e. 3,348,000 tons) are avoided thanks to weather forecasting activities of Météo-France** (aggregation of lower bounds of impact estimates in agricultural farming, forest fires, energy market and maritime transport). Moreover, weather forecasting allows other environmental benefits that could not be quantified, as well as considerable economic and social benefits that fall outside the scope of this study.

Regarding the CNES, the 2020 regulatory report on GHG emissions shows that CNES' **direct** emissions in 2019 amounted to 10,818 tons of CO2-eq[127]. Those are mainly due to emissions related to gas consumption in the Spatial Centre of Toulouse and represented almost 17% of the **total** emissions of the CNES' GHG emissions. Indirect emissions related to the energy generated by CNES' activities (electricity/heat/cold productions, transport and distribution) amount to 30,066 tons of CO2-eq. Those are mainly due to emissions related to electricity consumption in CNES' buildings and fugitive methane emissions during electricity generation in Guyana, and represented 47.5% of total emissions of the CNES. The 35.5% remaining emissions came from employees' home-work journeys and professional journeys that would have been emitted in the absence of the CNES as employees would have worked somewhere else. Nonetheless, **we cannot assess precisely emissions induced by Earth observation activities**. Fugitive methane emissions during electricity generation in Guyana were necessary for launch-related activities that are necessary to send Earth observation satellites but did not directly come from Earth observation activities. The same applies to electricity use in buildings located in mainland France. We cannot assess the share of electricity consumption that was dedicated to Earth observation. However, **as for weather forecasting activities, Earth observation activities generate numerous positive environmental impacts as well as economic and social benefits that are likely to largely compensate the emissions generated by such activities**. Moreover, the total emissions of the CNES' activities have been decreasing since 2011 with a 13% decrease in direct GHG emissions between 2011 and 2019 and a 67% decrease in indirect (scope 2) GHG emissions associated to energy.

[127] See https://cnes.fr/sites/default/files/drupal/202009/default/is_cnes_rapport_reglementaire_beges_2019_vdef.pdf

Earth observation, and CNES' activities as a whole, imply sending satellites into space, which contributes to space pollution. Space pollution is becoming an important worldwide issue as there are currently 30,000 objects of 10cm or more in size, including 1,400 active satellites, 750,000 objects of 1cm or more and 135 million objects of 1mm or more[128]. This includes deactivated satellites, upper stages, bonnets, straps, etc., which represent half of the known orbital debris. The other half is composed of fragments of all sizes due to the explosion of launchers or satellites. Those objects are mainly in low orbits (from 700 to 1,000km altitude) very used for Earth observation and meteorology and in the geostationary orbit (36,000km altitude) useful for telecommunications, meteorology and defence. Space pollution can cause two major problems:

- **In case of collision in orbit, even a very small piece of debris can cause great damage**. According to CNES, an object 1 cm in diameter will have in space the same energy as a saloon car travelling at 130km/h. Hence, any debris can be dangerous for functional satellites and astronauts. In 2015, the international space station manoeuvred five times to avoid collisions with space debris.
- **The debris eventually falls back to Earth**. Although most of it vaporises on re-entry, 10 to 20% reach the Earth's surface. In most cases, the impacts take place in submerged areas of the Earth, which has only 3% of its surface inhabited, but still represent potential threats to populations and the environment.

The CNES only partly contributes to space pollution and even more scarcely if we only consider Earth observation satellites. **However, it is actively involved in looking for and offering solutions to address this challenge.** For instance, it developed tools to predict collisions in orbit, operates the CAESAR service to operationally manage collision risks in orbit on the satellites it monitors, follows atmospheric re-entries at risk and provides the authorities with predictions of debris re-entry trajectories.

[128] Source: https://cnes.fr/fr/dossier-debris-spatiaux-ou-en-est

Analysis of meteorological and Earth observation activities regarding the European Taxonomy

The European Commission launched its Action Plan on Financing Sustainable Growth in March 2018, following recommendations from the High-Level Expert Group on Sustainable Finance. The Action Plan's stated objectives are to (i) reorient capital flows towards sustainable investment, (ii) manage the financial risks arising from climate change, environmental degradation and social issues, and (iii) foster transparency and long-termism in financial and economic activity[129]. In order to put in place a legislative framework around this action plan, the Commission published a proposal for a regulation, among others, establishing a framework to promote sustainable investments, known as the "EU Taxonomy". After two years of political negotiations and consultation, including the publication of recommendations by a European Commission's Technical Expert Group (TEG) on Sustainable Finance, the European institutions reached a political agreement in late 2019, and the Taxonomy Regulation was adopted in June 2020[130].

The European Taxonomy aims to determine whether an economic activity can be considered as "environmentally sustainable" through the lens of six environmental objectives: (a) climate change mitigation; (b) climate change adaptation; (c) the sustainable use and protection of water and marine resources; (d) the transition to a circular economy; (e) pollution prevention and control; (f) the protection and restoration of biodiversity and ecosystems. An economic activity will be considered compliant with the Taxonomy if it meets four criteria: i) it contributes substantially to at least one of the environmental objectives (ii) it does not cause significant harm to any of the other objectives (or "DNSH" principle), (iii) it is carried out in compliance with minimum social safeguards and (iv) it complies with the technical screening criteria set in the first two criteria (namely, substantial contribution and DNSH criteria). In this context, the Commission has mandated the TEG to develop principles and indicators for each activity to be assessed, linked to these criteria.

Once implemented, the Taxonomy will require financial and non-financial actors to disclose their "green" share in their investments, asset portfolios (for financial market participants); revenues, operating expenses, and capital expenditures (non-financial corporations), on the basis of quantitative and/or qualitative criteria defined in the European Taxonomy. Criteria are defined through official Delegated Acts. The European Commission adopted in April 2021 the first Delegated Act for the two climate objectives[131] – climate change mitigation and climate change adaptation – officially entered into force in December 2021 and is in application from 1st January 2022. Another Delegated Act on the 4 remaining objectives is expected to be published by mid-2022 for entry into application in January 2023.

The objectives of the Green OAT, whose achievement is assessed in this study, are climate change mitigation, climate change adaptation, biodiversity protection and pollution control. These objectives cover partly the EU Taxonomy objectives. **We present in this section the extent to which meteorological and Earth observation activities comply with the EU Taxonomy**, as regards the two first environmental objectives for which the Delegated Act has been published: climate change mitigation and adaptation. Compliance of an activity with the Taxonomy requires firstly that it is eligible, i.e. that the activity is referenced in the Taxonomy, and secondly that it is aligned, i.e. that it meets the criteria defined within the Taxonomy.

As there is no weather- and Earth observation-related sector or activity in the EU Taxonomy "climate" Delegated Act, one needed to identify close-related Taxonomy's activities for which eligibility criteria could be fulfilled by those organizations. Hence, the objective was to determine the extent to which it is possible to

[129] Source: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0097&from=EN
[130] Source : https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=FR
[131] Source: https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=CELEX:32021R2139

demonstrate eligibility and alignment of weather forecasting and Earth observation activities with the European Taxonomy given the absence of specific dedicated sectors in the European regulation.

The absence of these sectors makes it difficult to identify the correlation between the economic activities of the EU Taxonomy and the activities of the studied organizations (i.e. Météo-France, ECMWF, EUMETSAT, CNES and ESA), as it is not possible to refer to the NACE codes of the organizations[132]. The identification of such a correlation is therefore based on the description of the economic activities of the Taxonomy. One should note that, apart from the reporting of the green OAT, the absence of these sectors in the Taxonomy is not a problem for the organizations studied, as they are not obliged to report their alignment with the Taxonomy.

A. Meteorological activities

Météo-France's and the ECMWF's activities are quite similar as they consist in producing weather and climate forecasts and conducting research to improve the quality of those forecasts. EUMETSAT's activities are a little different as they operate satellites and provide observational data. However, such data are an upstream step in the production chain of a weather or climate forecast, and thus, have contributions for climate change mitigation and adaptation through activities carried out by Météo-France, the ECMWF and other European national meteorological services.

Weather and climate forecasting can be separated into five distinct tasks:

Table 5: Classification of weather and climate forecasting activities

Observation	All the spatial (EUMETSAT) and ground (Météo-France, ECMWF) segment for meteorological observation (satellites, stations, buoys, radiosondes, sensors…) aimed at collecting and providing data for the next steps of the chain
Modelling and computing for weather forecasts	From observations, meteorologists carry out modelling/simulations of atmosphere evolution at a given period for coming days and hours, using models implemented in supercomputers that make the computations (Météo-France and ECMWF)
Human expertise of forecasts	Experts use software to analyze models' outputs and to construct maps and bulletins transforming simulated scenarios into concrete information for users. They ensure a direct contact with certain users (Météo-France and ECMWF)
Climate expertise and services	Météo-France and ECMWF use numerical models with multiples variables representing the whole planet (atmosphere, ocean, ice…) and run simulations and re-analyses with supercomputers and climatic data (making exploitable by EUMETSAT) to construct climate scenarios. Those scenarios can be provided to various sectors for operational services
Research	Météo-France and ECMWF conduct research projects to improve our understanding of the planet and to improve weather forecasting quality. Météo-France research also focus on climate change predictions.

Source: authors' own elaboration

i. Climate change mitigation

Regarding climate change mitigation, we first analyzed the "Information and communication" sector and the activity "data-driven solutions for GHG emissions reductions" [133]. Météo-France, the ECMWF and EUMETSAT

[132] Météo-France's NACE code is O84.1.3 (Public administration and defense; compulsory social security), Eumetsat' and CNES' code is M72 (Scientific research and development), ESA's code is U99 (Activities of extraterritorial organizations and bodies). Those NACE codes do not appear in the Taxonomy as such types of institutions and their activities are not concerned by the reporting obligation.

[133] Activity 8.2 in the Taxonomy Delegated Act for mitigation, that could be associated with NACE code J63.11

use ICT solutions such as networks of spatial and ground measurement stations and other equipment for observations, as well as supercomputers for modelling. Weather forecasts can contribute to GHG emission reductions in the sense that they provide helpful support tools for actors such as renewable energy producers, which promotes green energy in the market and enables to reduce emissions (as seen before in Development of solar and wind energies). However, as the Taxonomy defines the activity, the *"development or use of ICT solutions… must be* ***predominantly*** *aimed at the provision of data and analytics enabling GHG emission reductions"*, which is not the case of weather forecasting activities. Hence, we cannot assess that those organizations are eligible to the requirements of this activity regarding climate change mitigation.

The same rationale applies to the sector "professional, scientific and technical activities" for the activity "close to market research, development and innovation"[134]. Research at Météo-France and the ECMWF aims at improving the quality of weather forecasting, which *in fine* will result in better support to various sectors, including renewable energy production, and hence will encourage the green transition toward decarbonate energy sources. However, research activities in these two organizations are not specifically dedicated to enabling GHG emission reductions but to improving forecasting and our understanding of climate and the atmosphere. Thereby, we cannot assess the eligibility to the Taxonomy for this activity either.

As weather forecasting activities require the use of supercomputers to store, manipulate and process data, Météo-France and ECMWF's activities can be eligible to the activity "data processing, hosting and related activities"[135] of the sector "Information and communication". Alignment criteria could also be met, provided that sufficient information is collected to prove it.

ii. Climate change adaptation

Regarding climate change adaptation, the activity "engineering activities and related technical consultancy dedicated to adaptation to climate change"[136] from the sector "professional, scientific and technical activities" appeared relevant to meteorological activities. Weather forecasting is not dedicated to adaptation to climate change as it only enables to provide short-range and seasonal-range forecasts. Research activities are not operational and cannot be considered as technical consultancy activities. However, Météo-France provides climate expertise services (by making long-run simulations with the ECMWF and using data provided by EUMETSAT) in operational environments such as to support the definition of policies for adapting territories and preserving biodiversity in the context of climate change. Météo-France designs, produces, and regularly disseminates regionalized climate scenarios to respond to requests from the government and local authorities. We can thus easily state that climate services provided by Météo-France (which does not include climate research) are eligible as they are dedicated to adaptation of numerous sectors to climate change.

- *Substantial contribution*

When looking at substantial contribution criteria for climate services of Météo-France, we conclude that **if some of them appear to be fulfilled, some criteria cannot be assessed as they require unavailable information** (see example in the next paragraph below). **Although we cannot conclude if this activity meets the requirements of the Taxonomy, we describe criteria that are met and difficulties, to show the extent to which Météo-France (together with ECMWF and EUMETSAT services) could be aligned with the EU Taxonomy criteria**.

[134] Activity 9.1 in the Taxonomy Delegated Act for mitigation, that could be associated with NACE codes M71.1.2 and M72.1
[135] Activity 8.1 in the Taxonomy Delegated Act for mitigation, that could be associated with NACE code J63.11
[136] Activity 9.1 in the Taxonomy Delegated Act for adaptation, that could be associated with NACE code 71.12

The first criterion[137] requiring the activity to support other economic activities for adaptation is fulfilled by climate services of Météo-France. Indeed, such services enable to help other economic activities of the Taxonomy to meet their respective criteria for adaptation (in particular to implement physical and non-physical solutions that substantially reduce the most important physical climate risks that are material to that activity). For instance, Météo-France has already brought climate services that could help urban construction activities such as carrying out evaluations of the consequences of urbanization policies on temperatures in cities with a modelling platform to guide choices in terms of greening roofs, widening streets, or reintroducing biodiversity (see section Heat waves and urban heat islands). As required by the Taxonomy, Météo-France uses most recent modelling techniques to assess climate change risks (ex: they provide the evolution of forest fire risk to the Civil Security), to model the past evolution of climate and to predict future scenarios. Moreover, it develops climate models and projections with the most recent IPCC reports and scientific peer-reviewed publications. More than this, Météo-France contributes to feed scientific research and publications and contributes actively to IPCC's reports. We can also state that the economic activity removes information capacity barriers to adaptation through those climate services, of which some of them are dedicated to operational actions – e.g., portals and web application created or for which Météo-France contributes such as "Climat HD" or "DRIAS, les futurs du climat" that present maps of numerous climate indicators, as well as climate services co-built with actors from different sectors to help them as described above for construction. Those services are now more accessible thanks to the "Centre of resources for climate change adaptation" to which Météo-France contributes, and mentioned in the previous section Heat waves and urban heat islands. However, we do not have sufficiently information to provide a map of the potential to reduce material impacts due to climate risks in other economic activities through a robust climate risk assessment in those other economic activities. Neither can we state if adaptation solutions implemented thanks to Météo-France's services in some economic activities may have adverse impacts on adaptation efforts of other economic activities as Météo-France provides numerous services for numerous actors from various sectors.

- *Do not significantly harm principle*

Regarding DNSH criteria, climate services are not undertaken for the purpose of fossil fuel extraction or fossil fuel transport. The criteria to sustainable use and protection of water and marine resources are not relevant to activities of Météo-France as they are not material and thus, have no impacts on water bodies. To justify this, we argue that Météo-France's activity, in a more general context, is not considered as causing significant harm to the sustainable use and protection of aquatic and marine resources in the sense of the article 17 of the Taxonomy Regulation[138] (see Annex F). Indeed, this activity is not detrimental to the good ecological status or potential of water bodies, including surface waters and groundwaters or the good ecological status of marine waters. As regard the other environmental objectives, the Taxonomy does not require any criteria to be aligned to the DNSH principle.

- *Minimum social safeguards*

Finally, we do not have enough information to check social safeguards. However, activity reports of Météo-France show that the institution is committed to develop strategies in favor of social responsibilities such as gender equality. For instance, Claire Doubremelle, Deputy Director of Research, has been appointed as the institution's gender equality officer for 2019, and, with a working group, developed a 2020 action plan for gender equality at Météo-France[139]. Moreover, as Météo-France is located in France and is an institution of

[137] "The economic activity is predominantly aimed at the provision of consultancy that helps one or more economic activities for which the technical screening criteria have been set out in this Annex to meet those respective criteria for substantial contribution to climate change adaptation, while respecting the relevant criteria for doing no significant harm to other environmental objectives."
[138] See https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=FR
[139] See 2019 activity report of Météo-France: http://bibliotheque.meteo.fr/exl-php/util/documents/accede_document.php?1631799307150

the State, we assume that the organization follows French regulations of the labor market and comply with Human Rights.

We conclude that we cannot assess the alignment with the EU Taxonomy because of lack of information. However, the analysis presented here suggests that climate services of Météo-France, supported by the ECMWF (for re-analyses) and EUMETSAT (for data provision) is eligible and may be aligned with the EU Taxonomy for the adaptation to climate change objective.

We then analyzed the activity "close to market research, development and innovation"[140] of the same sector. Météo-France develops research in forecasting (with ECMWF up to one year ahead) and climate fields, supported by observational products of EUMETSAT. Météo-France is a major contributor to the work of the IPCC, in close collaboration with its partners in the French scientific community (Cerfacs, IPSL, etc.) and internationally. All this work is of considerable importance to better understand climate change and to adapt to it. Hence, Météo-France produces products (publications) that help eventually for climate change adaptation. Some substantial contribution criteria defined in the Taxonomy for this activity seem relevant, such as the fact that the economic activity removes information capacity barriers to adaptation thanks to a better knowledge of climate change that is crucial to find a solution and raise awareness about the necessity to adapt to a changing climate. For instance, the construction sector is starting to consider global warming and is trying to develop more resilient building that could substantially reduce the most important physical climate risks that are material to that activity (heat stress, heat wave, storm, water stress, precipitation variability…). However, research at Météo-France does not comply with the fourth criterion defined in the Taxonomy, that requires the researched product (so climate change knowledge) to be used in an operational environment corresponding to at least Technology Readiness Level TRL 7. Météo-France's research in the understanding of climate and Earth is fundamental research that is not directly operated in operational environments but is crucial knowledge to guide public and private actors in their decisions.

Hence, we cannot conclude on an alignment of Météo-France's research and EUMETSAT's contribution to the EU Taxonomy.

iii. Conclusions and recommendations

We conclude from this analysis that **the European Taxonomy does not cover meteorological activities that have quite indirect impacts on mitigation and adaptation as seen throughout this report. Nevertheless, climate services provided by Météo-France, with the support of the ECMWF and EUMETSAT upstream, that are more operational could be aligned with the Taxonomy, provided that sufficient information is collected to prove it**.

Our suggestions for complementing and thus improving the EU Taxonomy for meteorological activities are the following:

- The EU Taxonomy covers economic sectors that contribute the most to GHG emissions within the European Union, so that environmental-friendly projects enabling to reduce those emissions are valued. Sectors that do not necessarily emit the most but still help other sectors to decrease their environmental impacts such as the meteorological sector have already been taken into account in the Taxonomy with enabling activities, but **such activities and their criteria would deserve to be better specified and less general**. To do so, the general presented sectors such as information and telecommunication could be separated into more specific activities than it currently is. In the TEG report of 2019 for instance, an example of a specific activity of information and telecommunication, related to provision of specialized

[140] Activity 9.2 in the Taxonomy Delegated Act for adaptation, that could be associated with NACE code M72

telecommunications applications for weather monitoring and forecast was presented for adaptation to climate change. However, when looking at the Delegated Act, this activity is not presented anymore, and the more general activity considered does not match to weather forecasting activities.

- **Definition of eligibility and alignment criteria should be more open to "enabling" activities that may indirectly bring significant contributions to the environment without being dedicated to doing so**. For instance, meteorological activities are not eligible to the Taxonomy regarding the climate change mitigation objective, as they are not specifically dedicated to GHG emission reductions, though enabling renewable energies to be viable, which has important impacts on energy-related emissions.
- Although research is included in the EU Taxonomy, the substantial criteria related to this activity **exclude fundamental research**. This lack of compliance is regrettable for the meteorological activity, largely based on the continuous improvement of climate knowledge, which, even at the research stage, is of essential use in public policy decisions for adaptation to climate change (e.g. IPCC reports used for COPs).

B. Earth observation activities

ESA and the CNES have similar activities but at different scales. ESA implements and coordinates space programs of its European member states while the CNES represents France at ESA council to participate into space program decisions and coordinates missions developed by France and its space industry. The CNES can be directly involved in some missions demanding a high level of technology. It also promotes the needs of its scientific community and helps it to exploit Earth observation data. EUMETSAT operates satellites for meteorology to provide Earth observations from space of the atmosphere and oceans to meteorological national and European services. EUMETSAT is thus already considered in the analysis of weather forecasting activities above as the highest step of the chain to produce such forecasts.

Activities carried out by the CNES and ESA are not represented in sectors included in the European Taxonomy. However, we investigate in this section the extent to which such activities could be eligible and aligned to activities covered in the European Taxonomy, and in particular enabling activities for other sectors. Activities of the Taxonomy analyzed for weather forecasting are also considered here as they seemed to be the most relevant. **Although the production and the dissemination of Earth observations are activities that can support various sectors, we will see that their contributions to such sectors appear to be much too indirect to consider those activities as eligible to the European Taxonomy**.

i. Climate change mitigation

Regarding climate change mitigation, conclusions are similar to the analysis of weather forecasting activities. The analysis of the "Information and communication" sector and the activity "data-driven solutions for GHG emissions reductions" seemed relevant as Earth observation activities require the use of ITC solutions such as satellites and ground stations. However, such solutions are not specifically dedicated to the reduction of GHG emissions as required by the Taxonomy (see analysis of Meteorological activities). More than that, data generated by those observations does not directly help other sectors to reduce their GHG emissions but partly contributes to the development of operational services that can be used to reduce GHG emissions in various sectors (e.g. services to optimize the location of renewable energy plants implementation). Hence, Earth observation activities are not eligible to this economic activity of the EU Taxonomy.

The sector "professional, scientific and technical activities" for the activity "close to market research, development and innovation" could also have matched to activities of ESA and the CNES that promote numerous research projects. However, the research conducted by the CNES and ESA aims to develop technological solutions to improve Earth observation and thus generate data that will help the scientific community or to create operational services. In other words, the research of these organizations, even if exploited at the operational level (launch of satellites and operation), does not directly allow other sectors to reduce their CO2 emissions.

Thereby, **we cannot assess the eligibility of ESA's and the CNES's activities to the European Taxonomy regarding climate change mitigation**.

ii. Climate change adaptation

Regarding climate change adaptation, the rationale is similar as for climate change mitigation. Contributions of Earth observations generated by activities of ESA and the CNES are too indirect to be eligible to the Taxonomy. As explained before, ESA and the CNES have the vocation to develop programs that will generate data and this data will contribute to the development of operational services, but ESA and the CNES are not the ones producing such services[141]. This is important because even if eligibility criteria of the Taxonomy allow for enabling activities supporting other sectors in the achievement of adaptation to climate change, activities of Earth observation are only contributor to the development of enabling activities. Organizations using spatial data to create their operational services to help other sectors could be eligible to the European Taxonomy. However, the support of ESA and the CNES can be essential to the development of such operational services. For instance, the CNES proposes the "Connect by CNES" platform, and more specifically the Lab'OT, which is designed to support start-ups and other actors wishing to offer services based on Earth observation data. The CNES thus facilitates their access to data and technologies that are essential for their services.

Regarding research activities, the same argument provided for climate change mitigation applies: research conducted by the CNES and ESA aims to develop technological solutions to improve Earth observation and thus generate data that will help the scientific community or to create operational services. In other words, the research of these organizations, even if exploited at the operational level (launch of satellites and operation), does not directly allow other sectors to adapt their activities to climate change.

Hence, **we cannot assess the eligibility and thus the compliance of activities carried out by these two organizations with the European Taxonomy regarding climate change adaptation**.

iii. Conclusions and recommendations

We conclude from this analysis that **the European Taxonomy does not cover space activities that have very indirect impacts on mitigation and adaptation** as seen throughout this report, even more indirect than weather forecasting activities. However, we argue that **spatial data is necessary to develop some operational services** that will support some sectors in reducing their GHG emissions and/or to adapt their activities to climate change, and thus to comply with criteria of the Taxonomy defined for their own sectors.

Although the contribution of Earth observation is too high in the chain of value, it does not make this activity less essential, and we recommend, as we stated in the analysis of weather forecasting activities, that **definitions of eligibility and alignment criteria should be more open to activities that may indirectly bring significant contributions to the environment without being dedicated to doing so.**

[141] Such services are developed by the EU (Copernicus services), private companies, the ECMWF, etc.

General conclusion

This report intended to assess ex-post environmental impacts of weather forecasting and Earth observation activities funded by Green OAT-eligible French public expenditures. In particular, those expenditures fund five organizations – part of Météo-France's and CNES's budgets and French contributions to the international organizations ECMWF, EUMETSAT and ESA – whose activities were specifically studied in this evaluation as regard the four Green OAT objectives pursued by France: climate change mitigation, climate change adaptation, biodiversity protection and pollution reduction. In the counterfactual scenario characterized by the absence of those public expenditures, it is clear that national organizations, namely Météo-France and the CNES, would not have the resources to properly run their activities. At the level of European organizations (ECMWF, EUMETSAT and ESA), interviews showed that the financial, technological and scientific involvement of France has been determinant in the development of Earth observation in Europe, letting us to assume important delay in this development in the counterfactual scenario. Analyses carried out to identify impacted sectors and to provide quantitative and/or qualitative assessments were based on the academic literature, case studies, interviews with sectorial experts and with the concerned organizations, and models developed using reliable data and explicit assumptions. Quantitative results must be taken with caution as they rely on uncertain assumptions. However, they provide scales of magnitude of environmental impacts that can be attributed to the concerned organizations. Moreover, one should note that those values are likely to be lower values as the assumptions they rely on are conservative.

Weather and climate forecasts are crucial in numerous sectors of the economy and are precious informative tools to prevent and decrease negative environmental impacts arising from human activities and natural events. Earth observation is an important contributor to weather and climate forecast production (as the first step of the production chain), providing essential data for numerical weather prediction models. However, the spectrum of Earth observation is actually much greater. In Europe, the development of numerous missions and, recently, of the Copernicus program have made it possible to make available a multitude of quality data freely accessible to all. These data constitute an incredible resource for environmental research, but also allows (together with other data sources, algorithms, AI, etc.) the development of operational services in many sectors which make it possible to limit or even reduce negative environmental impacts.

It was seen that meteorological activities require important levels of energy consumption leading to GHG emissions, particularly due to supercomputers running numerical weather prediction models, and that Earth observation poses a concern of spatial pollution with thousands of unused objects floating through space. Both activities are also the source of energy consumption explained by employee travel, heating of buildings, etc. However, Météo-France and the CNES are attempting to mitigate their impacts with more sustainable intern strategy plans and rely on technological developments in the future (for instance for less energy-consuming supercomputers). On the other hand, the evaluation showed a multitude of indirect positive impacts on the environment in a broad variety of sectors that, though not all quantified, largely exceed negative impacts arising from meteorological and Earth observation activities. Such activities play a key role in informing us about the behaviors, state and evolution of our environment – which is affected by the activities carried out in those many sectors – making stakeholders to undertake more informed, appropriate and anticipated decisions and actions to mitigate climate change, adapt to it, reduce pollution and protect biodiversity.

In particular, weather forecasting contributes to climate change mitigation through its support to optimize agricultural treatments, to enhance forest fire prevention and control, to manage solar and wind energies, and to optimize maritime routing. Earth observation shows promising results to better optimize farming treatments, to detect and map forest fires and to support authorities for more efficient wetland management and conservation, which all contribute to climate change mitigation. Regarding climate change adaptation, Météo-France provides climate projections and services to accompany various actors in making territories more resilient against global warming and increasing heat waves, while Earth observation has proved to be valuable for monitoring coastal erosion and sea level rise. Weather forecasts and Earth observation also contribute to the protection of biodiversity and pollution reduction, particularly through optimizing farming treatments and management of forest fires that are important threats to the fauna and flora. Such activities are also crucial to limit consequences of atmospheric pollution episodes and maritime pollution (oil spills). Finally, an important added value of such activities lies in their contributions to the research community to enhance the scientific knowledge on environmental fields, especially on climate change, which is an essential tool to political actors to implement relevant measures for climate change mitigation, climate change adaptation, biodiversity protection and pollution reduction.

The variety of activities using weather forecasts and Earth observation is already considerable and growing. Therefore, it was necessary to make a selection of the impacts to be studied, which is a limitation of this evaluation. In addition, the free and open access to Copernicus data made it difficult to identify all the services that use them. Although the interviews confirmed that the main sectors were indeed considered here, this study aimed to demonstrate the importance and the diversity of environmental impacts enabled by the existence of these data, more than to establish a completely exhaustive list of all services using these data and their environmental impacts. It is thus likely that Earth observation and weather forecasting bring additional environmental benefits to the ones mentioned in the report. Moreover, this evaluation considered Sentinels missions that have already been launched only. We can easily assume that the start of the next Copernicus missions (Sentinel-4, -5 and -6) in the coming years will bring additional resources and improvements to service providers and managing authorities and that services based on data provided by current missions (Sentinel-1, -2, -3) will become more and more effective and used. It is also important to note that the scope of this evaluation is limited to environmental impacts. However, weather and climate forecasting and Earth observation bring a very large number of social and economic impacts such as protection of infrastructures and people.

To conclude, we could not assess the alignment of weather/climate forecasting and Earth observation activities with the European Taxonomy Delegated Act on climate change. Although such activities and their impacts that have been demonstrated throughout this evaluation seem to match to what the European document describes as "enabling activities" (activities enabling other activities of different sectors to adapt to climate change and implement emission mitigation measures), they do not comply with all the required criteria. The main reasons rely on the fact that weather forecasting is not specifically dedicated to addressing an environmental issue such as the reduction of emissions and that Earth observation is a very indirect activity that the European Taxonomy cannot consider as an "enabling" activity but as an activity supporting "enabling" activities (i.e. activities creating operational services based on Earth observation data). Regarding climate prediction, it appeared that climate services proposed by Météo-France constitute an activity that seems to comply with the European Taxonomy and that could meet the screening criteria, provided that sufficient information is collected to prove it.

It will be interesting to extend the analysis of meteorological and Earth observation activities with regard to the coming second EU Taxonomy Delegated Act relating to the 4 other environmental objectives: sustainable use and protection of aquatic and marine resources, transition towards a circular economy, prevention and reduction of pollution, and protection and restoration of biodiversity and ecosystems.

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Annexes

A. List of the identified impacts of meteorological and Earth observation activities

Table A1: final list of the identified positive environmental impacts of weather forecast activities

Sector	Action using forecasts leading to impact	Mechanism	Time-scale	Mitigation	Adaptation	Biodiversity	Pollution
Energy	More reliable wind and solar energies to avoid market adjustments	Weather forecasting → wind and solar energy production more predictable → less errors in energy supply prediction → decreases need to adjust the balance between supply and demand with import of energy, including import from Germany of coal-based energy → less emissions	Short- and medium-range	X			
	Incentive to invest in wind and solar energies	Weather forecasting and climate projections (to map areas with regular wind and sun in the future) → wind and solar energy production more predictable → less failure regarding supply commitment → more profitable sector → incentive to invest in those sectors → development of green energies at the expense of other polluting energies → less emissions	Short-range, medium-range and long-range	X			
	More reliable hydraulic energy	Trends of temperature to predict risk of droughts and floods (e.g. through snow accumulation) → optimisation of water storage and use → hydroelectric sector more efficient and reliable → can be used at the expense of other polluting sources of energies in the market → less emissions	Seasonal range	X			
	Optimisation of future dams' locations	Climate projections for planning optimal dams' locations → efficiency of future dams → reliability of hydraulic sector in the long run despite climate change	Long-range		X		
	Prediction of future contaminated areas in case of nuclear accident	In case of nuclear accident, weather forecast of precipitation and wind to better anticipate particles and where radioactive particles will land → enables to predict contaminated areas	Short- and medium-range			X	X
	Interruption of nuclear plants in case of heat waves	Predictions of temperature → enables to anticipate heat waves → interruption of nuclear plants if necessary → avoids urgent release of hot water in rivers → hot water can be harmful to biodiversity not adapted	Medium-range and seasonal range			X	
Transport	Optimal management of ship trajectories and optimal timing	Forecast of weather in seas (wind, storms, rain) → anticipation of ship operators who decide to stay in port or change their course → avoids detours → reduces unnecessary consumption of fuel oil → reduces emissions	Medium-range	X			
	Minimising the risk of ship accidents	Forecast of weather in seas (waves, storms, visibility) → minimises the risk of collision with other ships or the risk for a ship to overturn → avoids release of ship debris or polluting products in seas → reduces risk of pollution	Medium-range			X	X
	Prediction of trajectories in case of oil or gas spills	In case of oil or gas spill, predictions of trajectories of oil and gas in waters (spreading, evaporation, dispersion…) → helps determining optimal response strategies and clean-up methods to be used → reduces environmental impacts on biodiversity	Medium-range			X	X

Sector	Action using forecasts leading to impact	Mechanism	Time-scale	Mitigation	Adaptation	Biodiversity	Pollution
	Optimal timing and management of salting in case of snowy events	Forecast of snowy events and areas with frost → helps local authorities to decide where and when salting roads → avoids useless salt, harmful for biodiversity (rivers, flora…)	Medium-range			X	
	Minimising risk of traffic jam in case of snowy events	Forecast of snowy events → helps local authorities to warn population → people can anticipate by reducing their travels and local authorities can act to remove snow from roads → reduces the risk of traffic jam → reduces car pollution caused by people staying longer on roads with multiple stops	Medium-range	X			X
Agriculture	Optimal timing of fertilisers and phytosanitary products use	Forecast of precipitation, wind, temperatures and humidity → avoids failed phytosanitary and fertilisers treatments because of bad weather conditions → reduces amount of those products ending up in the nature and useless consumption → 3 impacts: 1) at equal efficiency, less products used so decrease in production of fertilisers and phytosanitary products which leads to important emissions when manufactured; 2) avoids pollution of air, soils and rivers; 3) avoids eutrophication phenomena harmful to biodiversity	Short-range	X		X	X
	Efficient management of cultures	Trends of temperatures and precipitations → enables to anticipate future water availability → adaptation of the choice of cultures to grow accordingly → avoids overuse of water in case of droughts because anticipated with less water-demanding crops → preservation of aquatic ecosystems	Seasonal range			X	
	Adaptation of cultures and forestry management to climate change	Better knowledge of climate change → adaptation of agriculture and forestry to climate change with research and operational pilots (e.g. development of cultures less water-demanding, afforestation with less flammable trees…) → better preparedness to face water scarcity, fires increase…	Long-range		X		
	Efficient management of fodder cut to preserve livestock well-being	Weather forecasting → better view for fodder management → enables good quality and amount of fodder for animals (domestic biodiversity)	Short-range			X	
	Anticipation of weather dangers to protect livestock	Forecasting of weather dangers (floods, wind, storms, cool waves) → gives time to farmers to anticipate and protect their livestock (domestic biodiversity)	Medium-range			X	
Urbanism and urban planning	Monitoring of air pollution to take measures	Forecast of air pollution (according to weather conditions) → authorities can take measures such as traffic restrictions, free-fare public transports… → prevents too much pollution and to reduce it	Short- and medium-range	X			X
	Better district heating management in buildings	Forecast of temperatures (including cool waves) → anticipation of district heating operators (e.g. if cool waves of only few days, they will not activate heating if too far from cold season) → avoids heating too soon → less energy consumption → less emissions	Medium-range	X			
	Buildings adapted to warmer climate	Better knowledge of global warming → new buildings adapted to warmer climate to provide better thermal comfort (form and orientation of the building, better isolation…) → more prepared to global warming and will reduce energy consumption of residents for air-conditioning	Long-range	X	X		

Sector	Action using forecasts leading to impact	Mechanism	Time-scale	Mitigation	Adaptation	Biodiversity	Pollution
	Better transport planning to mitigate global warming	Better knowledge of global warming → shows the necessity to reduce GHG emissions → development of less polluting transport modes (bicycle paths, more public transports…) → will help reducing emissions and pollution	Long-range	X			X
	Development of solutions to address heat islands	Better knowledge of global warming → authorities intend to tackle heat island issues in cities (by implementing parks, trees, lakes, green roofs…) → will help reducing energy use for cooling and emissions of air pollutants (ozone)	Long-range	X	X		
Vigilance to natural extreme events	Efficient preparedness and prevention against forest fires and prediction and mapping of risky areas to fires in the long run	Heat, precipitation, wind, humidity forecast → information to implement fire management action plans (transfers of helicopters, of fixed-wing air tankers, fire fighters, equipment) to better control new and on-going fires (with short-range forecast) and for strategic decision-making such as pre-positioning resources in most critical areas (with medium-range forecast) → limits burned hectares of forests and the consequences (emissions and biodiversity destruction) Production of maps of areas and time periods with high fire risks → adaptation measures can be undertaken (awareness-raising campaigns in those areas, better preparedness and development of resources in strategic places, better management of forests by letting space between trees or setting firewalls for example, aid and support system at the EU scale…)	Short-, medium- and long-range	X	X	X	X
	Forecast of floods to regulate dams and reduce risks	Forecasts of precipitations and hydraulic conditions → better anticipation of dams' operators to regulate the water stock → can help mitigating the incoming flood and reduce risks for dams to be submerged or destroyed → avoids catastrophic consequences on biodiversity downstream	Short- and medium-range			X	
	Flood warning to protect toxic products	Forecasts of precipitations and flood risks to give the alarm → measures and instructions are given including protecting toxic products from floods → people (domestic products) and companies can help to avoid pollution of the environment through the release of those products, harmful for biodiversity	Short- and medium-range			X	X
	Forecast of intense El Nino helps anticipating important floods in America	Prediction of the intensity of the phenomenon El Nino → anticipation in America (including Guyanne) of incoming important precipitations, potential floods and landslides → can help population to limit environmental consequences	Seasonal range			X	X
	Mapping flood risks through time to improve preparedness and prevention	Climate predictions → mapping evolution of flood risk → reflexions to anticipate those scenarios, European measures for flood management in strategic places (creation of wetlands…) → will help to adapt territories where flood risk is increasing through time with climate change	Long-run		X		
	Better knowledge of sea level rising to take long-run measures	Climate predictions → predictions of sea-level rising → mapping of areas where water will submerge lands and where typhoons will lead to more floods → helps take protective measures (dikes, coastal forests, evacuation of people through time…)	Long-run		X		
	Forecasting of drought's duration for a better management of water	Forecasting of precipitations and temperatures → alert if a drought episode will go on → enables to take measures to save water and protect aquatic ecosystems (campaigns, no water for pools, irrigation, forbidden 1 day a week…)	Medium-range			X	

Sector	Action using forecasts leading to impact	Mechanism	Time-scale	Mitigation	Adaptation	Biodiversity	Pollution
	Better regulation of water stock to anticipate droughts	Trends of temperature to predict risk of droughts → optimisation of water storage and use → anticipation by avoiding too much consumption of water → protection of aquatic ecosystems despite the incoming drought	Seasonal range			X	
	Forecast of intense El Nino helps anticipating important droughts in Africa (Reunion island…)	Prediction of the intensity of the phenomenon El Nino → anticipation in Reunion island and Mayotte of incoming important droughts → can help to anticipate by regulating water stocks more efficiently and protect aquatic ecosystems	Seasonal range			X	

Table A2: final list of the identified negative environmental impacts of weather forecast activities

Organisation	Action leading to impact	Mechanism	Mitigation	Adaptation	Biodiversity	Pollution
Météo-France	Energy consumption	Activities to provide weather forecasting require lots of energy (e.g. construction and exploitation of supercomputers, consumption of infrastructures and buildings…)	X			
ECMWF	Energy consumption	Activities to provide weather forecasting require lots of energy (e.g. construction and exploitation of supercomputers, consumption of infrastructures and buildings…)	X			
EUMETSAT	Energy consumption	Activities to provide observational data require lots of energy (e.g. consumption of infrastructures, buildings, cooling systems…)	X			

Table A3: Examples of Copernicus EO-based services and their environmental impacts (non-exhaustive list)

Sector	EO-based service	Environmental impacts	Mitigation	Adaptation	Biodiversity	Pollution	Example of regions using services
Agriculture / fishery	Service to monitor irrigated areas	Prevent overuse of water, specifically during droughts			X		Southern Italy
	Services to monitor crops growth and vitality, vegetation indices, changes in biomass, water consumption over space and over time	Enable to optimise water, pesticide and fertiliser use	X		X	X	Greece, France, Belgium, Italy, Denmark, Sweden, South-Africa

Sector	EO-based service	Environmental impacts	Mitigation	Adaptation	Biodiversity	Pollution	Example of regions using services
	Service to monitor land use and land use change and practice	Facilitate the control of protected areas included in the Habitats Directive (EU regulation)			X		Castile and León (Spain)
	Service to monitor and measure ship density for different types of ship to analyse patterns	Will allow to generate time series of ship density maps which reflect trends in fishing effort and potential pollution. It will help to sustainably manage and protect waters and fisheries			X	X	United Kingdom
Forestry	Service to map tree species and make forest inventory	Help to preserve and enhance species underused today but adapted to climate change and that have potential to provide resources in the future		X			Alsace (France) with chestnut trees
	Services to monitor forest health by detecting and mapping disturbances (fires, diseases, droughts…)	Improve the planning and removal of disturbances with improved forest management: enables an increased capacity for capturing global carbon emissions (by securing volume of forests) and reduced ecological damages (water and air quality, habitats…)	X		X	X	Portugal, United Kingdom
	Service to assess and monitor large-area forest attributes with reasonable accuracy levels	Enable to make regular forest inventories (assessment of resources) which allows to detect relevant forest and land-use change and help forest management in ecological preservation			X		Portugal
Biodiversity and environmental protection	Services to identify the extent fires burned areas and a degree of severity	Better management of short term ecosystem restoration measures and measures to mitigate fires impacts (soil erosion…)			X		Spain, Greece
	Service to detect oil spill, location and source	Contribute to avoiding extension of ecological disasters by warning and helping for clean-up operations as well as identifying polluters			X	X	European Union
	Services to map and monitor biotope and habitats decline in remote areas and deterioration of grasslands	Enable to know about the decline to try to halt it or to slow it down with nature protection measures. Deterioration of grasslands implies quality reductions in ecosystem services			X		Austria, Latvia, Italy

Sector	EO-based service	Environmental impacts	Mitigation	Adaptation	Biodiversity	Pollution	Example of regions using services
	Service to map wetlands performance	Help to map ecosystem services, conservation management priorities and possible improvements in water resources management			X		Bretagne (France)
Climate and water	Service to provide dataset and information on coastal erosion and to map how foreshores can be used to reduce coastal flood and erosion risk	Service contributes to assessing the status of regional coastal zones for policymakers and managers and to help them take better nature-based solutions to reduce coastal flood and erosion risk		X			The Netherlands, Spain, Romania, UK
	Monitoring coastal ecosystems and erosional trends (provides physical and biogeochemical parameters)	Enables to help coastal managers optimise their risk mitigation strategies by knowing more about short- and long-term erosional trends and forecasting impacts of future coastal hazard		X	X		France (Nouvelle-Aquitaine)
	Monitoring of peatland restoration success	Help see efficiency of restoration, crucial to have healthy peatlands that absorb CO2, reduce flood risks and ensure high water quality for population	X		X	X	UK (Yorkshire)
	Monitoring of the development of renewables energies and estimation of the most suitable renewable energy source for an area (COP4EE service)	Data provided by Copernicus enable to estimate for a given area what would be the most efficient renewable source (solar, wind, biomass…) which enables a more efficient energy transition that will contribute in the long-run to climate change mitigation (with optimal site selection)	X				Germany

Sector	EO-based service	Environmental impacts	Mitigation	Adaptation	Biodiversity	Pollution	Example of regions using services
Urban planning and urbanism	Monitoring heat islands and green areas in urban environments	Copernicus climate change and land services provide data with Sentinel-2 satellites that give information on heat island, local climate evolution, land-use change and urban green spaces to: - help define urban planning (land-use and infrastructures) - locate sensitive areas affected by urban heat islands and identify areas where green areas are missing to adjust urban planning and mitigate heat islands Heat waves lead to important pollution (ozone and particles) and a better urban planning enables resilient cities to climate change		X		X	France (Rennes), Spain (Valencia), Czech Republic (Pilsen)
	Monitoring air pollution	With the Copernicus atmospheric service, monitoring of air pollution in Europe to undertake appropriate measures -> reduction in pollution				X	Europe

B. Scoring approach for selecting impacts of weather forecasting activities

The important number of impacts and the limited time to carry out the evaluation made necessary to establish a pragmatic selection of those.

We propose in this annex a qualitative method to prioritise the impacts.

For each activity using forecasts to implement actions that may have a potential environmental impact, **a score of importance has been attributed in order to classify them and to make a selection**. We note that this classification has only been made for positive environmental impacts that arise from specific actions in different sectors based on weather or climate predictions. On the other hand, the identified negative impacts were not included in the classification because they were not comparable to identified positive impacts. Indeed, they do not rely on actions undertaken in various sectors based on weather forecasts but depends on meteorological organisations' activities themselves (energy consumption of Météo-France's infrastructures…). Hence, they were not relevant to the system of classification described below. However, as they are not numerous (only three impacts) and as it would allow to also consider adverse effects from those activities and not only benefits, negative impacts were automatically selected and appear in the evaluation.

Regarding positive and indirect impacts, the classification by order of importance relies on two criteria: **magnitude and occurrence**. Each criterion is assigned a score of -1, 0 or +1 for each activity according to certain rules (see box below).

Description of the selection criteria

Two criteria are considered to set the importance of impacts:

1) Magnitude

- Definition: does the action taken by actors (based on weather or climate prediction) have an impact on the environment (mitigation, adaptation, pollution or biodiversity)?
- Scoring:
  - +1 = the action taken has a strong impact on the environment
  - 0 = the action taken has an environmental impact but more moderate
  - -1 = the action taken has non-environmental or very little environmental impact

2) Occurrence

- Definition: how often is the weather/climate forecast used to carry out the action that leads to the impact in the considered sectors?
- Scoring:
  - +1 = frequent (daily or weekly basis)
  - 0 = sometimes (seasonal/annual basis)
  - -1 = rare (occasional or only in case of major events)

Once a magnitude score and an occurrence score are attributed to an impact, we sum the two scores to get the final score that determines the degree of importance of the impact. We thus obtain different situations described in the table below.

Scoring system to prioritise activities having potential environmental impacts through the use of weather/climate forecasting activities

Magnitude / Occurrence	-1	0	+1
-1	**The impact is scored -2** weather/climate forecast is used **occasionally** to undertake actions that have **non-environmental impact or very little environmental impact**	**The impact is scored -1** weather/climate forecast is used **occasionally** to undertake actions that have a **moderate** environmental impact	**The impact is scored 0** weather/climate forecast is used **occasionally** to undertake actions that have a **strong** environmental impact
0	**The impact is scored -1** weather/climate forecast is used **sometimes** to undertake actions that have **non-environmental impact or very little environmental impact**	**The impact is scored 0** weather/climate forecast is used **sometimes** to undertake actions that have a **moderate** environmental impact	**The impact is scored +1** weather/climate forecast is used **sometimes** to undertake actions that have a **strong** environmental impact
+1	**The impact is scored 0** weather/climate forecast is **frequently** used to undertake actions that have **non-environmental impact or very little environmental impact**	**The impact is scored +1** weather/climate forecast is **frequently** used to undertake actions that have a **moderate** environmental impact	**The impact is scored +2** weather/climate forecast is **frequently** used to undertake actions that have a **strong** environmental impact

Although all impacts are interesting to explore, we decided to focus on impacts whose final score is +2 only and to select some scored +1 (in green in the table above). As a result, the list of positive and indirect environmental impacts **narrows down to 10 impacts** distributed over 5 activities using weather forecasts to implement actions that have one or several moderate or strong environmental impacts. We also selected some impacts scored +1 to cover other interesting topics, according to the time that we still had to study them.

Before showing the results of this protocol, we present few examples of scores' attribution:

1st case: prediction of future contaminated areas in case of nuclear accident (score of importance: -2)

Public actors use weather forecasting in case of a nuclear accident because radioactive particles are found in the air, and these will fall on the ground in case of rain. The forecast therefore makes it possible to anticipate the trajectory of these particles (particularly with wind forecast) and the areas likely to be exposed (with rain forecast).

- **Magnitude = -1** → the actors use forecasting to anticipate the affected areas but use this information mainly to protect the population and carry out evacuations. The actions implemented do not prevent the contamination of biodiversity. Hence, actions taken have non-environmental impacts.
- **Occurrence = -1** → the use of weather forecasting to carry out these actions is very rare as nuclear accidents are exceptional.

2nd case: buildings adapted to a warmer climate (score of importance: 0)

Actors in the construction sector use the knowledge that we have on global warming provided by climate projections carried out by the IPCC in cooperation with meteorological activities. As we all know, it is very likely that climate change will lead to more and more heat waves, including in France. Thereby, the construction sector will have to adapt by including this factor when building new constructions. Nowadays, techniques already exist to adapt new buildings to high temperatures and thus, to provide a better thermal comfort to future residents (form and orientation of the building, better isolation…). This will allow to be more prepared to global warming, but also to reduce energy consumption of future residents for air-conditioning, which will lead to less emissions and hence, less global warming.

- **Magnitude = +1** → the action consisting in constructing buildings more resilient to warmer air is quite important to adapt to climate change, especially in cities where thermal comfort is becoming more and more degraded during summers for inhabitants, which leads to an excess of energy consumption for cooling dwellings.
- **Occurrence = -1** → so far, the use of our knowledge on global warming to construct buildings adapted to climate change remains limited. With the implementation of new standards such as RE2020 coming into force this year, the issue will be more and more included in future construction projects. However, as the evaluation's temporal scope is *ex-post*, we argue that those last years, the use of such climate projections remains rare when designing new buildings.

3rd case: better district heating management in buildings (score of importance: 0)

Condominium associations use short- and medium-range weather forecasts to anticipate cold spells and the beginning of winter in order to activate the collective heating in the buildings at the right time (and conversely to deactivate heating at the beginning of the summer period). This optimisation avoids the need to restart the heating system too early in the year (e.g. during a temporary cold spell), which results in avoidable energy consumption and hence less CO2 emissions.

- **Magnitude = 0** → the timing of the action depends on weather forecasting and enables to avoid unnecessary energy consumption due to switching the heating too early (for example if the cold period is only going to last a few days). Hence, it does have an impact on the environment since heating requires energy whose production produces emissions. However, we state that the impact is moderate as it only applies to buildings with collective heating (which is not the major system in France) and for a rather limited period (from a few days to 1-2 weeks. If the cold wave lasts longer, the heating is usually turned on again).
- **Occurrence = 0** → the use of weather forecasting to undertake actions such as restarting collective heating is usually on a seasonal basis (twice a year, in autumn and in spring).

4th case: optimal timing of fertilisers and phytosanitary products use (score of importance: +2)

Farmers use weather forecasts to choose the right times to apply plant protection and fertiliser treatments. Without these forecasts, many treatments would be quickly washed away by wind or rain into rivers and groundwater, causing multiple consequences: pollution of soil, air and water, danger to biodiversity, and waste of products whose production produces high levels of greenhouse gases.

- **Magnitude = +1** → strong environmental impact because the efficiency of the actions of farmers are highly dependent on weather conditions and the forecasts are essential to better optimise treatments, which avoids for sure significant negative consequences on the environment (pollution, biodiversity).
- **Occurrence = +1** → the use of weather forecasting is frequent because treatments are carried out throughout the year by farmers.

We applied this approach to all the identified activities and obtained a more restricted selection. The table below presents those results. Note that the actions described in the second column are short names and not self-content. For more details about mechanisms, see Annex A. The last column displays the final score as well as the score of each criterion in brackets. For example, for the first impact, the magnitude score is +1 and the occurrence score is +1, leading to a final score of importance of +2.

Impacts colour-marked in yellow and orange were excluded from the scope of this study, as well as some impacts scored +1. We must precise that it does not mean that those latter are not important at all or do not exist, but choices needed to be made as we lacked time to cover all of them.

Results of the scoring approach to prioritise environmental impacts of weather/climate forecasting activities

Sector	Activities using forecasts to implement actions that have potential environmental impact	Mitigation	Adaptation	Biodiversity	Pollution	Score of importance (magnitude, occurrence)
Energy	**More reliable wind and solar energies to avoid market adjustments**	X				+2 (+1, +1)
	Incentive to invest in wind and solar energies	X				+2 (+1, +1)
	More reliable hydraulic energy	X				0 (0, 0)
	Optimisation of future dams' locations		X			0 (+1, -1)
	Prediction of future contaminated areas in case of nuclear accident			X	X	-2 (-1, -1)
	Interruption of nuclear plants in case of heat waves			X		+1 (+1, 0)
Transport	**Optimal management of ship trajectories and optimal timing**	X				+2 (+1, +1)
	Minimising the risk of ship accidents			X	X	+1 (0, +1)
	Prediction of trajectories in case of oil or gas spills			X	X	+1 (0, +1)
	Optimal timing and management of salting in case of snowy events			X		0 (0, 0)
	Minimising risk of traffic jam in case of snowy events	X			X	-1 (-1, 0)
Agriculture	**Optimal timing of fertilisers and phytosanitary products use**	X		X	X	+2 (+1, +1)
	Efficient management of cultures			X		+1 (+1, 0)
	Adaptation of cultures and forestry management to climate change		X			+1 (+1, 0)
	Efficient management of fodder cut to preserve livestock well-being			X		0 (0, 0)
	Anticipation of weather dangers to protect the livestock			X		+1 (+1, 0)
Urbanism and urban planning	**Monitoring of air pollution to take measures**	X			X	+1 (+1, 0)
	Better district heating management in buildings	X				0 (0, 0)
	Buildings adapted to warmer climate	X	X			0 (+1, -1)
	Better transport planning to mitigate global warming	X			X	+1 (+1, 0)
	Development of solutions to address heat islands	X	X			+1 (+1, 0)
Vigilance to natural extreme events	**Efficient preparedness and prevention against forest fires (including in long-run)**	X	X	X	X	+2 (+1, +1)
	Forecast of floods to regulate dams and reduce risks			X		+1 (+1, 0)
	Flood warning to protect toxic products			X	X	0 (0, 0)
	Forecast of intense El Nino helps anticipating important floods in America			X	X	-2 (-1, -1)
	Mapping flood risks through time to improve preparedness and prevention		X			+1 (+1, 0)
	Better knowledge of sea level rising to take long-run measures		X			0 (+1, -1)
	Forecasting of drought's duration for a better management of water			X		+1 (+1, 0)
	Better regulation of water stock to anticipate droughts			X		0 (0, 0)
	Forecast of intense El Nino helps anticipating important droughts in Africa (Reunion island…)			X		-1 (0, -1)

C. Methodologies used to quantify the impacts

Annex C.1: GHG emissions reduction arising from optimal farmers' treatments using weather forecasts

No literature has studied potential savings in fertilizers and plant protection products by optimizing application times according to the weather. However, according to experts interviewed during previous *Citizing* missions (3 interviews with farmers, 1 interview with a regional agricultural cooperative organized as an agricultural technical study center and with the technical institute Arvalis), **the proportion of failed treatments would lie between 1 and 5%** (expressed in mass). In order not to overestimate the impact, **we assume that 5% of treatments fail**. This statement must be taken with caution as it relies on a small sample. Nonetheless, **it allows to have a scale of magnitude on failed treatments that still occur despite the actual quality of weather forecasting service provided by Météo-France**.

Regarding the counterfactual, it is impossible to determine how many treatments would fail without access to local weather forecasts. We can think that farmers would rely on general trends, taking advantage of periods of generalized sun or rain in the region in which the risk of surprising weather is limited. However, such days are not so frequent, and heterogeneity are usually seen within regions, even within 27km areas. They could also rely on temperature forecasts as those latter do not vary much in a 27km area (except in mountainous areas where temperatures can change according to sun exposition and other factors). Moreover, farmers could develop solutions to monitor soil moisture. However, farmers would face the lack of reliable and localized wind speed and hygrometry conditions predictions that are essential for successful treatments but completely unpredictable in very local areas in the counterfactual scenario. Hence, it is likely that at least double of treatments would fail. In order to put environmental impacts into perspective, we look at their magnitude if we assume that **between 10 and 30% of treatments would fail in the absence of localized weather forecasts**. Although the magnitude is subject to debate, it is quite certain that we do not overestimate this number considering what we state above, particularly regarding the absence of localized wind speed forecasts.

We estimate the difference in wasted volumes of PPP and fertilizers between the project option and the counterfactual from 2016 to 2019 based on consumption of those products in France those years and deduce the annual mean. Volumes of consumed PPP in France[142] are extracted from a French association specialized in plant protection[143]. Volumes of consumed fertilizers[144] come from Eurostat database. However, only data on nitrogen and phosphorus are available. We thus decide to exclude potassium-based products from the analysis, but we should keep a good level or representativeness as France mainly consumes nitrogen-based products.

Production of PPP and fertilisers products implies relatively important emissions for manufacturing and after spreading. We want to quantify the difference in emissions between the project option and the counterfactual to capture the impact – at constant efficiency – of diminishing failed treatments. We use the Ademe database[145] to collect emission factors of such products. Regarding PPP, the database provides emission factors for the whole life-cycle (in kgCO2, kgCH4 and kgN2O/kg of the product). For fertilisers, the database provides emission factors for manufacturing (in kgCO2-eq/kg of the product) and after spreading for nitrogen (in kgN2O/kg of the product applied). However, the latter factor has important uncertainty (from -80% to +400%) as it depends on various natural phenomena. Still, we show the range of values between this uncertainty interval to quantify it, because N2O from spreading (through fertilisers decomposition in fields) is usually the main factor for fertiliser. The uncertainty on values for manufacturing fertilisers and the whole life cycle of PPP – valid for Europe – is 30%. Based on the ranges of values of the avoided amount of farming products consumed that we determined above, we can deduce the potential avoided emissions of greenhouse gases enabled by less production (at constant efficiency) of PPP and fertilisers explained by a better optimisation of agricultural treatments compared to a situation in which farmers would not have access to precise weather forecasts.

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[142] Between 55 and 73kt over 2016-2019 period
[143] UIPP: Union de la Protection des Plantes et des cultures
[144] Between 2 130 and 2248kt of nitrogen and between 181 and 191kt of phosphorus over 2016-2019 period
[145] See https://www.bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?engrais_et_composes_azotes.htm

Annex C.2: biodiversity harm reduction arising from optimal farmers' treatments using weather forecasts

The rationale behind the volume of failed treatments, both within the project option and the counterfactual is the one described in annex C.1.

We intend to quantify (still within an interval based on the counterfactual going from 10 to 30% of failed treatments as described in annex C.1) **the avoided environmental impact on biodiversity from less failed nitrogen-based treatment**.

According to Savci (2012), even in ideal conditions, between 2 and 10% of nitrogenous fertilisers interfere surface and ground water. 50% of nitrogenous fertilisers applied to soil is used by plants, 2-20% lost through evaporation and 15-25% react to organic compounds in the clay soil. Hence, in the case of failed treatments caused by bad weather conditions (such as heavy rains), plants would not have the time to absorb the product before this latter is carried away through run-off or drainage to surface water, and organic compounds in the clay soil could not react to absorb enough of the product before this latter reaches ground water, as the leaching would be too fast because of the rain. We thus exclude the share of product ending up in waters even in ideal conditions (i.e. 2-10%) as well as products lost through evaporation. However, we assume that under bad conditions that would make the treatments to fail, the usual share of products absorbed by plants and the clay soil would end up in water (surface and ground), meaning that **70% of nitrogen fertilisers ends up in water when treatments fail.**

Based on this assumption, **a precise weather forecasting service that allows to decrease the number of failed treatments could enable to avoid between 76.5 and 382 kt of nitrogen to end up in water bodies**.

Cosme and Hauschild (2017) estimated biodiversity damages of nitrogen excess in water bodies based on damage factors which represent the ability of nitrogen emissions to cause hypoxia-related eutrophication impacts. Using a species sensitivity distribution, particularly in Europe, they estimate the indicator "potentially disappeared fraction of species" (PDF) by kg of nitrogen in water. This analysis is carried out for nitrogen coming from soil (agriculture) and directly injected into water (freshwater or coastal water). In our case, we utilise the former to measure the impact of agricultural activities.

A review of biodiversity metrics[146] defines the PDF indicator as *"the rate of species loss (or in ecological terms the extinction rate) in a particular area of land or volume of water during a particular time due to unfavourable conditions associated with land conversion, land occupation, toxicity, increase in average global temperature, or eutrophication"*.

Cosme and Hauschild find in Europe an average of $140(PDF)m^3.year.kgN^{-1}$. As France's biodiversity is quite heterogeneous (several rivers, the Atlantic Ocean, the Mediterranean Sea, the sea Channel), **it seems reasonable to use the average European value as the biodiversity variety is large and not too specific**.

Using this estimate and the difference in nitrogen volumes ending in water bodies, we can compute the avoided damage on biodiversity arising from optimizing nitrogen applications using weather forecasts.

[146] A Review of Biodiversity and Land-Use Metrics, Indices, and Methodologies as Related to Agricultural Products. Christy Melhart Slay, Ph.D.

Annex C.3: GHG emissions reduction arising from optimal forest fires management using weather forecasts

We want to estimate the difference in burned areas in France between the option project and the counterfactual, attributed to the quality of weather forecasts provided by Météo-France, along with the ECMWF medium-range forecasts and Earth observations provided by EUMETSAT.

As the occurrence and the intensity of forest fires largely vary from year to year, **we only compare trends over time-periods to smooth the annual heterogeneity**. For this reason, the project option (i.e. the real situation) that is compared to the counterfactual for this impact is the time-period 2010-2019 as it clearly shows the most recent fire trend and encompasses the Green OAT-period (from 2016).

Regarding the counterfactual, we decide to use data over the period 1976-1990. The rationale is the following: during this period, the French level of weather forecasting service was limited to the Emeraude model at Météo-France that had a resolution of 35km (length of each grid cell) which is almost equivalent to the level of the American GFS over Europe today (28 km). The Arpege model appeared a bit later (1992) with 30km grid cells. Hence, this period is a reliable counterfactual as it enables to get data on burned forest in a situation where a similar level of support as our counterfactual is provided to the civil security. Nevertheless, although we use data of the 1976-1990 period for the counterfactual, we want to compare the real situation (2010-2019) to what would have happened without public subsidies over this same period. In other words, even if we consider a level of forecasting equivalent to the 1976-1990 period, the context has changed since then, and we need to actualize data from this period as if the Emeraude model was actually the only available model between 2010 and 2019. Hence, before comparing burned areas between the 1976-1990 period and the 2010-2019 period, one must consider several aspects and adjustments:

- **The surface of forest cover has increased since the first period**, hence raising risk of fires. According to the forest inventory made by the Institut national de l'information géographique et forestière, the forest cover increased in France from 14.1 million ha in 1985 to 16.1 million ha in 2009 up to 16.9 million ha in 2019. Hence, forests covered an average of around 16.5 million ha over the period 2010-2019. Restraint by lack of data, we suppose that the coverage in 1985 is equal to the average coverage over the 1976-1990 coverage. We know that over this period, the annual mean of burned surface from forest fires was 45,000 ha (see above), which represented around 0.32% of the total forest. During the last decade, this proportion of burned surface would represent around 53,000 ha. In order to consider the increase of forest cover in the counterfactual, we add those extra 8,000 ha to the burned forest of the 1976-1990 period.
- **The climatic risk has also increased since this period**, mainly explained by global warming. One of the consequences is the rising risk of forest fires represented by the Fire Weather Index (FWI). Chartry et al. (2010) stated in their report for Météo-France that the annual mean of FWI over the period 1991-2009 was 20% higher than over period 1976-1990. According to their simulations, the annual mean of FWI should increase by 15% around 2040 because of global warming. They also argue that between 1976-1990, the annual average burned surface was 45,000 ha and should have increased by 10,000 ha in the 1991-2009 period because of the rising forest cover and the increasing FWI. Given the data on forest cover they provide, we deduce that 6,000 additional ha would be explained by rising forest cover which means that 4,000 additional ha can be explained by the increased FWI. Considering that our reference period is 2010-2019, it is likely that the annual mean of FWI lightly increased compared to the 1991-2009 period. Therefore, we assume an additional 5,000 ha of burned forest in our counterfactual that we add to the burned forest surface over 1976-1990. As a result, the burned forest area in our counterfactual raises to 45,000 (data in 1976-1990 period) + 8,000 (forest cover) + 5,000 (climatic risk) = 58,000 ha (29% increase).
- Lastly, one should consider that **the civil security's actions and resources have improved** since the period 1976-1990 and **preventive measures have been implemented, such as forestry management and forest fire risk management plans** since 1995. Those evolutions, along with weather forecast progress, may have contributed to a decrease in burned surface trends. Although we cannot assess the shares of the decrease explained by forest management measures, civil security's resources and weather forecast support, it is likely that the latter is the major contributor. Indeed, Chartry et al. (2010) reminds that if the increase in the means

of prevention and control is certainly a cause of this decrease, these means could only be used as effectively as improvement of risk forecasting on the territory was made (particularly through climate projections in the long run). Hence, the key factor of this improvement seems to be the increased use of meteorological forecasting. **We assume that the difference in burned area is moderated by 30%,** meaning that forest management and civil security's improvement, independently of weather forecast services of quality (supposedly absent in the counterfactual), have contributed to 30% of the decrease in annual mean of burned surface of forest between the adjusted period 1976-1990[147] (counterfactual) and the period 2010-2019.

The annual mean of burned forest over the 2010-2019 period was 11,805 ha (DGSCGC). Hence, we find a difference in burned area of (58,000 ha – 11,805 ha) x 70% (70% being the share of the decrease explained by weather forecasting), which is equal to **around 32,000 ha per year on average**.

Vilén and Fernandes (2011) computed CO2 emissions coming from wildfires in France between 1980 and 2008. Based on the annual mean burned area over this period (28,460 ha/year), an estimation of the amount of burned biomass (depending on the burned area, the average organic matter per unit area and the biomass burning efficiency) and the emission factor (weight of released CO2 per weight of dry matter burned), they found that wildfires in France led to an average of 1,340,682 tons of CO2 emissions per year. The authors computed combustion factors and emission factors based on Mediterranean conditions which is relevant as most fires in France happens in the Mediterranean area.

We can deduct from their results that on average, around 47 tons of CO2 are emitted per burned hectare. We emphasize that this latter figure is an average and highly depends on the type of forest burning. However, as the literature is quite modest on this subject and the figure does not seem to be unreasonably high, we are confident that the estimate does not lead to an overestimation of the impact. However, we cannot exclude the possibility of underestimated results.

From this estimate, combined with the difference in burned areas between the project option and the counterfactual attributed to weather forecasting, we can then compute the volume of avoided CO2 emissions per year.

[147] This percentage is applied to data of forest burned in the period 1976-1990 after adjustments to the rising forest cover and climatic risk. Indeed, forest management measures and improvement of civil security resources have enabled to contribute to the decrease in fires despite the evolution of the risk.

Annex C.4: GHG emissions reduction arising from less errors in wind production forecasts

We intend to estimate avoided CO2 emissions explained by less adjustments in the energy market with fossil sources, arising from less errors in wind power production predictions (avoiding an underproduction compared to the demand).

Based on data from RTE[148], we computed the cumulated errors between predicted production (both at D-1 and H-7 ahead) and the effective production over the year 2019. Those cumulated errors are expressed in MWh. By dividing the total volume overestimated over the year by the total volume effectively produced, we find an error rate. **For predictions at D-1 ahead, the error rate is 6.1% while at H-7, this rate decreases to 5.9%**. We notice that not much difference in the error rate is observed, and we know that RTE starts to adjust from 2-3 hours before real-time. Ideally, we should use predictions at H-2 but we do not have such data. Hence, we decide to keep H-7 errors, but while keeping in mind that this rate might be a little lower because based on forecasts nearer real-time. Therefore, we consider that **5.9% of wind production was overestimated and needed to be adjusted for balance**.

Regarding the counterfactual, **no literature can be found on the effect of good weather forecasts on wind production forecasts compared to non-localized and less reliable forecasts as the GFS model would provide**. However, Wang et al. (2019) showed that **between a "low fidelity" and a "medium fidelity" wind forecasting model, the latter could reduce the annual wind power generation forecast error by 10-11% compared to the former**. They also indicate that **between a "low fidelity" and a "high fidelity" wind forecasting model, the latter could reduce the annual wind power generation forecast error by more than 15% compared to the former**. The extrapolation of those results is limited for our study as we do not have details about those 3 models and particularly the "low fidelity" that may be different from the American GFS model supposed to be used in our counterfactual.
However, we decide to **assume that models providing current forecasts in France can be considered as medium to high fidelity models and the GFS model as a low fidelity model as an interview with RTE confirmed that the GFS model would not be reliable for their wind production forecasts**. This will enable to provide a scale of magnitude of the impact but must be taken with caution as it depends on this uncertain assumption. Therefore, **we suppose that weather forecasts in the project option allow to reduce errors by 10 to 20% compared to our counterfactual** (we try with a little more than 15% as models of Météo-France and the ECMWF are supposedly of high quality).

Now that we have the difference in error rate of wind production forecasts, we quantify the effect on adjusted volumes and particularly on volumes adjusted using fossil sources (both from domestic production and foreign production). We know that in 2019, the total adjusted volume (upward) was 3.52 TWh, of which 5.1% was adjusted with domestic fossil production and 36.6% with imports. **We want to know precisely volumes adjusted with domestic oil, domestic gas, domestic coal, foreign oil, foreign, gas and foreign coal**.

Regarding domestic fossil production, we use the energy mix of France in 2019 provided by International Energy Agency, and compute shares of oil, coal and gas among the total production of energy with fossil sources in France (coal: 12.6%, oil: 12.7%, gas: 74.7%). We then apply those shares to the volume adjusted by domestic fossil sources (5.1% of total volumes).

Regarding imports, we know from RTE that in 2019, imports from the UK represented 10% of total imports, 52% came from Germany, 22% from Switzerland, 1% from Italy and 15% from Spain. We now look at the energy mix in 2019 in each of those countries (IEA data) and apply shares of imports according to countries and shares of coal, oil and gas in each country. For instance, we compute adjustments made with foreign coal:

$$volumes\ adjusted \times share\ adjusted\ with\ imports \times (share\ imports\ from\ the\ UK \times share\ of\ British\ production\ with\ coal \\ + share\ imports\ from\ Germany \times share\ of\ German\ production\ with\ coal\ \ldots)$$

[148] Source: https://www,services-rte,com/fr/telechargez-les-donnees-publiees-par-rte,html?activation_key%3Df32049d5-0ac9-4fb0-9e4b-0033463184f2%26activation_type%3Dpublic=true&category=generation&type=actual_generations_per_production_type

Finally, **we estimate the avoided CO2 emissions by using factor emissions provided by RTE**[149] that come from the ADEME database. Coal electricity production contributes by 0.986 tCO2-eq / MWh produced, oil source contributes by 0.777 tCO2-eq / MWh and gas source contributes by 0.429 tCO2-eq / MWh on average in life-cycle emissions.

We then multiplied differences in adjustments, made with each of the fossil sources, by their respective emission factors and find avoided CO2-eq emissions in 2019 attributed to weather forecasting provided by Météo-France, the ECMWF and EUMETSAT.

[149] Source: https://www.rte-france.com/eco2mix/les-emissions-de-co2-par-kwh-produit-en-france

D. Recent and to be launched projects in which the CNES has contributed (for research in environmental fields)

Project	Mission	Objective	Operational / research	Partners	Start date	End date
Aeolus	Measure wind of atmosphere	Improve weather forecast and climate knowledge	R	CNES, ESA	2018	-
Biomass	Map biomass and forest height and quantify annual decrease of biomass (deforestation)	Better understand role of forests on carbon cycle and climate changes	R	CNES, ESA, CNRS…	2022	2027
Calipso	Locate cloud layers and aerosols, measure their altitude and reveal their optical properties	Better understanding of how clouds and aerosols affect the climate	R	CNES, NASA	2006	2023
CfoSat	Measure waves properties and wind intensities and directions on oceans	More accurate marine weather forecasting, with the ability to anticipate extreme events such as severe storms and cyclones	O (weather)	CNES, CNSA	2018	2021
Copernicus (Sentinel-2 and -3)	Monitor land cover, characterize bio-geophysical variables over land, predict the state of the oceans, assist in crisis management in areas affected by natural or industrial disasters, monitor chemical composition and air quality, re-analyse essential climate variables and develop tools for the provision of climate services		O, R	ESA, UE, MS, CNES	2012	-
Cryosat	Measure the thickness of sea ice (pack ice) and land ice (Antarctic and Greenland ice sheets) to the nearest cm	Monitor the extent, volume and validate forecasts of ice melt related to global warming	R	ESA, CNES	2010	2017
Earthcare	3D mapping of the cloud and aerosol gas layer, while measuring exactly how much solar and thermal radiation from the earth is reflected	Scientific teams will refine the meteorological models, but also better understand the evolution of global warming and its consequences	R	ESA, CNES, JAXA	2022	2025
Flex	Studies the emission of fluorescent light by vegetation, produced by the process of photosynthesis	Scientific teams will try to improve the overall understanding of the effects of photosynthesis on the circulation of carbon between vegetation, atmosphere and the water cycle	R	ESA, CNES	2022	2026
Grace	Detailed maps of the Earth's gravity field to a spatial resolution of 200 km that highlight the temporal evolution of water, snow or ice masses	Provides crucial information to the study of the Earth's oceans and climate, particularly in the context of global warming	R	CNES, NASA, DLR	2002 *(ng: 2018)*	2017
Hy-2a	Physical study of the oceans: height and temperature of the seas, wind speed at their surface	Better knowledge on oceans and climate change	R	NSOAS, CNES	2011	-

Jason 3 and Sentinel-6	Ensures continuity of ocean height data. Part of Copernicus (Sentinel-6)	Measures the rise in global sea level and provides a better understanding of the gigantic system of currents that run through the oceans both at the surface and at depth	O, R	CNES, NASA, Eumetsat...	2016	2021
Megha-Tropiques	Study of the water cycle and energy exchange in the tropical atmosphere	Understand the climate, the water cycle and the energy balance. Understand climate change and better predict extreme events	R	CNES, ISRO..	2011	-
Merlin	Measure the concentration of methane in the atmosphere	Better understand the sources of this greenhouse gas	R	CNES, DLR	2024	2027
Microcarb	Mapping, on a global scale, the sources and sinks of the main greenhouse gas: CO2	Measure CO2 emissions in white areas to better understand origins and impacts of global warming	R	CNES, CEA...	2021	2026
Smos	Measuring soil moisture and ocean salinity (allows the detection of ocean currents that has a strong influence on weather and climate)	Measure of ocean salinity enables a better understanding of the role of the oceans in the carbon cycle. Soil moisture measurements provide information on the interactions between the Earth's surface, vegetation and the atmosphere, making weather forecasts more accurate. These data also help to better assess the risk of floods and droughts	R	CNES, ESA, CDTI	2009	2017
Swot	Comprehensive measurement of water levels in rivers, lakes and flooded areas, oceans, offshore and coastal areas	Improve river hydrodynamic models leading to estimates of flows and to determine temporal variations in water stock. Also enable to observe swirls or filaments, to refine oceanographic and climate models...	R	CNES, NASA, CSA, UKSA	2022	2025
Trishna	Measuring the surface temperature of the entire globe	Understand the local evolution of biological (water stress, transpiration), physical (evaporation, sublimation, plume zones) and climatic (global observation over time) phenomena in relation to the water cycle	R	CNES, ISRO	2024	2029
Vegetation	Monitoring of vegetation cover on a regional and global scale (carried on Spot-4, Spot-5 and the European mission Proba V)	Provide an increasingly detailed view of land use and the impact of global warming	R	CNES, EC, Belgium...	1998	-
Venµs	Fine and regular monitoring of terrestrial vegetation (provide images of more than 100 sites distributed all over our planet: forests, cultures, protected natural areas...)	To determine the influence of environmental factors, human activities and climate change on continental surfaces	R	CNES, ISA	2017	2021

E. Example of analysis of Taxonomy criteria for adaptation for an activity of Météo-France

Steps	Taxonomy criteria	Activity: climate expertise and services
Adaptation 9.1: Engineering activities and related technical consultancy dedicated to adaptation to climate change		
Taxonomy-eligibility	Engineering activities and related technical consultancy dedicated to adaptation to climate change An economic activity in this category is an **enabling** activity	**Eligible** → Climate expertise requires observation and treatment of data and aims at providing long-range and seasonal predictions but also **consultancy services**: **to support the definition of policies for adapting territories** and preserving biodiversity in the context of climate change, Météo-France designs, produces and regularly disseminates regionalized climate scenarios. In particular, it responds to requests from the State and local authorities
Substantial contribution	The economic activity is predominantly aimed at the provision of consultancy that helps one or more economic activities for which the technical screening criteria have been set out in this Annex to meet those respective criteria for substantial contribution to climate change adaptation, while respecting the relevant criteria for doing no significant harm to other environmental objectives. The economic activity complies with one the following criteria: **(a)** it uses state-of-the-art modelling techniques that: (i) properly reflect climate change risks (ii) do not rely only on historical trends (iii) integrate forward-looking scenarios **(b)** it develops climate models and projections, services and assessment of impacts, the best available science for vulnerability and risk analysis and related methodologies line with the most recent Intergovernmental Panel on Climate Change reports and scientific peer-reviewed publications. The economic activity removes information, financial, technological, and capacity barriers to adaptation. The potential to reduce material impacts due to climate risks is mapped through a robust climate risk assessment in the target economic activity. Activities in architectural design take into account climate proofing guidelines, climate-related hazards modelling and enable the adaptation of construction and infrastructure, including building codes and integrated management systems. The adaptation solutions implemented: (a) do not adversely affect the adaptation efforts or the level of resilience to physical climate risks of other people, of nature, of cultural heritage, of assets and of other economic activities (b) favour nature-based solutions or rely on blue or green infrastructure to the extent possible (c) are consistent with local, sectoral, regional, or national adaptation plans and strategies (d) are monitored and measured against pre-defined indicators and remedial action is considered where those indicators are not met (e) where the solution implemented is physical and consists in an activity for which technical screening criteria have been specified in this Annex, the solution complies with the do no significant harm technical screening criteria for that activity.	***Box in orange as we cannot demonstrate every criterion to prove the compliance to the Taxonomy, but the analysis reveals that this compliance is very likely*** (a) Météo-France uses modelling techniques to assess climate change risks (ex: for the Civil Security the evolution of forest fire risk), to model the past evolution of climate and to predict future scenarios (b) Detailed knowledge of past climate developments and the study of possible futures is an essential starting point. Météo-France works with the IPCC to develop climate projections for their report, which relies on a solid scientific knowledge. They also provide climate services for operational actions toward adaptation: **portals and web application** ("Climat HD"," DRIAS, les futurs du climat") that present maps of the evolution of numerous climate indicators until the end of the century, as well as more targeted **climate services**, co-built with actors from different sectors to help them, more accessible thanks to the "Resource Centre on Adaptation to Climate Change" of which Météo-France is a partner. This center aims to support any actor involved in an adaptation process by giving them access to a complete set of resources adapted to the various sectors of action. All the themes of adaptation to climate change are covered: the impacts of climate change on health, water, agriculture, forestry, soils, biodiversity, natural hazards, urban planning, mobility, fishing and aquaculture, tourism, and the financial sector *Example: evaluate the consequences of urbanisation policies on temperatures in cities with a modelling platform to guide choices in terms of greening roofs, widening streets, or reintroducing biodiversity* **Hence, the economic activity removes information barriers to adaptation**. *"The potential to reduce material impacts due to climate risks is mapped through a robust climate risk assessment in the target economic activity"* → *difficult to get such information* "The adaptation solutions implemented…" → difficult to get such information
DNSH	(1) The activity is not undertaken for the purposes of fossil fuel extraction or fossil fuel transport	The activity is indeed not undertaken for the purposes of fossil fuel extraction and transport
	(3) The activity complies with the criteria set out in Appendix B to this Annex.	The activity is not detrimental to the good ecological status or potential of water bodies, including surface waters and groundwaters or the good ecological status of marine waters (accordingly to article 17 of Taxonomy Regulation) as the activity is not material
	(4) N/A	N/A
	(5) N/A	N/A
	(6) N/A	N/A
Social safeguards	Compliance with the OECD guidelines on Multinational Enterprises and the UN Guiding Principles on Business and Human Rights	Yes: Météo-France must follow French regulations on the labor market

F. Relevant extract of the Taxonomy Regulation

Taxonomy Regulation – Article 17: Significant harm to environmental objectives

1. For the purposes of point (b) of Article 3, taking into account the life cycle of the products and services provided by an economic activity, including evidence from existing life-cycle assessments, that economic activity shall be considered to significantly harm:

(a) climate change mitigation, where that activity leads to significant greenhouse gas emissions;
(b) climate change adaptation, where that activity leads to an increased adverse impact of the current climate and the expected future climate, on the activity itself or on people, nature or assets;
(c) the sustainable use and protection of water and marine resources, where that activity is detrimental:
- (i) to the good status or the good ecological potential of bodies of water, including surface water and groundwater; or
- (ii) to the good environmental status of marine waters;

(d) the circular economy, including waste prevention and recycling, where:
- (i) that activity leads to significant inefficiencies in the use of materials or in the direct or indirect use of natural resources such as non-renewable energy sources, raw materials, water and land at one or more stages of the life cycle of products, including in terms of durability, reparability, upgradability, reusability or recyclability of products;
- (ii) that activity leads to a significant increase in the generation, incineration or disposal of waste, with the exception of the incineration of non-recyclable hazardous waste; or
- (iii) the long-term disposal of waste may cause significant and long-term harm to the environment;

(e) pollution prevention and control, where that activity leads to a significant increase in the emissions of pollutants into air, water or land, as compared with the situation before the activity started; or
(f) the protection and restoration of biodiversity and ecosystems, where that activity is:
- (i) significantly detrimental to the good condition and resilience of ecosystems; or
- (ii) detrimental to the conservation status of habitats and species, including those of Union interest.

2. When assessing an economic activity against the criteria set out in paragraph 1, both the environmental impact of the activity itself and the environmental impact of the products and services provided by that activity throughout their life cycle shall be taken into account, in particular by considering the production, use and end of life of those products and services.