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Links to Copernicus data and services

Status and recommendations

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Executive Summary

This report presents a comprehensive overview of the current status of use of Copernicus data and products in the work of the European Environment Agency (EEA) and provides recommendations to make better use of Copernicus information focusing in particular on the activities of the European Topic Centre for Air pollution, Transport, Noise, and Industry pollution (ETC/ATNI), one of seven EEA's Topic Centres. It is highly relevant to respond to the European Commission's Action 7 to Streamline Environmental Reporting, namely, "Making better use of data generated through the Copernicus programme" as proposed in the Reporting and monitoring fitness check report of June 2017 (COM (2017/312 final). The Conclusions and Recommendations of this report are presented in Chapter 4 of this report.

The Copernicus program has a service and the satellite component. The six Copernicus services are briefly presented here, although the main focus is naturally on the Copernicus Atmosphere Monitoring Service (CAMS), on the Copernicus Land Monitoring Service (CLMS) and on the Copernicus Climate Change Service (C3S) as these are the most relevant services with regard to the activities at the ETC/ATNI. The Copernicus space component is also presented here, introducing the Sentinel program and the state-of-the-art satellite and associated instruments.

The report shows that EEA, in relation to the work conducted by the ETC/ATNI and its precursor ETCs, has been making use of Copernicus services data since the beginning of the program, while the use of the satellite data has so far been more limited.

An overview of the use of Copernicus data in ETC/ATNI is provided in the Table at the end of this summary. Data from the CAMS service, its regional air quality results, has been used in mapping activities, as auxiliary data and form the basis for forecasts and gap-filling in EEA's air quality index. The CAMS assessment reports are referred to and taken into consideration in current versions of EEA's annual "Air Quality in Europe" report. Data from the CLMS service have been used to a lesser degree in mapping activities, to distinguish rural and urban areas. However, the CLMS products on landscape fragmentation pressure and on land take have been used as indicators to support transport activities. More importantly, CLMS land cover information has been used in relation to noise pollution, for example to characterize quiet areas. Data from the C3S is currently used in at the ETC/ATNI as meteorological driver in trend studies and for physical indicators. The only Earth Observation (EO) data directly used so far at ETC/ATNI is NO_2 OMI data as ancillary data in support of ETC mapping activities.

Further use of the Copernicus data is both feasible and recommended in this report. The potential future use of both service and satellite data is indicated in the Table at the end of this summary. Special attention should be provided to enhancing the use of satellite data. Already now, available data from Sentinel 1, 2, 3 and Sentinel 5P can be useful to support checking of emission inventories, mapping activities and urban sustainability studies. With the expected launching of Sentinel 4 in 2023, an unprecedented set of satellite information will become available with potential to increase the quality of this type of ETC/ATNI assessments. It is highly recommended to prepare for that event by evaluating the capabilities of the available Sentinel 5P.

Recommended activities to make better use of Copernicus data involve mapping and emission activities at ETC/ATNI, trend analysis, noise, and air quality assessments as well as the development of on-line air quality services and the implementation of urban sustainability studies.

Mapping Activities

To further improve the ETC mapping results, we recommend using both EMEP with the CAMS ensemble as background model and to use the TROPOMI products from Sentinel 5p in the mapping routines. Concerning TROPOMI, it is expected that the characteristics of this product, both with respect to higher spatial resolution as well as the improved retrieval scheme and instrument characteristics, can have a substantial impact on ETC mapping accuracy for NO_2 and ozone. We also recommend investigating the potential of mapping SO_2 and using aerosol optical depth (AOD) as an additional proxy variable in ETC mapping. Sentinel-3 data is the only satellite within the Copernicus Space Component that has the capability to provide AOD data. While the relationship between AOD and surface particulate matter (PM) is highly complex and conversion between the two variables is usually subject to significant uncertainties, it is nonetheless reasonable to assume that the overall spatial patterns are somewhat similar. Therefore, it is worth investigating how Sentinel 3 data may improve PM mapping results at ETC/ATNI.

Emission activities

A key area where the Copernicus products offer significant capabilities is for the evaluation of the spatial and temporal distribution of emissions. Different Copernicus products can be used for this purpose. One possibility is to rely on the capabilities of the CAMS emission data series, another is to directly use satellite data, and a third one is to use the CAMS service modelled results. Here, we indeed propose to use the CAMS emission inventories to evaluate the spatial distribution datasets reported by the countries under the National Ceiling Directive (EU, 2016) and initiate a dialog with European Union Member States in order to support an improvement of the spatial distribution in the EU emission inventory reported under the Gothenburg Protocol of the Convention on Long-range Transboundary Air Pollution (UNECE, 2012). Further we propose to conduct an uncertainty analysis of European emission data based on available modelled data from the CAMS policy services.

The use of satellite data to evaluate and improve the emission estimates from bottom-up emission inventories is definitively one of the most interesting potential applications of EO data for the future ETC/ATNI work. While there are still various challenges in the quantification of actual emissions due to limitations in inversion methodologies, EO data can be useful to determine an improved spatial and temporal resolution of emissions. We recommend using TROPOMI nitrogen dioxides (NO_x) tropospheric column data from Sentinel-5p to improve the current temporal resolution of emissions. Another promising application of EO products is in the evaluation of large point source industrial emissions. We propose to conduct a feasibility study to demonstrate the quantification of NO_x and SO_2 emissions from large industrial point sources, such as large power plants for NO_x and metal sulfide ore smelters for SO_2.

Trend analysis

The work in ETC/ATNI often revolves around analyzing trends of pollutants over time and identifying the reasons behind the observed trends. Copernicus meteorological trend data from C3S has been used as reference meteorological parameter in the trend work conducted at ETC. However, neither satellite products nor CAMS re-analysis results have been yet used in the context of ETC trend work.

One of the most promising research applications of EO products is long-term trend analysis since it also allows to study areas where no or only few observations at ground measurement stations are available. We recommend comparing satellite-inferred nitrogen dioxide (NO_2) trends over Europe with station-based trends previously computed in the ETC/ATNI to complement the analysis and identify possible inconsistencies. Satellite retrieval products for NO_2 are generally quite mature and accurate enough for trend analysis.

Noise assessments

The Green Infrastructure Strategy recognizes that the protection, restoration, creation, and enhancement of green infrastructure becomes an integral part of spatial planning and territorial development. In addition, green infrastructure also allows to establish a direct link with health and quality of life from a multifunctional perspective. Therefore, the assessment of the status of green infrastructure, particularly in urban areas, is of relevance as a response to some of the challenges addressed by ETC/ATNI. This is especially true regarding air quality and noise pollution. In this context the data provided by the Copernicus services (CLMS, C3S, CAMS) are relevant. We recommend developing a cross-cutting analysis -to assess the effect of existing green infrastructure in European cities on mitigating noise exposure and addressing at the same time the capacity of the green infrastructure to capture air pollutants. It is recommended to establish links with the work done in the context of the ETC on Urban, land and Soil systems (ETC/ULS) since there are several commonalities.

Online air quality services

The development of the European Air Quality Index at EEA is a successful example for the uptake of Copernicus air quality data for public use. This service is planned be extended from now-casting to forecasting in order to provide a forecast of the Air Quality Index at all the monitoring stations. We also propose to develop a new on-line service: an "Online early-warning system for exceedances." The proposal is to combine EEA's up-to-date air quality information system with CAMS policy source allocation to identify exceedances of limit values as they occur. The service would not only provide an early-warning when and where exceedances of limit values take place but would also explain online the potential impact of different long-range sources and natural sources on the observed exceedances. In addition, work at ETC/ATNI should continue in order to identify the driving factors that lead to air pollution episodes. Such information can be used as guidance to evaluate different mitigation strategies and to quantify costs and benefits of such strategies.

Urban sustainability assessments

Urban sustainability is a key parameter in urban development. The current aim to promote climate neutral cities with improved quality of life requires the development of appropriate indicators to trace evolution towards these sustainability goals. The combination of data from CAMS, CLMS and C3S services, in addition to Sentinel 1, 2, 3 and even Sentinel 5p data can provide a series of layers of relevant information to facilitate the creation of an urban environmental sustainability indicator. These developments should be aligned with the EEA framework of urban environmental sustainability to be published in 2020.

There is considerable potential to increase the use and impact of Copernicus service and satellite data at ETC/ATNI. We trust that this report can guide the identification of priorities aiming to enhance the uptake of Copernicus products in its work during the next few years.

Overview of current and potential use of Copernicus data in ETC/ATNI. P indicates Potential Future Use.

ETC/ATNI \ Copernicus		Mapping activities	Emission activities	Noise activities	Trend analysis	Air quality assessments	On-line air quality services	Urban sustainability
CAMS	Regional air quality forecasts						Air quality index (AQI)	
	Regional air quality re-analysis	Model proxy for spatial air quality mapping		P	P	P		P
	Interim Assessme					Air Quality in	P	

ETC/ATNI / Copernicus		Mapping activities	Emission activities	Noise activities	Trend analysis	Air quality assessments	On-line air quality services	Urban sustainability
	nts Reports					Europe report		
	Source Receptor information					Cost-effectiveness of measures	P	
	CAMS emissions		P					
CLMS	Corine Land Cover	Spatial AQ concentration +exposure fields	P	Proxy for quiet areas outside agglomerations				P
CLMS	Urban Atlas		P	Noise pollution as spatial concept				P
CLMS	Imperviousness			Tranport landscape fragmentation				P
CLMS	Natura 2000			Quiet areas outside agglomerations				P
C3S	ERA re-analysis		P		Meteorological trends			
Satellites	Sentinel 1							p
Satellites	Sentinel 2		P					P
Satellites	Sentinel 3	P	P					P
Satellites	Sentinel 5p	P	P		P			P
Satellites	Sentinel 4	P	P		P	P	P	P

1 Introduction

Copernicus([1]) is the European Union's Earth Observation (EO) Programme. The goal of Copernicus is to provide freely and openly EO information to help service providers, public authorities and other international organisations improve the quality of life for the citizens of Europe. It has also a clear potential and ambition to contribute to job creation, innovation, and growth. The information provided by Copernicus is user-driven and intended to support a wide range of socially relevant applications, including urban area management, sustainable development and nature protection, regional and local planning, agriculture, forestry and fisheries, health, civil protection, infrastructure, transport, and mobility, as well as tourism.

The Copernicus programme consist of two different components: a space and a service component. The Copernicus **space component** includes a set of dedicated satellites (the Sentinel families) and contributing missions (existing commercial and public satellites). The Sentinel satellites are specifically designed to meet the needs of the Copernicus services and their users. In addition to satellite information, Copernicus also collects information from in-situ systems such as ground stations, airborne and seaborne measurement systems. The in-situ information is under the coordination of the European Environment Agency that ensures that relevant in-situ observations generated and maintained by the Member States and research activities at European level are provided to the programme. The Copernicus **service component** transforms this wealth of satellite and in-situ data into value-added information by processing and analysing the data with the help of models and data assimilation techniques. These value-adding activities are currently organised in thematic areas resulting in the six currently established Copernicus services**: atmosphere, marine, land, climate change, emergency, and security.**

The Copernicus programme is coordinated and managed by the European Commission. It is implemented in partnership with the Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecast (ECMWF), EU Agencies and Mercator Ocean.

The European Environment Agency has an important role in Copernicus. EEA plays a key role in the technical coordination of the Land Monitoring Service and in coordinating in-situ observations in co-operation with Member States. Despite this prominent role in the programme, EEAs use of Copernicus data and information in regular production is still moderate.

The **objective** of this report is to provide an overview of the current status of use of Copernicus data and products in the work of the European Environment Agency, here the Programme on Health and Sustainable Resource Use and in particular of one EEA's Topic Centres, namely, the European Topic Centre for Air pollution, Transport, Noise, and Industry pollution (ETC/ATNI). Based on such overview, we will propose ways to extend and optimize the use of Copernicus data in the work of the ETC/ATNI for relevance to the EEA. In this way, we will follow the recommendations from the European Commission's reporting and monitoring fitness check report of June 2017 (COM (2017) 312 final), identifying actions to making better use of data generated through the Copernicus programme.

This report is organised in two parts, dealing with each of the two different components of the Copernicus program. We begin, in Chapter 2, with an evaluation of the use of Copernicus Service data, because the added value of model data has been more extensively demonstrated in the ETCs and EEA work in the past than that of satellite data. Given that the focus of the report is on the work of the ETC/ATNI, we consider primarily information from the atmosphere, land, and climate services of Copernicus. We continue with the evaluation of the use of Copernicus Satellite data in Chapter 3. Both

([1]) https://www.copernicus.eu/en/about-copernicus.

chapters have a similar structure: we provide first an overview of available Copernicus products, we continue with a review of the status of current use of these products at ETC/ATNI and finally, we propose on ways to extend or make better use of these Copernicus products in the ETC/ATNI work. At the end of Chapter 3, we include a specific section (3.4) on the use of satellite data for evaluating emissions, reviewing latest scientific literature advances, and proposing ways to use them for the EEA's work. The final chapter, Chapter 4, summarizes our recommendations and proposes ways to include Copernicus data and information in the short term at the ETC/ATNI work to respond to societal and environmental challenges relevant to the EEA´s work.

2 Links to Copernicus Services

The mandate of the EEA to provide sound, independent information on the European environment can also be facilitated by linking to the data from the Copernicus Services. All Copernicus Service data and products are timely, open, free of charge and of documented quality, characteristics that make these data especially valuable for EEA's work.

Below follows a short description of the six different Services as presented in the Copernicus webpages([2]). An overview of the organization of the six Copernicus Services in presented in .

- **The Copernicus Atmosphere Monitoring Service (CAMS)** provides continuous data and information on atmospheric composition. The service describes the current situation, forecasts the situation a few days ahead, and analyses consistently retrospective data records for recent years. It provides daily information on the global atmospheric composition by monitoring and forecasting constituents such as greenhouse gases (carbon dioxide and methane), reactive gases (e.g., carbon monoxide, oxidized nitrogen compounds, sulphur dioxide), ozone and aerosols. It provides near-real-time analysis and 4-day forecasts, as well as reanalysis, of past European air quality, thus enabling a permanent assessment of the air we breathe. CAMS is implemented by ECMWF in co-operation with sub-contractors and has been operational since July 2015.

- **The Copernicus Marine Environment Monitoring Service (CMEMS)** provides regular and systematic reference information on the physical and biogeochemical state, variability and dynamics of the ocean and marine ecosystems for the global ocean and the European regional seas. The observations and forecasts produced by the service support all marine applications, including marine safety; marine resources; coastal and marine environment. Many of the data delivered by the service (e.g., temperature, salinity, sea level, currents, wind, and sea ice) also play a crucial role in the domain of weather, climate, and seasonal forecasting. This service is implemented by Mercator Ocean in co-operation with sub-contractors and has been operational since May 2015.

- **The Copernicus Land Monitoring Service (CLMS)** provides geographical information on land cover and its changes, land use, vegetation state, water cycle and earth surface energy variables to a broad range of users in Europe and across the World in the field of environmental terrestrial applications. It supports applications in a variety of domains such as spatial and

([2]) https://www.copernicus.eu/en/services.

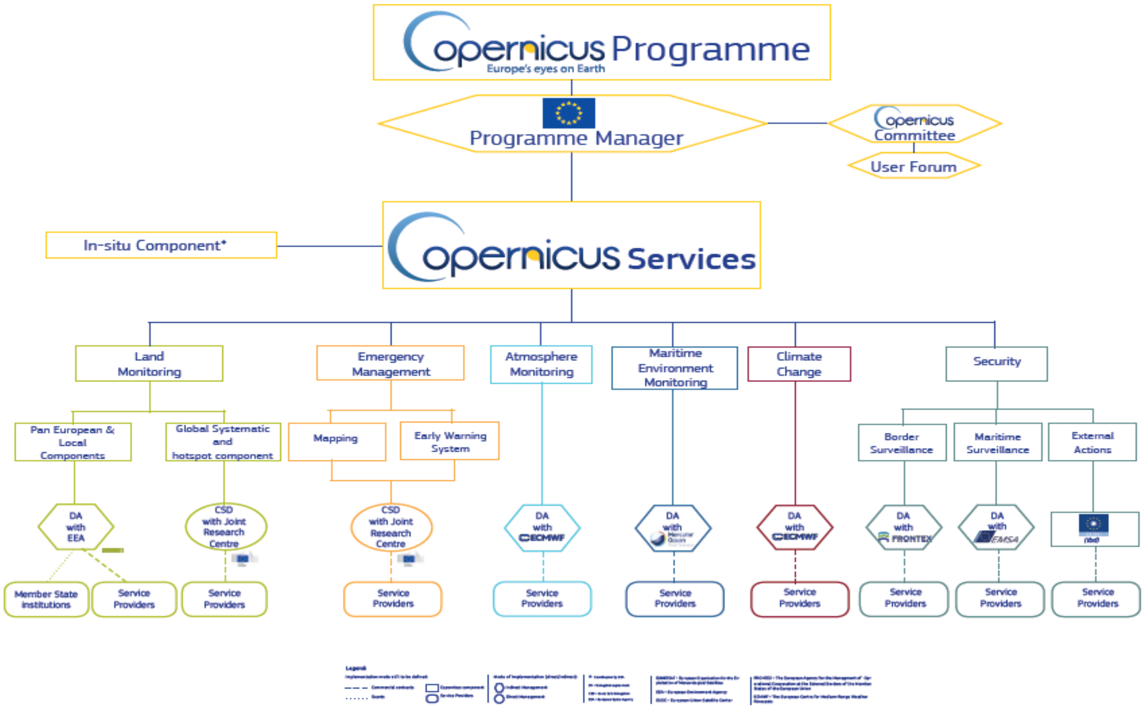
urban planning, forest management, water management, agriculture and food security, nature conservation and restoration, rural development, ecosystem accounting and mitigation/adaptation to climate change. This service is jointly implemented by the European Environment Agency and the European Commission DG Joint Research Centre (JRC) and has been operational since 2012.

- **The Copernicus Climate Change Service (C3S)** provides authoritative information about the past, present and future climate in Europe and the rest of the World. The C3S mission is to support adaptation and mitigation policies of the European Union by providing consistent and authoritative information about climate change. C3S relies on climate research conducted within the World Climate Research Programme (WCRP) and responds to user requirements defined by the Global Climate Observing System (GCOS). C3S provides an important resource to the Global Framework for Climate Services (GFCS). This service is implemented by ECMWF in co-operation with sub-contractors and has been operational since 2018.

- **The Copernicus Emergency Management Service (CEMS)** provides all actors involved in the management of natural disasters, manmade emergency situations, and humanitarian crises with timely and accurate geo-spatial information derived from satellite remote sensing and completed by available in situ or open data sources. The Service has a mapping and an early-warning component. The mapping component has a worldwide coverage, while the early-warning component includes the European Flood Awareness System (EFAS), the European Forest Fire Information System (EFFIS), the European Drought Observatory (EDO), the Global Flood Awareness System (GLOFAS), the Global Wildfire Information System (GWIS) and the Global Drought Observatory (GDO). The service is implemented by JRC and has been operational since April 2012.

- **The Copernicus Service for Security** provides information in response to Europe's security challenges in three key areas: border surveillance; maritime surveillance and support to EU External Action (SEA). For border surveillance, the main objectives are to reduce the death toll of undocumented immigrants at sea, to increase the internal security of the European Union and to the fight against cross-border crime by providing near real time data on what is happening on land and sea around the EU's borders. This part of the service is implemented by the European Border and Coast Guard Agency (FRONTEX) and has been operational since November 2015. Maritime surveillance related to safety of navigation, support to fisheries control, combatting marine pollution, and law enforcement at sea are implemented by the European Maritime Safety Agency (EMSA) and have been operational since December 2015. The Support to External Action (SEA) component is designed to assist the EU help third countries in a situation of crisis or emerging crisis with geo-information on remote, difficult to access areas, where security issues are at stake. This part of the service is implemented by the European Satellite Centre (EU SatCen) and has been operational since October 2016.

Figure 2.1: Overview structure of the programme service component: the six Copernicus Services (Source: Copernicus, DG-Grow)



In this chapter, we consider how the ETC/ATNI takes best advantage of the access to Copernicus Service data for their work at EEA. Our evaluation involves all six Copernicus Services but with main focus on the work of CAMS, C3S and CLMS.

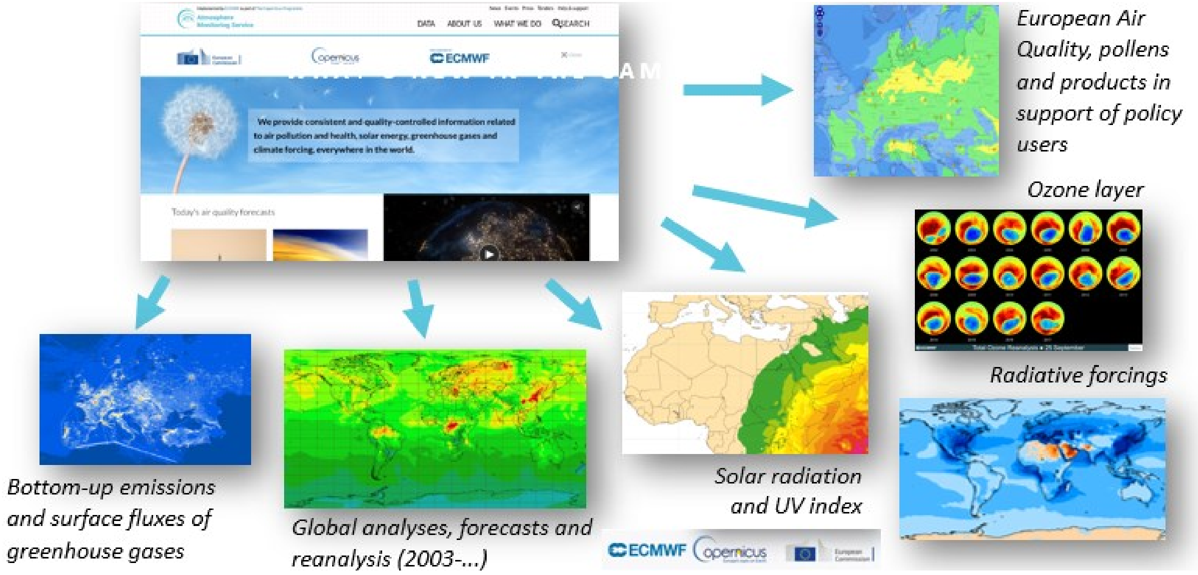
2.1 Copernicus Atmosphere Monitoring service - CAMS

The Copernicus Atmosphere Monitoring Service delivers products and services to describe past, current, and future air pollution fields and atmospheric composition in Europe and at the global scale. To this end, observations from in-situ networks and Earth observations are combined with model results to take stock of all available data and information and elaborate a set of new and high-quality products. The CAMS product portfolio([3]) involves six main segments as indicated in Figure 2.2.

- European Air quality, pollens, and products in support of policy users
- Ozone layer
- Emissions and surface fluxes of greenhouse gases
- Solar radiation and UV index
- Global analyses, forecast and re-analysis
- Radiative forcings

([3]) https://atmosphere.copernicus.eu/ and https://atmosphere.copernicus.eu/sites/default/files/2018-12/CAMS%20Service%20Product%20Portfolio%20-%20July%202018.pdf.

Figure 2.2: Synthesis scheme of CAMS portfolio (Source: ECMWF)



A significant strength of the CAMS services is that the production chain is completely controlled by scientific expert providers selected in open tenders by ECMWF. So, global, and regional modelling activities which require several input data fields do not depend on external contribution. This approach increases the robustness and the quality of the service: meteorological fields come from ECMWF, and emission inventories are elaborated by a dedicated service which develops global and European historical datasets using the most up-to-date methodologies.

In Europe, the CAMS emission inventory is already used by several modelling teams (besides the CAMS regional services themselves), for instance in the framework of the Eurodelta modelling inter-comparison exercises performed as part of the EMEP([4]) programme (Bessagnet et al., 2014; Colette et al., 2017). It is important to note that in terms of total (annual) sectoral emissions, the CAMS regional emission inventory is consistent with the official data reported by the EU Member States under the National Emission reduction Commitments Directive, NECD 2016/2284/EU, (NEC, 2016). EEA member countries and countries, which are Parties to the UN ECE Convention on Long-range Transboundary Air Pollution (CLRTAP)([5]) under CLRTAP's amended Gothenburg Protocol. In addition, CAMS also provides emission inventories, that for instance correspond to the 2020 and 2030 targets of the NECD. The main advantage of the CAMS European gridded emission data its high spatial resolution which is about 7x7 km^2 and the consistency of the methodology for gridding emissions all through Europe. Bottom-up emissions inventories are regularly updated.

The CAMS services described above are now fully operational([6]) and freely available. A data store infrastructure archives all products and results delivered by the various services and multi-level help desk ensures user support.

2.1.1 Available products from CAMS

The portfolio of products delivered by CAMS is organised into four main categories and 13 product groups, as outlined in the Table 2.1. In this table, "analyses" or "re-analyses" refer to products which

([4]) Evaluation and Monitoring of air pollutants in Europe programme from the Convention on Long Range Transboundary Air pollution (www.emep.int).
([5]) United Nations Economic Commission for Europe.
([6]) Several Key Performance Indicators (KPI) allows ECMWF to monitor the accuracy and operationality of the products.

are obtained by combining different streams of observations using a modelling system: in analyses this is done in real time while in re-analysis the combination is done in hindcast mode.

Table 2.1: Overview of available CAMS products (courtesy of ECMWF)

CAMS product Portfolio	Product groups	Short description
A. European air quality	Real-time analyses	European-scale air quality analyses for every hour of the previous day at a horizontal resolution of about 10 km and which include information from surface observations available in Near-Real-Time (i.e., up-to-date data reported to EEA under the EU's Air Quality Directives).
	Real-time forecasts	European-scale air quality forecasts for every hour up to 4 days in advance at a horizontal resolution of about 10 km.
	Interim annual re-analyses	Re-analyses delivered annually by mid- of year N for every hour of year N-1 at a horizontal resolution of about 10 km and which include information from surface observations in an interim stage of validation (i.e., provisional up-to-date data reported under the EU's Air Quality Directives).
	Annual re-analyses	Re-analyses delivered annually for every hour of year N-2 at a horizontal resolution of about 10km and which include information from fully validated surface observations data as reported under the EU's Air Quality Directives.
B. Global atmospheric composition	Real-time analyses	Global-scale atmospheric composition analyses with a 6-hourly resolution and available twice daily at a horizontal resolution of about 40 km and which include information from several satellite observation data streams available in Near-Real-Time.
	Real-time forecasts	Global-scale atmospheric composition forecasts up to 5 days in advance at a horizontal resolution of about 40 km, with a 3-hourly resolution and refreshed twice daily.
	Re-analyses	Global-scale atmospheric composition reanalysis over the period 2003-2017 at a horizontal resolution of about 80 km, with a 3-hourly resolution based on the assimilation of a comprehensive set of satellite datasets and using consistent models throughout the time period.
C. Supplementary products	Policy support products	4 main products: assessment reports based on interim regional re-analyses; assessment reports based on regional re-analyses; daily updated "green scenarios" forecasts and the tools included in the Air Control Toolbox (ACT); regional source-receptor calculations (how much the local air pollution can be attributed to local sources and how much is imported through long - range transport?); country source-receptor calculations (on demand in the case of large episodes).
	Solar radiation	2 main products: worldwide UV index forecasts up to 5 days in advance; time series of Global, Direct, Diffuse Irradiations on horizontal surface, and Direct Irradiation on a normal plane (DNI) for actual weather conditions (field of view of MeteoSat) and for clear-sky conditions (worldwide).
	Greenhouse gas flux inversions	Monthly global surface fluxes of carbon dioxide (CO_2; since 1979), methane (CH_4; since 2001) and nitrous oxide (N_2O; since 1996) obtained from inversion of observations.
	Climate forcings	Climate radiative forcings (as defined by e.g., the IPCC) from changes in atmospheric composition since the pre-industrial period: CO_2, CH_4, N_2O, ozone (stratosphere and troposphere), aerosol (interactions with radiation and interactions with clouds).
D. Emissions products	Anthropogenic emissions	Comprehensive emissions inventory datasets for the globe (about 50 km resolution) and for Europe (about 8 km resolution).
	Fire emissions	Daily biomass burning emissions of various aerosol, greenhouse gas, and chemical species based on Fire Radiative Power (FRP) satellite observations.

For the ETC/ATNI purposes, the most relevant products are those related to European air quality (Segment A) and the Policy Support Supplementary products (Segment C) in addition to emission products (Segment D). The global products relate to the description of the chemical composition of the atmosphere at the global scale. Various compounds are included: greenhouse gases responsible for climate changes, reactive gases and aerosols that impact air quality in the various parts of the world and may impact climate indirectly.

The regional products relate to air pollution issues and target chemical substances that have harmful effects on human health and ecosystems. They are named "air pollutants," and include sulphur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM) and ground-level ozone (O_3) and some of their precursors like ammonia (NH_3). Since the EU's air pollution legislation covers such air pollutants, the regional services which focus on the European domain are particularly interesting with respect to EEA's (assessment) work.

The production chain is coordinated by Méteo-France and INERIS([7]). These institutions deal with regulated main air pollutants (according to the Ambient Air Quality Directive 2008/50/EC) and pollens. Forecasts and analyses of concentrations of SO_2, NO_2, O_3, and PM (PM_{10} and $PM_{2.5}$) are provided every day in a fully operational way([8]). A posteriori re-analyses based on validated observations and re-analyses of meteorological fields are also elaborated every year for the same air pollutants. The production chain addressing concentrations of grass, birches, olives, and ragweed pollen is still under development.

Regional CAMS set-up is briefly described in the bullet points below. Some of the set-up, like the geographical coverage, have been defined in order to comply with EEA's requirements. The set-up is as follows:

- The CAMS geographical domain is large enough to include EEA's member countries, also covering Iceland in the Northern and Turkey in the Eastern part of the domain;
- The modelled spatial resolution is quite high: 10 km x 10 km over the whole domain;
- The hourly concentrations result from an ensemble multi-modelling' approach: this means that modelled concentrations are the combination (median average in the current system) of several (10 in the current set-up) chemistry-transport model results. This approach increases robustness and accuracy of the final results taking benefits of the various models involved;
- The analyses and re-analyses result from data assimilation and data fusion techniques (see Box 1) to improve raw model simulations with an available set of observations. Within CAMS, both in-situ (i.e., data from ground-based monitoring stations) and satellite observations are used([9]) in such processes, which minimize the difference between model results and observations where available;
- A stringent evaluation process frames CAMS operational production. All results delivered are evaluated hour by hour against an independent set of in-situ observations, i.e., air quality measurement data provided by EEA, which is not used to build-up the analyses and the re-analyses, i.e., the comparison of modelled with measured values. Statistical scores indicators (bias, root mean square error, fractional gross error, correlation coefficient) are calculated for each individual model involved in the service and for the ensemble and

([7]) Institut national de l'environnement industriel et des risques (INERIS).
([8]) There is a commitment from service providers to implement the appropriate infrastructure (software and hardware) to guarantee the daily provision of expected forecasts and analyses.
([9]) Each of the 10 regional chemistry models run in CAMS has its own data assimilation infrastructure and if they all assimilate in-situ data reported to EEA, they do not assimilate the same set of Earth observations.

published on the website so that users can get transparent information about the actual performance of the CAMS modelling system;

- Air quality data reported by the Member States to the EEA under the ambient Air Quality Directive 2008/50/EC and available in EEA's e-reporting database([10]) is the main observation dataset used in the CAMS regional services. Access to near-real-time or up-to-date data (from the so-called "E2a" regulatory datasets) is facilitated by close cooperation between the EEA, ECMWF, and the regional services providers.

While forecasting and analysis processes develop on a day per day basis, the re-analysis process follows a different timeline with a two-steps approach, which sticks to the e-reporting regulatory process implemented according to the air quality directives([11]):

- "Interim" re-analyses are computed twenty days after the target day assuming that this delay is long enough to get verified observations to be assimilated in the models. "Verified" does not mean "validated" but at least it is expected that the re-analyses which result from this process are of better quality than daily analyses (because more data is available and because the verification steps should be achieved by the data providers).

- "Validated" re-analyses are computed once validated observations are available. According to the implementation provisions of the air quality directives, EU Member States have to report no later than the 30th September of the year Y+1 the validated observations for the year Y. During a verification period that follows, the EEA proceeds a large number of QA/QC checks. The date by when Member States can resubmit data is being moved to November Y+1. This means that validated re-analyses for year Y cannot be produced before the beginning of the year Y+2. Aggregated air quality indicators (averages, exposure indicators, exceedance indicators) are then compiled in a CAMS validated air quality assessment report published during summer of year Y+2. To increase transparency, EEA and the European Commission are trying to speed up the reporting process, i.e., reducing the time period for verification and resubmission of data. Differently to global reanalysis products, regional re-analyses are produced annually in order to take benefit of the gradual improvement of model quality, but it also means that inter-annual consistency of the reanalysis (for trend analyses) is not guaranteed with the regional reanalysis.

Finally, CAMS includes specific policy-oriented services. The yearly production of interim and validated air quality assessment reports is an example of such services. Therefore, interim re-analyses are used to elaborate an interim air quality assessment report each year in May for the previous year that describes air quality levels in Europe over the target year, focusing on episodes that occurred within this period.

Policy services include the development of policy support tools as well. There is the Air Control Toolbox (ACT) which is an online toolbox that allows to simulate the impact on ambient PM and ozone concentrations of sectoral (industry, road traffic, residential heating, and agriculture) emission reductions defined by the users themselves. Another product relies on a source/receptor allocation service which provides forecasts of the distribution of local versus non-local emissions to PM

([10]) See for example: http://aqportal.discomap.eea.europa.eu/.
([11]) Since the EEA e-reporting database is the most important observation data source used to elaborate the CAMS regional products.

concentrations in about 40 European cities. Information on the neighbouring countries participating to the non-local contribution is proposed as well.

Box 2.1: Differences between data assimilation and data fusion (Adapted from Hall and Llinas, 1997)

Data assimilation and data fusion: two approaches for the same goal

Building-up best estimates of air pollution maps regarding the air concentrations levels but also their patterns are the main objective of data assimilation of data fusion techniques. In both cases, the idea is to take stock of all available datasets: in-situ or satellite information, model results but also ancillary variables fields or measurements (like emissions, meteorology, topography, and land cover…).

- **Data fusion**: Hall and Llinas in "An introduction to multisensor data fusion,"provided the following well-known definition of data fusion: "*Data fusion techniques combine data from multiple sensors and related information from associated databases to achieve improved accuracy and more specific inferences than could be achieved by the use of a single sensor alone*." In this context, improved information means less expensive, higher quality, or more relevant information. Data fusion techniques aim at aggregating variables and data from different sources to reduce the uncertainty of the individual datasets. They can be based on regression statistical techniques, kriging, etc…

- **Data assimilation** also aims at improving the description of the state of a system but requires observation data to be combined, in a smart way with a modelling system that describes the dynamic and physical principles that manage the system. Thus, data assimilation approach refers to the "correction" or improvement of the raw model results minimizing the difference, where observations exist, between the model prediction and the actual measurement. Finally, all data assimilation methods are based on least-squares methods, with the final estimate being chosen to minimize the uncertainty of the final estimate.

2.1.2 Current use of CAMS data at ETC/ATNI

The work at EEA has been linked to different aspects of CAMS since the beginning of the programme. EEAs in-situ component supports CAMS by providing up to date (UTD) and validated air quality measurement data, which the EU Member States and the EEA member and co-operating countries report to EEA under the EU's Air Quality Directives. CAMS uses this data within their European air quality products. Some of the in-situ monitoring stations are used to assimilate measurement data into the runs of regional AQ models, some to check and validate the modelling results against measurement data. EEA has also been a CAMS user, particularly during the period when the service was developed through a series of EU-funded Research Framework precursor projects (GMES, MACC([12])). EEA was for

([12]) MACC (Monitoring Atmospheric Composition and Climate) was a FP7 research project series that was the research precursor of the operational CAMS service, initiated in 2009 until 2014.

several years in the MACC user advisory board, guiding the development of the CAMS products to also support the work of its European Topic Centers. Consequently, the ETC/ATNI and its precursors have used a few Copernicus products in their applications. These products relate to air quality analyses and re-analyses for Europe as described in detail in the sections below.

2.1.2.1 Use of CAMS data at ETC/ATNI mapping activities

The ETC/ATNI and its precursor ETC/ACM have used the CAMS regional service products to support EEA's mapping activities. The co-operation began during the period when the service was developed through a series of EU-funded precursor projects (GMES, MACC), starting in 2005. The EEA and the ETC/ACM cooperated in the past with CAMS precursor projects, examples are:

- https://acm.eionet.europa.eu/reports/ETCACM_TP_2013_9_AQmaps_with_MACCproducts,
- https://acm.eionet.europa.eu/reports/ETCACM_TP_2012_9_GMESsatdata_NOx_Euromap,
- https://acm.eionet.europa.eu/reports/ETCACM_TP_2012_5_urbanAQmapping_meth_GMES
- https://acm.eionet.europa.eu/reports/ETCACM_TP_2017_14_Improved_AQ_NO2mapping.

Thus, the EEA and its former Topic Centre ETC/ACM started to investigate the added-value of the Copernicus atmosphere services for improving air quality maps in 2012, with the first two studies that aimed at evaluating the products delivered by CAMS precursor projects. Those investigations demonstrated the potential brought by the Copernicus services but also highlighted they were not completely mature enough at that time for the operational production of maps, especially at the urban scale since most models used then spatial resolution above 25 km x 25 km whereas now, they all operate at 10 km x 10 km resolution. Note however that this resolution is still insufficient for urban scale applications.

The other studies investigated more in-depth the methodologies that could be implemented by the EEA and its Topic Centre to take stock of increasing availability of satellite observations for elaborating high-resolution air quality maps (with a focus on the NO_2). The results indicated that satellite data giving NO_2 tropospheric columns at a spatial resolution of approximately 10 km × 10 km provide significant improvements in mapping accuracy as compared to geo-statistical interpolation of solely station data. This is very promising considering the new generation of satellite products that is coming with the Sentinel program (Sentinel 5p already available and geostationary Sentinel 4 to be launched in 2023). Various methods and scientific approaches to use satellite observations and CAMS products, based on regression, interpolation and kriging, and data merging techniques have been assessed and evaluated to prepare and facilitate use of Copernicus services for air quality assessment work coordinated by the EEA.

2.1.2.2 Use of CAMS data in EEAs air quality index

Since 2017, EEA produces maps of a harmonized European air quality index (EEA, 2019a), which are updated on an hourly basis and are being built-up upon up-to-date (UTD) in-situ measurements taken in the EEA member and cooperating countries([13]) observation networks and reported to the EEA under the EU's Air Quality Directives. The UTD reporting chain was established in cooperation with the Member States and the rest of reporting countries in 2015 to comply with European air quality legal obligations. In some countries, for some monitoring stations, pollutants, and days, UTD data can be missing. Gap-filling is therefore necessary to publish a complete map. The EEA decided to use CAMS

([13]) Some other countries also report data on a voluntary basis, as Andorra and Georgia.

analyzed hourly data to gap-fill. In addition, the service has a forecasting AQI capability available since the end of 2019 where CAMS data is used as basis for the forecasting. How CAMS data is used is described in Box 2.2 below.

Box 2.2: Use of CAMS modelling results to gap-fill air quality index maps (EEA, 2019a)

Missing data and gap filling

When data is not reported for a given hour, values are approximated, or 'gap-filled' using CAMS modelled air quality data. In such cases, it is marked as 'modelled data' (see below).

The method used for gap-filling depends on the pollutant.

- For NO_2, $PM_{2.5}$ and PM_{10} we use the difference method.
- For O3 we use the multiplicative method.
- No gap filling is performed for SO2

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

Multiplicative method: The value is approximated by taking the CAMS modelled value, and applying a correction factor. This correction is the average ratio between the previously measured values and the CAMS modelled values for the same hour for at least three of the four previous days.

In cases where there are no measured values for the same hour over three of the four previous days, the value for the given pollutant is not calculated and is reported as 'no data'

Forecast index

Forecast values are shown as transparent dots. To calculate the forecast values for the following 24 hours, CAMS modelled air quality data are used and corrected using the gap-filling methods described above. No forecast values are provided for SO_2.

2.1.2.3 Use of CAMS products in EEA's annual Air quality in Europe report

The EEA publishes every year an "Air quality in Europe" report which describes air pollution status and trend developments in Europe. It is based on measurements of air pollutant concentrations reported by the EEA reporting countries. It also uses the interpolated fused maps to estimate exposure of population to certain pollutants (and attributed health impacts) and exposure of vegetation to ozone. These interpolated maps are constructed using, among other supplementary data, the EMEP model results. Indeed, EEA, CAMS and EMEP under the Convention on Long-range Transboundary Air Pollution (CLRTAP) all produce regular (annual) air quality assessments for Europe. The reports have very different purposes and complement each other. In the 2017 report, information produced by CAMS in its 2016 interim assessment report (Tarrasón et al., 2016) was used for the first time to elaborate on PM and ozone episodes that occurred in Europe in 2015 (EEA, 2017a). The selection of PM episodes proposed by CAMS and their interpretation was used by the EEA in a specific box section focused on episodes, while information on the ozone episodes was provided in the main text. The climatological characterization of recent years proposed in the CAMS assessment reports, and in the interim reports, is also used in the EEA's Air quality reports. Still, wider use of the re-analyses maps could be envisaged in the future to complement the information based on observations already available in the EEA reports.

The characterization of the origin of air pollution episodes and the climatological characterization of pollution years has for example been discussed in EEA's air quality pollution assessments, i.e., the Annual Air Quality report (EEA, 2018a) and the State of the Environment 2020 report (EEA, 2019b).

It is important to note that consistency between CAMS re-analyses maps of aggregated indicators (averages and exposure indicators) with the information published in the EEA reports and available on the EEA data viewers (EEA, 2019a) has been carefully checked and confirmed by CAMS teams over the 3 past years.

2.1.3 Perspectives for future use of CAMS products

Because operational production of air quality data for Europe by CAMS only started in 2015, use of CAMS data by the EEA is currently still modest. We have mentioned the use of the episode analysis performed in the interim assessment reports in the last three EEA´s Air quality in Europe reports and gap filling and forecast in the air quality index maps. However, considering available products, the use of CAMS data by the EEA could be extended for several applications that are listed below:

- **Contribution to the air quality reports**: CAMS re-analyses maps are available and can be used to illustrate the EEA air quality report. The question of duplication of work within the EEA reports and the CAMS assessment reports has been already discussed several times. The complementarity of the various reports, which propose different angles to describe and interpret air pollution patterns in Europe has been highlighted as well. CAMS proposes a two-step approach: the interim report is based on interim re-analyses of air pollution fields that are themselves based on the assimilation of up to date (non-validated) observation data. CAMS validated assessment reports are based on validated re-analyses built-upon fully validated observation datasets and the most updated versions of the models and their input data (emissions, meteorology). Current experience shows that although interim re-analyses are very valuable for a first and quick analysis of air pollution events during the target year, validated assessments are of better quality, especially for drawing air quality indicator maps. However, in the 5-10 coming years we can expect that both processes (validated and interim) could align. So, our recommendation would be that:
    - The EEA could expand the use of episode analysis proposed in the CAMS interim reports to support interpretation of specific air pollution patterns;
    - The EEA could use the CAMS interim or validated ensemble re-analyses of background air pollutant concentrations to support the production of higher resolved maps using data fusion technique, which would be complementary to maps based on measurement results. As more data becomes available from measurements in Eastern European countries, CAMS interim analyses (IRA) could even be used in that context, at the condition that they are combined with validated observations in the data fusion process. Even if the observations assimilated in CAMS IRA are UTD, this dataset should be considered in the future as a possible an improvement over using the raw EMEP model (not assimilating any observation) in the data fusion. Besides, CAMS IRA are available very early in Y+1 for year Y making it appealing to produce EEA indicator and exposure maps.
- **Support in managing emissions reported by the member states:** EU Member States officially report emission data under the National Emission Ceilings Directive (EU, 2016). Further, the EEA compiles the EU emission inventory report under CLRTAP. The report and its accompanying data constitute the official submission by the European Commission on behalf of the EU as a Party to the UNECE Executive Secretary. **This official dataset is the basis of the CAMS emission inventory work.** The CAMS emission inventories are regularly updated, the latest one at the moment is for 2015 (Keunen et al, 2018). The CAMS added-value relates to the spatial distribution of the emissions that are used as model inputs and to expert analysis for some sectors (residential heating for example). Uncertainties in spatialized emissions can

arise depending on the targeted spatial resolution and the quality and accuracy of proxy data. This is precisely the technical field where CAMS puts a lot of effort in delivering gridded emission datasets appropriate to air quality modelling. Therefore, CAMS emission inventories could be useful to help assessing/verifying spatialized datasets reported by the countries under the NECD or the Gothenburg Protocol. Since the total emissions are the same (CAMS emission inventories stick to official datasets reported by the countries), the idea is to support spatial distribution challenges that countries face.

- **Expert analysis of emission data,** CAMS services (both regional air quality productions and policy services) provide excellent areas for investigations. They are based on model runs which obviously depend on sound emission input data. The CAMS model evaluation processes (against observations) can help in qualifying potential underestimations in emissions (especially for PM). The policy services (for instance the source/receptor allocation services) can be used to assess sensitivity of model responses to emissions and to mitigation strategies.

- **Support in the assessment of mitigation strategies**: the EEA is also assessing the efficiency of emission control strategies. In that perspective the policy tools developed by CAMS (Air Control Toolbox and source/receptor allocation tool) could be used to support such assessments, especially regarding the driving factors that lead to air pollution episodes. The task 1.2.2.2 of the ETC/ATNI 2019 work plan aimed at assessing the relevance and reliability of current integrated modelling tools used to derive cost-benefits analyses of air pollution mitigation strategies and assess the cost of air pollution. The potential value-added of ACT and its current limitations are discussed in this report, highlighting options for future applications. In that perspective CAMS could develop to support EEA and the ETC/ATNI in using the CAMS policy tools for health and economical assessments.

- **Support in establishing the influence of natural emissions**: CAMS global services develop an aerosol segment which includes forecasts and re-analyses of natural compounds (desert dusts and sea salts). In the CAMS framework such inputs are used as boundary conditions of the regional services, but they can also be used to support PM episode analysis in a regulatory reporting perspective. For example, periods of dust events impacting EU countries can be monitored, as the intensity of the events. Similarly, influence of forest fire emissions on air quality in the EU region can be investigated thanks to the CAMS Global Fire Assimilation System (GFAS) which provides everyday estimates of emissions from wildfires and biomass burning using satellite observations of the intensity of these fires. Interim air quality assessment reports (IAR) already take stock of these functionalities, but they could be directly used by the EEA or its Topic Centers to evaluate the potential impact of natural sources on air quality in Europe.

2.2 Copernicus Land Monitoring service - CLMS

The Copernicus Land Monitoring Service (CLMS) provides geographical information on land cover to a broad range of users in the field of environmental terrestrial applications. This includes information on land cover characteristics and changes, land use, vegetation state, water cycle and Earth surface energy variables. The CLMS has been jointly implemented by the European Environment Agency (EEA) and the EC's Joint Research Centre (JRC). CLMS consists of five main components:

- **Systematic biophysical monitoring** produces a series of qualified bio-geophysical products on the status and evolution of the land surface. This is produced at a global scale every ten days with a mid-spatial resolution and is complemented by a long-term time series. The products are used to monitor vegetation, crops, water cycle, energy budget and terrestrial cryosphere variables. It includes about 30 data sets which cover data on cryosphere, energy, vegetation, soil moisture and water.
- **Land cover and land use mapping** produces land cover classifications at various level of detail, both within a pan-European and global context. At the pan-European level, these are complemented by detailed layers on land cover characteristics, such as imperviousness, forests, grassland, water and wetness and small woody features. At global level, the land cover mapping follows the modular-hierarchical Land Cover Classification System of the Food and Agriculture Organization (FAO) of the United Nations. In Figure 2.3 the detailed thematic layers are visualized.
- **Thematic hot-spot mapping** aims to provide tailored and more detailed information on specific areas of interest, known as hot-spots. Hotspots in the context of CLMS are prone to specific environmental challenges. Hotspot monitoring focuses on high resolution data for specific areas of relevance because land use in those areas is very intense (e.g., Urban Atlas), or they are of high natural value (Natura 2000, Riparian – see Figure 4). These products are intended to support sustainable management of natural resources.
- **Imagery and reference data** provide satellite image mosaic display in high and very high resolutions and reference datasets. This includes, on the one hand, satellite image mosaic displays from contributing missions covering the territory of Europe as well as Sentinel-2 image mosaic production at global level. On the other hand, it consists of reference datasets providing homogeneous pan-European coverage of some key geospatial themes, such as hydrography and elevation.

In addition to the four above-mentioned components, a new European Ground Motion activity is being set up. The activity will measure ground displacements, including landslides and subsidence, as well as deformation of infrastructure.

Figure 2.3: Overview of CLMS products: detailed thematic layers (Dufourmont, 2018)

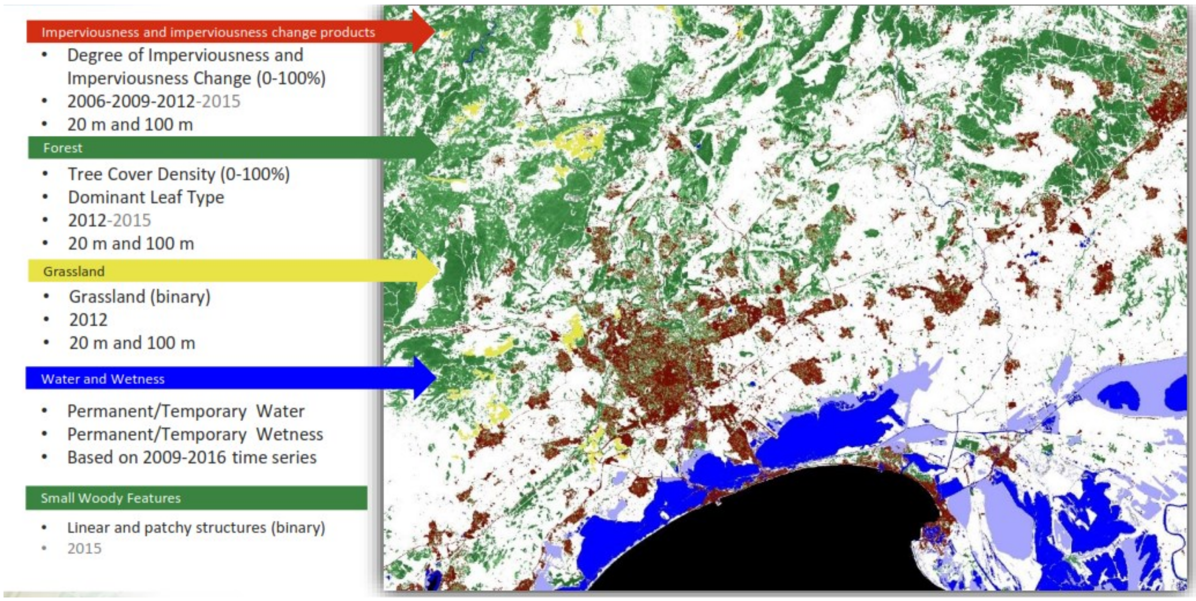
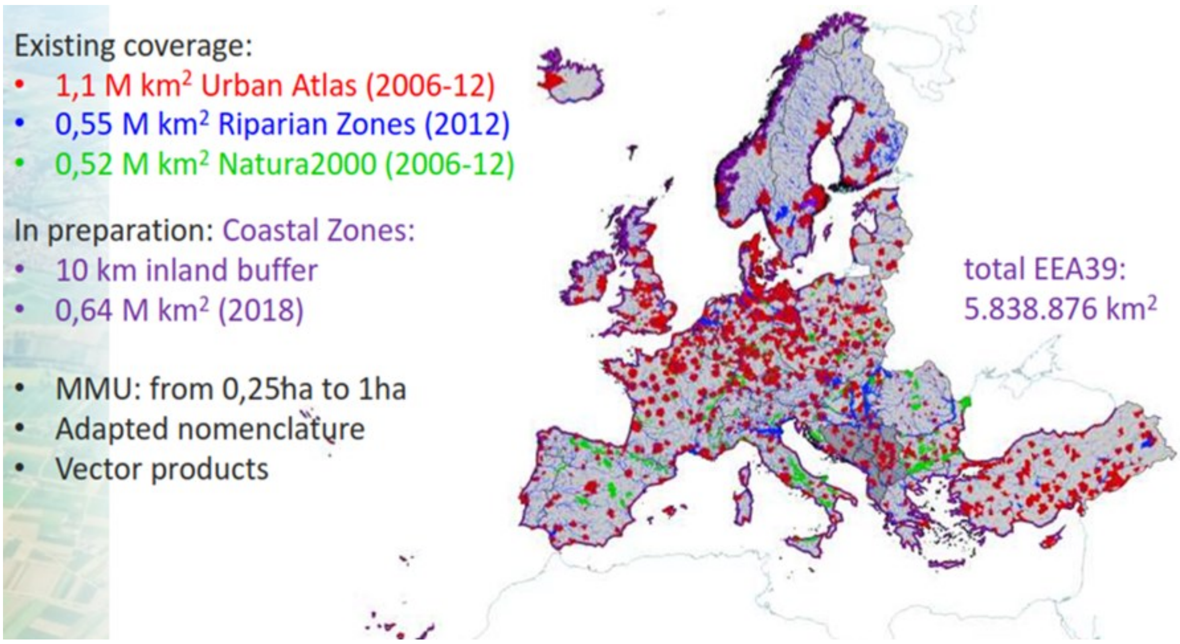


Figure 2.4: Characteristics and coverage of CLMS thematic hotspot mapping (Dufourmont, 2018). MMU: minimum mapping unit



2.2.1 Available products from CLMS

CLMS products have been used in almost all environmental topics at the EEA. The table below provides some examples.

Table 2.2: Example of uses of CLMS products in different environmental topics by the EEA

Topic	CLMS data	EEA product
Climate change adaptation	Corine Land Cover, Urban Atlas, Forest	Urban Adaptation Map Viewer This map viewer provides an overview of the current and future climate hazards facing the European cities, the Vulnerability of the cities to these hazards and their adaptive capacity. The map viewer collates information from various sources on the observed and projected spatial distribution and intensity of high temperatures, flooding, water scarcity and wildfires. https://climate-adapt.eea.europa.eu/knowledge/tools/urban-adaptation
Biodiversity-Ecosystems	Corine Land Cover	Natural capital accounting in support of policymaking in Europe (EEA, 2019a) Maintaining 'natural capital', i.e., ecosystems and the services they provide, is fundamental to human economic activity and well-being. The need to conserve and enhance natural capital is therefore an explicit policy target in the EU's Biodiversity Strategy to 2020 and its Seventh Environment Action Programme. Approaches to measuring the stocks of natural resources that yield benefits as natural capital have gained considerable traction in recent decades. By providing regular, objective data that are consistent with wider statistical data, natural capital accounting can provide the fundamental evidence base required for informing economic and environmental decision making that delivers on these ambitions for natural capital.
Biodiversity-Ecosystems	Corine Land Cover, HRL Imperviousness, HRL Grassland, HRL Small woody features	Mapping Europe's ecosystems (EEA, 2019d) The EU Biodiversity Strategy to 2020 calls on Member States to conduct a mapping and assessment of ecosystems and their services (MAES, Maes et al., 2013). As such, an EU-wide ecosystem assessment was launched to provide harmonized information on the condition of ecosystems and biodiversity, and their capacity to provide ecosystem services.
Urban environment	Urban Atlas	**Interactive map:** green infrastructure indicators Green infrastructure will play a key role in achieving EU policy objectives, especially when using nature-based solutions to preserve natural capital. Creating and improving the knowledge base remains one of the strategic developments for the implementation of the EU Strategy on green infrastructure.

Topic	CLMS data	EEA product
		https://www.eea.europa.eu/themes/sustainability-transitions/urban-environment/urban-green-infrastructure/urban-green-infrastructure-1
Land use	Corine Land Cover	Landscapes in transition (EEA, 2017b) The EEA report 'Landscapes in transition: an account of 25 years of land cover change in Europe,' takes a closer look at the emerging trends over the last two and a half decades in land use and their environmental impacts.

2.2.2 Current use of CLMS data at ETC/ATNI (and the former ETC/ACM)

Data provided by CLMS has been barely used in the context of the activities of ETC/ATNI and its predecessor ETC/ACM. This is partly explained by the fact that air quality and noise already have the corresponding Directives which require regular reporting from EU Member States. Moreover, the assessments are generally very much focussed on emissions and concentrations, or people exposed, which are remotely connected with the data provided by CLMS, as seen in Table 2.3: .

Table 2.3: Current status of use of CLMS products at ETC/ATNI

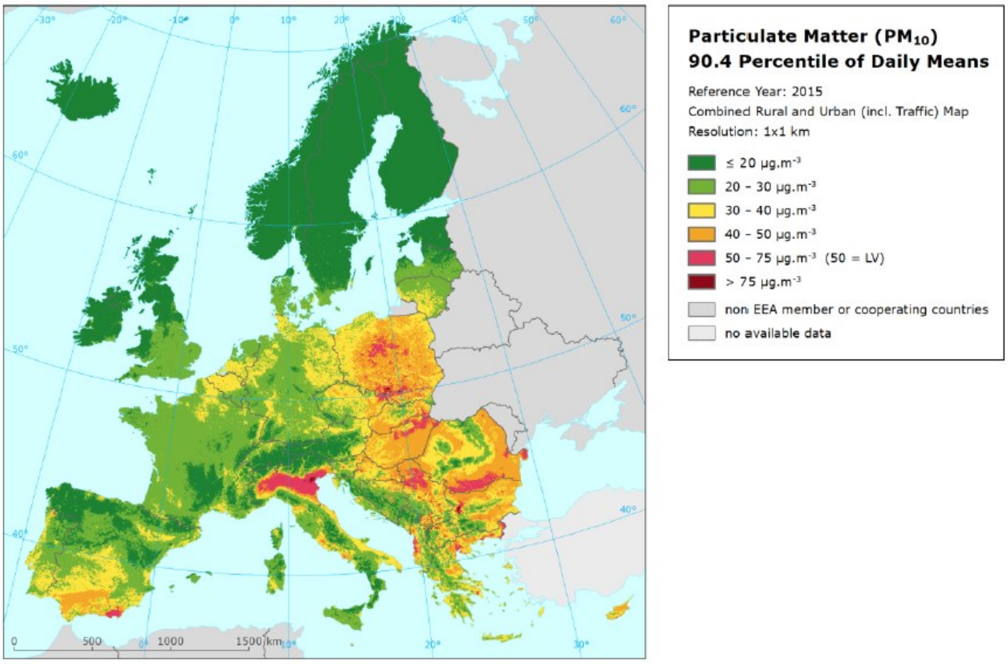
Area	Assessment	CLMS data sets			
		Corine Land Cover	Urban Atlas	Imperviousness	Natura 2000
Spatial air quality maps	Spatial air pollutant concentration (exposure) fields (basis for health impact assessments)	x			
Critical loads	Exposure of Europe's ecosystems to acidification, eutrophication and ozone (EEA CSI 005)	x			x
Transport	Landscape fragmentation	x		x	
	Land take				
Noise	Noise pollution as spatial concept		x		
	Quiet areas outside agglomerations	x			x

Area	Assessment	CLMS data sets			
		Corine Land Cover	Urban Atlas	Imperviousness	Natura 2000
	Quiet areas inside agglomerations	X (as proxy while latest version of Urban Atlas not available)	x		

2.2.2.1 Use of CLMS data for mapping air pollutant concentrations and population exposure

Corine Land Cover has been used for mapping air pollutant concentrations and population exposure. In particular, the distinction of monitoring stations between rural and urban is relevant for interpolation (kriging) and obtain a continuous map of Europe (see example below from Horálek et al., 2018a).

Figure 2.5: Concentration map of PM_{10} indicator 90.4 percentile of daily means combining land cover and traffic mapping. Source: Horálek et al., 2018a



2.2.2.2 Use of CLMS data for transport activities

There are two CLMS products that provide information on transport: Corine Land Cover and Urban Atlas (Table 2.4). Corine Land Cover has a full geographic extent, but its resolution only captures the wider networks and larger infrastructures. On the other side, Urban Atlas provide a higher resolution, but only for the Functional Urban Areas. Since the information on transport available at both Corine Land Cover and Urban Atlas is measured as an area, this data is not suitable for analysis of connectivity or accessibility between two points. Data on port and airport areas is more suitable to analyse the existing infrastructure and its change (expansion) over time.

Additionally, there is the Global Roads Inventory Dataset (GRIP)([14]) which provides highways, primary, secondary, tertiary, and local roads in vector format (latest available data from 2018).

Table 2.4: Land cover classes related to transport in Corine Land Cover and Urban Atlas

Properties	Corine Land Cover	Urban Atlas
Land cover class		
1.2.2 Road and rail networks and associated land	Minimum mapping unit 25 ha Minimum mapping width 100 m	Minimum mapping unit 0,24 ha Minimum mapping width • 10 m for rail • 6 m for road
1.2.3 Port areas	Minimum mapping unit 25 ha	Minimum mapping unit 0,25 ha Minimum mapping width 10 m
1.2.4 Airports	Minimum mapping unit 25 ha	Minimum mapping unit 0,25 ha Minimum mapping width 10 m
Coverage	EEA 39 (full geographic extent)	800 Functional Urban Areas (EEA 39)

The use of Copernicus products in transport activities is limited to two EEA indicators that are not exclusively focused on transport: a) Landscape fragmentation pressure from urban and transport infrastructure expansion. In that case an additional data set, the Open Street Maps, has been used to extract information on transport networks and b) Land take. The indicator assumes the limitations (or minimum mapping unit) of Copernicus Corine Land Cover (CLC).

Landscape fragmentation pressure from urban and transport infrastructure expansion([15])

Landscape fragmentation, as described in this indicator, is understood to be the physical disintegration of continuous ecosystems, habitats, or landscape units, excluding freshwater ecosystems (see Figure 2.7). Such disintegration into smaller sized units, or patches, is most often caused by urban and transport expansion.

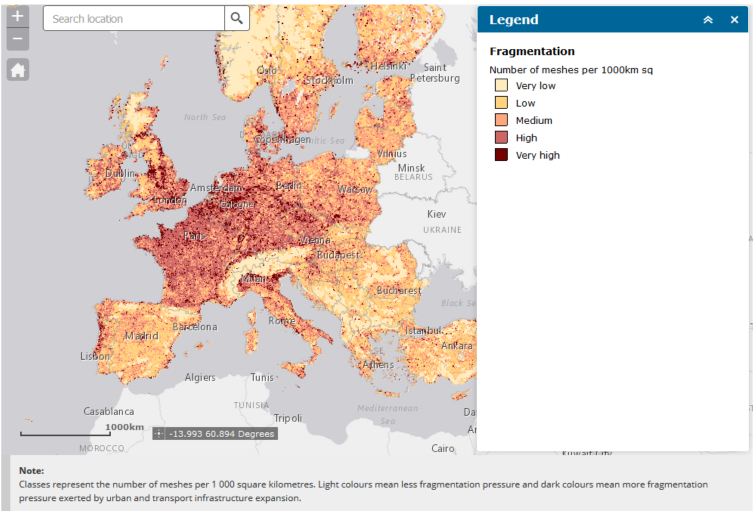
The methodology is based on the effective mesh size as described in Jaegger et al. (2011) and the following data is used:

- Copernicus High Resolution Layer (HRL) on Imperviousness Density (IMD)
- Copernicus Corine Land Cover
- Transport network derived from Open Street Map.

As has been explained before, the transport network is obtained from another source than Copernicus.

([14]) https://datacatalog.worldbank.org/dataset/grip-global-roads-inventory-dataset-2018-road-density.
([15])https://www.eea.europa.eu/data-and-maps/indicators/mobility-and-urbanisation-pressure-on-ecosystems/assessment.

Figure 2.6: Fragmentation pressure of urban and transport infrastructure expansion
Source: EEA, 2018b



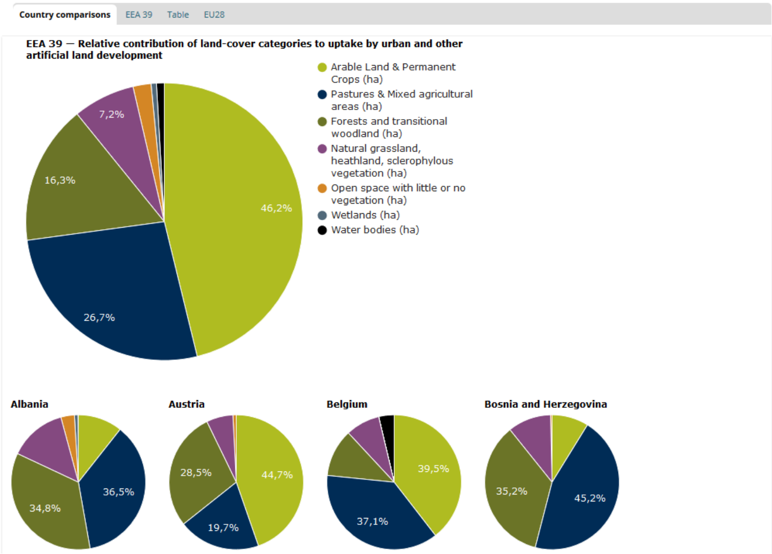
Land take

This indicator looks at the change in the amount of agricultural, forest and other semi-natural and natural land taken by urban and other artificial land development([16]). It includes areas sealed by construction and urban infrastructure, as well as urban green areas, and sport and leisure facilities. The main drivers of land take are grouped in processes resulting in the extension of housing, services, and recreation; industrial and commercial sites; transport networks and infrastructures; mines, quarries, and waste dumpsites; construction sites.

The indicator is based on Copernicus CLC following the EEA Land Accounting approach (see Figure 2.7). Land accounts track changes in the stock of different land cover types and analyse which land cover type conversions ('land cover flows') are the most important. Land accounts help us to understand the major trends that impact land and soil as key environmental resources.

([16]) https://www.eea.europa.eu/data-and-maps/indicators/land-take-2#tab-data-used.

Figure 2.7: Relative contribution of land-cover categories to uptake by urban and other artificial land development
Source: EEA, 2018c



2.2.2.3 Use of CLMS data in noise activities

The use of CLMS data sets is relevant for noise to better understand the context where noise pollution is occurring and to characterise quiet areas. These two topics have been developed in several EEA reports as described below.

Noise pollution as a spatial concept

Noise pollution is a spatially dependent phenomenon. Geographic information systems can help in the analysis of this pollutant and assist the understanding of how noise affects an ecosystem and its population. The location of noise sources as well as the analysis of the area exposed to different levels of noise can give an overall picture of where the major problems in the European territory are occurring. By analysing the noise contour maps, it is possible to identify where potential conflicts can be expected (e.g., high densely populated areas exposed to high levels of noise) and if more than one noise source is affecting the same area (e.g., major road and major railway running in parallel and affecting the same village), among others. This assessment was based on the Copernicus Hot-Spot Urban Atlas and was published in EEA's Noise in Europe report (EEA, 2014a). Examples are given in Figure 2.8 and Figure 2.9.

Figure 2.8: Land cover classes affected by noise (>= 55 dB) in Warsaw Chopin Airport
Source: EEA, 2014a

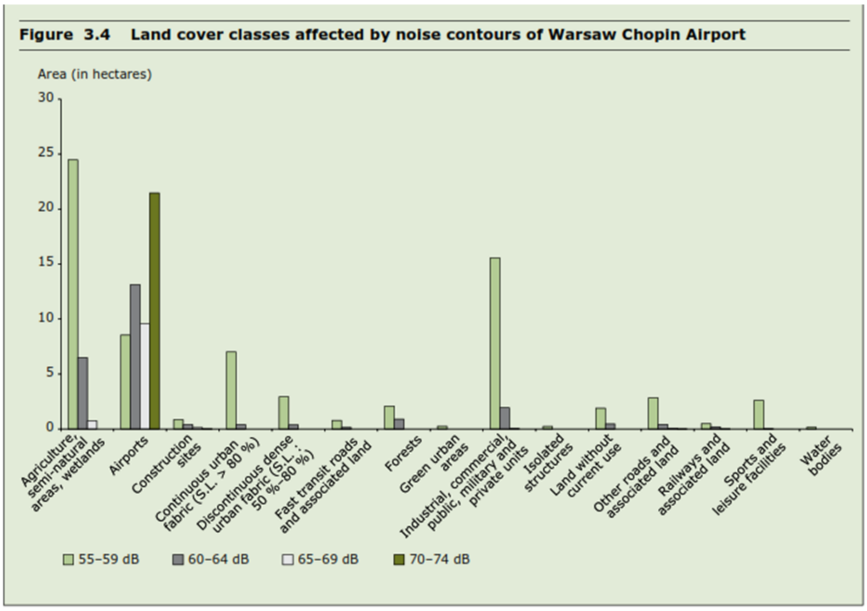
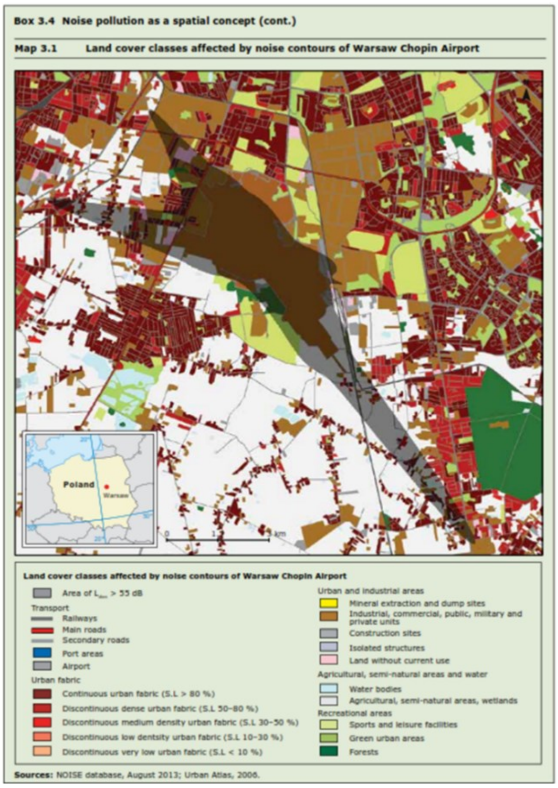


Figure 2.9: Land cover classes affected by noise >= 55 decibels (dB) in Warsaw Chopin Airport.-
Source: EEA, 2014a



Quiet areas outside of agglomerations

Noise pollution is a major problem for Europe's environment. Transport and industry are the main sources of concern and prolonged exposure can damage human health and adversely affect ecosystems. European legislation aims to reduce noise pollution and highlights the need to preserve areas that are currently unaffected. These so-called quiet areas are an important component of the European soundscape and may offer better areas away from noise pollution.

The EEA developed the Quietness Suitability Index (QSI, EEA, 2014b) to provide a tool to facilitate the identification of potential quiet areas in the European countryside in Europe. Copernicus CLC was used for the calculation of the QSI as shown in Figure 2.10 and Figure 2.11.

Figure 2.10: Methodological approach for the Quietness Suitability Index
Source: EEA, 2014b

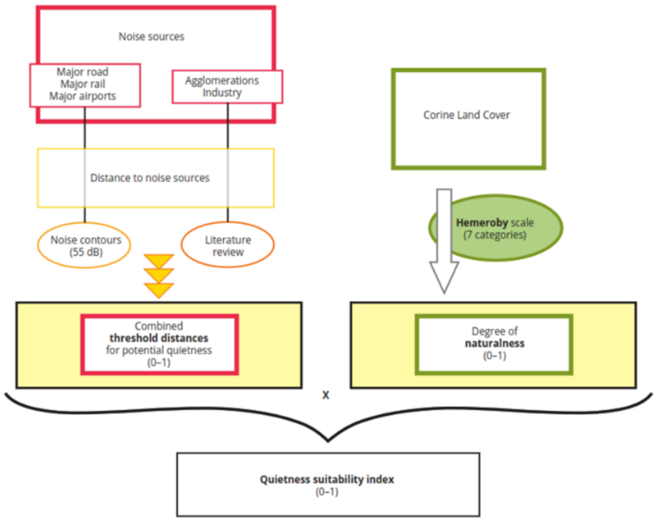
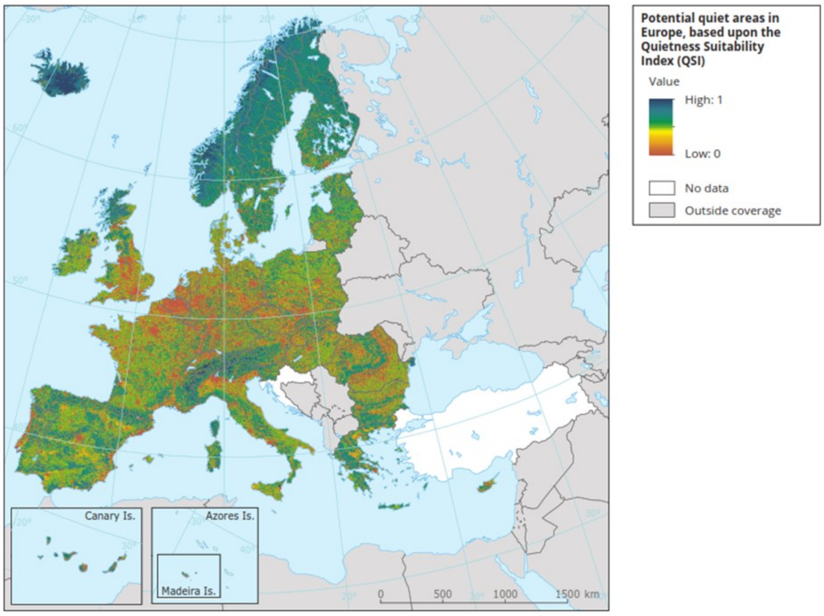


Figure 2.11: Potential quiet areas in Europe
Source: EEA, 2014b



Quiet areas inside agglomerations

As a follow up of the previous work on quiet areas in the countryside, a methodology is currently under development for quiet areas inside agglomerations. This geographic distinction is relevant since it is explicitly included in the Environmental Noise Directive, and it requires different approaches given the nature and objective in different contexts. Quiet areas inside agglomerations have a primary objective to improve quality of life of people, while quiet areas in the countryside have also a strong component related to conservation of biodiversity.

The methodology is currently based on Copernicus CLC (as shown in Figure 2.11) because this is the most recent land cover data available, which is needed to align with the noise data. However, the most suitable data would be the Copernicus Hot-Spot Urban Atlas, which it is expected to be used when an update will become available. The outcome of this assessment will be integrated in the forthcoming EEA's Noise in Europe report (publication planned for end of 2019). Some examples are given in Figure 2.12.

Figure 2.12: Methodology for the identification of quiet areas inside agglomerations
Source: ETC/ATNI, 2014a

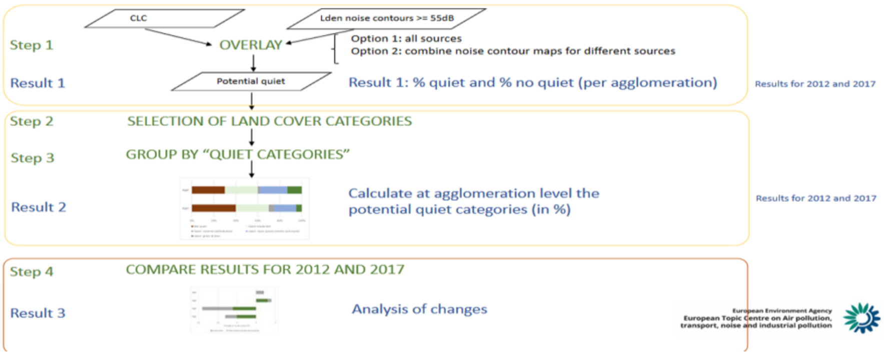
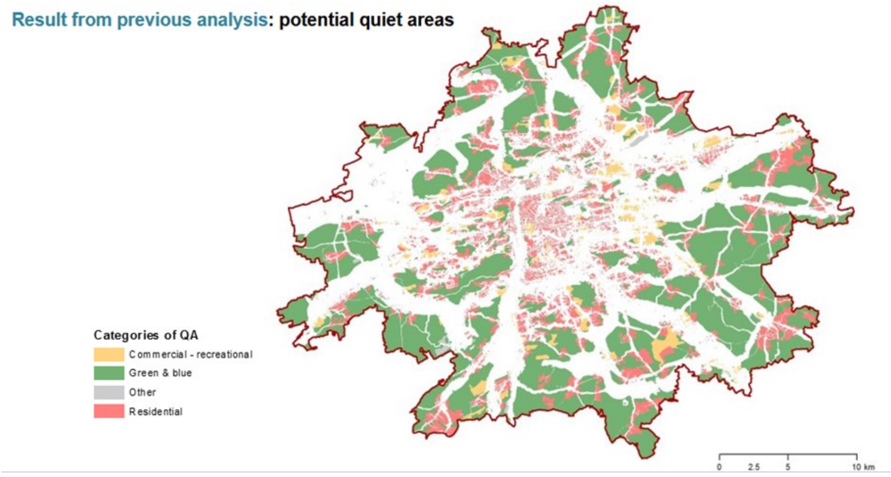


Figure 2.13: Land use of potential quiet areas in Prague. In white, areas not classified as quiet
Source: EEA, 2014b



2.2.2.4 Use of CLMS data in industrial activities at ETC/ATNI

At present there is not any reference on the use of CLMS data for industrial activities. However, it should be noted that both CLC and Urban Atlas include a class on industrial areas.

2.2.3 Perspectives for future use of CLMS products

There is growing recognition and awareness that nature can help providing viable solutions that use and deploy the properties of natural ecosystems and the services that they provide in a smart, 'engineered' way. These nature-based solutions promise to provide sustainable, cost-effective, multi-purpose and flexible alternatives for various objectives. Working with nature, rather than against it, can further pave the way towards a more resource efficient, competitive, and greener economy. It can also help to create new jobs and economic growth, through the manufacture and delivery of new products and services, which enhance the natural capital rather than deplete it.

In this context the Green Infrastructure Strategy recognises that the protection, restoration, creation, and enhancement of green infrastructure become an integral part of spatial planning and territorial development whenever it offers a better alternative, or is complementary, to standard ‘grey’ choices. Therefore, the assessment of status of green infrastructure, in urban areas, is of primary relevance as a response to some of the challenges addressed by ETC/ATNI, especially concerning air quality and noise pollution. Moreover, green infrastructure also allows to establish a direct link with health and quality of life from a multifunctional perspective.

So far green infrastructure has been addressed from two angles:

- General description and characterisation([17])
- Part of the quiet areas as described in the previous section

One of the major challenges of these assessments is its limitation to land use data from CLMS. There are important attributes that need to be further explored:

([17])https://www.eea.europa.eu/themes/sustainability-transitions/urban-environment/urban-green-infrastructure/urban-green-infrastructure-1.

- Density of green areas inside agglomerations
- Structure (height, differentiation of trees from other type of vegetation such as shrubs and grasses)
- Use of biophysical parameters like NDVI for better characterization (also to differentiate deciduous from perennial)

These elements could be derived from existing biophysical data or high-resolution layers provided by CLMS.

2.3 Copernicus Climate Change Service –C3S

The Copernicus Climate Change Service (C3S) provides high-quality information about the past, present and future climate in Europe and the rest of the World. The information at C3S relies on the existing infrastructure, knowledge, and competence from the established range of meteorological and environmental services that each European country already has in place and on the experience gathered over many years of operations at the European Centre from Medium-Range Weather Forecast (ECMWF), the coordinator of the service. It is also closely linked to climate research conducted within the World Climate Research Programme (WCRP) and secures maximum benefit by involving national climate service providers as well as relevant academic communities in the implementation of C3S.

Core efforts are dedicated to the dissemination and accessibility of existing climate data through the Climate Data Store (CDS). The CDS facilitates access to a wide range of quality-assured climate datasets including observations, historical climate data records, estimates of Essential Climate Variables (ECVs) derived from Earth observations, global and regional climate re-analyses, seasonal forecasts, and climate projections, in addition to data to support mitigation and adaptation strategies. It consists of three main elements: the CDS Toolbox, the CDS Application Program Interface (API) and the C3S Forum.

- The **CDS Toolbox** is an interactive service that allows users to browse and combine online considerable amounts of raw data, build their own applications, and create their own visualization maps and graphs online in real time.
- The **CDS API** is the Climate Data Store Application Program Interface, a programmatic service that allows direct machine access to the database. This service also includes explanations and examples showing how to program access to relevant climate information.
- Users of the CDS that access these tools and develop their own applications online can also join the **C3S Forum** for exchange of experiences and inter-action with other users.

Other key products from the Copernicus Climate Change Service include monthly and annual climate bulletins and information from demonstrator projects. The C3S demonstrator projects provide a large range of show-cases around key climate-related issues, where industrial partners and expert communities explore the use of the CDS data to help drive adaptation and mitigation solutions to climate change challenges in different sectors. Such demonstration and use cases involve different industrial sectors, including energy, water management and agriculture.

2.3.1 Available products from C3S, via the Climate Data Store (CDS)

Since the CDS launch in June 2018, the amount of climate data available from the system has been systematically increasing. The CDS is still far from complete but there is currently information available for a variety of climate datasets, including observations, reanalysis of past observations, seasonal forecasts, and climate model projections. There are still few observations (just 13 selected data sets of ECVs from satellite data) available in the CDS but there are plans to include in-situ observations in the course of 2019. The ERA Reanalyses are available in the CDS these are among the most-used datasets in geophysical sciences. These reanalysis of the global atmosphere and surface conditions combine past observations with models to generate consistent time series for a large set of climate variables and can potentially be very useful for EEA.

The following data and information are currently available in the CDS (May 2019), see Table 2.5.

Table 2.5: Overview of data currently available from the Climate Data Store

Monthly State of Climate information	Global Climate Reanalysis data	Seasonal Forecasts	Essential Climate Variables (ECVs)	Climate Projections
Average surface air temperature monthly maps from August 2015 onwards Monthly sea-ice maps from March 2017 Monthly summaries of precipitation, relative humidity, and soil moisture from April 2017 onwards Monthly and yearly State-of-the-European-climate reports (documentation)	ERA5 data (1950 to present) ERA-Interim data (1979 to present) UERRA regional reanalysis for Europe (1961 to present)	MSLP charts SST maps NIÑO-index time-series 2m Temperature charts 850mb Temperature charts Geopotential height at 500Pa charts Precipitation charts	Sea ice concentration sea ice edge and type, sea ice thickness Sea level Sea surface temperature (SST) Ozone Total column and vertical aerosol information Carbon dioxide and methane Soil moisture Glaciers and ice caps Surface albedo, leaf area index (LAI) and the fraction of absorbed photosynthetic active radiation (FAPAR)	CMIP5 data, daily and monthly, on pressure levels and single levels

In addition to the raw climate data, the Copernicus Climate Change Service includes showcase applications that use the comprehensive set of software available from the CDS toolbox. The data from the showcase applications is still not available at the CDS, but the plan is to include such data also in the CDS as they become available. The showcases currently under development include a set of sectoral applications, such as energy, water management, tourism. They constitute the so-called Sectoral Information System (SIS) component of C3S. The SIS consists of several applications that demonstrate how climate data can be accessed, transformed, and made relevant to address specific climate- relevant questions. The following cases are currently under development:

- **ENERGY Sector**: European Climatic Energy Mixes (ECEM) and CLIM4ENERGY
- **INSURANCE Sector:** Windstorm Climate Service (WISC)
- **AGRICULTURE & FORESTRY Sector**: Agricultural Climate Advisory services (AgriCLASS)
- **HEALTH and INFRASTRUCTURE Sector**: Climate Information for European Cities (Urban SIS)
- **WATER Sector**: End-to-end Demonstrator for improved decision making in the water sector in Europe (EDgE) and Service for Water Indicators in Climate Change Adaption (SWICCA).

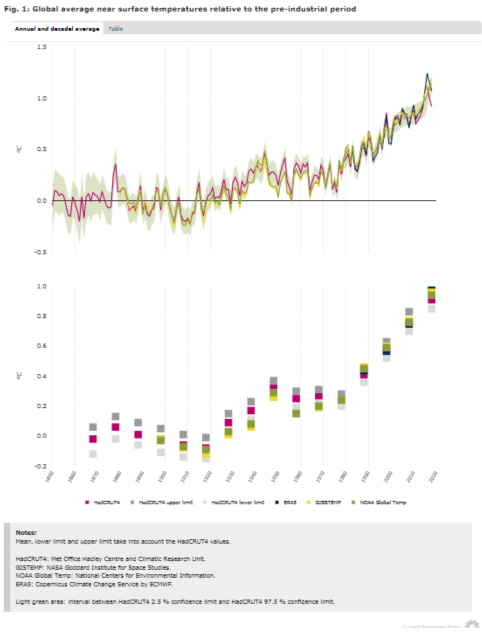
2.3.2 Current use of C3S data at ETC/ATNI

Copernicus meteorological trend data from C3S has been used as meteorological input data for the trend work conducted in the ETC/ATNI. The ETC/ATNI evaluation of air concentration trends over time aims at identifying the reasons behind the observed trends (Colette et al., 2018; Solberg et al., 2018a), and conclude whether these are either due to emission controls or to meteorological variability. The ETC/ATNI trend work relies primarily on the air quality monitoring data reported to EEA, and additionally, it relies on sensitivity model runs to determine the relative influence of meteorological and emission data on the observed trends. To that purpose, the meteorological trends from the climate re-analysis data set called 'ECMWF ReAnalysis', fifth global reanalysis produced by ECMWF (ERA 5) serve as input for the CHIMERE model runs used to interpret the reasons behind the trends in observed air quality monitoring data.

The use of meteorological trend data from the climate re-analysis dataset ERA5 as input for the determination of in air pollution trends is currently the only reported use of C3S data at the ETC/ATNI.

Otherwise, physical meteorological data is used directly as input for indicator work, as shown in Figure 13 (EEA indicator ‘Global average near surface temperatures relative to the pre-industrial period’.

Figure 2.14: Use of C3S data as basis for meteorological indicator data
Source: EEA, 2019a



2.3.3 Perspectives for future use of C3S products

Climate adaptation and mitigation activities will largely profit from including information of the Sectoral Information System (SIS) component of C3S. For the ETC/ATNI activities, a key focus of climate adaptation and mitigation is urban sustainability. The current aim to promote climate neutral cities with improved quality of life requires the development of appropriate indicators to trace evolution towards these sustainability goals. C3S data can support the development of such indicators. Parameters such as temperature, wind and relative humidity from the Copernicus Climate Change service could be used to determine thermal comfort in European cities. The information could be combined with physical building and land-use information from Sentinel 2. Other external datasets could also be included, including data on socio-economic and demographic variables, to explore spatial associations between dimensions of social vulnerability and environmental pressures in urban areas.

The recommendation is thus to investigate the use of Copernicus data for developing urban sustainability indicators. This implies the combination of data from CAMS, CLMS and C3S services, in addition to Sentinel 1 and Sentinel 2 data in order can provide a series of layers of relevant information to facilitate the creation of an urban environmental sustainability indicator.

3 Links to Copernicus Satellite data

Due to the proliferation of satellite instruments in recent decades, Earth observation (EO) data has become ubiquitous. Particularly the European Copernicus programme with its space component (EC, 2015) and its series of Sentinel satellites for a wide variety of applications is currently adding significantly to the global observing capacity, averaging currently at approximately 4 Terabytes of data per day. This number will further increase over the coming years with several more satellites being launched and the Copernicus Space Component nearing completion. EO is defined by the Group on Earth Observations (GEO) as data collected about the Earth system, ranging from atmospheric through terrestrial to oceanic (GEO, 2016). In its broadest definition such data includes observations from Earth-observing satellites, aircraft-borne instruments, and ground- and water-based instruments. In standard usage, however, the term EO is typically used to refer to satellite instruments and this is the scope of the term we will adhere to within this document.

Air quality is one of the focus areas of the European Topic Centre on Air pollution, Transport, Noise, and Industrial pollution (ETC/ATNI). Despite considerable improvements in the past decades, Europe is still far from achieving levels of air quality that do not pose unacceptable hazards to humans and the environment. Main concerns in Europe are exceedances of particulate matter (PM), ground-level ozone (O_3), benzo(a)pyrene (BaP) and nitrogen dioxide (NO_2) limit or target values (EEA, 2019c). While overall sulphur dioxide (SO_2) emissions have decreased in recent years, regional concentrations can still be high in some areas. Carbon monoxide (CO) represents a relatively minor air pollution problem in Europe, but during wildfires CO levels can be significantly elevated.

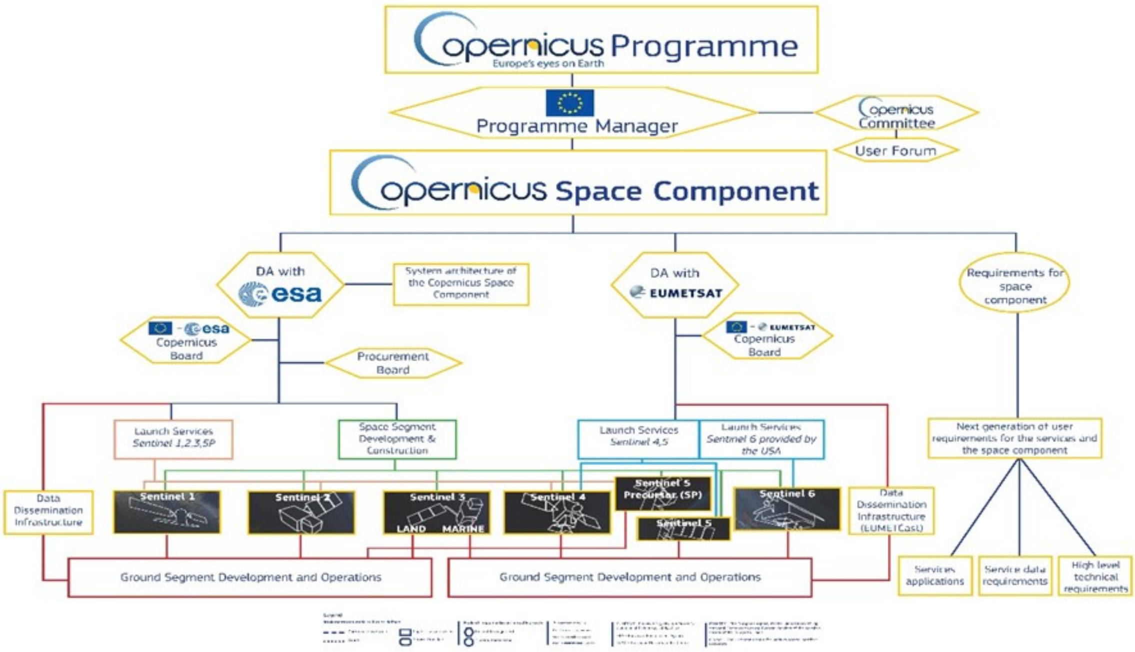
As part of the legislative Framework of ambient air quality protection within the European Union, air quality monitoring in Europe is carried out by a monitoring network of stations equipped with reference instrumentation. The characteristics of this network are defined by the EU Ambient Air Quality Directives (2004/107/EC, 2008/50/EC and (EU) 2015/1480). Compared to the surface air quality monitoring network, EO data has tremendous potential to increase our observing capacity of air pollution, primarily through an increase in spatial coverage. This expansion in spatial coverage offers the possibility to improve our knowledge of air pollution and its related processes as well as improving our ability to forecast air quality operationally. EO measurements of air quality are not without limitations, however. Typical data products from EO satellites provide measurements of atmospheric composition as column-integrated values and are not directly comparable to surface observations at air quality monitoring stations. This is the case, for example, for NO_2 products, where the data is given in the number of NO_2 molecules in the troposphere per square centimetres, or for aerosol([18]) optical depth (AOD). Note that at this point no EO satellite instruments are capable directly of measuring particulate matter (PM) concentrations - such estimates can only be derived from AOD products with the help of statistical or physical models. Instruments on board low Earth orbit (LEO) satellites are further limited by lower observing frequency (generally daily under cloud-free conditions) compared to the surface observing network, which somewhat limit their utility for air quality monitoring. Geostationary (GEO) satellite missions aim to reverse this drawback and multiple such missions are upcoming in the next several years. Further limitations affect instruments in both LEO and GEO orbits: limited spatial resolution of the observations, and, of key importance for certain trace gases (aerosols are less affected by this limitation), the sensitivity of these types of instruments to trace gases at the surface, in the boundary layer, and the lower troposphere.

([18]) An aerosol is a suspension of fine solid particles or liquid droplets in the air.

Here we

- present an overview of relevant satellite products from the Copernicus Space Component and other sources,
- provide a summary of the current use of EO data within the ETC/ATNI,
- discuss potential future applications of EO data with a particular focus on those from the Copernicus Space Component within the work of the ETC/ATNI, and finally
- summarize the current status quo of EO-derived emission estimates.

Figure 3.1: The organisation of the Copernicus Space Component.
Source: Copernicus. Europe's eyes on Earth



3.1 Overview of satellite data available for ETC/ATNI

EO satellites have been orbiting the Earth for many decades and a vast amount of data has been collected on a wider variety of geophysical variables. In the following we present a short overview of the satellites that are currently or will soon be operated as part of the Copernicus Space Component (EC, 2015), summarize the use of Copernicus satellite data within three relevant Copernicus Services, and briefly discuss non-Copernicus satellite instruments that might be relevant for the work within ETC/ATNI.

3.1.1 The Copernicus Space Component

One of the most ambitious recent operational EO initiatives is the Space Component of the European Copernicus programme (EC, 2015). Copernicus is a large-scale programme for providing a global, high-quality, continuous and wide-range EO capability, and is coordinated and managed by the European Commission in partnership with the European Space Agency (ESA) and the EU Member States. With a set of state-of-the-art satellite instruments dedicated to all major components of the Earth system including the land surface, the atmosphere, and the oceans, and with funding secured for several decades of operations, the Copernicus Space Component provides a robust long-term perspective for the global space-based observing system (Berger et al., 2012).

The following Table 3.1 provides an overview of the operational and planned Sentinel missions within the Space Component of the Copernicus programme. For more details see the following sections with short descriptions of each mission.

Table 3.1: Overview of the operational and planned Sentinel missions as part of the Copernicus Space Component

Satellite (series)	Launch	Short description
Sentinel-1	2014/2016	Synthetic aperture radar for all-weather land and ocean applications.
Sentinel-2	2015/2017	High-resolution imagery in the visible, near-, and shortwave infrared. Mainly land surface applications.
Sentinel-3	2016/2018	Ocean- and land imaging in the visible, near-, shortwave-, and thermal infrared at medium resolution with daily coverage.
Sentinel-4	ca. 2023	Atmospheric composition, geostationary orbit, Europe only, hourly sampling.
Sentinel-5P	2017	Atmospheric composition, low-earth orbit, global, daily coverage.
Sentinel-5	ca. 2023	Atmospheric composition, low earth orbit global, daily coverage.
Sentinel-6	Launched sequentially ca. 2020/2026	Radar altimeter for high-precision altimetry, primarily for sea surface topography applications.

Sentinel-1

The Sentinel-1 mission (Torres et al., 2012) is a constellation of two satellites sharing the same orbital plane. Currently these satellites are Sentinel-1A and Sentinel-1B, which in future will be complemented/replaced with Sentinel-1C and Sentinel-1D. Sentinel-1A was the first satellite to be launched as part of Copernicus Space Component in April 2014. The primary payload instrument on-board of the Sentinel-1 satellites is a C-band imaging synthetic aperture radar (SAR). Using radar wavelengths (in this case around 5.4 GHz) has the major advantage of providing information about the Earth surface both day and night without being affected by the presence of clouds. The instrument provides multiple imaging modes with a spatial resolution of up to 5 m and a swath width of up to 400 km. Typical applications of Sentinel-1 data are land- and sea monitoring, natural disasters mapping, sea ice observations, ship detection, and soil moisture mapping.

Sentinel-2

Sentinel-2 is Copernicus' mission designed for acquiring high-resolution optical (visible to shortwave infrared wavelengths) imagery at high spatial resolution about 10 m to 60 m (Drusch et al., 2012). Currently two Sentinel-2 satellites, labelled Sentinel-2A and Sentinel-2B are in orbit, launched in June 2015 and March 2017, respectively. Each satellite only carries a single payload instrument, namely the Multi-Spectral Instrument (MSI). The instrument has a field of view of 290 km and provides a revisit time of 5 days under the same viewing conditions. It measures the electromagnetic spectrum in 13 bands ranging from 442 nm to 2202 nm. The primary applications of Sentinel-2 data include land management, agriculture and forestry, disaster control, humanitarian relief operations, coastal water mapping, risk mapping, and security.

Sentinel-3

The series of Sentinel-3 satellites (Donlon et al., 2012) are primarily designed for marine applications but also have significant applications for the land surface. Currently two Sentinel-3 satellites are in orbit. Sentinel-3A was launched in February 2016 and Sentinel-3B was launched in April 2018. Each Sentinel-3 satellite carried primary instruments, namely the Ocean and Land Colour Instrument (OLCI), the Sea and Land Surface Temperature Instrument (SLSTR), the SAR Radar Altimeter (SRAL), and the Microwave Radiometer (MWR). The primary variables that are observed include sea surface topography, sea and land surface temperature, and ocean and land surface color. Additional important products are aerosol optical depth and fire radiative power.

Sentinel-4

Sentinel-4 is a planned geostationary mission dedicated to measuring atmospheric composition over Europe at hourly sampling (Ingmann et al., 2012). The Sentinel-4 mission will be included on-board Meteosat Third Generation platforms MTG-I and MTG-S and will provide two main instruments, namely the S4 UVN Multispectral Spectrometer and the Infra-Red Sounder (IRS). The mission is expected to provide hourly data over Europe of the key air quality parameters NO_2 (nitrogen dioxide), O_3 (ozone), SO_2 (sulphur dioxide), HCHO (formaldehyde), CHOCHO (glyoxal), and aerosols. Currently the launch of Sentinel-4 is planned for 2023.

Sentinel-5P

Sentinel-5P is a Precursor mission to Sentinel-5 (Veefkind et al., 2012). It was designed to bridge the gap between heritage instrument such as for example SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) on Envisat, which ceased operating in 2012, and Sentinel-5, which is currently planned to be launched in 2023. Sentinel-5P was launched in October 2017. It provides one primary payload instrument called TROPOMI (TROPOspheric Monitoring Instrument), which measures in the ultraviolet (UV), visible (VIS), near (NIR) and short-wavelength infrared (SWIR) at very high spectral resolution. The resulting spectra are used to derive information about key atmospheric species, including NO_2, O_3, CO, HCHO, SO_2, CH_4, as well as the UV aerosol index and aerosol layer height, and information on cloud and UV radiation. TROPOMI provided these products initially at already unprecedented spatial resolution of ca. 7 km by 3.5 km at nadir at nearly daily global coverage. Due to the good signal-to-noise ratio of the instrument the spatial resolution has been further improved to ca. 5 km by 3.5 km at nadir on 6 August 2019. For more details on Sentinel-5P/TROPOMI and the operational products it provides see Section 3.3.4.

Sentinel-5

The Sentinel-5 mission will be the main operational low earth orbit atmospheric composition mission of Copernicus (Ingmann et al., 2012). It will be included on-board of the Meteosat Third Generation platform with the launch currently scheduled for the year 2023. While the overall mission shares some similarities with the Sentinel-5P mission, the two instruments are developed with somewhat different requirements and as such are not identical. There might be some differences in terms of the data products to be delivered. Due to sharing the downlink bandwidth with other instruments on board, the atmospheric composition products provided by Sentinel-5 will not reach the same spatial resolution as Sentinel-5P. It is currently planned to be 7.5 km by 7.5 km at nadir. It is planned to launch three Sentinel-5 instruments in sequence, thus providing an overall mission lifetime of at least 21 years.

Sentinel-6

The Sentinel-6 mission is a future constellation of two satellites to be launched sequentially ca. in 2020 and 2026 (Scharroo et al., 2016). The satellites will carry a radar altimeter and will be able to provide high-precision measurement on the topography of the sea surface. In addition, they will provide information on ocean currents, wind speed, and wave height.

Sentinel-7 (unconfirmed)

The European Commission and the European Space Agency are considering extending the current observing capacity of the Copernicus Space Component with additional satellite platforms. If it is decided to be built and launched, there is currently a relatively high probability that Sentinel-7 could become a constellation of satellites monitoring carbon dioxide (CO_2) at relatively high spatial resolution and providing close to daily global coverage.

3.1.2 Non-Copernicus satellite data relevant for ETC/ATNI

In the following we will give a short summary of satellite instruments relevant for the work in ETC/ATNI that are operated outside the European Copernicus program. Due to the very large number of earth observation satellites in general such an overview must be by its very nature incomplete. We focus here primarily on some instruments providing data products related to air quality applications and to a couple of general-purpose instruments that provide a wide array of products and a long archive of data.

3.1.2.1 Instruments dedicated to atmospheric composition

OMI

Operational satellite remote sensing of atmospheric composition has been conducted since 1995 when the Global Ozone Monitoring Experiment (GOME) (Burrows et al., 1999; Richter and Burrows, 2002) was first launched. Beginning in 2002, the observations were continued by the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY) sensor on-board of the Envisat platform (Bovensmann et al., 1999; Gottwald et al., 2011), and subsequently complemented in 2004 by the Ozone Monitoring Instrument (OMI) (Levelt et al., 2006) on-board of the Aura satellite operated by the National Aeronautics and Space Administration (NASA). OMI is based on the experiences acquired from both GOME and SCIAMACHY and combines their advantages, measuring the complete spectrum in the ultraviolet/visible spectrum wavelength range at a comparatively high spatial resolution of 13 km × 24 km, while providing daily global coverage. The OMI instrument is flying on the National Aeronautics and Space Administration’s Earth Observing System Aura platform as part of the A-train constellation of satellites. OMI has an equator crossing time of approximately 13:30 LST in the afternoon, and therefore probes the Earth’s atmosphere under different conditions than its heritage instruments. Aura/OMI was launched in 2004 and has been continuously providing data, providing an unprecedented single sensor record of atmospheric composition of over 15 years. Beginning in June 2007, OMI has suffered from several row anomalies, resulting in a reduced number of usable observations per orbit. While it is likely that the Aura platform with the OMI instrument will reach the end of its lifetime in the upcoming years, its long consistent record of data on atmospheric composition and air quality is still of relevance for ATC/ATNI tasks concerned with atmospheric composition, and nicely complements current missions like Sentinel-5P backwards in time.

GOME-2

The Global Ozone Monitoring Experiment-2 (GOME-2) (Munro et al., 2006) has a similar heritage as OMI described above. GOME-2 is a scanning spectrometer on-board of the MetOp series of satellites. As a modified and improved successor of ERS-2's GOME instrument, GOME-2 measures in a spectral range of 240 nm to 790 nm with a varying spectral resolution between 0.24 nm and 0.53 nm (Callies et al., 2000). Its main drawback in comparison to the OMI instrument on Aura or the TROPOMI instrument on Sentinel-5P is its very coarse spatial resolution of 80 km by 40 km. While this spatial resolution makes GOME-2 unsuitable for local-scale applications, its data can still be valuable for continental-scale or global-scale applications.

AIRS

The Atmospheric Infrared Sounder (AIRS) instrument on the NASA-operated Aqua satellite has been providing operational data on weather and climate since the year 2002. It provides validated data products on the three-dimensional physical state of the atmosphere (air temperature, water vapor, clouds) and the distribution of trace gas constituents O_3, CO, CO_2 and CH_4,). Just like the MODIS instrument (please see below under 3.1.2.2) it has long exceeded its planned lifetime so the instrument could potentially fail in the near future, however even then AIRS' very long data record will still make it very valuable for working with historical data.

IASI

The Infrared Atmospheric Sounding Interferometer (IASI) instrument is a Fourier transform (FT)([19]) spectrometer flying on the series of MetOp satellite operated by Eumetsat. It provides height-resolved information on temperature and humidity of the troposphere and lower stratosphere. It further measures fractional cloud cover and cloud top temperature and provides the total amount of zone and the column-integrated content of carbon monoxide, methane, and nitrous oxide.

OCO-2

The Orbiting Carbon Observatory-2 (OCO-2) is a NASA-operated instrument with the primary goal of making high-precision measurements of CO_2at comparatively high spatial resolution of 1.29 km × 2.25 km at nadir, although at quite narrow swaths of approximately 10 km.

GOSAT

The Greenhouse Gases Observing Satellite (GOSAT) is a mission developed and operated by the Japan Aerospace Agency (JAXA). Launched in 2009, the satellite with its TANSO-FTS and TANSO-CAI instruments has been providing measurements of $CO_2$and CH_4. In contrast to OCO-2 it provides a much better spatial coverage; however, its spatial resolution is significantly coarser.

3.1.2.2 Relevant general-purpose instruments

MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a twin instrument on both the Terra and Aqua platforms built and operated by NASA. It has been providing a wide variety of data products, including data on vegetation, land surface, and the atmosphere. The MODIS instruments have been providing data in an operational fashion since the year 2000. While they are still functioning very well at this point, they have long exceeded the planned lifetime and it is quite possible that the data stream

([19]) FT decomposes a function of time (a signal) into its constituent frequencies.

from the instruments will stop or be limited in the next few years. However, due to its already long consistent data record and the wide variety of data products, the instrument will likely continue to be a workhorse for historical periods.

VIIRS

The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on-board the Suomi-NPP platform operated by the United States National Oceanic and Atmospheric Administration (NOAA) is a scanning radiometer that provides a wider variety of EO products related to the land, the atmosphere, the cryosphere, and the oceans. The platform was launched in 2011 and as such the instrument has already been providing close to a 10-year record of data.

SEVIRI

The Spinning Enhanced Visible and Infra-red Imager (SEVIRI) is an instrument onboard of the geostationary Meteosat Second Generation satellites. They provide 12 spectral channels between the visible range the thermal infrared and have a repeat cycle of 15 minutes while sampling at 3 km spatial resolution (at the sub-satellite point). The primary mission objectives are meteorological; however, some products are available for volcanic ash and AOD (e.g., Zawadzka and Markowicz, 2014).

3.1.3 EO products currently used in the Copernicus Services (CAMS, CLMS, C3S)

3.1.3.1 Copernicus Atmosphere Monitoring Service

The satellite products currently assimilated in CAMS regional systems include NO_2 and SO_2 column retrievals from Aura/OMI and MetOp/GOME-2, MOPITT CO profiles, and IASI CO partial columns. In the global systems the use of satellite data is more comprehensive as indicated in the tables below from the CAMS's website at https://atmosphere.copernicus.eu/satellite-observations. CAMS also uses satellite observations to estimate daily emissions from wildfires and biomass burning, to provide time series of incoming solar energy for any location in the world and to monitor the exchange of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) at the surface of the Earth.

Table 3.2. Satellite observations that are assimilated in the global real-time forecast system.

Instrument	Satellite	Space Agency	Data Provider	Species
MODIS	EOS-Aqua, EOS-Terra	NASA	NASA	AOD
MLS	EOS-Aura	NASA		O_3 profile
OMI	EOS-Aura	NASA	KNMI	O_3, NO_2, SO_2
SBUV-2	NOAA-19	NOAA	NOAA	O_3 profile
IASI	METOP-A, METOP-B	EUMETSAT/CNES	ULB/LATMOS	CO
MOPITT	EOS-Terra	NASA	NCAR	CO
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	AC-SAF	O_3, NO_2, SO_2
OMPS	Suomi-NPP	NOAA	EUMETSAT	O_3
PMAp	METOP-A, METOP-B	EUMETSAT	EUMETSAT	AOD
TROPOMI	Sentinel-5p	ESA/NSO	ESA/KNMI/DLR	O_3

Table 3.3. Satellite observations that are monitored in the global real-time forecast system.

Instrument	Satellite	Space Agency	Data Provider	Species
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	AC-SAF	HCHO
TROPOMI	Sentinel-5p	ESA/NSO	ESA/KNMI/DLR	NO_2, SO_2, CO, HCHO
SEVIRI	METEOSAT	EUMETSAT	LandSAF	O_3

Table 3.4. Satellite observations that are planned for the global real-time forecast system.

Instrument	Satellite	Space Agency	Data Provider	Species
TROPOMI	Sentinel-5p	ESA/NSO	ESA/KNMI/SRON/DLR	CH_4
SLSTR	Sentinel-3	ESA/EUMETSAT	EUMETSAT	AOD/FRP
IASI	METOP-A, -B	EUMETSAT/CNES	ULB/LATMOS	O_3
AHI	Himawari-8	JMA	JMA	FRP
VIIRS	Suomi NPP	NASA/NOAA	EUMETSAT	AOD
SEVIRI	MSG	EUMETSAT	ICARE	AOD

Table 3.5. Satellite observations that are assimilated in the global delayed-mode system.

Instrument	Satellite	Space Agency	Data Provider	Species
TANSO	GOSAT	JAXA	SRON	CH_4
TANSO	GOSAT	JAXA	U. of Bremen	CO_2
IASI	METOP-A/B	EUMETSAT/CNES	LMD	CH_4

Table 3.6. Satellite observations that are planned for the global delayed-mode system.

Instrument	Satellite	Space Agency	Data Provider	Species
OCO-2	OCO-2	NASA	NASA	CO_2
IASI	METOP-A/B	EUMETSAT/CNES	LMD	CO_2

.

Table 3.7. Satellite observations that are assimilated in the global reanalysis.

Instrument	Satellite	Space Agency	Data Provider	Species
MODIS	EOS-Aqua, EOS-Terra	NASA	NASA	AOD
AATSR	ENVISAT	ESA	ESA	AOD
MLS	EOS-Aura	NASA		O_3 profile
OMI	EOS-Aura	NASA	KNMI	O_3, NO_2
SBUV-2	NOAA-14, -16, -17, -18, and -19	NOAA	NOAA	O_3 profile
SCIAMACHY	ENVISAT	ESA	KNMI	O_3, NO_2, CH_4, CO_2
MIPAS	ENVISAT	ESA	ESA	O_3 profile
MOPITT	EOS-Terra	NASA	NCAR	CO
GOME-2	METOP-A/B	EUMETSAT/ESA	AC-SAF	O_3, NO_2
TANSO	GOSAT	JAXA	SRON/ U. of Bremen	CO_2, CH_4
IASI	METOP-A, METOP-B	EUMETSAT	EUMETSAT	CO_2, CH_4

Table 3.8. Satellite observations that are used in GFAS - CAMS Global Fire Assimilation System.

Instrument	Satellite	Space Agency	Data Provider	Species
MODIS	EOS-Aqua, EOS-Terra	NASA	NASA	FRP

Table 3.9. Satellite observations that are planned for GFAS.

Instrument	Satellite	Space Agency	Data Provider	Species
SEVIRI	MSG	EUMETSAT	EUMETSAT	FRP
Imager	GOES-E, GOES-W	NOAA		FRP

Table 3.10. Satellite observations that are used in GHG flux inversions.

Instrument	Satellite	Space Agency	Data Provider	Species
TANSO	GOSAT	JAXA	SRON	CH_4

Table 3.11. Satellite observations that are planned for the GHG flux inversions

Instrument	Satellite	Space Agency	Data Provider	Species
OCO-2	OCO-2	NASA	NASA	CO_2

Table 3.12. Satellite observations that are used in the solar radiation service

Instrument	Satellite	Space Agency	Data Provider	Species
SEVIRI	MSG	EUMETSAT	EUMETSAT	Cloud information

3.1.3.2 Copernicus Land Monitoring Service

The main EO products used in CLMS are Image 2012 and Image 2018. Both are composed by a pan-European multi-temporal ortho-rectified satellite imagery covering all 39 participating countries in Corine Land Cover with 12 nautical miles' sea buffer, with all spectral bands and cloud masking. The specifications are provided below.

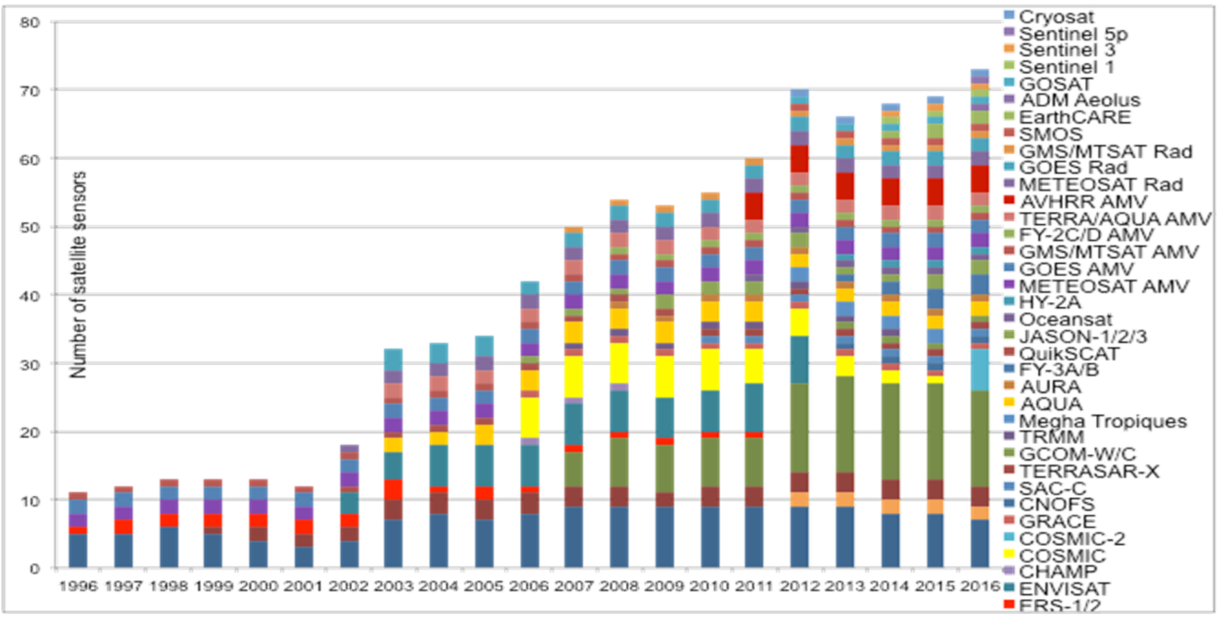
Table 3.13. Specifications for the main satellite Image 2012 and Image 2018 products used in CLMS.

	IRS Resourcesat 1,2 (coverage-1)	RapidEye (coverage-2)	SPOT-4 and SPOT-5 (coverage-1 and 2)
swath width (km)	141	20	60 – 80 (depending on looking angle)
No. of bands	4	5	4
bands	Green, red, NIR, SWIR	Blue, green, red, red-edge, NIR	Green, red, NIR, SWIR
ground sampling distance (m)	23.5	6.5	20 and 10
bit depth	7	12	8
to be found in DWH	Core_01	Core_01	Core_01
delivered resolution (m)	20	20	20
projection	national	national	national

3.1.3.3 Copernicus Climate Change Service - C3S

The number of EO products used in the Copernicus Climate Change Service is too extensive to be reported here. The service use of satellite products draws from the experience of numerical weather prediction and climate modelling. It has been growing exponentially over the last 20 years as indicated in the figure below, where the satellite instruments used in ECMWF numerical weather predictions operations from 1996 to 2016 is depicted.

Figure 3.2: Satellite sensors used in ECMWF numerical weather predictions operations from 1996 to 2016
Source: ECMWF, 2018

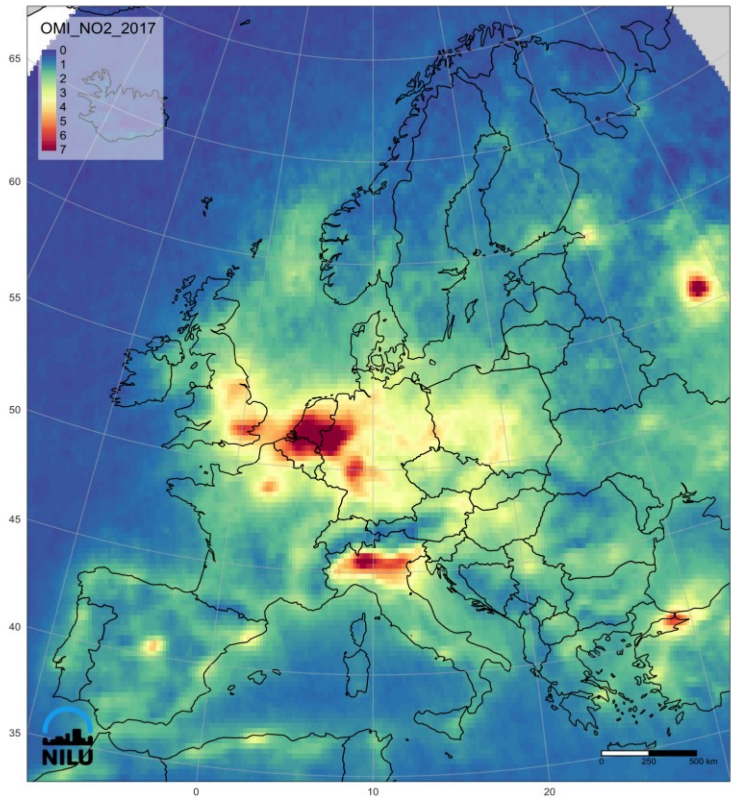


3.2 Current use of EO data at ETC/ATNI

The use of EO data has so far been quite limited within the work carried out by the ETC/ATNI and its precursor ETCs. However, one specific application area of the ETC in which the direct use of satellite data has been evaluated in recent years is the mapping of air pollution at the European scale. Mapping air quality in Europe has been a very important focus of the work carried out by the European Topic Centre for Air Pollution and Climate Change Mitigation (ETC/ACM) in previous years (Denby et al., 2011a; Denby et al., 2011b; Denby et al., 2010; De Smet et al., 2010, 2009; Horálek et al., 2007, 2008, 2017) and continuous to be carried out within the ETC/ATNI. A variety of mapping approaches and a multitude of input datasets have been utilized within the ETC mapping activities over the years and a reliable and robust methodology has been developed. The most current version of the mapping algorithm is described in Horálek et al. (2017) and the latest mapping results and their uncertainties are discussed in Horálek et al. (2018a).

The maps resulting from applying this methodology are provided annually by the European Environment Agency to the end-user (for example EEA, 2019c). While Europe-wide station data provides the core information for the mapping procedure, auxiliary data is generally needed to provide additional information about spatial patterns of the parameter in question and to guide the interpolation procedure. The current mapping approach (Horálek et al., 2017) uses therefore also auxiliary data in the form of model output generated by the Unified EMEP atmospheric chemistry model (Fagerli et al., 2004; Simpson et al., 2003), provided originally at a spatial resolution of 50 km × 50 km but now increasing to about 10 km x 10 km, as well as digital elevation models and data on population density.

Figure 3.3: Annual average NO_2 column from OMI shown over Europe for the year 2017. This type of dataset is currently being used as an auxiliary dataset for spatial mapping of NO_2 within Task 1.1.1.3 of the ETC/ATNI project. Units in 10^{15} molecules/cm^2. See Horálek et al. (2018b) for more information



A first attempt to use EO data as an additional auxiliary variable for European-scale mapping within the ETC was carried out by Schneider et al. (2012). They used an annual average dataset of tropospheric NO_2 column measured by the OMI instrument as an auxiliary variable to spatially interpolate station observations of NO_2 over Europe using geo-statistics. The specific technique was residual kriging which is the same as used in the mapping approach of the ETC. However, in detail the methodology deviated substantially from the regular ETC method, i.e., it did not carry out separate analyses for urban and rural areas with a subsequent merging of these two maps. As such the findings are not necessarily representative for the performance of this auxiliary within the operational setting, however it could be seen as indicative. One result was that using the OMI NO_2 satellite data as an auxiliary variable within the geo-statistical framework provided significant improvements in mapping accuracy as compared to geo-statistical interpolation of solely the station data (ca. 10% reduction in root mean square error). As such it was demonstrated that a satellite based tropospheric NO_2 column dataset has potential as a spatial proxy variable.

More recently, this work has been continued by Horálek et al. (2018b). They integrated OMI NO_2 tropospheric column data into the routine mapping methodology of the ETC and tested the value of it as an additional auxiliary variable. This was carried out for the year 2014. Figure 3.3 shows an example of an annual average tropospheric NO_2 column from OMI as it was used in this report. It was found that inclusion of OMI-based satellite data of tropospheric NO_2 column improve the mapping result for rural and background areas, however it should be noted that quantitatively the increase in mapping accuracy was not very high, which could be related to some extent to the limited spatial resolution of the used OMI product. Nonetheless the recommendation of this report therefore was to include satellite information on NO_2 in the routine mapping for ETC for rural and urban background areas. This recommendation is particularly relevant in the light of the new TROPOMI instrument on Sentinel-5P which can provide significantly higher spatial resolution than OMI and is therefore expected to further improve the mapping results.

3.3 Recommendations for use of EO data in future ETC/ATNI work

We provide here an overview of potential applications of EO data within the ETC/ATNI. Note that this overview necessarily is somewhat incomplete and subjective, primarily reflecting the interests and the background of the authors. However, we think that the areas highlighted here can potentially contribute significantly to the work to be carried out within the ETC/ATNI in the upcoming years. We describe four specific areas where we think that direct use of EO data is the most promising for the work carried out within the ETC/ATNI.

1. Inferring emissions from space-borne observations, which we only describe very briefly here as the topic is discussed in comprehensive detail in Section 3.4.
2. Using additional EO datasets for European-scale mapping applications aside from the already assessed OMI NO_2 product (for example, aerosol, O_3, or SO_2), going beyond what has already been investigated.
3. Using EO-based trend analysis, which we think has great potential for use within the ETC/ATNI in order to complement the trend estimate from the air quality monitoring stations network (EEA, 2018a).
4. Providing a more general overview of the products available from the TROPOMI instrument on-board of the Sentinel-5P satellite, as it will play a crucial role for satellite-based air quality monitoring in the coming year, is the most likely candidate for use within the work conducted by the ETC/ATNI and as such might open areas of applicability that are not foreseeable yet.

3.3.1 Emissions

Using satellite data to evaluate and improve the emission estimates from bottom-up emission inventories is one of the most interesting potential applications of EO data for the ATC/ANI work. However, it is also one of the most challenging and is mostly subject of various research activities currently. While there is potential in using EO data for correcting existing bottom-up emission inventories, the use of EO data for emissions within a policy context continues to have various challenges and limitations. Section 3.4 provides a comprehensive overview and a thorough discussion of the possibilities and challenges involved in inferring emissions from satellite data within the context of policy applications.

3.3.2 Mapping

While some investigations of the use of EO-based NO_2 data in the routine annual air quality mapping within the ETC has already been carried out (Horálek et al., 2018b; Schneider et al., 2012), there is significant potential for more EO use in this aspect of the ETC work. This relates to two main areas, namely

1. the use of higher-resolution TROPOMI/Sentinel-5P NO_2 data and
2. the use of satellite-based variables other than NO_2 for mapping.

As for point 1., previous work has shown that the use of OMI-based NO_2 products within the routine annual mapping for the ETC can result in improved accuracy, albeit the improvement is relatively minor and mostly relevant for rural areas. With the availability (since the year 2018) of operational TROPOMI/Sentinel-5P data of NO_2 with a significantly improved spatial resolution of ca. 3.5 km x 7 km, we recommend investigating the use of the TROPOMI NO_2 product within the routine mapping within the ETC. It is expected that the characteristics of this product (namely both the spatial resolution as well as the improved retrieval scheme) will have a substantial impact on the mapping accuracy for NO_2. More information about the specific products available from Sentinel-5P/TROPOMI will be given in Section 3.3.4.

Regarding point 2., several potential satellite-derived variables come to mind. One of the main species that is mapped within the ETC work is $PM_{2.5}$ and PM_{10}. As such it could be valuable to investigate the potential of using aerosol optical depth (AOD) as an additional proxy variable. While the relationship between AOD and surface PM is highly complex and conversion between the two variables is usually subject to significant uncertainties, it is nonetheless reasonable to assume that the overall spatial patterns are somewhat similar. As the geo-statistical approach taken by the routine mapping operations in the ETC generally rely mostly on the spatial patterns of the used proxy variables rather than the absolute numbers, it is conceivable that AOD can provide additional information regarding the spatial distribution of the particles and as such increase the accuracy of the routine PM mapping. We therefore recommend exploring this topic further in future ETC/ATNI work. The only satellite within the Copernicus Space Component that provides AOD data is Sentinel-3, however at the time of writing this AOD product was not yet available from the Copernicus Open Access Hub. In addition, Sentinel-5P provides an operational UV aerosol index product which might be used for similar purposes. Furthermore, several non-Copernicus satellite instruments provide AOD data operationally (e.g., MODIS, VIIRS) and could be used for such an investigation.

Aside from AOD, another species that could be investigated as a potential auxiliary variable for routine mapping purposes is ozone. Ozone is annually mapped within the ETC and even though most EO-based ozone retrieval focus on stratospheric ozone, Sentinel-5P/TROPOMI provides a tropospheric ozone product that could be assessed for use as a proxy variable in the operational mapping routine.

Another, slightly fewer interesting species within the context of the ETC since it is not routinely mapped, is sulphur dioxide (SO_2). Sentinel-5P/TROPOMI provides a SO_2 product that can to some extent detect large anthropogenic sources, and as such has potential as a spatial proxy for the geo-statistical interpolation. However, SO_2 emissions in Europe have decrease significantly over recent years, so mapping SO_2 might not be relevant anymore at the European scale.

3.3.3 Trend analysis

The work in ETC/ATNI often addresses the analysis of trends in air pollutants (Colette et al., 2018; EEA, 2018a; Solberg et al., 2018a; Solberg et al., 2018b). It is therefore important to note that one of the most promising research applications of EO products is long-term trend analysis. The reason for this is that earth observing satellites can provide consistent information on the temporal dynamics of air pollutants even in areas where typically no air quality monitoring stations equipped with reference instrumentation are located. The satellite instrument can thus provide the "big picture" in terms of trends and complement the trends obtained from ground-based stations as typically shown in the series of annual air quality reports of the EEA (EEA, 2017a; 2018a; 2019c).

Trend analysis is promising for NO_2, for which the satellite retrieval products are generally quite mature and accurate enough and at the same time NO_2 levels tend to vary enough over just a few years to show statistically significant trends even for relatively short periods of 10 years or less. Here we provide a very short overview of recent work on satellite-based trends analysis of NO_2. Several studies have investigated temporal trends in tropospheric NO_2 provided by space-borne platforms. Richter et al. (2005) were the first to study space-based NO_2 trends and provided an analysis based primarily on GOME NO_2 data over China. Later on, van der A et al. (2006) and van der A et al. (2008) combined data from the GOME and the SCIAMACHY instruments and provided a trend analysis focused on China and over the entire globe, respectively. A combination of GOME and SCIAMACHY data was also used by Ghude et al. (2009) for studying regional trends in tropospheric NO_2. Using a similar methodology, NO_2 trends over emission hotspots in India were further investigated by Ghude et al. (2008). Summertime trends in European NO_x emissions were studied by Konovalov et al. (2008) using a combination of GOME, SCIAMACHY, and a continental-scale air quality model. The methodology was later extended to study non-linear NO_2 and NO_x trends for several urban agglomerations in Europe and Asia, using method based on a probabilistic approach and artificial neural networks (Konovalov et al., 2010). The same combination of satellite instruments was further used by Kim et al. (2006) to quantify decreases in NO_x emissions over power plants in the United States. Russell et al. (2012) studied the effect of emission control measures and the impact of the economic recession in the U.S. using OMI data.

De Ruyter De Wildt et al. (2012) further investigated trends of tropospheric NO_2 over some of the major shipping lanes in the world. Schneider and van der A (2012) made use of a homogeneous 9-year time series acquired by the SCIAMACHY instrument and provided the first single-sensor global trend analysis of NO_2, thus avoiding the merging of datasets with substantially different spatial resolution and possible inter-sensor calibration issues. They further analysed trends over some of the major megacities but did not provide much detail on this issue. Although significant progress has been made in techniques on combining data from multiple instruments (Hilboll et al., 2013), computing trends from homogeneous time series based on a single instrument still has the advantage that the computed trends are very likely to be real trends and not affected by characteristics of different instruments. Recent studies have also looked at NO_2 trends, particularly over large urban agglomerations worldwide (Schneider et al., 2015). Changes in satellite-inferred nitrogen dioxide over Europe have also been attributed to environmental policy and economic factors (Castellanos and Boersma, 2012; Schneider et al., 2015). Abrupt trend changes in the Middle East resulting from air quality control and political factors were reported by Lelieveld et al. (2015). In addition to trends in actual concentrations, satellite observations have also been used to infer trends in NO_x emissions over Europe (e.g., Curier et al., 2014). See Section 3.4 for more detail on deriving emissions from EO data.

Figure 3.4: Relative trends in tropospheric nitrogen dioxide column over Europe observed by the OMI instrument between October 2004 and April 2019, shown in average percent change per year. Note that only areas with statistically significant trends at the 95 % level are shown. Trends were only calculated for land areas with a minimum average tropospheric NO_2 column of 1.5 x 10^{15} molecules/cm^2. The methodology uses here is based on that introduced by Schneider and van der A (*2012*) and Schneider et al. (*2015*)

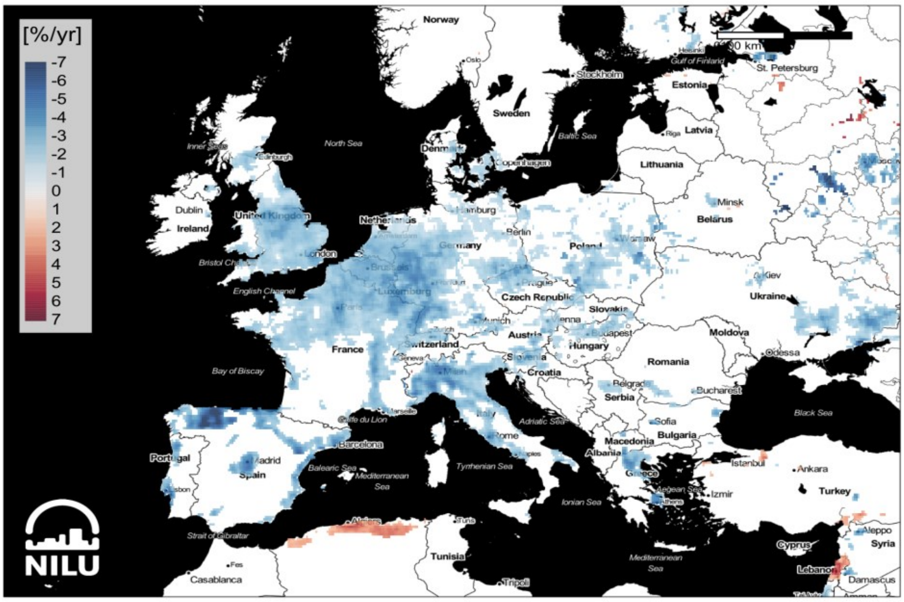
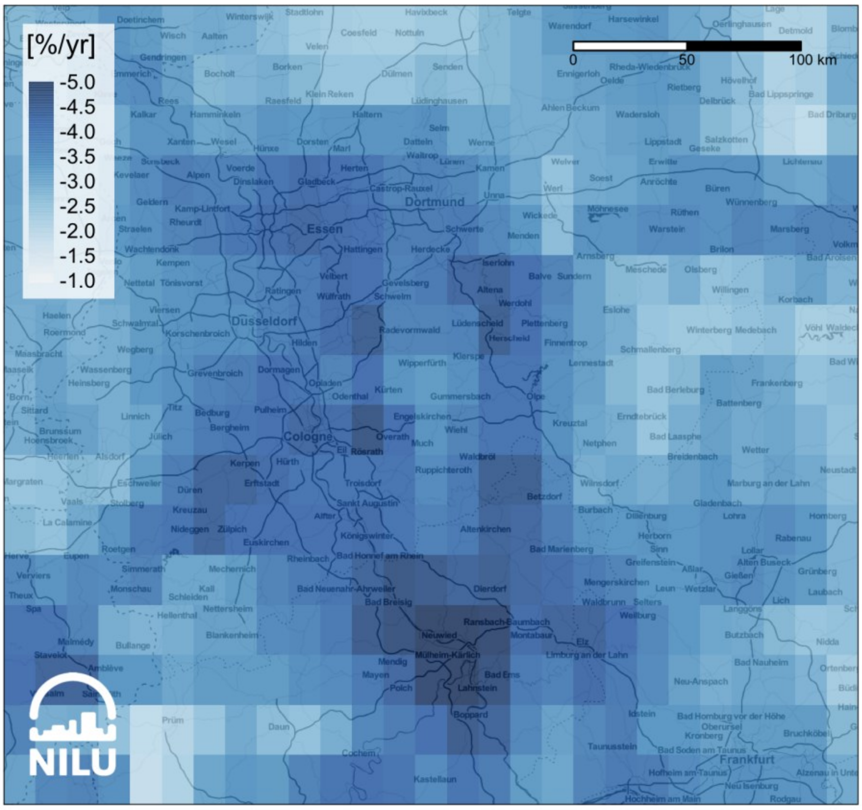


Figure 3.4 shows an example of how satellite data can be used for determining consistent trends of a pollutant over relatively long periods. What is shown here are areas of statistically significant change of the tropospheric nitrogen dioxide column as observed by the OMI instrument between October 2004 and April 2019. Similarly, Figure 3.5 shows the same data but only for the Ruhr area of Germany to better highlight the spatial patterns in trends that can be derived from such datasets. The data indicates that large areas of Europe have shown statistically significant decreases in NO_2 columns over the study period with average rates of change approximately between -2 percent per year and -7 percent per year. This is overall consistent with trends derived from air quality monitoring stations but has the advantage that it can be carried out anywhere, i.e., even in regions where no stations observations are available. Both figures are based on similar methodology as that reported previously in Schneider and van der A (2012) and Schneider et al. (2015).

Figure 3.5: Same as previous Figure 3.4. but showing only the spatial patterns of relative trends in the Ruhr area of Germany. The methodology uses here is based on that introduced by Schneider and van der A (*2012*) and Schneider et al. (*2015*).



3.3.4 Available Sentinel-5P products

While the previous sections focused on some specific potential application of EO data within the ETC/ATNI, there are likely to be other applications that cannot be foreseen at this point. Given that air quality is one of the major focus areas of the ETC/ATNI and further given that the recently launched Sentinel-5P satellite with its TROPOMI instrument onboard is a mission dedicated to monitoring the atmospheric composition, it is expected that the data produced by this mission has significant potential for ETC/ATNI work in the years to come. We therefore give below a short overview of the currently available operational data products. While not all of these products are likely to be immediately valuable for the ETC/ATNI, they have significant potential for atmospheric composition monitoring over Europe.

3.3.4.1 S5P Level-1 products

Level-1 products typically provide the spectra measured by the satellite instruments without any further retrieval of particular geophysical variables of interest. As such, they are only mentioned here for completeness, but Level-1 products are likely not very relevant for direct use within the ETC/ATNI.

3.3.4.2 S5P Level-2 products

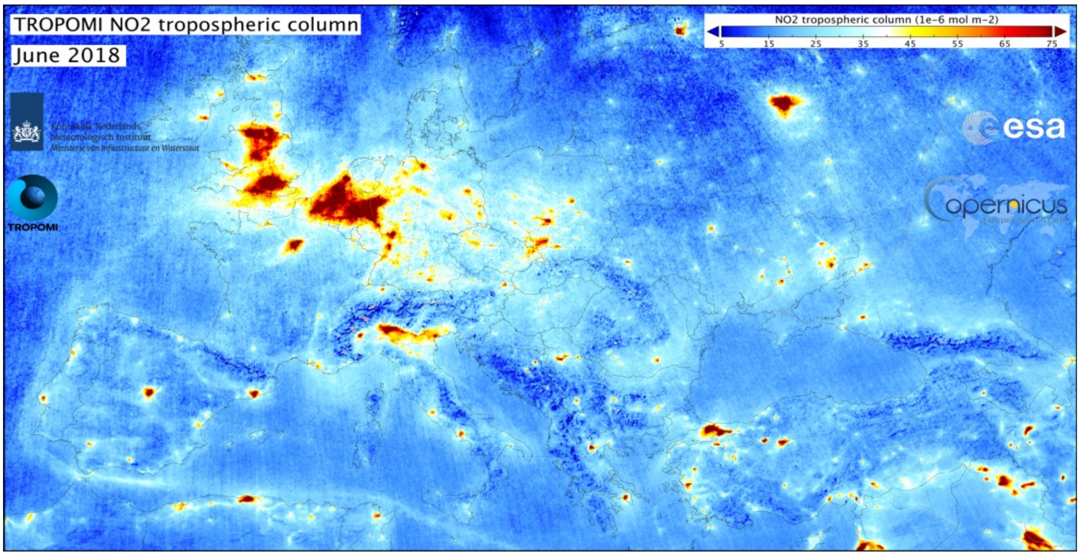
Level-2 products from satellite instruments typically provide an estimate of a geophysical quantity of interest, which is derived from Level-1 data using a physical retrieval algorithm. Therefore, these products tend to be of interest to end users, although the product format can sometimes be challenging to work with. In such cases end users might prefer Level-3 products, which tend to be easier to use, however they are not always operationally available for each satellite instrument and variable of interest. This is the case for example for Sentinel-5P/TROPOMI, which is why we focus here on the available Level-2 products.

We give an overview of the Level-2 products that are operationally produced by the various retrieval teams and that are distributed in near real-time through the official channels provided by the Copernicus program. At the time of writing this report, this data is provided through the Sentinel-5P Pre-Operations Data Hub located at https://s5phub.copernicus.eu/dhus/#/home, although as soon as the validation is completed for all species and all products are officially released, it is expected that the S5P/TROPOMI data will join the regular standard Copernicus Open Access Hub hosted at https://scihub.copernicus.eu/dhus/. The following overview is based to a large extent on the information available at http://www.tropomi.eu.

Nitrogen dioxide

The S5P/TROPOMI NO_2 product builds upon a long heritage and decades of experience from previous NO_2 retrieval algorithms for other satellite instruments. The product, which is provided in a CF-compliant NetCDF format([20]), provides at its core data on total as well as tropospheric column NO_2. The retrieval algorithm is based on a combined retrieval-assimilation-modelling system and is used in the TM5-MP chemistry transport model at a resolution of 1x1 degree as an essential element. More information about the algorithm used for retrieval of the NO_2 product can be found in the Algorithm Theoretical Basis Document (ATBD) (Geffen et al., 2019). Figure 3.6 shows an example of a one-month average of the S5P/TROPOMI NO_2 product over Europe available at http://www.tropomi.eu/data-products/nitrogen-dioxide. It shows the typical spatial patterns that were to some extent also visible in predecessor instruments (see Figure 3.3 for an example), however it provides significantly higher spatial resolution of approximately 3.5 km x 7 km at the nadir and improved noise characteristics.

Figure 3.6: Example of the S5P/TROPOMI NO_2 tropospheric column product for June 2018 over Europe. Source: KNMI

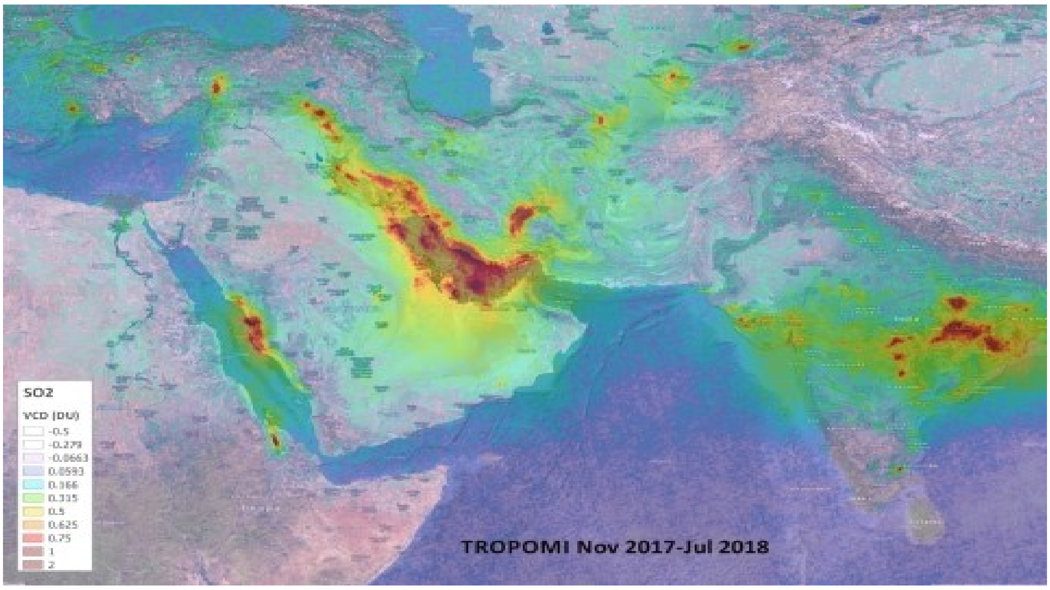


([20]) NetCDF (Network Common Data Form) is a binary machine-independent file format for representing array-oriented scientific data. Climate and Forecast (CF) compliance indicates that a NetCDF file uses a standardizes metadata format.

Sulphur dioxide

Anthropogenic SO_2 emissions are still of concern in many parts of the world, although in Europe these have become quite minor. SO_2 further plays a major role in volcanic emissions. Figure 3.7 shows an example of the S5P/TROPOMI SO_2 product over the Middle East, here given as the average of approximately half a year. The Level-2 SO_2 product is provided at a spatial resolution of 3.5 km x 7 km at nadir, thus providing finer details than previous instruments and the detection of much smaller SO_2 plumes than previously possible. The retrieval algorithm of the S5P/TROPOMI Level-2 SO_2 product is given in Theys et al. (2018).

Figure 3.7: Example of the S5P/TROPOMI SO_2 product averaged over the period November 2017 to July 2018 for the Middle East. Source: BIRA-IASB.



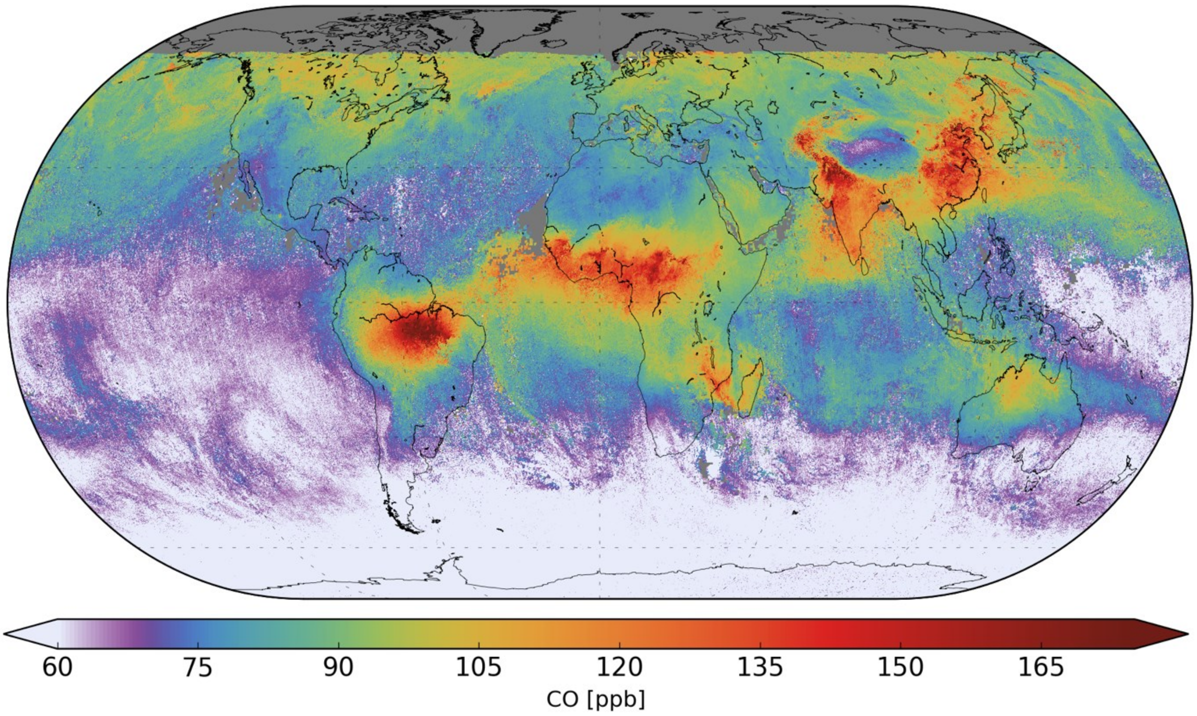
Ozone

Three separate products are released for ozone: Total column ozone, tropospheric column ozone, and ozone profiles (not available at the time of writing, planned to be released in late-2019). The details for the total column, tropospheric column, and profile products are given in Spurr et al. (2018), Heue et al. (2018), and de Haan (2015), respectively.

Carbon monoxide

S5P/TROPOMI provides a Level-2 product on carbon monoxide, which is an important trace gas for understanding various processes in atmospheric chemistry. It is emitted as a major atmospheric pollutant in urban areas where it is a results of fossil fuel combustion. Oxidation of isoprene, primarily emitted by tree species and an O_3 precursor, and biomass burning play a major role in the tropics. The carbon monoxide (CO) retrieval algorithm uses the data collected within the short wavelength infrared spectrum at around 2.3 µm. More information about the CO retrieval can be found in Landgraf et al. (2018) and Borsdorff et al. (2018).

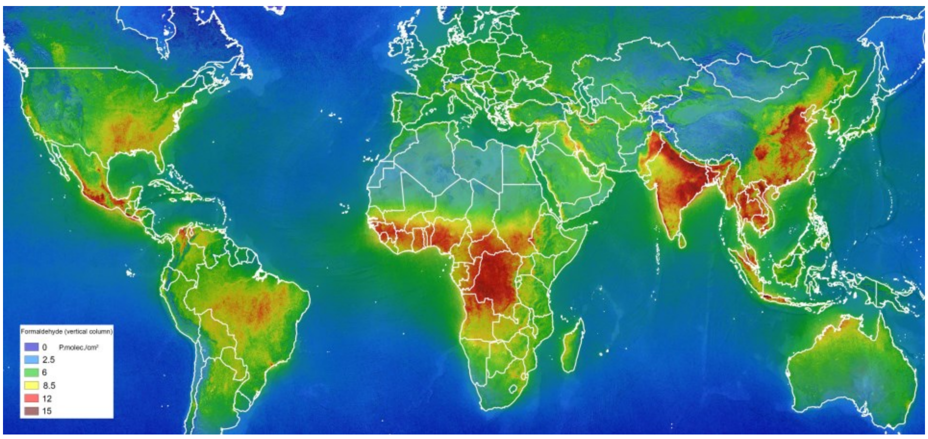
Figure 3.8: Example of carbon monoxide retrieved from S5P/TROPOMI over the period November 13th to 19th, 2017. Source: Borsdorff et al. (2018)



Formaldehyde

Formaldehyde (HCHO) acts as an intermediate gas in most oxidation chains of non-methane volatile organic compounds (NMVOC). Due its lifetime of only a few hours, HCHO concentrations in the boundary layer can be directly related to the release of short-lived hydrocarbons, which typically cannot be directly observed from satellite instruments. The S5P/TROPOMI HCHO Level-2 product provides column-integrated HCHO concentrations at a spatial resolution of 3.5 km x 7 km at nadir. More information about the Formaldehyde product and its specific retrievals can be found in the respective Algorithm Theoretical Basis Document (ATBD) (De Smedt et al., 2018). Figure 3.9 shows an example of a global map of formaldehyde averaged for the period of November 2017 through June 2018.

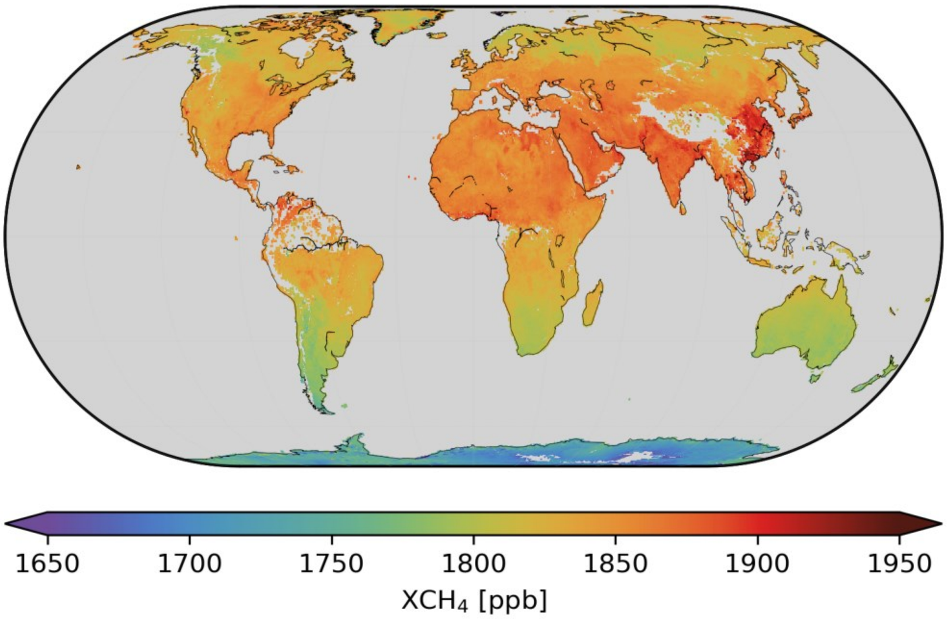
Figure 3.9: Example of formaldehyde retrieved from S5P/TROPOMI over the period November 2017 through June 2018. Source: BIRA-IASB.



Methane

Methane (CH_4) is a potent greenhouse gas, and it is important to monitor its concentration in both space and time. S5P/TROPOMI uses the Oxygen-A Band (760nm) and the SWIR spectral range to retrieve methane and provides a Level-2 CH_4 product at the standard spatial resolution of 3.5 km x 7 km at nadir. Figure 3.10 shows an example of a global map of CH_4 averaged over the period May 2018 through January 2019. More information about the methane retrieval algorithm can be found in Hasekamp et al. (2019) at https://www.earth.com/news/global-atmospheric-methane-ozone/.

Figure 3.10: Example of the mixing ratio of methane retrieved from S5P/TROPOMI between May 2018 and January 2019. Source: SRON.



Aerosols

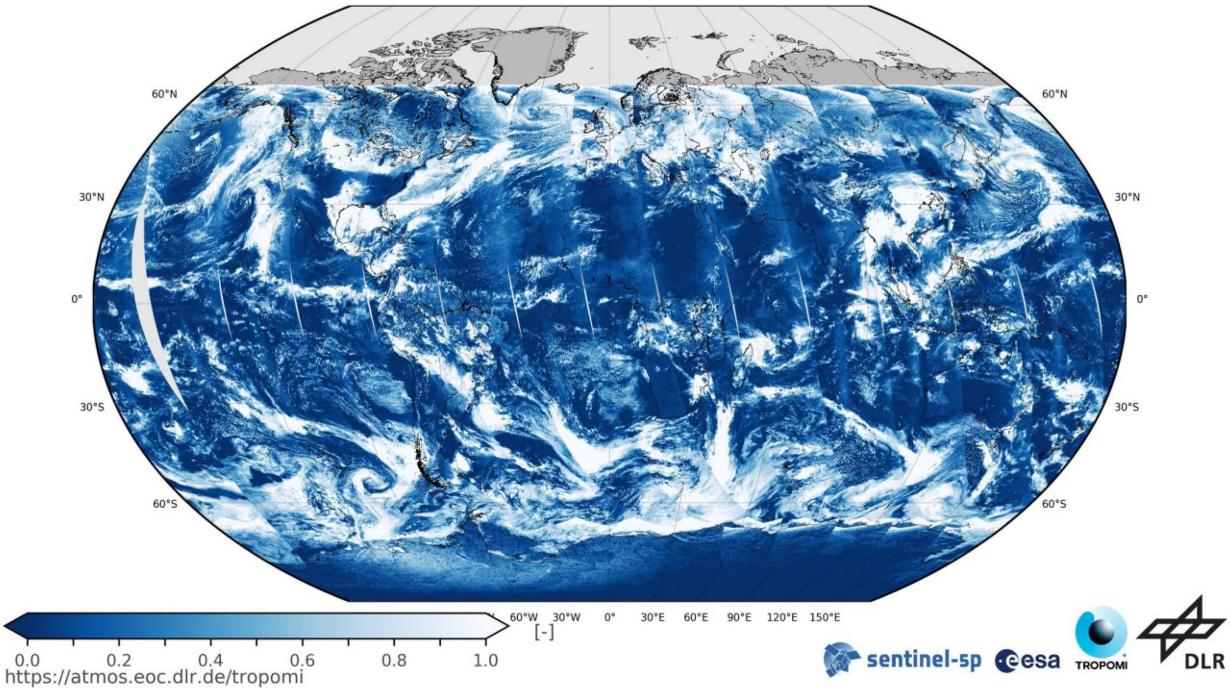
Two products are provided by S5P/TROPOMI that are relevant for aerosols: The UV Aerosol Index and the Aerosol Layer Height. Note that S5P does not provide an aerosol optical depth (AOD) product. This can be acquired from Sentinel-3 or a multitude of other satellite instruments. More information about the UV aerosol index product and its retrieval algorithm can be found in Stein Zweers (2018). The retrieval algorithm of the aerosol layer height product is described in Sanders and de Haan (2016).

Other

In addition to the atmospheric composition products, S5P/TROPOMI also provides Level-2 products on clouds and UV radiation. The cloud product contains data on cloud fraction, cloud albedo (cloud optical thickness), and cloud top pressure, whereas the UV product provides information on surface irradiance and erythermal dose([21]). More information on the cloud product can be found in the ATBD (Loyola et al., 2018). Figure 3.11 shows an example of the cloud fraction product from S5P/TROPOMI.

([21]) Irradiance is the flux of radiant energy per unit area. Erythermal dose is the amount of UV radiation a person is exposed to.

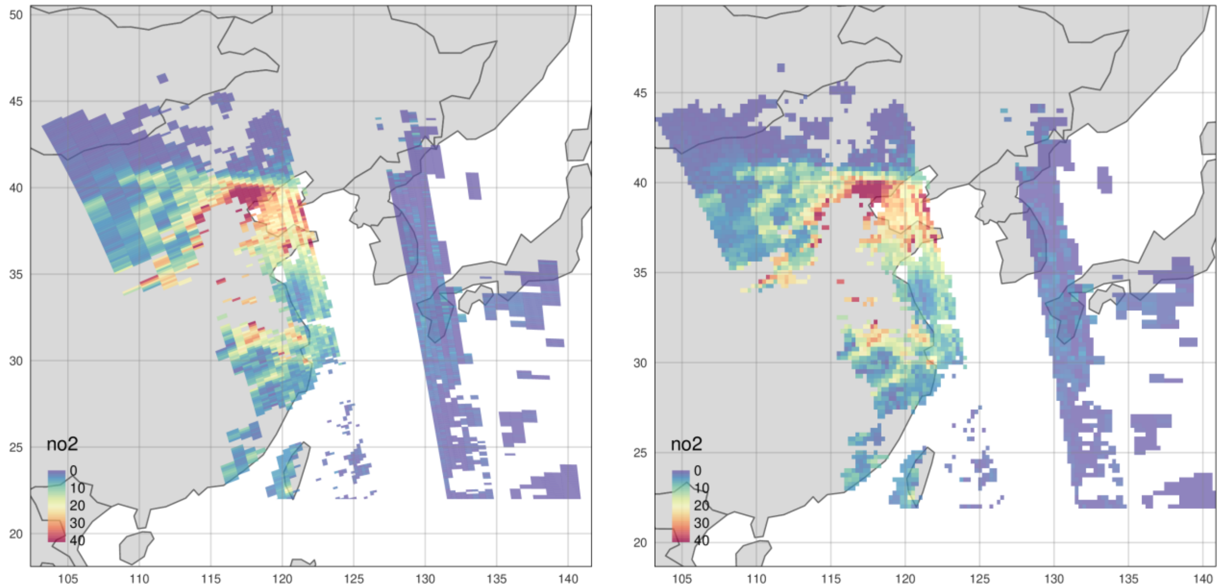
Figure 3.11: Example of cloud fraction derived from S5P/TROPOMI on 2 January 2018. Source: DLR



3.3.4.3 S5P Level-3 products

For end users such as the ETC/ATNI, typically Level-3 products tends to be easier to use as they are not in swath geometry anymore but have been already gridded to a uniform grid in either a regular latitude/longitude array or a projected coordinate system (see Figure 3.12 as an example). However, the retrieval teams and the European Space Agency (ESA) do not operationally produce Level-3 products of the various Level-2 datasets that are available, so it is up to the end users to conduct this task. One way to accomplish this is to use *HARP*, provided at https://github.com/stcorp/harp/releases/tag/1.6/. *HARP* is a set of tools for ingesting, processing, and inter-comparing satellite products with a specific focus on European atmospheric missions and is composed of a set of command line tools, a C library of analysis functions, and import/export interfaces for Python, Matlab, and IDL (Interactive Data Language). Using the *harpconvert* tool with the *bin_spatial* operator allows for easily re-gridding all S5P/TROPOMI Level-2 products from swath geometry to a gridded Level-3 product with a specified custom domain and resolution.

Figure 3.12: Visualization of the Level-2 to Level-3 gridding procedure, using an OMI swath of tropospheric NO2 column over China for 1st January 2018. The left panel shows the original pixel geometry as stored in the Level-2 file. The right panel shows the same dataset after gridding to 0.25 degree by 0.25 degree using the gridding routine outline above. Units are given in both panels as 10^{15} molecules/cm^2



3.4 Use of EO Satellite data for emissions

EO data have a strong relevance to the ETC/ATNI through their potential application in support of monitoring, reporting and verification of air pollutant emissions. Currently, official reporting of emissions at a national level represents one of the best available emission datasets in terms of accuracy. Further, they offer the necessary traceability back to emission factor and activity data that makes them relevant in a policy context. Despite this, there is no way to directly measure and validate the emissions. Two methods are currently used to try to indirectly validate the emissions:

- Expert review of the emission compilation methodologies.
- Modelling efforts involving running models with the emissions and then comparing them to in-situ observations.

Emission estimates from EO offer an attractive additional validation approach. In addition to this, estimation of emissions using EO data could offer some potential advantages:

- Timely updates to bottom-up emission inventories.
- Potential estimation of temporal variability see, e.g., Streets et al. (2013).
- Estimation of emission sources that are difficult to quantify in traditional emission inventories, e.g., unconventional oil/gas extraction, shipping, biomass burning, and biogenic emissions (Streets et al., 2013).

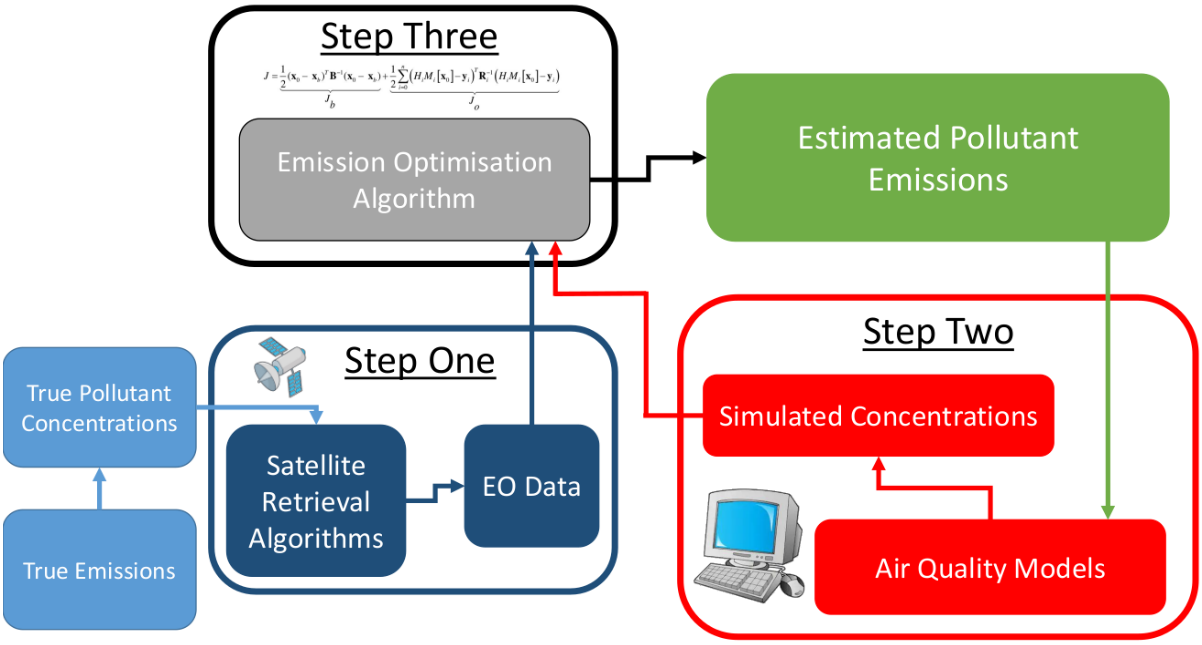
We therefore present here an overview of the past, present, and potential future usage of EO data for emission estimation/inversion with a perspective of their use for policy support. We first define key terminology. EO can be used to perform *emission inversion* whereby observations are used to infer the emissions by indirect means. Inversion in this context means a reversal of the standard problem in air quality modelling, i.e., one of models simulating concentrations based on emissions towards methods to estimate emissions based on observed concentrations. Using EO in this way provides *top-down* emission estimates, i.e., it is a method where bulk/large scale observations/data are used to infer emissions at finer spatial scales or to greater detail. This is as opposed to *bottom-up* methods, i.e., where emissions are estimated from first principles based on activity data, and for example technological emission factors, etc.

3.4.1 Current methods and use of EO Data for emission estimation

3.4.1.1 Overview of Data Assimilation and Emission Inversion Methods

Emissions of pollutants are extremely difficult to measure directly using observations in the real world over large areas. Instead, emissions can only be inferred from observations of pollutants using emission inversion methodologies, and the resulting emissions are so called top-down estimates.
Emission inversion methods can be broadly described as a mathematical framework relating observed pollutant concentrations to inferred emissions. Figure 3.13 presents a schematic of such a mathematical framework including all its components, i.e., EO observations based on satellite data, some kind of model relating emissions to atmospheric concentrations, and some means to optimise the emissions according to the discrepancy between the model and observations.

Figure 3.13: A schematic diagram showing the flow of data and information within the emission inversion problem for top-down emissions. 'Step One' in dark blue shows satellite retrieval algorithms used to derive EO data from the true pollutant concentrations. 'Step Two' in red shows air quality models simulating concentrations using estimated pollutant emissions. 'Step Three' in grey represents an emission optimisation algorithm that combines EO data and simulated concentrations from models to derive pollutant emissions



We now give a short overview of each component and highlight how their uncertainties and limitations contribute to the intrinsic uncertainties of emission inversion. Intrinsic uncertainties within each step of the emission inversion problem impact on the accuracy of the final inferred emissions.

Understanding and accounting for these uncertainties in the proper way is one key requirement for emission estimates achieving policy relevance.

'Step One' - Satellite retrievals: Satellite retrievals infer atmospheric concentrations of pollutants based on observations of Earth's atmosphere. The satellite data products differ from traditional ground-based air quality monitoring observations. For instance, satellite observations of NO_2 measure the total amount of NO_1 in the column of atmosphere within the troposphere or the whole atmosphere, and while ozone vertical profile products do exist, their sensitivity to ozone near the surface is very limited.

Limitations and uncertainties: Satellite retrievals have intrinsic uncertainties and so EO data can be highly uncertain. Uncertainty in the measured quantity of the pollutants directly impacts on the inferences made in the emission inversion process. Further, both column measurements, and issues stemming from the lack of surface sensitivity, mean that it is often difficult and complicated to relate EO data products to the actual pollutant concentrations and emissions at the surface. EO data products therefore require special treatment to achieve this, and this is often a technically challenging task that adds additional uncertainty onto the resulting emission estimation.

Special mention needs to be given to the limitations of EO data in relation to $PM_{2.5}$ and PM_{10}. Due to the technical challenges of observing PM, it is not possible to observe the concentrations of PM directly at all. Instead, the only data we can retrieve is what is termed as aerosol optical depth (AOD), but this retrieved quantity varies according to many different aerosol properties aside from just the PM concentration, and so it is impossible to infer directly what the concentrations are. Emission inversion using AOD data therefore requires additional assumptions be made that further contribute to errors in the inversion process.

'Step Two' - Models: Models range in complexity from relatively simple Gaussian plume models representing a pollution plume from a single source all the way up to global models representing a complex range of atmospheric chemistry processes.

Limitations and uncertainties: Model uncertainties can arise due to errors in model processes, the model representativity, and due to errors in the pollutant emission calculations. To perform the emission optimisation in *Step Three*, it is essential to be able to separate the intrinsic model uncertainties arising from process and representativity errors from those arising from emission errors. However, it is extremely difficult to estimate intrinsic model errors in such a way that they are characterised independently from emission errors. Methods to estimate intrinsic model error such as running a large model ensemble are not used due to the computational expense. Model climatology (and its associated standard deviation) from long model simulations have been used on occasion to estimate model error, but this relies on assuming that model variability is equivalent to model error, which is not the case. Estimating model errors has no consistent or robust solution and poses a serious challenge for carrying out accurate emission inversions. Errors in the model's representation of concentrations will create intrinsic uncertainties in the resulting emission inversion estimates.

'Step Three' Emission Optimisation Methods: Methods for optimising emissions range from simple «by-hand» emission tuning up to complex data assimilation (DA) methods that optimise emissions. We will largely ignore «by-hand» tuning methods, but significant issues exist with this methodology: lack of reproducibility of method, time consuming, and inaccurate. DA methods attempt to formalise the emission optimisation process into a consistent mathematical framework that aims to minimise model minus observation differences by optimising the emission model parameters. This optimised estimate results in what is termed a model analysis.

Data assimilation methods can be separated into two broad methods: variational methods (Elbern et al., 2007, 2010; Müller and Stavrakou, 2005; Stavrakou et al., 2008a) and ensemble methods. Without going into many details, the key advantages and disadvantages of variational and ensemble methods are summarised in Table 3..

Table 3.14.: The key advantages and disadvantages of variational and ensemble data assimilation methods

	Advantages	Disadvantages
Variational	• Relatively cheap to run computationally. • Allows optimization of emissions hours/days prior to observation.	• Difficult to estimate model errors • Requires the model ad joint (i.e., the ability to run the model going back in time).
Ensemble	• Can robustly estimate model errors.	• Computationally expensive. • Can only optimize emissions during the observation time window.

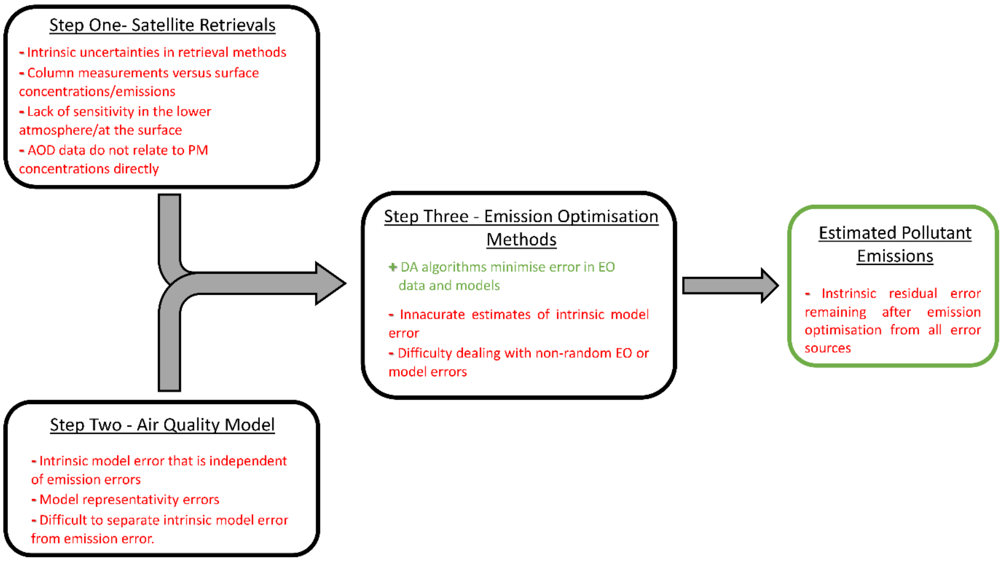
In practice, as noted in *Step Two*, it can be extremely difficult or impractical to estimate model errors, and so a key advantage of ensemble methods is their ability to better represent such errors. They achieve an improved estimate of model errors by running an ensemble of model runs each with small perturbations to the model parameters. This creates a 'spread' of the ensemble that acts as a proxy for the true model error. The key advantage of variational methods is their ability to estimate emissions prior to when observations were made, which could be key in certain applications, e.g., those in relation to long range transport. This is particularly applicable to 4d-variational data assimilation that combines running a forward model with a backwards version of the model, which is called an ad joint. This gives the capability to relate observations in the present to model events in the past, and to correct or update the past model state according to model-observation differences.

Lastly, we discuss emission optimisation methods with respect to the model atmospheric photochemistry. A key assumption with different emission inversion methods is whether the chemistry is linear or non-linear. Linear chemistry assumes that changes in emissions to not perturb the photochemical state in the model and that concentrations are directly proportional to emissions. Non-linear means there is feedback between changing emissions, the photochemical state, and the pollutant concentrations. The former method is sometimes used in relation to CO emission inversion where this assumption is reasonable. The latter is nearly always applied in the case of NOx emission inversion due to the complex photochemistry and short lifetimes of NOx.

Limitations and uncertainties: Data assimilation (DA) can consider EO and model errors to determine an optimal solution weighted according to the errors on both. DA methods are specifically designed to account for EO/model error in an optimal way and should produce a model analysis with reduced error compared to either the EO data or model alone. However, DA cannot remove the errors completely, which means resulting emission estimates have residual intrinsic uncertainties. Further, some DA methods are only designed to account for random errors without bias. Bias errors can result in the assumptions underpinning the DA method to be invalidated. Lastly, a major limitation of the emissions estimates derived from the inversion is the difficulty in directly validating them without using another air quality model.

The uncertainties and limitations in each step are summarised in Figure 3.14, which shows the progression of errors through the entire emission inversion chain.

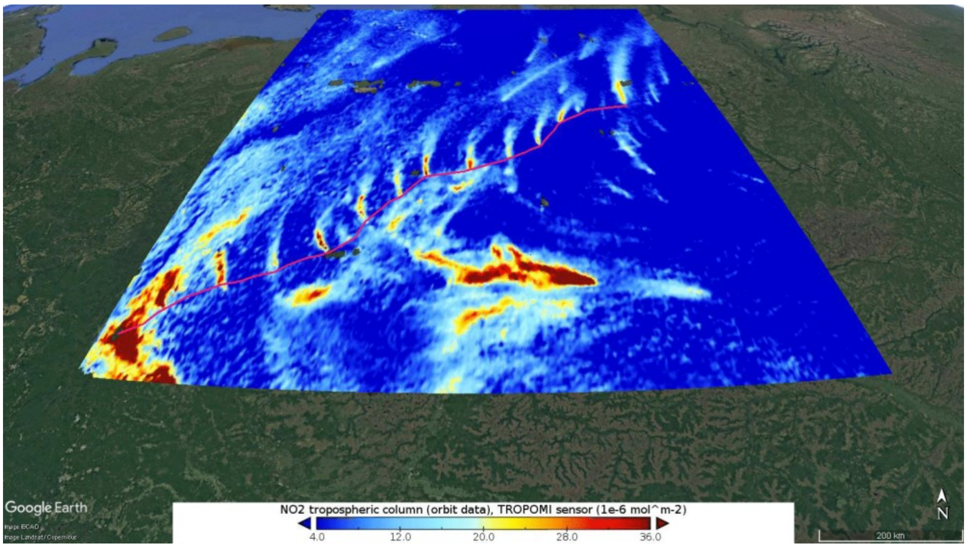
Figure 3.14: A schematic diagram showing how different uncertainties in the emission inversion production chain feed into uncertainties in the emission estimates. Red notations with a positive sign show factors that contribute to increased uncertainty in the estimated emissions, and green notation with a negative sign show factors that reduce uncertainty in the estimated emissions.



3.4.1.2 Qualitative Information on Emissions Derived from EO Data

EO data can be used to provide qualitative information on emissions rather to than quantify them. In this case, EO data can be used to provide key information regarding emissions that might otherwise be missing from compiled emission inventories. This method works in cases where the information provided identifies a new source that can be directly attributed to a specific type of activity. For example, recent work published from Sentinel 5P data shows hitherto unknown sources of NO_2 produced from gas flaring along the Urengoy–Pomary–Uzhhorod pipeline in central Siberia (see Figure 3.15). In this case the EO data from Sentinel 5P was used to identify a novel pollution source not covered by the existing emission inventories. This information could be used in the future to update the emission inventories. An important caveat is that this method works best in areas that are relatively clean without other large emission sources.

Figure 3.15: Map of NO_2 columns from the TROPOMI instrument onboard Sentinel-5P over central Siberia showing NO_2 plumes produced from gas flaring along the Urengoy–Pomary–Uzhhorod pipeline. Source: ESA.



3.4.1.3 *An In-Depth Review of the Existing Scientific Research on Pollution Emission Inversion Studies*

In Annex A, we provide an overview of relevant studies looking at the following trace gases (listed to relevance to air quality in Europe): NO_2, HCHO, SO_2, and CO. Except in the case of HCHO, the observed trace gases relate directly to the emission being studied. Also note that, typically, the presented studies use NO_2 observations to resolve NOx emissions. However, for HCHO, the emission inversion studies relate observed HCHO in the atmosphere to emissions of biogenic volatile organic compounds (BVOCs). The BVOCs are in turn related to air quality due to the important role they play in photochemical O_3 production during summertime when radiation is high.

For the trace gases we also give an overview of what is termed multi-constituent emission inversion. This is where the emissions of more than one trace gas are estimated simultaneously using observations of more than one trace gas. This is a more complicated approach, but it can yield significant benefits in terms of reduced errors because of the feedbacks and interactions between different pollutants. For example, optimizing NOx emissions without also optimizing VOC emissions can lead to significant errors in the resulting emission estimates (Hamer et al., 2015). In this example, assimilating only NO_2 and optimizing NOx emissions forces the inversion system to fix model errors using the emissions for this one group of chemical components in the photochemical system even though there is a sizeable model error resulting from VOC emission errors. (Hamer et al., (2015) demonstrated that failing to conduct multi-constituent assimilation and inversion leads to significant residual error in the emissions and the resulting ozone forecast.

We also present studies on the estimation of PM emissions based on aerosol optical depth measurements and other satellite-based aerosol data products.

3.4.1.4 *Nitrogen Dioxide*

The successful emission inversion of NO_2 represents one of the biggest technical challenges. Due to the high reactivity of NOx, this requires the use of a non-linear emission inversion scheme. This also increases the uncertainties on the emission inversion, since small errors in model chemistry, which are very difficult to diagnose, can have large impacts on the simulated concentrations. However, as the review makes clear, the majority of existing studies for NOx emission inversions that follow in some way the work of (Martin et al., 2003) and (Beirle et al., 2011) assume linear chemistry and idealised transport, which creates large uncertainties and biases in their estimates; one study (Liu et al., 2016a) estimates these to be as large as 55-91% for the (Beirle et al., 2011) methods and another (Zhao and Wang, 2009) estimates these to be approximately 50% for the methods following (Martin et al., 2003). There is a sizeable body of literature describing the application of such methods for NOx emission inversion. This literature is summarised in the Annex Table A1.

3.4.1.5 Formaldehyde and BVOC Emissions

As well as being a primary pollutant, HCHO is also a major tracer for VOC oxidation in the troposphere. Given the dominance of the emitted VOC budget by biogenic sources it is possible to therefore infer BVOC emissions. The literature on this subject is summarised in the Annex Table A2.

3.4.1.6 Sulphur Dioxide

SO_2 does remain an issue in Asia and its volcanic emissions can cause local air quality concerns in Iceland. Emission inversion for SO_2 has therefore generally focused on these two case types. The literature on this subject is summarised in the Annex Table A3.

3.4.1.7 Carbon Monoxide

CO has been the target for a variety of emission inversion studies owing to the relative ease of measurement/good quality of observation, its importance in tropospheric photochemistry, and the fact it is a good marker of biomass burning. The literature on this subject is summarised in the Annex Table A4.

3.4.1.8 Multi-Constituent Emission Estimates

We provide an overview of the multi-constituent emission inversion studies in the Annex Table A5.

3.4.1.9 Particulate Matter

Satellite observations of PM are only available in the form of AOD (see Sect. 5.2.1) and therefore have only limited applicability for estimating PM emissions. Nevertheless, there are studies that use AOD to infer information about PM concentrations and then from this infer emissions of PM. The literature on this subject is summarized in the Annex Table A6.

3.4.2 Current capabilities and limitations of EO data for emission validation

Based on the review of the literature in Sect. 3.3.1 we can identify applications of EO data for emission estimation and validation based on current capabilities. Emission inversion systems that provide high quality quantitative estimation of emissions (suitable for quantitative verification of bottom-up emission estimates) are difficult to apply operationally over large domains and for long timescales. However, there are several examples of methodologies that have lower computational and logistical requirements, allowing them to be applied for long timescales over large domains, that still provide emission estimates at low overall quality. Specific examples include the mass balance methodologies applied for NO_x emission inversion (Beirle et al., 2011; Martin et al., 2003), SO_2 emission inversion

(Kristiansen et al., 2010), and NH_3 emission inversion (Van Damme et al., 2018). Such methodologies are suitable for the qualitative evaluation of only the temporal variation of emissions (Beirle et al., 2011; Kristiansen et al., 2010) from, e.g., industrial point sources, only the spatial distribution of emissions (Van Damme et al., 2018), e.g., for identifying missing emission sources such as flaring or other unknown activities, or of both (Martin et al., 2003), e.g., suitable for qualitatively verifying the temporal variability of the existing emission inventories at large spatial scales.

Despite these capabilities, the review of existing literature points out a series of limitation related to the use of EO data for emission validation or verification. In the following, we outline our perspective on the requirements for emissions derived from EO data to be valuable for policy support and list the current limitations to fulfil such requirements. We consider the requirements for both general research applications and those necessary for a potential future system for emission verification.

Sectoral information: To help formulate effective public policy for air quality management policymakers need not only quantitative information on pollutant emissions in a country, region, or city but also information on the individual sectoral contributions. Without information on the sectoral contributions, it is not possible to formulate a policy that can target a particular polluting sector. Existing studies on inversions of anthropogenic emissions, which relate primarily to NO_x, CO, and SO_2, cannot distinguish the source of the emissions in terms of its sector, but only create estimates of the bulk emissions. This limitation is particularly pronounced for area source emissions where several source sectors combine. It is less significant in cases where large emissions from a single sectoral source dominate a particular geographical area. One example is very large NO_2 point sources from remotely located industries. We see that only a minority of available studies try to distinguish anthropogenic emissions from natural sources, and some of these studies even distinguish between different natural sources. Note that BVOC emission inversions, by their definition, refer to an emission inversion from a particular source, i.e., biogenic from vegetation, and so therefore do not suffer from this limitation.

Activity and emission factor data: bottom-up emission inventories are based on information on activity data and emission factors used to compile the inventory dataset, which allows to identification particular high-volume activities or particularly polluting technologies. This knowledge can in turn inform policymakers and allow them to target specific types of air pollutant sources. Again, *top-down emission estimates from EO data must provide information that can be linked back to the activity and emission factor data* to be relevant for air quality management. There are major limitations with current emission inversion methods that prevent the emission estimates from being related back to the activity and emission factor data.

Uncertainties in emission inversions: Emission estimates from EO offer an attractive solution to the problems of traditional emission validation methods. Only indirect validation of methods and with models, but to fully reconcile the differences between top-down and bottom-up emission estimates, the intrinsic uncertainties on top-down estimates must be fully characterised. It is therefore *vital that top-down emission estimates from EO provide thorough uncertainty analysis* considering all the sources of uncertainty outlined in Section 3.3.1 and summarised in Figure 3.14, which will provide the necessary means to reconcile differences with bottom-up estimates. This is the only way to provide confidence to act if significant differences compared to bottom-up estimates occur. Most emission inversion studies do not carry out quantitative uncertainty analysis addressing the emission inversion estimates that are directly calculated by the inversion methodology. Most studies attempt to estimate uncertainties on the emissions, but this is done separately from the emission calculation itself. Further, errors are typically specified in general terms, i.e., errors are given as an expected range as opposed to a definite error on a single emission estimate.

Operational Reporting: Official reporting of emissions at a national level is made on an annual basis, and their reporting is organised into coordinated international reporting frameworks (FN, EMEP, and NECD). These officially reported emissions are based on a range of methodologies using different levels of details in the input data (from Tier 1 to Tier 3) as specified under the EMEP-EEA Guidebook([22]). These emission datasets are available on open access databases (for instance at Centre on Emission Inventories and Projections([23]), EEA's NEC Directive data viewer, and EEA's LRTAP data viewer) . This reporting system offers some major advantages: it facilitates the assessment and inter-comparison of different years and by sector/sub-sector e.g., allowing complex trend analysis, easy data access is ensured using open access databases (please see above). Ideally then, emission estimates from EO data should be reported on a continuous basis and be made publicly available via open access to provide complementarity to existing reporting systems. Current emission inversion studies using EO data have been carried out in a research-driven setting on an ad-hoc basis, i.e., case studies were carried out based on the research interests of the scientists and wider scientific community. These studies were carried out without any needs for producing long time series of emission datasets or of making the data products available in an open access server. We see many studies focussed on short time periods, which greatly limit any additional information that can be gained from an emission estimate independent of bottom-up inventories. Where possible the top-down emission estimates should be made available for testing and analysis. Unfortunately, the datasets are not frequently advertised as being publicly available requiring a user to contact the author of a scientific study and ask for the data.

Additional limitations: High uncertainties stemming from the use of methods, i.e., those based on (Martin et al., 2003) and (Beirle et al., 2011), who use of linear chemistry and simplistic or idealised assumptions regarding transport drive these errors. Further, lack of error characterisation or treatment of observation of model errors compounds these faults. (Liu et al., 2016a) estimates that the errors arising from the (Beirle et al., 2011) methodology could be as large as 55-91%. Zhao and Wang, 2009 estimates approximately 50 % errors for the methods following (Martin et al., 2003).

Many of the more simplistic NO_x emission inversion studies time average the satellite data and emission inversion estimate to the monthly level or even annual level. This removes a lot of the temporal information that could be useful for evaluating bottom-up emission inventories. Some of these studies do try to perform emission estimates on a daily basis, but this approach can be limited by factors affecting reliable production of the retrieval, e.g., cloud cover over the target.

None of the studies we have highlighted for NO_2 and NO_x address a major concern that was raised by Valin et al., (2011), who demonstrate that model resolution directly impacts simulated NO_2 concentrations from models, which will in turn have an impact on the emission inversions based on models. Valin et al. demonstrate that errors arising from this effect will only start to become <10% in models with a horizontal resolution of between 4 to 12 km. It is very likely that many of the existing studies with coarser spatial resolution neglect this effect in their evaluation. It is currently not possible to run models globally at high resolutions of between 4 to 12 km and therefore this remains an ongoing problem.

3.4.3 Development needs and recommendations for emissions

In this section we consider first the main development needs currently necessary to enhance the use of EO Data to improve emissions and then in the final chapter of this report we provide a series of more specific recommendation for EEA/ETC/ATNI work on emissions.

([22]) https://www.eea.europa.eu/publications/emep-eea-guidebook-2019.
([23]) https://www.ceip.at.

There are three possible developments that could be made to address limitations with respect to **sectoral, activity, and emission factors**:

- Targeted application of current emission inversion methodologies towards cases where unequivocal source attribution can be made. Examples are applications focussing on remote pollution sources such as shipping, very large point sources at relatively clean locations, and the Urengoy–Pomary–Uzhhorod pipeline highlighted in Figure 3.15. We provide three concrete recommendations (for HCHO/BVOCs, NOx emissions, and dust emissions) on approaches that could achieve this in the discussion below.
- Higher temporal sampling from Sentinel-4 to differentiate sources with different temporal variability. This will overcome limitations of the existing satellite platforms in low Earth orbit that have repeat times of at best a day.
- Combining EO air pollution data with other EO data types and ancillary data from other sources.

Developments with respect to reporting: Move away from ad-hoc emission inversion studies with a research-driven focus that suffer from limited temporal coverage with output that isn't open access. Move towards systems that produce emission inversion analysis on an operational basis that provide data in an open access fashion.

Different developments to properly account for uncertainties: Implementation of DA algorithms that allow the quantification on the intrinsic uncertainty of the emission inversion methods considering uncertainties from all sources.

We recommend that multi-constituent DA to perform simultaneous emission inversion for different pollutants should be pursued. This is one of the most effective ways to reduce model uncertainties using EO data. This should lead to a consequent improvement in emissions estimates from emission inversion methodologies (Hamer et al., 2015; Miyazaki et al., 2012, 2017).

One solution to the problems of high uncertainty in the studies based on approaches used by Beirle et al.(2011) and Martin et al.(2003) is to focus not on single case studies or short time periods, but to instead examine trends and time series. This will still give useful qualitative information about the evolution of emissions over time. Liu et al. (2016b), for verifying information given in bottom-up inventories regarding changing technologies in Chinese power plants.

Building advanced prior knowledge of correlations between different pollution sources could support emission inversion. This will greatly help to differentiate different anthropogenic emission sources, but this approach is only suitable for emission inversion systems using advanced algorithms, e.g., ensemble Kalman filter and variational methods.

Usage of the Sentinel-4, which will be launched into geostationary orbit in the coming year, will provide observations at much high frequency than the current low earth orbit satellites. This could potentially allow estimation of emissions at much high temporal frequency and resolution as demonstrated by preparatory studies for the similar TEMPO satellite planned by NASA (Chance et al., 2000; Zoogman et al., 2011, 2014).

Despite the large uncertainties and limitations, some of the simpler methods for estimating emissions, i.e. those based on Beirle et al., 2011 and Martin et al., 2003 could have applications for qualitative verification of trends in emissions on monthly to yearly timescales. Furthermore, such methods would be suitable to identify new sources and to crudely quantify them. In addition, they could qualitatively identify regions where emissions are not reported correctly. Note, however, that the (Beirle et al., 2011) method is only suitable for quantification of large point sources. Although these methods require only limited technical development, which makes them attractive to use, they are not suitable for verification of the absolute magnitudes of emissions. Nevertheless, these methodological options offer an attractive means to provide qualitative support when compiling official emission inventories.

The most promising possibilities for creating a system capable of providing verification of emissions for policy support comes from the more advanced inversion methods based on data assimilation systems using either the ensemble Kalman filter or 4D-variational algorithms. Furthermore, multi-constituent data assimilation and emission inversion of more than one pollutant offers the best possibility of reducing model errors and therefore estimating trace gas emissions with the least amount of error. Hamer et al. (2015), Miyazaki et al. (2012, 2017), and Müller and Stavrakou (2005) clearly show the added value of assimilating more than one pollutant to place additional constraints on pollutant emissions. Indeed, the review by Streets et al. (2013) recommends this as a path forward in the field. Only a small number of teams internationally have developed this capability, but this represents a critical path forward for advancing on current methodologies.

We recommend further work on assimilating HCHO EO data to estimate BVOC emissions that will yield emission estimates that are specific to a single natural source contribution. Current methods for estimating BVOC emissions based on assimilation of HCHO EO data are effective at constraining the biogenic component of VOC emissions. This is mainly because VOC emissions are dominated by the biogenic component and due to the high reactivity and, consequently, high yields of HCHO formed in the atmosphere from BVOC oxidation.

Current methods for estimating NOx emissions from EO data cannot reliably differentiate between different anthropogenic sources of NOx except in exceptional circumstances, e.g., remote point source emissions. Therefore, a strong recommendation is to support methods that use ancillary data from other sources to differentiate emissions sources.

Various systems now exist to estimate natural dust emissions, which could be important for identifying the influence of desert dust intrusions into southern and mainland Europe. This could be useful for pollution episode analysis to be able to identify cases that had a large natural influence.

Operational tools for assessing SO_2 emissions from volcanic eruptions (Eckhardt et al., 2008; Kristiansen et al., 2010; Seibert et al., 2011) could be repurposed as operational tools for monitoring SO_2 from power plants and industrial point sources using old technologies outside of Europe.

4 Conclusions and Recommendations

The European Commission's reporting and monitoring fitness check report of June 2017 (COM (2017) 312 final) includes ten 'Actions to Streamline Environmental Reporting'. Action 7 is "Making better use of data generated through the Copernicus programme". This report identifies the data and information generated by Copernicus so far used by the ETC/ATNI and its precursors, both in terms of the Service and the Space components of the program. It shows that EEA, in relation to the work carried out by the ETC/ATNI and its precursor ETCs, has been making use of Copernicus service data since the beginning of the program, while the use of the Earth Observation (EO) data has so far been more limited.

Data from the CAMS service, in particular its regional air quality results, is used for ETC/ATNI mapping activities, as auxiliary data. The CAMS regional air quality data is also used in EEAs air quality index and CAMS assessment reports are considered in EEA's annual "Air Quality in Europe" report. Data from the CLMS service have been used to a lesser degree by the ETC/ATNI and its precursors, mostly as a land cover indicator for the ETC/ATNI mapping activities, to distinguish rural and urban areas. CLMS products on landscape fragmentation pressure and on land take are used as indicators to support transport activities. More importantly, land cover information is used to understand where noise pollution is occurring and to characterise quiet areas. Data from the C3S is currently used in the ETC/ATNI as meteorological driver in trend studies. However, data of climate variables (ECV) have a potential to be used for emissions work or cross cutting issues such as urban sustainability, which could be further explored within the ETC/ATNI. The only EO data directly used so far is NO_2 OMI([24]) data, which has mainly been used to support ETC mapping activities.

Further use of the Copernicus data is both feasible and advisable. In the following, we provide our recommendations to make better use of Copernicus data in the ETC/ATNI including a discussion on the current potential for further use of this data to improve the ETC/ATNI products. The recommendations for the enhanced use of Copernicus data are provided for the following areas of the ETC/ATNI work-plan:

- Mapping activities
- Emission activities
- Trend analysis
- Noise assessments
- Air quality assessments
- On-line air quality services
- Urban sustainability studies

4.1 Better use of Copernicus data in ETC/ATNI mapping activities

Mapping air quality in Europe is a key product of the EEA that complements the mapping carried out in other programs such as CAMS or EMEP. The European-wide mapping activities in ETC/ATNI rely on measurement data and, since is used for further analysis considering population exposure to air pollutants, tries to identify as good as possible hotspot and urban areas. In contrast, the mapping activities at CAMS or EMEP derive background air quality indicators. The fusion between in-situ observation and modelled background data as done for instance in the ETC/ATNI mapping products are more appropriate to be used as basis for exposure calculations than the background indicators from CAMS or EMEP. This justifies their routine annual elaboration and the use of the mapping product as basis for the air quality assessments at ETC.

([24]) NASAs Ozone Monitoring Instrument – OMI.

The mapping activities at ETC are in constant development to ensure an improved accuracy of this product. A variety of mapping approaches and a multitude of input datasets have been utilized within the ETC mapping activities over the years and a reliable and robust methodology has been developed. The most current version of the mapping algorithm uses Europe-wide data from official air quality measurement stations (Horálek et al., 2017). This data provides the core information for the mapping procedure, but auxiliary data is generally needed to add information about spatial patterns of the parameter in question and to guide the interpolation procedure. The auxiliary data include background model calculations, as well as digital elevation model results and data on population density. Direct use of EO satellite data as auxiliary data for the ETC mapping of air pollution at European scale has also been evaluated and included in the case of NO2 in recent years.

To further improve the ETC mapping results, our main recommendations for implementation in the short-term are:

Use of both EMEP and the CAMS ensemble as the background models. The current mapping approach used in the ETC includes model output generated by the Unified EMEP atmospheric chemistry model (Fagerli et al., 2004; Simpson et al., 2003), which is provided at a spatial resolution of about 10 km^2 as auxiliary data. This data is similar in resolution to the data provided by the CAMS regional ensemble. The choice of background model has only a small effect on the final accuracy of the ETC mapping because monitoring data drives the actual results (Horálek et al., 2019). The CAMS ensemble interim re-analysis data are available in January after the year of study, which gives the opportunity for timely mapping to be carried out. On this basis, we recommend the production of preliminary (or interim) spatially interpolated air quality maps based on the up to date (UTD) measurement data reported under the 2008 Air Quality Directive and the CAMS ensemble as the background model. This is to ensure consistency with CAMs results, even if it has small effect on the final accuracy of the results (Horálek et al., 2019). The CAMS re-analysis is ensemble-based, and it should therefore be a more robust modelling approach compared to applying the EMEP model alone. However, to maintain the year-to-year consistency of the existing mapping approach based on the use of the validated air quality data reported under the directive we recommend considering the continued use of the EMEP model data for this purpose.

Use of TROPOMI/Sentinel-5P NO_2 data. NO_2 tropospheric column data from the OMI instrument has previously been introduced into the routine mapping methodology of the ETC and evaluated as an additional auxiliary variable (Schneider et al., 2012; Horálek et al., 2018b). The use of OMI-based NO_2 products within the routine annual mapping for the ETC results in improved mapping accuracy, albeit the improvement is relatively minor and mostly relevant for rural areas. With the availability (since the year 2018) of operational TROPOMI/Sentinel-5P data of NO_2 with a significantly improved spatial resolution of about 3.5 km x 5.5 km (3.5 km x 7 km before August 2019), we recommend investigating the use of the TROPOMI NO_2 product within the routine mapping within the ETC. It is expected that the characteristics of this product, both with respect to higher spatial resolution as well as the improved retrieval scheme and instrument characteristics, will have a substantial impact on the mapping accuracy for NO_2. In addition, the currently used OMI instrument is nearing the end of its lifetime and it is strategically important to evaluate adequate replacements before it is out of commission.

Introduce EO data as auxiliary data for mapping of $PM_{2.5}$ and PM_{10}. We recommend investigating the potential of using aerosol optical depth (AOD) as an additional proxy variable in the ETC mapping. While the relationship between AOD and surface PM is highly complex and conversion between the two variables is usually subject to significant uncertainties, it is nonetheless reasonable to assume that the overall spatial patterns are somewhat similar. As the geostatistical approach taken by the routine mapping operations in the ETC rely mostly on the spatial patterns of the used proxy variables rather than in the absolute numbers, it is conceivable that AOD can provide additional information regarding the spatial distribution of the particles and as such increase the accuracy of the routine PM mapping. The only satellite within the Copernicus Space Component that has the capability to provide AOD data is Sentinel-3. In addition, several non-Copernicus satellite instruments provide AOD data operationally (e.g., MODIS, VIIRS) and thus could be used for such an investigation. There are also research AOD products for the geostationary SEVIRI([25]) instrument.

Introduce EO data as auxiliary data for mapping of O_3 and SO_2. We recommend investigating the potential of using the Sentinel-5P/TROPOMI tropospheric ozone product as a proxy variable in the operational mapping routine for ozone. In addition, Sentinel-5P/TROPOMI provides a SO_2 product that can to some extent detect large anthropogenic sources, and as such has potential to be used as spatial proxy for the geostatistical interpolation of the ETC/ATNI mapping. Although sulphur dioxide (SO_2) is not routinely mapped within the ETC, this component might be interesting when analyzing trends. The introduction of EO data for both ozone and sulphur dioxide from Sentinel 5p may also be interesting related to trend analyses in the future.

4.2 Use of Copernicus data in ETC/ATNI emissions activities

EU Member States officially report emission data under the National Emission Ceilings Directive (EU, 2016). Further, the EEA compiles the EU emission inventory and informative inventory report under CLRTAP. The report and its accompanying data constitute the official submission by the European Commission on behalf of the EU as a Party to the UNECE LRTAP Convention. The emission data is based on emission factors and activity data compiled at national level. The emission data is usually based in annual statistics and both their temporal and spatial resolution are derived based on ancillary data and documented methodologies (EMEP/EEA Guidebook, 2019). The evaluation of the spatial and temporal distribution of emissions is a key area where the Copernicus products offer significant capabilities.

Below we propose different ways of contributing to the improvement and validation of emission activities at ETC/ATNI. One is to rely on the capabilities of the CAMS emission data series, another is to rely on the direct use of satellite data, or even on the modelled air quality results provided by the CAMS service.

Use of CAMS emissions to improve the spatial distribution of reported emissions. The CAMS emission inventories are constrained by the reported national emissions. This means that both national and sector total emissions are the same in CAMS as the officially reported ones. The value added by CAMS relates to the spatial distribution of the emissions that are used as model inputs and to expert analysis for some sectors (residential heating for example). Uncertainties in spatially explicit emission inventories can arise depending on the targeted spatial resolution and the quality and accuracy of proxy data. This is precisely the technical field where CAMS puts a lot of effort to deliver gridded emission datasets appropriate to air quality modelling. Therefore, we recommend initiating a feasibility study with the purpose to use the CAMS annual emission inventories to evaluate the spatial distribution datasets reported by the countries and initiate a dialog with Member States to support an improvement of the spatial distribution in the EU emission inventory reported to LRTAP and under the NEC Directive.

([25]) METEOSAT Spinning Enhanced Visible and Infrared Imager – SEVIRI.

Use of satellite data to improve the spatial and temporal resolution of emissions. The use of satellite data to evaluate and improve the emission estimates from bottom-up emission inventories is one of the most interesting potential applications of EO data for the ETC/ATNI work. However, it is also one of the most challenging and currently subject of extensive research. While there is potential in using EO data for correcting existing bottom-up emission inventories, the use of EO data for emissions, the so-called "top-down" emission estimates, is still challenging and has limitations within a policy context. In particular, the currently used emission inversion methodologies are still constrained by lack of vertical profile data. So, at present, it is difficult to quantify actual emission data from satellites, but EO data can still be useful to determine an improved spatial and temporal resolution of emissions. The temporal resolution of the emissions used in most air quality forecasting services, and in CAMS, is a major drawback for the use of these services in policy applications. As the emission data is updated only once a year, usually years arrears, this hampers the capability of using up-to-date emissions in the current air quality forecasting systems and in some cases also affects the capability of the modelling systems to assess the effectiveness of air quality control measures. In addition, emissions are mostly provided as annual totals, which leaves uncertainties concerning their temporal variability on weekly, monthly, and yearly timescales and it is up to the individual modelling teams to apply their own time variations. To initiate a process to include satellite information in the development and evaluation of emission inventories, we propose to conduct a feasibility study. The goal of the study will be to develop a system to evaluate the current reporting of emissions of nitrogen oxides with the help of Sentinel-5p satellite data by addressing their temporal resolution. The idea is to develop a system to timely estimate the temporal variability of NO_x emissions using TROPOMI NO_2 tropospheric column data. The system will allow us determining the temporal evolution of emission data at weekly to monthly timescales and the examination of short-term effects such as weekday versus weekend differences. The study is relevant to EEA in their assessment of European emissions.

Use satellite data to evaluate emissions from industrial point sources. Another promising application of EO products is the evaluation of large point source industrial emissions. Analyzing single large emission sources removes some of the problems of inverting more complex combined pollution sources, i.e., that emissions cannot be separated on a sectoral basis and that complex models and data assimilation systems are required to reduce the uncertainties of the emission estimates. The work of Beirle et al. (2011) demonstrates the potential of inverting single large NO_x pollution sources. The work of Eckhardt et al.(2008), Kristiansen et al. (2010) and Seibert et al. (2011) demonstrates that SO_2 emissions from volcanoes can be quantified; these methodologies can be repurposed for estimating large SO_2 industrial emission sources such as from metal ore smelters. We propose to conduct a feasibility study to demonstrate the quantification of NO_x and SO_2 emissions from large industrial point sources. For example, this could include large power plants for NO_x and metal sulfide ore smelters for SO_2. The feasibility study will also compare the EO emission quantification with the official emission reporting to evaluate the potential of the current inverse methodologies for emission validation purposes.

Uncertainty analysis of emission data. Validation of emissions data relies often on the evaluation of modelled results driven by these emissions with observations, i.e., in situ measurement results**.** The CAMS services (both regional air quality productions and policy services) provide excellent areas for investigations. They are based on model runs, which obviously depend on emission input data. The CAMS model evaluation processes (against observations) can help in qualifying potential underestimations in emissions (especially for PM). The CAMS policy services (for instance the source/receptor allocation services) can be used to test sensitivity of model responses to emissions and to inform the impact of mitigation strategies.

4.3 Better use of Copernicus data in ETC/ATNI trend analysis

The work in ETC/ATNI often revolves around analysing trends of pollutants over time and identifying the reasons behind the observed trends (Colette et al., 2018; Solberg et al., 2018a). The ETC/ATNI trend work relies primarily on the air quality monitoring data reported to EEA, meteorological and emission data as well as modelled air quality data. The latter are used as support data to interpret the reasons behind the trends in observed air quality monitoring data.

Copernicus meteorological trend data from C3S has been used as meteorological parameter reference in the trend work carried out in the ETC. However, neither satellite products nor CAMS re-analysis results have been yet used in the context of ETC trend work. These are our recommendations to enhance the use of Copernicus data in ETC/ATNI trend analysis:

Use of EO products for determination long-term trends. One of the most promising research applications of EO products is long-term trend analysis. The reason for this is that earth observing satellites can provide consistent information on the temporal dynamics of air pollutants even in areas where typically no air quality monitoring stations equipped with reference instrumentation are located. Satellite observations can thus provide spatially comprehensive information and complement the trends obtained from ground-based stations as typically shown in the annual air quality reports of the EEA. We recommend initiating the use of EO products in trend analysis at ETC with focus on NO_2. This is because satellite retrieval products for NO_2 are generally quite mature and accurate enough for trend analysis. At the same time NO_2 levels tend to vary substantially enough over just a few years to see statistically significant trends even for relatively short periods of 10 years or less. We recommend comparing satellite-inferred nitrogen dioxide trends over Europe with station-based trends previously computed in the ETC/ATNI to complement the analysis and identify possible inconsistencies, following similar methodology as that reported previously in Schneider and van der A (2012) and Schneider et al. (2015). The study will be especially relevant in regions where no, or only few, in situ observations are available.

Use of CAMS ensemble re-analysis in future applications. The current CAMS ensemble re-analysis product is not yet appropriate for applications aiming at establishing air quality indicator trends. This is because the current set of CAMS ensemble re-analysis has had different quality over the years (because of the positive evolution of the system) and because the current set does not use updated emissions from year to year. Now, the most appropriate modelling data set for use in trend analysis is the one produced by the EMEP program. The EMEP modelling system uses updated meteorology and emission data to drive the air quality model results. Therefore, any planned comparison of modelled and observed trends will profit from a reference to this EMEP dataset. In the future, however, we recommend that CAMS considers regular updates of the CAMS regional ensemble re-analysis for trend analysis. ETC/ATNI work will benefit if CAMS could carry out a multi-year re-analysis because a) the modelling ensemble is more robust and b) the CAMS emission time-series from 2010 to 2018 is currently available. Such trend re-analyses will however not be relevant to assess the contribution of meteorology to observed changes, as only sensitivity simulations (with constant emissions for instance) can answer that question. For sensitivity simulations, single model approaches are a more feasible approach.

4.4 Better use of Copernicus data in ETC/ATNI noise assessments

The Green Infrastructure Strategy recognises that the protection, restoration, creation, and enhancement of green infrastructure become an integral part of spatial planning and territorial development. In addition, green infrastructure also allows to establish a direct link with health and quality of life from a multifunctional perspective. Therefore, the assessment of the status of green infrastructure, in urban areas, is of significance as a response to some of the challenges addressed by

ETC/ATNI, especially regarding air quality and noise pollution. In this context the data provided by the Copernicus through its CLMS will be particularly relevant.

Noise mitigation and green infrastructure. We recommend developing a system to assess the effect of existing green infrastructure in European cities to mitigate noise exposure. The system would compile existing information on effects of the type of vegetation (tree, shrub, other species; density; height) on mitigating noise exposure. The following data would be needed: noise mapping (available); building height (part of the information included in Copernicus CLMS Urban Atlas); street tree layer (currently under revision), phenological information (useful to identify perennial/deciduous, grass, probably some shrubs -will be available by mid-2020). The idea is to develop a methodology, based on the available data and references in the literature, to test the methodology in selected cities where ancillary data is accessible or similar analysis has been performed (e.g., Barcelona) and where feasibility to extend to all the cities included in the Environmental Noise Directive and Urban Atlas has been assessed. The proposal is currently focused on noise, but the approach could potentially be extended to also evaluate the capacity of the green infrastructure to capture air pollutants. The proposal could thus constitute an interesting cross-cutting analysis.

4.5 Better use of Copernicus data in ETC/ATNI air quality assessments

The question of duplication of work within the EEA report and the CAMS and EMEP assessment reports has been already discussed several times. The complementarity of the various reports which propose different angles to describe and interpret air pollution patterns in Europe has been highlighted as well. The EEA reports focus, on one side, on pollutant concentrations from measurements officially reported by EEA member, cooperating and other reporting countries and, on the other side, on human and ecosystem exposure to air pollution and thus rely for these exposures on the current mapping routines at ETC/ATNI that are optimised to describe the air pollution situation particularly in hot-spots and urban areas. By contrast, both the EMEP and CAMS assessment reports focus on the long-range component of pollution and the regional component. Both EMEP and CAMS provide source-allocation information on the regional scale. At present, EMEP is useful for trend analysis while the CAMS interim re-analysis results, based on up to date (UTD) data have an increased timeliness with respect to the other reports. Soon, however, it is also expected that the ETC mapping results will be elaborated based on UTD data.

Extended contribution to the air quality reports. The CAMS ensemble interim re-analysed maps are available while the EEA air quality report is still being drafted, and the maps have been referred to and used for interpreting air pollution episodes in the EEA reports. Our recommendation is that the EEA could expand the use of episode analysis proposed in the CAMS interim reports to support interpretation of specific air pollution patterns.

4.6 Use of Copernicus data in EEAs on-line air quality services

The development of the Air Quality Index at EEA is a successful example of uptake of Copernicus data on air quality for public use. Below additional ideas on how a link to existing Copernicus data could be used to develop on-line air quality services significant to the EEA user community.

Air quality index forecasting. The EEA is already extending the information of the air quality index maps to the up-coming 24h hours (in forecast mode) and is doing so based on the ensemble forecasts delivered by CAMS. The air quality index service at EEA provides thus forecasted air quality index at monitoring stations using CAMS data at the monitoring sites.

Support in the assessment of mitigation strategies. The EEA carries out assessments of the efficiency of emission control strategies. The policy tools developed by CAMS, in particular the Air Control Toolbox (ACT) and source/receptor allocation tool could be used to support such assessments, especially regarding the identification of the driving factors that lead to air pollution episodes. Work aiming to assess the relevance and reliability of current integrated modelling tools used to derive cost-benefits analyses of air pollution mitigation strategies and assess the cost of air pollution (such as in Task 1.2.2.2 in the 2019 ETC Action Plan) already shows the potential added value of using the ACT. However, it also shows the tools' current limitations and highlights options for future applications. The recommendation is to continue work at the ETC/ATNI to further use the CAMS policy tools for health and economical assessments.

On-line early-warning system for exceedances. EEAs up-to-date data (viewer) system identifies exceedances of limit values as they occur. While Member States need to evaluate the origin of these exceedances themselves, the data available at CAMS can help to determine the origin of exceedances when related to long-range episodes. The current episode warning system in CAMS provides detailed source allocation information but is only activated by the service 5 times a year depending on the regional pollution situation, while there is a need for an episode early-warning system providing data on the origin of exceedances at local/urban level when and where these take place.

The proposal is to develop a warning system at EEA that will be provided for all stations that register an exceedance. The on-line warning system will gather existing CAMS forecasting and source-allocation information to provide a timely characterisation of the regional background sources affecting the monitoring station in exceedance. The characterisation will also help to evaluate the influence of natural emissions. CAMS global services develop an aerosol segment which includes forecasts and re-analyses of natural compounds (desert dust and sea salt). In the CAMS framework such inputs are used as boundary conditions of the regional services. However, they can also be used to support particulate matter (PM) episode analysis in a regulatory reporting perspective. For example, periods of dust events impacting EU countries could be monitored and CAMS results could be used as an indication as to when and where Member States could subtract PM caused by natural sources in their reporting under the AQ Directives.

Similarly, the influence of forest fire emissions on air quality in the EU region can be investigated thanks to the CAMS Global Fire Assimilation System (GFAS). The system provides estimates of emissions from wildfires and biomass burning using satellite observations of the intensity of these fires every day. We recommend following the approach already developed under the CAMS interim air quality assessment reports (IAR) and develop an on-line early-warning system to help Member States characterise the potential contribution of long-range and natural sources in the exceedances of air quality limit values when registered in their monitoring stations.

4.7 Better use of Copernicus data in ETC/ATNI urban sustainability assessments

Urban sustainability is a key parameter in urban development. The current aim to promote climate neutral cities with improved quality of life requires the development of appropriate indicators to trace evolution towards these sustainability goals. Copernicus data can support the development of such indicators.

Use of Copernicus data in a possible urban sustainability indicator. The combination of data from CAMS, CLMS and C3S services, in addition to Sentinel 1 and Sentinel 2 data can provide a series of layers of relevant information to facilitate the creation of an urban environmental sustainability indicator. The index could combine different EEA datasets, including for example monitoring data on air quality, with data from CAMS on emission sources, water, noise exposure, as well as Corine Land Cover data from Copernicus Land Monitoring Service. Parameters such as temperature, wind, and relative humidity from the Copernicus Climate Change service, C3S, could be used to determine thermal comfort combined with physical building and land-use information from Sentinel 2. Other external datasets could also be included, including data on socio-economic and demographic variables, to explore spatial associations between dimensions of social vulnerability and environmental pressures.

There is considerable potential to increase the use of Copernicus products in the work of the ETC/ATNI. We are confident that this report will serve as a guide to identify priority ETC/ATNI tasks linked to Copernicus for the next few years.

4.8 Possible user requirements defined by the EEA to the Copernicus services

The analysis above has also identified areas within Copernicus that require further development to facilitate the uptake of these products by the EEA. The two main recommendations for Copernicus are 1) for the CAMS regional products, to be regularly updated with actual yearly emission data to facilitate their use in trend analysis and 2) for the EO activities, to enhance the number of vertical profile air concentration data to facilitate the evaluation of emissions from space. These two improvements could have a high impact on the future uptake of Copernicus products by the EEA within ETC/ATNI related activities.

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Annex A

Table A1: Summary of existing literature on NOx emission inversions using NO2 EO data. Unless otherwise stated, studies do not provide sectoral information or are not classifiable as data assimilation methods as defined in Sect. 3.4.1.

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Beirle et al., 2011)	Aura	OMI	Tropospheric column	Isolated point source outflow model	Examples given for Riyadh	2005 to 2009	Single megacity	Simplistic method with basic assumptions leading to high uncertainties, e.g., linear chemistry and idealised transport. Applicable for large isolated point sources under ideal conditions only. Only includes error characterisation from observations and model errors are ignored.
(Cheng et al., 2010)	Aura	OMI	Polluted column	Adaptive nudging scheme. No details given.	China	2006	12 km^2	Deals with column vs. surface observations very crudely resulting in large uncertainties. Emissions only estimated as monthly means. Details poorly described. Impossible to assess quality of work.
(Ghude et al., 2013)	Aura	OMI	Tropospheric column	Mass balance optimisation scheme	India	2005	55 km^2	Optimisation scheme leads to large uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Emissions only estimated as monthly means.
(Gu et al., 2014)	EUMETSAT / Aura	GOME-2 / OMI	Tropospheric column	Mass balance optimisation scheme	China	2011	70 km^2	Optimisation scheme following (Martin et al., 2003) leads to large uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Emissions only estimated as monthly means.
(Gu et al., 2016)	EUMETSAT / Aura	GOME-2 / OMI	Tropospheric column	Mass balance optimisation scheme	China	August, 2007	36 km^2	Basic optimisation scheme causes large uncertainties from observation error. Includes simple treatment of non-linear chemistry. No way to characterise errors. Emissions estimated as monthly means.
(Souri et al., 2016)	Aura	OMI	Tropospheric column	Bayesian inversion	Southeast USA	September, 2013	~20 km2	Bayesian inversion gives emission estimates that considers model and observation errors. Careful application of the inversion method gave sectoral estimation of emissions. Attempt made to evaluate emission uncertainty using independent observations. High quality.
(Jaeglé et al., 2005)	EUMETSAT	GOME-2	Tropospheric column	Mass balance optimisation scheme	Global	2000	$2° \times 2.5°$	Optimisation scheme following (Martin et al., 2003) leads to large uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Emissions only estimated as monthly means. Some limited sectoral information gained using assumptions and independent wildfire data.
(Kemball-Cook et al., 2015)	Aura	OMI	Tropospheric column	Mass balance optimisation scheme	USA	Spring / summer, 2006	36 km^2	Optimisation scheme following (Martin et al., 2003). See related studies for evaluation. Monthly mean estimates only. Two separate satellite retrievals are used; both given very different results, which highlights

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
								the effects of satellite retrieval error on emission estimate uncertainty.
(Konovalov et al., 2008)	EUMETSAT/ENVISAT	GOME-2 / SCIAMACHY	Tropospheric column	Bayesian inversion	Europe	1996 to 2005	1° × 1°	Only long-term trends are derived by country with no estimation of emission magnitude. Inversion scheme considers model and observation error but cannot estimate uncertainties.
(Konovalov et al., 2010)	EUMETSAT/ENVISAT	GOME-2 / SCIAMACHY	Tropospheric column	Bayesian inversion	Megacities in Europe / Middle East	1996 to 2008	1° × 1°	Only long-term trends are derived per megacity with no estimation of emission magnitude. Inversion scheme considers model and observation error but cannot estimate uncertainties.
(Lamsal et al., 2011)	ENVISAT	SCIAMACHY	Tropospheric column	Mass balance optimisation scheme	Global	2003 to 2009	1° × 1.25°	Optimisation scheme following (Martin et al., 2003) leads to large uncertainties from observation error. No way to characterise errors. Simple treatment of non-linear chemistry helps to reduce uncertainties. Emissions only estimated as yearly means.
(Lin, 2012)	Aura	OMI	Tropospheric column	Multivariate regression	East china	2006	0.25° × 0.25°	Emissions differentiated between anthropogenic and the natural sources.
(Liu et al., 2016a)	Aura	OMI	Tropospheric column	No inversion methodology	China	2005 to 2015	Not relevant	Not an emission inversion study. This is a long trend analysis of NO_2 satellite data in support of bottom-up inventories for large power plants. Satellite observations give qualitative support of bottom-up emission data.
(Liu et al., 2016b)	Aura	OMI	Tropospheric column	Multi point source Gaussian outflow model	USA and China	2005 to 2013 (May-September)	For individual point plants	Advancement over the Beirle et al. (2011) methodology allows treatment of multiple interacting plumes. Only capable to estimating emissions from large point sources. Simple linear chemistry and transport creates large uncertainties.
(Martin et al., 2003)	ERS-2	GOME	Tropospheric column	Mass balance optimisation scheme	Global	September 1996 – August 1997	2° × 2.5°	Early Optimisation scheme now widely applied. Has large uncertainties from observation error and linear chemistry assumptions. Monthly mean estimates only.
(Mijling et al., 2012)	EUMETSAT/ENVISAT	GOME-2 / SCIAMACHY	Tropospheric column	Kalman filter	China	Summer, 2008	25 km²	Emissions estimated on a daily basis in short timeframes. Can consider model and observation error but lacks robust means to estimate model error.
(Napelenok et al., 2008)	ENVISAT	SCIAMACHY	Tropospheric column	Kalman filter	USA	Summer, 2004.	36 km²	Kalman filter inversion method considers both model and observation errors and shown to be theoretically sound in this case. Emissions only estimated as three-monthly means.
(Qu et al., 2017)	Aura	OMI	Tropospheric column	4D-var	East Asia	2005 to 2012	0.5° × 0.667°	Highly advanced data assimilation system. Emissions differentiated for anthropogenic and natural sources.
(Stavrakou et al., 2008b)	EUMETSAT/ENVISAT	GOME-2 / SCIAMACHY	Tropospheric column	4D-var	Global	1997 to 2006	5° × 5°	Highly advanced data assimilation system. Uncertainties are considered on observations and model, and the emission estimate has an uncertainty

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
								analysis. Emissions differentiated for anthropogenic and natural sources.
(Tang et al., 2013)	Aura	OMI	Tropospheric column	Kalman filter	Texas, USA	Summer, 2006	12 km^2	Kalman filter inversion method considers both model and observation errors. This is not an ensemble method and therefore model errors are poorly quantified.
(Wang et al., 2007)	ERS-2	GOME	Tropospheric column	Mass balance optimisation scheme	East China	1997, 1998, and 2000	$2° \times 2.5°$	Optimisation scheme following (Martin et al., 2003) leads to large uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Emissions only estimated as monthly means. Limited partitioning of emissions between anthropogenic and microbial sources.
(Zhang et al., 2007)	ERS-2 / ENVISAT	GOME / SCIAMACHY	Tropospheric column	No inversion methodology	China	1996 to 2004	Not relevant	Not an emission inversion study. This is a long trend analysis of NO_2 satellite data in support of bottom-up inventory. No emission inversion methodology makes comparison complicated. However, satellite observations give qualitative support of bottom-up emission data.
(Zhao and Wang, 2009)	Aura	OMI	Tropospheric column	Mass balance optimisation scheme	China	July 2007	70 km^2	Optimisation scheme following (Martin et al., 2003) leads to large uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Daily emission estimates.

Table A2: Summary of existing literature on BVOC emission inversions using HCHO EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Bauwens et al., 2013)	EUMETSAT	GOME-2	Column	4D-var	Global	2007 to 2012	2° × 2.5°	Uses an advanced data assimilation system capable of considering model and observation errors. Cannot easily estimate model errors though. Emissions are available publicly. The emission inversion scheme makes quite large modifications to the a priori emissions, but there is no evaluation of the output emissions.
(Millet et al., 2008)	Aura	OMI	Column	Mass balance optimisation method	USA	June to August 2006	1° × 1°	Independent yet similar to (Martin et al., 2003) method. Cannot consider observation or model error. Errors directly propagate into emission estimate. Assumptions of linear chemistry and simple transport create large uncertainties.
(Stavrakou et al., 2016)	Aura	OMI	Column	4D-var	China	2005 to 2012	2° × 2.5°	Assimilation of HCHO is used to detect an underestimation of agricultural waste burning in China. They use an advanced data assimilation system that considers model and observation errors. Model error are not well estimated though. This is a study targeting a single anthropogenic source. The results are verified with independent data. High quality work.
(Zhu et al., 2017)	Aura	OMI	Column	Long term mass balance optimisation scheme	North America	2005 to 2014		This method tracks the changes in atmospheric burden of HCHO and infers the trends in BVOC emissions by noting the year-to-year HCHO variability. This method assumes linear chemistry and simple transport, which leads to high uncertainties. Results show continental scale changes in BVOC emissions

Table A3: Summary of existing literature on SO_2 emission inversions using SO_2 EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Boichu et al., 2015)	MetOp-A	IASI	Column	Linear least squares fitting	Etna, Italy	10th April 2011 eruption	12 km2	Estimates degassing SO_2 emissions from Mount Etna. It is inferred that the EO based emission estimates are better than the ground-based estimates. CALIOP EO Lidar data are used to verify the emission injection height. Stated limitation is that this method needs suitable wind conditions to setup an observable plume with the right characteristics.
(Carn et al., 2007)	Aura	OMI	Column	Emissions inferred from burden	Peru	2004 to 2005	13 × 24 km	Focuses on SO_2 emissions from a copper smelter in Peru. Only calculates annual emissions using inferences from observed burdens. No emission inversion performed – emissions inferred by assuming the size of the natural components that are uncertain.
(Eckhardt et al., 2008)	Aqua / Aura / CALIPSO / EUMETSAT	AIRS / OMI / CALIOP / SEVIRI	Column for OMI, AIRS and SEVIRI. CALIOP gives altitude of volcanic aerosol cloud	Bayesian inversion	Jebel at Tair, Yemen	30th September 2007	0.3° × 0.3°	SO_2 emissions calculated for the Jebel at Tair eruption in September 2007. Inversion methodology considers model and observation error. Method allows calculation of emission estimate errors. The emission inversion method is very fast to operate and can be setup to run at very short notice in the event of a large eruption.
(Heng et al., 2016)	Aqua	AIRS	Column	Sequential importance resampling	Nabro volcano, Eritrea	June, 2011	From 13.5 × 13.5 km to 41 × 21.4 km	SO_2 emissions from the Nabro eruption in June 2011. Inversion method ignores model and observation error leading to large uncertainties in the emission estimate. The emission estimates were evaluated with independent satellite data in a qualitative sense.
(Itahashi et al., 2012)	Aqua / Terra	MODIS on both platforms	Fine mode aerosol optical depth (AOD)	Mass balance optimisation scheme	China	2000 to 2010	0.5° × 0.5°	AOD is assumed to relate to SO_2. Assumed linear chemistry for SO_2 oxidation into aerosol. Large uncertainties due to lack of consideration of model or observation errors.
(Kristiansen et al., 2010)	Aqua / Aura / EUMETSAT	AIRS / OMI / GOME-2	Column	Bayesian inversion	Kasatochi volcano, USA	2008 eruption	0.5° × 0.5°	SO_2 emissions calculated for the Ksatochi eruption in 2008. Inversion methodology follows (Eckhardt et al., 2008) and considers model and observation error. Method allows calculation of emission estimate errors. The emission inversion method is very fast to operate and can be setup to run at very short notice in the event of a large eruption. Emission estimates evaluated using independent data and show a successful inversion.
(Lee et al., 2011)	ENVISAT / Aura	SCIAMACHY / OMI	Column	Mass balance optimisation scheme	Global	2006	2° × 2.5°	Optimisation scheme following (Martin et al., 2003) leads to uncertainties from observation error and linear chemistry assumptions. No way to characterise errors. Emissions only estimated as monthly means.
(Li et al., 2010)	Aura	OMI	Column	No inversion method	Power plants in China	2005 to 2008	0.25° × 0.25°	Not an inversion study. This study uses trends in satellite SO_2 observations to evaluate trends in bottom-up emission inventories and tries to identify undocumented changes in power plant technology aimed at reducing SO2 emissions.

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Seibert et al., 2011)	Aqua / Aura / EUMETSAT	AIRS / OMI / GOME-2 / SEVIRI	Column	Bayesian inversion	Kasatochi volcano, USA	2008 eruption	0.3° × 0.3°	Gives uncertainty estimates on the output emissions. Builds on (Eckhardt et al., 2008; Kristiansen et al., 2010) and now includes estimate of uncertainties on emissions. Considers both model and observation uncertainties. This system can be run operationally at very short notice in the event of an eruption.
(Sellitto et al., 2016)	Terra / Aqua	MODIS	Column	Isolated point source outflow mass balance model	Etna, Italy	October 2013 eruption	1 × 1 km	Linear chemistry gives minor uncertainties. Uses an advanced transport modelling system that should reduce transport model errors. No way to assess observation and model errors in emission estimate. No uncertainty analysis on output emissions
(Wang et al., 2015)	Aura	OMI	Column	Emissions inferred from burden	Power plants in China	2006 to 2013	2° × 2.5°	Focuses on SO_2 emissions from power plants in China. Only calculates burdens. No emission inversion performed – emissions inferred by assuming the size of the natural component of the burden, which is uncertain.

Table A4: Summary of existing literature on CO emission inversions using CO EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area		Emiss. Time	Emiss. Res.	Notes
(Arellano et al., 2006)	Terra	MOPITT	Column	Bayesian inversion	Global		September 1999 to April 2001	22 × 22 km	Inversion method considers model and observation error. They analytically calculate uncertainties on the emission estimates. Includes some limited differentiation between biomass burning and bio/fossil fuel combustion. Their method captures biomass burning variability, but uncertainty analysis shows they cannot estimate bio/fossil fuel use variability. High quality work.
(Chevallier et al., 2009)	Terra	MOPPITT	Vertical profile	3d-var	Africa		2000 to 2006	2. 5° × 3.75°	Inversion method considers model and observation error. No way to reliably calculate model error. Biomass burning emissions are estimated. Independent data show improvement in the emission estimates.
(Fortems-Cheiney et al., 2011)	Terra	MOPITT	Vertical profile	3d-var	Global		2000 to 2009	3.75° × 2.75°	Inversion method considers model and observation error. No way to reliably calculate model error. Independent data demonstrate improvement in emission estimate. Notable findings: modified estimates of northern hemispheric seasonal CO emissions and of a modified biomass burning seasonality.
(Kopacz et al., 2010)	Terra / Aqua / Aura / Envisat	MOPITT / AIRS / TES / SCIAMACHY	CO Vertical profile / CO vertical profile / CO vertical profile / CO column	4D-var	Global		2004 to 2005	4° × 5°	Advanced data assimilation algorithm that considers model and observation uncertainties. Model uncertainties not well estimated. Assimilates CO data from four platforms. No direct estimation of sectoral contributions, but inferences made about vehicle cold starts and residential heating based on seasonality of emission estimates.

Table A5: Summary of existing literature on multi-constituent emission inversions using EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Fortems-Cheiney et al., 2011)	Aura / Terra	OMI / MOPITT	HCHO column / CO vertical profiles	4D-var	Global	2005 to 2010	3.7° ×2.75°	Advanced data assimilation system capable of accounting for model and observation error. This is a variational method and therefore lacks a means to estimate model error. Assumes linear chemistry, which increases the model errors.
(Miyazaki et al., 2012)	Aura / Terra	OMI, TES, MLS / MOPITT	NO_2 column, O_3 vertical profile, O_3 and HNO_3 vertical profile / CO vertical profile	Ensemble Kalman Filter	Global	2006 to 2007	2.5° × 2.5°	Estimates NOx and CO emissions. Being run semi-operationally. Specific aim of multi-constituent assimilation is to correct model biases and therefore reduce error on estimated emissions. Separates anthropogenic and lightning NOx emissions. Assimilation system considers model and observation error. Ensemble approach gives good estimate of model error.
(Miyazaki et al., 2017)	EUMETSAT / ENVISAT / Aura / Terra	GOME-2/ SCIAMACHY / OMI, TES, MLS / MOPITT	NO_2 column / NO_2 column / NO_2 column, O_3 vertical profile, O_3 and HNO_3 vertical profile / CO vertical profile	Ensemble Kalman Filter	Global	2005 to 2014	2.8° × 2.8°	Estimates NOx and CO emissions over a 10-year period. Being run semi-operationally. Specific aim of multi-constituent assimilation is to correct model biases and therefore reduce error on estimated emissions. Separates anthropogenic and lightning NOx emissions. Assimilation system considers model and observation error. Ensemble approach gives good estimate of model error.
(Müller and Stavrakou, 2005)	ERS-2	GOME	NO_2 column	4D-var	Global	1997	5° × 5°	CO in-situ and ground-based column measurements are also assimilated. NOx and CO emissions are estimated. 4D-var assimilation system allows emission estimation in the past. NOx and CO emissions are inverted according to different sources. There is no sectoral breakdown of anthropogenic sources though.

Table A6: Summary of existing literature on PM emission inversions using AOD EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Escribano et al., 2016)	Terra / Aqua	MODIS	AOD	3D-var	Sahara and Arabian Peninsula	2006	Emissions estimated on sub-regional grids	Estimate of soil dust emissions. Inversion method considers model and observation error but cannot estimate model error. Emission estimates give improved fit to independent data for the model.
(Escribano et al., 2017)	Terra / Aqua / PARASOL / EUMETSAT	MODIS, MISR, POLDER, SEVIRI	AOD	3D-var	Sahara and Arabian Peninsula	2006	Emissions estimated on sub-regional grids	Estimate of soil dust emissions. Inversion method considers model and observation error but cannot estimate model error. Several different satellite datasets are tested. Each satellite gave different results due to the different observing and error characteristics of each instrument. This demonstrates the potential for observation errors to influence the results.
(Huneeus et al., 2013)	Terra / Aqua	MODIS	AOD	Optimal estimation	Global	2010	3.75° × 2.5°	Emission estimate of SO_2 and primary aerosol emissions. Inversion method considers model and observation error but cannot estimate model error.
(Saide et al., 2015)	Terra / Aqua	MODIS	Aerosol optical depth	3D-var	California Rim Fire, USA	August to October, 2013	4 km^2	Estimate of fire emissions. Data assimilation consider model and observation error. Variational method cannot estimate model errors well. Extensive tests demonstrate is robust. Satellite data were combined with ground-based data, but satellite data were shown to add significant value.

Table A7: Summary of existing literature on methanol and ammonia emission inversions using EO data

Publication	Satellite	Instrument	Obs. Type	Inversion Method	Emiss. Area	Emiss. Time	Emiss. Res.	Notes
(Van Damme et al., 2018)	MetOp	IASI	NH3 Column	Simplistic mass balance model	Global	2008 to 2016	0.01° × 0.01°	Global emission inversion based solely on satellite observations and only a very simple representation of atmospheric loss processes. This method probably has high uncertainty since observation errors are propagated directly into the emission estimates and the inversion assumptions are crude. This study does however perform an extensive source attribution for global hotspots for ammonia emissions.
(Wells et al., 2014)	Aura	TES	Methanol profile	4D-var	Global	2008 to 2009	4° × 5°	First study to carry out methanol emission inversion using EO data. Advanced assimilation system. Emission inversion considers model and observation error. Emissions evaluated against independent data. High quality work.
(Zhu et al., 2013)	Aura	TES	NH_3 profile	4D-var	North America	2006 to 2009	2° × 2.5°	First study to carry out ammonia emission inversion using EO data. Advanced assimilation system. Emission inversion considers model and observation error. Emissions evaluated against independent data. High quality work.

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