National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

User needs for satellite data regarding emissions

RIVM letter report 2022-0088

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DOI 10.21945/RIVM-2022-0088

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This investigation was performed by order and for the account of the Netherlands Space Office.

Published by:
National Institute for Public Health and the Environment, RIVM
P.O. Box 1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

Synopsis

User needs for satellite data regarding emissions

Satellites are used, among other things, for measuring emissions of greenhouse gases and pollutants into the air. These data are used by various organisations, such as RIVM, and by public authorities and researchers. Satellites are getting better and better and are able to make ever more precise measurements.

In view of these developments, it is important for the Netherlands to be well prepared for the use of satellite data in the future. This is why the Netherlands Space Office (NSO) has asked RIVM to identify the needs among existing or future users of greenhouse gas or air pollutant emissions data. The NSO can use the results in its strategic decisions on the satellites of the future.

For the purpose of this study, we have interviewed 24 existing and potential users of satellite data. The most notable finding is that the problems they encounter are mostly of a practical nature. For example, they have difficulty finding the data they need or do not know how to use them. Or they lack the funds to work with the data.

There is a need for funding and knowledge to make the data more accessible and user-friendly. An important step in that direction will be made if organisations intensify their cooperation, for example to share knowledge. The interviewees themselves proposed this as a solution. This could be achieved by organising a more open community - in the Netherlands, but preferably also internationally.

In addition to practical needs, interviewees expressed technical wishes and demands, as well as needs and interests of a scientific nature. For example, existing and potential users need more precise measurements of small surfaces, enabling them to identify substances emitted by ever smaller sources. A combination of satellite measurements and other data sources, such as more extensive ground measurements, is expected to yield many new insights. While satellite instruments will not be able to replace existing data sources, they can provide important supplementary data.

Keywords: satellites, earth observation, emissions, air quality, user needs

Publiekssamenvatting

Satellietdata voor emissies: gebruikersbehoeften

Satellieten worden onder andere gebruikt om te meten hoeveel broeikasgassen en vervuilende stoffen er worden uitgestoten in de lucht. Verschillende organisaties, zoals het RIVM, overheden en onderzoekers, gebruiken deze data. Satellieten worden steeds beter en kunnen steeds preciezer meten.

Vanwege deze ontwikkelingen is het voor Nederland belangrijk om goed voorbereid te zijn op het gebruik van data van satellieten in de toekomst. Daarom heeft het Netherlands Space Office (NSO) het RIVM gevraagd in kaart te brengen welke behoeften gebruikers of toekomstige gebruikers van de data over de uitstoot van broeikasgassen of luchtvervuilende stoffen hebben. De NSO kan deze uitkomsten gebruiken om strategische beslissingen te nemen over satellieten van de toekomst.

Voor het onderzoek zijn 24 (mogelijke) gebruikers van satellietdata geïnterviewd. De opvallendste uitkomst hieruit is dat zij vooral tegen praktische problemen aanlopen. Ze kunnen bijvoorbeeld de data niet goed vinden of ze weten niet hoe ze data kunnen gebruiken. Of ze hebben geen geld om met de data aan de slag te gaan.

Er is geld en kennis nodig om de data gebruiksvriendelijk en makkelijker toegankelijk te maken en ze betekenis te geven. Een belangrijke stap naar een oplossing hiervoor is dat organisaties meer gaan samenwerken om bijvoorbeeld kennis uit te wisselen. De geïnterviewden stellen dit zelf als oplossing voor. Een mogelijkheid hiervoor is een meer open community te organiseren in Nederland, maar het liefst ook internationaal.

Naast de praktische behoeften zijn er technische wensen en eisen, en wetenschappelijke behoeften en interesses. Zo hebben (mogelijke) gebruikers de behoefte aan preciezere metingen van kleine oppervlakten zodat van steeds kleinere bronnen kan worden achterhaald welke stoffen die uitstoten. Naar verwachting kan de combinatie van satellietmetingen met andere databronnen, zoals uitgebreidere metingen op de grond, veel nieuwe inzichten geven. De satellietinstrumenten kunnen bestaande databronnen niet vervangen, maar er wel een belangrijke aanvulling op zijn.

Kernwoorden: satellieten, aardobservatie, emissies, luchtkwaliteit, gebruikersbehoeften

Contents

Summary — 9

1 Introduction — 11
1.1 Atmospheric emissions and emission monitoring — 11
1.2 Scope of the research — 12
1.3 Goals and objectives — 13
1.4 Methodology — 13

2 Literature review — 15
2.1 Overview past, current and future satellite instruments — 15
2.2 Climate change studies — 17
2.3 Human health studies — 19
2.4 Environmental studies — 21
2.5 Inventory reports — 22

3 Interviews — 25
3.1 General practical obstacles and satellite requirements — 25
3.1.1 Practical challenges for potential users — 25
3.1.2 General satellite requirements — 28
3.2 Domain specific needs — 29
3.2.1 Climate change studies — 29
3.2.2 Human health studies — 31
3.2.3 Environmental studies — 32
3.2.4 Inventory Reports — 32

4 Discussion — 35
4.1 Practical challenges and needs — 35
4.2 Technical requirements and needs — 36
4.2.1 Improvements in spatial and temporal resolution — 36
4.2.2 Instrument sensitivity — 37
4.2.3 Aerosol properties — 37
4.2.4 Natural sources — 38
4.2.5 Presence of clouds — 38
4.3 Satellite data in a broader perspective — 38

5 Conclusion — 39

6 Literature — 41

Summary

The RIVM inquired into the needs and wishes of (potential) satellite data users with regard to emissions. The research consisted of a literature study and interviews with 24 (potential) users. The list of people to be interviewed was based on contacts provided by NSO and RIVM and was further extended with contacts suggested by interviewees. The interviewees are working in different domains: climate change studies, human health studies, environmental studies, and inventory reports. In the literature review, we listed satellite missions, and identified their applications and shortcomings. According to literature, there is a need for a higher spatial and temporal resolution over the coming years to enable points source attribution of emissions. Furthermore, there is a wish for an increased instrument sensitivity and improved detection in the atmospheric boundary layer. The dependence on sunlight is also deemed to be a limitation, limiting measurements in the absence of sunlight. An expansion of ground surface station measurements is beneficial for satellite calibration and validation for which investments in retrieval algorithms and modelling are evenly important. For some components more specific needs were identified. During the interviews, interviewees mentioned similar technical needs as identified in the literature (e.g. higher spatial and temporal resolution). Remarkably, practical challenges were put forward as important factors restricting satellite data usage, and suggestions were given to address these challenges. Examples include allocating more resources for data analysis and for converting data into useable products and increasing the user friendliness of satellite data for new/novice users. Also, a need for broader collaboration and a more open community was expressed. These practical needs and challenges seem to point the way towards quick wins, to improve use of satellite data and extend the pool of users.

1 Introduction

1.1 Atmospheric emissions and emission monitoring

According to the IPCC, the last four decades have been successively warmer than any decade before, since 1850. Global surface temperatures have been increasing, with a resulting global warming of 0.99 ^{o}C when comparing 2001-2020 to 1850-1900 (IPCC, 2021). These climatic changes are partly driven by carbon dioxide (CO_2) emitted from e.g. combustion processes (Nassar et al., 2017). In addition, methane (CH_4) concentrations reached 1867 parts per billion (ppb) in 2018 and concentrations are rising faster than any time since 1999 (Wang et al., 2019). The probably third most important long-lived greenhouse gas (GHG), nitrous oxide (N_2O), is also rising in emissions from 275 ppb in mid-19th century to 328 ppb in 2015 (Kanter et al., 2016).

Besides the emission of GHGs, the (anthropogenic) emissions of other gases have direct and indirect far reaching consequences for human health and the environment (Timmermans et al., 2019). Air pollution is one of the major environmental factors affecting human health, leading to over 500.000 estimated premature deaths in Europe in 2015, when considering particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and ozone (O_3) pollution (Fairburn et al., 2019). The natural environment is threatened, i) directly by air pollution through biodiversity loss caused by eutrophication and acidification processes (EEA 2020, Timmermans et al., 2013), and ii) indirectly by global warming driven by GHGs, since these are accelerating the adverse effects on biodiversity (IPCC, 2021).

To minimize impacts of air pollution, the European Union (EU) and World Health Organization (WHO) have set-up legislation and guidelines, respectively. According to the EU Air Quality Directive (EU, 2008), yearly averaged levels of NO_2 should remain below 40 µg m^{-3}, PM_{10} below 40 µg m^{-3} and $PM_{2.5}$ below 25 µg m^{-3}. Guidelines of the WHO have been recently updated (2021) and are 10 µg m^{-3} for NO_2, 15 µg m^{-3} for PM_{10} and 5 µg m^{-3} for $PM_{2.5}$ (WHO, 2021). To reach these values, emissions need to be limited which is safeguarded by the EU in the National Emissions reduction Commitments (NEC) (EU, 2016). Furthermore, many countries have signed the Paris Agreement, stating the need and desire to remain below a global warming of 1.5 ^{o}C (UN, 2015). Within the Netherlands, the Dutch government aims to decrease CO_2 emissions by 60% in 2030, by 70% in 2035 and by 80% in 2040 (Rijksoverheid, 2021). To monitor whether these legal limits, guidelines and agreements are met, air pollutant concentrations should be well-known. Especially, since it is clear that even below these limits for $PM_{2.5}$ and PM_{10}, concentrations PM are still associated with higher mortality (Chen & Hoek, 2020).

Emissions can be monitored and captured in inventories, which is compulsory for certain gasses (nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2), ammonia (NH_3) and fine particulate matter ($PM_{2.5}$)) for EU-member states (EU, 2016). Moreover, reliable Pollutant Release and Transfer Registers

(PRTR) are a prerequisite for understanding and evaluating effective mitigation measures (Borge et al., 2014; Kuenen et al., 2014) since these are an essential part in atmospheric modelling for emission abatements (Russo et al., 2019; Thunis et al., 2021). An example of a European wide inventory is the TNO-MACC inventory, constructed by using official emissions as submitted by European countries. However, inventories do not necessarily provide information on the spatial distribution of emissions (Timmermans et al., 2013). Some European cities have set up bottom-up inventories, which are expected to be more accurate than a downscaling of national inventories (Timmermans et al., 2013). At the same time, these local and regional inventories can be the most uncertain factor within atmospheric models, making assessments of mitigation strategies difficult (Borge et al., 2014; Thunis et al., 2021; Wang et al., 2019). Alternatively to bottom-up atmospheric modelling, Inverse Modelling (IM) can be a tool to support emission monitoring. By applying prior emission estimates in an atmospheric transport and chemistry model, the modelled concentration output can be compared to actual in situ and/or remote observations of concentrations. The prior emissions can then be adjusted to obtain an optimal agreement between the calculated and observed concentrations. This will result not only in an improvement of the inventories, but will also provide information on the quality of the inventories (ETC/CME, 2021). This technique has already been used for certain components in Switzerland and the United Kingdom and here IM emission estimates have proven to be a valuable tool for emission inventory evaluation (Wang et al., 2019). The use of satellite data as complementary remote observation source in IM is attractive, since these show a superior spatial coverage over surface observations networks (Houweling et al., 2017).

Within this study, the current possibilities of applying satellite observations in emission monitoring were addressed by a literature review and future demands of potential users of satellite data were identified in interviews. This way, it became clear how and to what extent space observations can be suitable for solving future issues within science and society.

1.2 Scope of the research

Within this study, the focus was on the future needs of actors in the Netherlands who are active in the field of emissions of air pollutants or greenhouse gases and potential users of satellite data. They work within different domains and sectors, such as research institutes and governmental authorities. The main emphasis was on user needs. What are their wishes for future instruments? What tools and information would help them? How could the use of satellite data be made more effective? Or easier? Or appealing to a larger group of users? We cast a wide net of questions to haul in a wide range of needs, wishes, and suggestions.

As agreed with NSO, demarcations of this study are:

- Technical possibilities of satellite missions and instruments are not assessed
- Financial aspects of using satellite data are not taken into account

- Technical feasibility of data products and thus instruments are not judged
- Considering climate, we focus on mitigation, since emissions are rarely relevant in climate adaptation
- Focus is on the Dutch perspective
- We give no priorities or ranking for the identified needs or wishes

1.3 Goals and objectives

The main goal of this study was to identify and categorize the issues and resulting needs of actors working with (anthropogenic) emissions, in regard of future space-missions. To achieve this, the following objectives were formulated:

- Identify the current possibilities, advantages and shortcomings of satellite products
- Identify and categorize potential future users
- Identify current application of satellite products within user groups (domains)
- Identify issues and future data needs for different user groups in interviews

We combined these deliverables into one product, namely this report.

1.4 Methodology

The report starts with a literature study, resulting in an overview of satellite missions up to now (see section 2.1). The current possibilities, advantages and shortcomings of satellite data derived products are described for multiple user groups, as defined in a user inventory. For each user group, we concluded with the existing challenges and resulting future demands (section 2.2 – section 2.5).

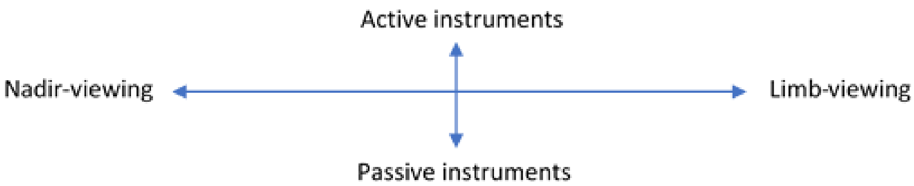
The inventory of user groups was based on contacts from NSO and RIVM, extended with contacts suggested by interviewees. During the 24 interviews, current and future issues were identified and linked to the possibilities and challenges found in the literature research for their domain.

2 Literature review

2.1 Overview past, current and future satellite instruments

In the past decades, the importance of satellite retrievals has gained more and more attention and major advances have occurred (Streets et al., 2013). Researchers and (local) governmental authorities have been discovering the value of satellite retrievals to monitor air pollution and climate change, but also for monitoring infectious diseases and algal blooms for example (Seltenrich, 2014).

Illustrating these advances, were the launches of multiple satellites, with different purposes and objectives (see table 1). These satellites can be roughly subdivided into four categories according to their viewing geometry and instrument type:



Nadir viewing satellite instruments look downward towards the earth, while limb viewing instruments look at an angle towards the Earth (Lee et al., 2009). Both kinds of orbit and instrument have their own pros and cons. In short, nadir-viewing instruments can be sensitive for components in the boundary layer, but do not provide information on the vertical distribution of measured components at the same resolution as limb-viewing instruments. In contrast, limb-viewing instruments are less suitable for boundary layer measurements, but can retrieve the vertical distribution of components (Gonzalez Abad et al., 2019). Passive instruments depend on the reflectance of sunlight, while active instruments emit radiation themselves yielding a smaller swath-width but enabling measurements in the absence of sunlight (Gonzalez Abad et al., 2019). In addition, satellites can perform these measurements, while being in a polar-orbit or in a geostationary position.

Table 1 Overview of previously launched satellites related to air quality and greenhouse gases. For complete overview see http://database.eohandbook.com/database/instrumenttable.aspx

Name and developer	**Timespan**	**Resolution**	**Global coverage (days)**	**Components**
TOMS by NASA [1]	1978	47 x 47 km^2	NA	O3
GOME by ESA [2]	1995-2003	40 × 320 km^2	3	O3, NO2, SO2, PM, NMVOC
MODIS by NASA [2]	2000 -	1 x 1 km^2	1-2	PM
MOPITT by NASA [2]	2000 -	22 x 22 km^2	3	CO, CH4
MISR by NASA [2]	2000 -	17.6 x 17.6 km^2	9	PM
AIRS [2]	2002 -	50 x 50 km^2	1	SO_2, CO, CH_4, CO_2

Name and developer	Timespan	Resolution	Global coverage (days)	Components
SCIAMACHI by NASA [2]	2002-2012	30 × 60 km^2	6	NO_2, SO_2, CO, CH_4, NMVOC, PM, CO_2
TES by NASA [2]	2004-	5.3 x 8.5 km^2	2	CO, CH_4, NH_3, CO_2
OMI by NASA [2]	2004-	13 × 24 km^2	1	O_3, NO_2, SO_2, NMVOC, PM
IASI by NASA [2]	2006-	50 x 50 km^2	0.5	SO_2, CO, CH_4, NMVOC, NH_3, CO_2
GOME-2 by ESA [2]	2006 -	40 x 80 km^2	1.5	O_3, NO_2, SO_2, HCHO
GOSAT by TANSO- FTS [3]	2009-	10 x 10 km^2	3	CH_4, CO_2
CrIS by JPSS [4]	2011-	14 km diameter circles	0.5	NH_3
OCO-2 by NASA [3]	2014-	1.29 x 2.25 km^2	16	CO_2
GHGSat [5]	2016-2021	50 x 50 m^2	14	CH_4, CO_2
TanSat by CAS/MOST/CMA [6]	2016-	2 x 2 km^2	16	CO_2
TROPOMI by ESA [7]	2017-	7 x 7 km^2	1	O_3, NO_2,SO_2, CO, CH_4,CH2O and aerosol properties
TEMPO by NASA [8]	2018	2.1 x 4.4 km^2	North-America	O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$, BrO, IO
GOSAT-2 [3]	2018-	10 x 10 km^2	6	CO_2
EMI by SAST [9]	2018-	12 x 13 km^2	1	NO_2, HCHO
OCO-3 by NASA [10]	2019-	1.6 x 2.2 km^2	NA	CO_2, SIF
GEMS by NIER [1]	2020-	7 × 8 km^2	No, geostationary	O_3, NO_2 , SO_2 , HCHO, and glyoxal (CHOCHO)
GeoCarb by NASA [11]	early 2020s	5 x 10 km^2	No, geostationary	CO_2, CO, CH_4
MethaneSat by EDF [13]	2022	400 x 100 m^2	3-4	CH_4, CO_2
MicroCARB by CNES [12]	2023/2024	4.5 x 9 km^2	21	CO_2, CH_4
UVN by ESA [14]	2023	8 x 8 km^2	No, geostationary	NO_2, O_3, SO_2, H_2CO, $C_2H_2O_2$ and aerosols properties
UVNS by ESA [15]	2023	7 x 7 km^2	1	O3, NO_2, SO_2, HCHO, CO, CH_4 and aerosol properties
SPEXone by SRON, Airbus, TNO [16]	2023	4.6 x 5.4 km^2	30	Aerosol properties
MERLIN by CNES [17]	2024	< 50 km^2	28	CH_4
MAIA by NASA [18]	>2024	1 x 1 km^2	~3	Aerosol properties
CO2M by ESA [19]	2025/2026	2 x 2 km^2	2-3	CO_2, NO_2

1 Naeger et al. (2021), 2 Streets et al. (2013), 3 Pan et al. (2021), 4 Shephard and Cady-Pereira (2015), 5 Varon et al. (2020), 6 Pan et al. (2021), 7 Veefkind et al. (2012), 8 Zoogman et al. (2017), 9 Zhang et al. (2020), 10 Eldering et al. (2019), 11 O'Brien et al. (2016), 12 Cugny et al. (2017), 13 Staebell et al. (2021), 14 Riedl et al. (2019), 15 Kampf et al. (2017), 16 Van Amerongen et al. (2019), 17 Ehret et al. (2013), 18 Liu and Diner (2017), 19 Sierk et al. (2021)

At present, there are several satellite instruments monitoring air quality components, valuable for environmental professionals. Among the measured components are NO_2, SO_2, CO, NH_3, VOCs, aerosol optical depth (AOD) and $PM_{2.5}$ (Duncan et al., 2014). All these components have different impacts and effects on the earth's system and human health, leading to different fields of application. For example, space-based observations can yield added value for assessing tropospheric air pollution and these observations even have the potential to infer emission strengths (Streets et al., 2013). Regarding climate change research, emissions of CO_2, CH_4 and CO from different point sources may by monitored from space (O'Brien et al., 2016).

The advantage of these satellites is that they provide independent observations for the whole globe with a more or less uniform quality and help validate (national) emission inventories or emission reports by industry. This is valuable in itself, but on top of that the average cost of satellite monitoring/validation is lower compared to conventional bottom-up methods, if calculated source specific (Pan et al., 2021). However, despite these (potential) advantages, satellite retrievals also have drawbacks/shortcomings. The main issue with satellite retrievals is the dependence on the reflectance of sunlight. If clouds or aerosols are present, satellite retrievals lose quality or do not provide information at all. Unfortunately, aerosols may be particularly present over polluted areas where interest in emissions is high (O'Brien et al., 2016). Possible solutions (using active instrumentation, elliptical orbit or larger measurement swath) have not been tested out in space to our knowledge (Houweling et al., 2017). In-situ measurements are crucial to calibrate, validate and perform bias corrections (Reynolds & Rayner, 2002). Besides, the obvious shortcoming is the temporal resolution of one or fewer observations per day for non-geostationary satellites leading to the inability to monitor the diurnal cycle of pollution (Naeger et al., 2021). Furthermore, computational limitations or restrictions still exist, and retrieval algorithms are not completely comparable for all instruments. Moreover, the impact of a specific algorithm can be substantial on the retrieval of the observations. In other words, not only the measurement itself is important, optimization of algorithms is beneficial as well (Yue et al., 2016).

We identified the following fields of application: climate change studies (GHGs emissions, aerosols), human health studies (trace gases and aerosols), environmental studies (NH_3 emissions and deposition) and inventory reports (all emissions). In the next sections, we will elaborate on the (satellite) research performed within these different domains from past to present and we will describe the main existing knowledge gaps.

2.2 Climate change studies

Regarding climate research, satellites have drastically increased our knowledge since the 1960s. To a large extent due to the global coverage, encompassing areas where no ground observations are available (Liang et al., 2019; Neumeier et al., 2021). Initially, studies focused on monitoring and identification of concentration fields of multiple GHGs. Over time, satellite retrievals have increased our knowledge on the earth's climate system and have increased our understanding of the impact of anthropogenic actions on the climate (Thies & Bendix, 2011).

Progress in technical possibilities and software development have increased the sensitivity of these satellite instruments (Thies & Bendix, 2011). As a result, scientists have been improving the investigations of not just GHG concentration fields, but of emissions as well. There is a growing number of initiatives, to make use of this satellite potential and a number of initiatives have already been undertaken (Aganaba-Jeanty & Huggins, 2019). These satellite instruments are expected to increase the certainty about land-cover and land-use change related GHG emissions and may help identify emission hot-spots. This is also of added value for effective policy, since national and regional emissions of CO_2 could be monitored and contributions to mitigate climate change become more transparent (Sellers et al., 2018; Neumeier et al., 2021).

In short, many satellites have been launched, aimed at the monitoring of GHGs. SCIAMACHY, GOSAT, OCO-1, IASI, AIRS, TES, OCO-3, and MicroCarb are or have been in orbit (Yue et al., 2016). The AIRS satellite instrument has given new information and insights on the CO_2 fields, monitored from space and SCIAMACHY has increased our knowledge on CH_4 columns (Thies & Bendix, 2011). Emission estimates of these GHGs are becoming available, based not solely on bottom-up methods, but partly derived from these satellite measurements. For CH_4, emissions can already be inferred from satellites on a local scale (based on mass balance equations or by measuring ratios of co-emitted species at the source) and larger scales (based on Chemistry Transport Models (CTMs)) (Jacob et al., 2016). This way, satellites have been used to quantify CH_4 emissions and discover hotspots. Using multiple satellite products (including GOSAT and TROPOMI), multiple emission hotspots were identified in Turkmenistan (Irakulis-Loitxate et al., 2022) and emissions over tropical land were estimated (Feng et al., 2022).

Nevertheless, there are challenges in the field of climate research, which have not yet been solved. The European Union’s commitment to stabilizing climate change is captured in the European Climate Law, stating a net zero emission of GHGs by 2050 (EEA, 2021). Therefore, monitoring and independent verification of human induced emissions is important. Environmental processes modulate and affect atmospheric lifetimes, resulting in changing concentration fields. Therefore, apart from emission monitoring, possible natural sinks should be investigated as well (Sellers et al., 2018). The OCO-2 and GOSAT satellite were both launched, with the main task to reduce uncertainties in these natural carbon sources and sinks (Nassar et al., 2017). The climate impact of aerosols also requires more research. First, better source apportionment is needed, to obtain e.g., a better distinction between anthropogenic and natural sources. Second, knowledge on the cloud-aerosol interactions should be increased. The impact of aerosols on climate partly depends on cloud formation (Sorensen et al., 2019). Regarding satellite instruments, higher spatial and temporal resolution would be beneficial in assessing GHG emissions. Furthermore, for isolating the lower troposphere in satellite retrievals from the stratospheric attribution, short-wave infrared incoming radiation (SWIR) and thermal infrared radiation (TIR) measurements should be combined. To study the arctic regions, active spectroscopy is needed since the solar radiation there is limited (Jacob et al., 2016).

2.3 Human health studies

Regarding air quality, satellites have been measuring trace gases since 1970s. Initially, the aim was to measure stratospheric ozone (O_3), but in the wake of this, retrievals for more trace gases became available (e.g. NO_2, HCHO, and SO_2), with an increased resolution (Naeger et al., 2021). Aerosol observations were initially performed using ground stations and aircrafts or balloons. Since the launch of the Multi Spectral Scanner, global observations became available as well (Lee et al., 2009). Models and retrieval algorithms are under constant improvement, converting satellite data to more and more useful products. Consequently, over the last couple of years, the use of satellite data in epidemiological studies has increased with reasonable reliability (Sorek-Hamer et al., 2016).

Satellite observations have been helpful in analysing NO_x-emission areas, especially in poorly characterized areas and retrievals help in improving knowledge on natural emission sources (e.g., soils). This development and increasing reliance on satellites is related to the growing complexity of air quality models. Satellite observations help in validating and constraining concentration field outputs of these models, in combination with surface observations. The satellite retrievals (vertical column densities) can be directly compared to model estimates, resulting in emission modifications. Validating profile output of these models is much more complicated with satellite observations, since information in the vertical is very limited. In order to achieve both, low-earth orbit lidar observations would be needed (for sensing aerosols) (Hidy et al., 2009).

An important aspect of epidemiological studies on the impact of air pollutants is exposure assessment. Traditionally, this type of research depended on stationary monitoring. This dependence on ground-based measurement stations causes/results in exposure miscalculations due to the limited spatial density of measurements, especially since stations are placed in emission-heterogeneous areas (Yarza et al., 2020). From the 1990s, models have been emerging for relating air quality to health impacts within epidemiological studies (Zou et al., 2009). The latest and most advanced types of models (hybrid models) make use of multiple data-sources, including satellite derived products, in order to assess pollutant levels at high spatiotemporal resolution. These types of models have become widely used in the last decade and applied to NO_2 and PM (Yarza et al., 2020). Satellite data may also help indirectly in identifying microenvironments where local emissions may be higher/lower. These microenvironments can be used in further algorithms to improve exposure assessment (Brokamp et al., 2019). This way, satellite retrievals provide a unique opportunity to give indirect information on estimates of air pollution and emissions (Zou et al., 2009). Given the obtained global coverage of high-resolution data, applications of satellite data in the field of human health studies are expected to rapidly expand (Sorek-Hamer et al., 2016).

Since for studying health impact the concentration at ground level is needed instead of an integrated column, it is convenient that both satellite products of MODIS and MISR show a linear relationship between ground-level concentration measurements and the integrated satellite products, at least under certain conditions. The correlation is stronger, if satellite products are combined with chemical transport models. This way, Evans et al. (2013) determined the attributed global mortality to $PM_{2.5}$ pollution based on satellite retrievals, yielding reasonable results. These results can be further improved by combining retrievals of multiple satellites or combining retrievals with Land-Use-Regression (LUR) models (Sorek-Hamer et al., 2016). In addition to the health impacts of $PM_{2.5}$, Prud'homme et al. (2013) investigated the health impact of NO_2 as well, with the OMI satellite retrievals using the relationship between the satellite retrievals and ground-level concentrations. The results were in line with results obtained with regulatory monitoring networks and at the same time available for a much wider area. Nevertheless, the spatial resolution of 10x10 km^2 is likely to be too coarse to capture the spatial heterogeneity and local sources of NO_2 (Prud'homme et al., 2013).

In line with this, a key concept of future improvements should be aimed at the derivation of higher resolution $PM_{2.5}$ and NO_2 estimates. As for climate research, a geostationary satellite would be beneficial, since these deliver a better predictor of daily average concentrations than polar-orbiting counterparts (Yarza et al., 2020). The new generation of satellites provide us with daily global observations of certain trace gases, but if these are polar-orbiting satellites, monitoring the diurnal cycle of air pollution will be impossible (Naeger et al., 2021), unless they are being launched within a constellation, like CO2M (Landgraf et al., 2020; Sierk et al., 2021). The future launch of geostationary satellites are expected to supply an unprecedented view on air quality. However, these measurements ask for effective data assimilation systems, including chemical and aerosol measurements at ground level (Baklanov & Zhang, 2020). Therefore, ground-level measurements remain an essential part of air quality monitoring (Seltenrich, 2014). Not only for the use in models, but according to Yarza et al. (2020) future research should also be aimed at the relation between ground-based measurements and satellites observations of the vertical profile of pollutants. Moreover, knowledge on the vertical distribution (prescribed profile) might be used, to improve retrievals themselves (Sorek-Hamer et al., 2016).

Another field of improvement involves aerosol characterization. Not all $PM_{2.5}$ particles may have the same health effects, but more research is needed to determine the toxicities of different PM particles and PM-sources (Evans et al., 2013). The composition of the particles may well be the most important knowledge gap regarding aerosols (Liu & Diner, 2017). This knowledge gap may be filled by the launch of Multi-Angle Imager for Aerosols (MAIA) and SPEXone. The MAIA instrument will yield comprehensive information on particle size and shape at a spatial resolution of 1x1 km^2 (Liu & Diner, 2017).

Finally, as mentioned in the previous chapter, the presence of clouds is still a major limitation when sensing from space. Clouds add most to the uncertainty in satellite retrievals regarding aerosol observations. In addition, bright land surfaces often deteriorate the aerosol retrievals, when accurate knowledge on surface reflectance is unavailable (therefore aerosol monitoring was only possible over the ocean before the 1980s) (Lee et al., 2009).

2.4 Environmental studies

In regard of environmental studies, the most important element to trace are nitrogen components, such as NO_2 and NH_3. Emissions and deposition of nitrogen components have large implications for ecosystems (and indirectly on climate) (Kharol et al., 2018). The recent developments and improvements in remote sensing techniques have enabled the scientific community to capture the nitrogen component concentrations over larger areas. As explained earlier, these fields have been used to derive emission estimates for NO_2. However, for environmental studies the main interest is in where this nitrogen is deposited. Excessive deposition of nitrogen can cause eutrophication and acidification, and lead to a loss of biodiversity. This deposition is measured only at very few ground-based sites being only representative for a specific ecosystem. Therefore, information from satellites can be of added value and used in atmospheric chemistry models to estimate deposition fluxes (Van der Graaf et al., 2018). This is important since in Europe the uncertainty of annually emitted NH_3 on country level is at least around 30% (Van der Graaf et al., 2022).

For North America, Kharol et al. (2018) determined N-deposition (NO_x and NH_3) by combining a dry deposition model and satellite observations from Cross-track Infrared Sounder (CrIS). The results were in line with previous work on deposition maps. However, direct comparisons between modelled depositions and measurements remains challenging. Direct measurements are expensive and not widely available. Nevertheless, the ability to estimate the deposition over remote areas, can be an important tool for policymakers in analysing mitigation strategies (Kharol et al., 2018). In follow-up studies, satellite annual emission estimates were twice the values reported in bottom-up inventories for a certain region in Canada. This indicates the potential uncertainty in bottom-up inventories (see Section 2.5) (Shephard et al., 2020). In research of Van der Graaf et al. (2018) IASI-retrievals were used in combination with a chemistry model to estimate the dry deposition of ammonia. However, they did not find a significant and consistent improvement in the estimations compared to raw model output where no IASI-data was used. This is partly a result of the limited knowledge on the vertical profile of ammonia, which requires more research and observations. Furthermore, more research on the surface exchange of ammonia is recommended (Van der Graaf et al., 2018). This surface exchange is bi-directional and Liu et al. (2020) investigated dry NH_3 deposition taking this into account. Modelled deposition, partly based on IASI satellite retrievals, compared reasonably well with monitoring sites, but some overestimation for Europe still existed. For the wet deposition of NH_4^+, Liu et al. (2021) combined satellite retrievals from the same satellite with a chemistry model. Results were a little better than for dry deposition, when comparing modelled values to local observations. In 2022, Van der

Graaf et al. (2022) published a report in which they assimilated the CrIS satellite retrievals with a chemistry model, using two different methods. Best results were achieved by feeding satellite retrievals into the chemistry model with local ensemble Kalman filtering, yielding a moderate correlation between modelled and observed wet deposition of NH_4^+ within the Netherlands, Belgium and part of Germany.

These methods may be particularly helpful in estimating nitrogen deposition in remote areas where impact of nitrogen can be evaluated. These methods all have their own uncertainties and can be used complementary. Therefore, the development in all directions is important (Jia et al., 2016). Among others, special attention should be paid at the bi-directional parameterization of dry deposition and the conversion of column concentrations to surface concentrations in satellite retrievals (Zhang et al., 2021). The proposal of Nitro-sat could help in overcoming some of these issues, by enabling scientists to assess nitrogen emissions from individual sources and improve agricultural characterization with satellite observations at 500 meter resolution (Coheur et al., 2021).

Apart from the deposition of NH_3, a lot of research has been performed on forest fire occurrence and intensity, and forest fire emissions. Forest fires emit, among others, CO, CO_2 and PM (Van der Werf et al., 2017). These components may be measured directly or estimated based on fire activity and intensity, which can be derived from satellite observations. Guo et al. (2017) estimated CO_2 emissions from forest fires over Russia with reasonable results, based on direct GOSAT CO_2 measurements. However, indirect emission estimates based on fire activity and intensity measurements of VIIRS and MODIS over the arctic region showed high uncertainties and low correlation with official estimates (McCarty et al., 2021). Still, remote sensing is one of the key techniques for monitoring forest fire occurrences with global coverage. Near real-time (NRT) availability and higher spatial and temporal resolution of measurements should be a main priority. Furthermore, instrument and algorithm development should be encouraged to meet the future demands (temporal resolution 1-6 hours, spatial resolution 0.25-3 km and retrieval uncertainty of 10%). To validate the retrievals and determine uncertainties, reference data should still be available on larger scale in the future (Wooster et al., 2021).

2.5 Inventory reports

All information on national emissions is captured in National Inventory Reports (NIR) and Informative Inventory Reports (IIRs) for GHG and Air Pollutants, respectively. Accurate information on emissions is essential in assessing the effectiveness of mitigation measures (Aganaba-Jeanty & Huggins, 2019). These inventory reports are built following a bottom-up approach. In other words, emissions are calculated based on emission factors and (statistical) activity data at emission-sources and collected in national reports, an obligation for EU-member states. For large point sources, emissions are reported individually, also under EU regulations. However, these reports can also be validated using top-down techniques (Houweling et al., 2017). For evaluating emissions based on bottom-up methods with a top-down approach, a model infrastructure is needed

(Inverse Modelling, IM) in which concentration fields are used to estimate the emissions leading to this concentration field.
Although one would expect that the conventional bottom-up method for calculating national GHG emissions results in reasonably accurate emissions for each source and GHG, unfortunately this is not always the case (Bergamaschi et al., 2018). It has been known for many years that differences in emission estimates between bottom-up and top-down methods can be substantial. Furthermore, within the bottom-up approach, natural emission sources add complexity. In 2018, the JRC published a report on verifying inventory reports with top-down methods (Bergamaschi et al., 2018). Below, the main findings are described:

- For some gases inventory reports are more accurate than for others. For example, F-gases are emitted only from specific industrial processes which makes it easier to implement them in inverse modelling as well. It is therefore not surprising, that the first promising results regarding IM were achieved for these type of gases. For N_2O the uncertainties in top-down methods may be even smaller than for bottom-up counterparts. To extent the top-down technique to other gases it is important to continue improvements in modelling and expand observational networks, including remote sensing.
- The expansion of observations, and implementation of remote sensing specifically, would allow a much stronger constraint on emission estimates. Current results for CO_2 for example, still vary a lot, depending on the models and retrieval algorithms. Apart from adding more observations, these observations (e.g. satellite retrievals) should be of a higher spatial resolution and precision to resolve local emission sources. According to the latest research, 2 x 2 km^2 and a precision of 1 ppm for CO_2 and 10 ppb for CH_4 should be sufficient to half the emission errors for urban areas/large powerplants. The temporal resolution (< a week) is important as well, especially for natural sources which show a seasonal variation.
- Instead of using a single satellite, launching a constellation of three satellites would be even more beneficiary, since cloud coverage would be less of an issue. This constellation could contribute to the future system for top-down emission verification.
- Source appropriation and verification of inventory reports may be further enhanced by measuring C-isotopes (14C) (Bergamaschi et al., 2018). In previous studies this was already shown for methane (Röckmann et al., 2016).

In line with the conclusions of Bergamaschi et al. (2018), the EU is aiming to launch a satellite system, enabling countries to accurately quantify CO_2 emissions at a scale of megacities, industrial sites and on global scale (Aganaba-Jeanty & Huggins, 2019). Furthermore, scientific research and development is aimed at IM which could lead to an operational product and application of IM in NIRs (e.g. projects 'VERIFY' and 'CoCO2'). In the coming years, the Copernicus Atmospheric Monitoring Service (CAMS) will start to develop emission products for European countries, based on this future satellite system and IM progress made in CoCO2. Whether this approach will be available for all domains in NIRs is not yet clear, since for land-use changes (LULUCF) for example, fundamental differences in emission calculations between top-down and bottom-up methods may be insurmountable (ETC/CME, 2021).

3 Interviews

During the interviews we conducted, multiple generally applicable user needs were identified. These are listed in section 3.1. In section 3.2, we give the component specific needs and requirements. We elaborate on the (potential) user needs and summarise them in a table. In this report, the (potential) users we interviewed are anonymised and indicated with a domain-indicating prefix (Climate Change: CC, Health: H, Environmental: E, Inventory Reports: IR), followed by a number (0-9). We interviewed in total 24 people employed at universities, research facilities, and governmental institutions in the Netherlands (e.g., municipalities and ministries). Two participants filled in a questionnaire.

3.1 General practical obstacles and satellite requirements

In several interviews, we received similar feedback on satellite data and satellite products. These feedback points can be seen as challenges which, when overcome, can increase the usefulness of satellite data, and also the number of potential users, in addition to specific needs on satellite instruments themselves. In many cases the interviewees also give suggestions on how to improve the situation. These general points of feedback are listed in section 3.1.1. The technical requirements on satellite missions/instruments valid for all domains, are given in section 3.1.2.

3.1.1 Practical challenges for potential users

The practical challenges and recommendations as identified in the interviews are:

- Allocate more resources on *data-analysis* and the conversion of data to useable products
- Integrate a *multidisciplinary* approach in satellite mission-plans
- Facilitate *collaboration* across institutes for example by building a (national) community or network. NSO could play a role in the coordination.
- Increase *accessibility* of the satellite community for new organizations and institutions
- Ensure *consistency and continuity* by use of *standard classifications* within satellite products and by harmonizing different products
- Build a coordinated and *central database,* including ground-measurements of various components
- Improve *user friendliness* and *visibility* of satellite data (products)
- A shift in policy; *(re)formulate policy questions* such that satellites come into view to be used, switch to a more *data-driven* workflow or mindset
- *Near real-time* availability of data-products

More resources for data-analyses

Maybe the most important point of feedback we identified is the lack of resources for data-analysis regarding satellite missions (CC2, H1, E1, H2, H6). Although satellite missions are dependent on enormous investments, a relatively small budget is set aside for analysing the data gathered during this satellite mission and converting data into products. More budget for the analysis, also for past and current mission, would make it possible to exploit the data more fully. Some interviewees think that there is still plenty to learn from the data gathered already (CC2, H1). An example of this is an analysis performed by NASA, converting MIRS and MODIS retrievals to applicable products (CC3). More effort and resources should be put into building an infrastructure in which big data can be handled with ease. This is becoming increasingly important with the future launches of higher resolution (geostationary) satellites (E1). Moreover, future satellite missions require a model infrastructure in which high resolution data can be processed and used to deduce desired products. Investments have to be made, to stay/become compatible with the satellite retrievals (E1, H6). These aspects do not receive sufficient attention, partly because responsibilities for these activities (e.g., instrument development, retrieval algorithms and model development) are divided amongst multiple parties (H2). One of the proposed solutions is to put a certain percentage of the mission investments aside for these developments (CC2), or -even better - to consider data-analyses as part of the future satellite missions (H2).

Multidisciplinary approach
During the interviews, a second point of critique identified was the tunnel vision of specialists in performing research based on satellite data. According to multiple interviewees, specialists work on their own research questions defined within their own field of expertise. However, for future satellite missions a multidisciplinary team should collaborate, driven by a shared interest (H5, E0). This can enhance cross-pollination among the different domains involved and safeguard optimal usage of different data-sources. These data-sources include the multiple (existing or developed) satellite products, but datasets available within participating domains/organizations as well. Investigating the health impact of traffic emissions, instead of focusing on traffic emissions alone, would be a good example of a multidisciplinary approach (H5).

Facilitate collaboration across institutes
In line with the previous two points, a broad collaboration between different institutions and specialists, would enable a more optimal use of existing data sources and expertise (H6, E1, H1). Such a broad collaboration on a national level would benefit from a coordinating party organizing and chairing, bringing together institutions from the different domains, building a broad community. This coordinating party needs to have knowledge on the (scientific) possibilities of satellites, making the NSO a good candidate to take up this role (E1). Also, the NSO could act as broker closing the existing gap between research institutes and ministries (H5). A broad collaboration would also be able to safeguard capacity-building and bringing scientific models into practice (H6, E1). An example of such a collaboration will soon be brought into practice under the name '*satellietmetingen en ensemble modellering*' and is part of the 'Nationaal Kennisprogramma Stikstof' (NKS) (E2). Within this consortium different institutes and ministries work together, aiming to improve nitrogen flux estimates. The first results are expected in 2024 and this could be the first step in using satellite data more often in operational products (E2). A beautiful example can also be found in

Belgium, Low-Earth and Geostationary Observations of BELgian Air Quality (LEGO-BEL-AQ)[1] which is a collaboration program between satellite experts and an environmental agency, IRCEL-Celine, in the field of NO_2. A third example is the 'Kennisnetwerk Luchtkwaliteit', a collaboration to connect science with society, between research institutes and other interested parties, like Longfonds, De Waag and DCMR.

Accessibility of the satellite community
Building on the previous points of concern, interviewees mentioned the limited accessibility of the satellite community, experienced by members outside of this community (IR1, IR4). The community seems to be composed of a relatively small group of experts who, to some extent, are inward-looking. For parties outside of the community it is hard to get access to the expertise needed to work with satellite data. This is putting constraints on the aforementioned multidisciplinary collaboration and prevents them to get to know and use satellite derived products.

Consistency and continuity of observations
To ensure optimal usability of the data(products) gathered from satellites, it is essential to maintain continuity and consistency in measurements. This is important for parties interested in evaluating emission trends and policy mitigation strategies (E1, IR1). It is tempting to focus on further developing satellite instruments, but keeping existing services and satellite instruments online is important too (H2). Whenever parties need to switch to successor instruments, launched within new programs, it is important to work with standard classifications (e.g., using the same units for components). This would also ease the linkage between different data sets. This could for example be captured within a Community of Practice (IR1).

Central database
In the interviews the added value of a central database, collecting data from multiple source holders was mentioned. The database (e.g., data-cubes (CC3)) should not only contain data derived from satellites, but attention should be paid to the presence of ground station measurements as well (CC0). The resulting database could easily be used as a central source for digital-Twins (IR2) or quickscans (H4), connecting satellite data to other data sources and creating action perspectives. This would also enhance the findability of different data and once again ease their linkage (IR3, H2, H5). The infrastructure set-up for weather forecasts, in which data is NRT made available to third users may be taken as an example (IR2).

User friendliness and accessibility of satellite data
Apart from the availability of the satellite data, the complexity of the data is one of the obstacles to potential users. Some potential users experience a high threshold for using satellite data (e.g., H4, IR0, IR1, IR2). This threshold is partly caused by the complexity of satellite data and the lack of knowledge on how to apply satellite data. To overcome this, some Proof of Concepts or demos can be helpful (IR0). Other products or services that would help are manuals (IR1) or a QGIS plugin

[1] https://lego-bel-aq.aeronomie.be/

(H4). This could also contribute to the awareness of existing satellite data and its application opportunities (IR2, E0). Furthermore, more actively sharing experiences and knowledge on existing services can be very helpful, like the HARP-package and Panoply (IR4). Nevertheless, the user friendliness (and correct use) of satellite data for individual users will always be challenging, since knowledge on the interpretation of the data remains essential (E1, IR4). Again road collaborations or building a community in which expertise can easily be exchanged can play an important role in resolving this issue.

Reformulate research questions
To increase the usage of satellite data it is important that commissioning parties (re)formulate research questions in such a way that satellite data can be of added value. The lack of such research questions assigned to research institutes constrains the knowledge building within these research institutes (H5). Examples include the research on nitrogen deposition, with potential help of satellites (E0). Currently, many research projects are funded by external parties at an international scale (H6). The lack of research commissioned on these types of questions is partly the result of the unawareness of the possibilities and services of satellite data/products and what purposes these might serve. More communication, education and outreach activities aimed at policy makers could perhaps help to raise awareness of the possibilities of satellite data. In addition, there is no legislation on the use of satellite data or satellite products within NIRs, which are still based on bottom-up inventories, making it less tempting to invest money into address these (research) questions (IR0, IR3).

Besides the reformulation of research questions, interviewees mentioned the paradigm shift towards a more data-driven workflow (H5, IR2). This might also be beneficial for the former point, since reformulating questions based on the data available could put satellite data more into the spotlight.

Near real-time availability
Some interviewees emphasized the importance of NRT availability of satellite data. This is needed for capturing calamities (H3) and enable teams to respond in time. Furthermore, this magnifies the pressure for behavioral change since data refer to recent actions and activities. This would also be important for observing platform activities over sea (IR5), for example.

3.1.2 *General technical satellite requirements*
Apart from the aforementioned challenges, some general technical demands and wishes were formulated based on the interviews. These were identified for all domains and are the following:
- An increase in the spatial resolution
- An increase in the temporal resolution
- An increase in the detection limit and surface-level sensitivity

Spatial and temporal resolution
Within all domains, an almost unanimous wish or need for higher resolution satellite data was expressed (e.g. CC0, H1, E0, IR4). For aerosols for example, the lifetime is relatively short which requires both

a high spatial as temporal resolution to deduce the sources. An example of the resolution needed would be SPEXone (CC0; 4.6 x 5.4 km^2). For components affecting human health, emissions should be known on a finer scale, like sub-urban scale (CC0) or 2x2 km^2 (H6). Other interviewees go even further to a resolution of 1x1 km^2 (H1) or 100x100 m^2 (H0) and would need to be able to make a distinction between road segments and ship emissions (H4). A higher resolution might allow assessment of health outcomes on a neighbourhood level covering multiple countries with the same satellite technique (H5). Therefore, the current resolution of satellite data makes it difficult to apply the data for certain users (e.g., H4). The needed necessary resolution can also be extracted from models, like has been done for Nitro-Sat, yielding a proposed resolution of 1x1 km^2 (E0; literature states 500 x 500 m^2).

Some interviewees expressed a wish for a temporal resolution of at least one measurement every day (H3, H6), whereas others expressed the wish for an even higher temporal resolution (H1, H3) for example to measure episodes. For plume-detection of components, you ideally have a geostationary satellite, measuring continuously or delivering at least 3 to 4 measurements a day (CC1, IR4). For the desired night-time measurements, an active instrument technique is desired, since solar radiation is then absent (CC1).

Sensitivity and detection-limit
A third point of technical feedback that was mentioned was the desire for higher sensitivity for components close to the surface and consequently a lower detection limit. A higher sensitivity and lower detection limit would allow detection of point sources within the Netherlands (CC2). According to some interviewees the sensitivity also refers to the sensitivity close to the surface (E0), for example for NH_3 (E1). An increase in the sensitivity for SO_2 would be needed to improve the assessment of aerosol emissions (CC0) and the same needs apply for methane (H6) and N_2O (H1, E0). These needs have not been quantified during the interviews.

3.2 Domain specific needs

As indicated in the previous sections, some user needs are applicable to all components. For other aspects the user needs depend on the specific component.

3.2.1 Climate change studies

Regarding the atmospheric constituents affecting climate change, various user needs have been identified during the interviews.

Surface level measurements on land and sea
The importance of surface level measurements was mentioned by multiple interviewees. These measurements are also needed to validate the satellite retrievals. At present, GHGs are measured at the Ruisdael Observatory in Cabauw including vertical profiles. This infrastructure is very important and expansion would be needed to validate satellite observations, especially with the increasing resolution of satellite retrievals (CC0, CC2, H2, E0). No similar infrastructure as the Ruisdael Observatory is available over sea, while this would be important for

improving satellite retrievals over sea. Examples are concentration measurements at surface level and LIDAR observations for vertical profiles (H2) measured at sea. In addition, the satellite measurements over sea could be improved, since these are in general only useable in the presence of direct sun glint (CC2). Satellite observations over sea would be interesting to monitor ship emissions and the activity of offshore platforms (IR5).

Improving aerosol products
Satellite observations of aerosols have been available for a long time, but issues remain regarding the correct interpretation of the satellite retrievals. Multiple interviewees mentioned the interaction between aerosols and clouds as a knowledge gap. Research on this interaction is needed and future satellite missions should not solely focus on aerosols, but include cloud observations (H2). This could improve the knowledge on the interaction, which can improve atmospheric chemistry models (CC0). Direct measurements on rainfall are also of added value in improving satellite aerosol retrievals (H2, CC1). First steps have been taken with the combination of SPEXone and HARP.

Besides measuring aerosol characteristics (e.g. Aerosol Optical Depth), it is important to measure aerosol precursors to improve aerosol emission estimates, e.g. measurements of SO_2 and NH_3 emissions. Probably, these measurements should be performed with ground stations, due to the resolution needed (e.g. sub-urban scale) and in combination with PM measurements (CC0).

Combining the previous two points within a satellite mission would be valuable, even if lower resolution is achieved (CC0, CC1). This requires the combination of a LIDAR instrument, a Polarimeter and a spectrometer. This would allow for better aerosol composition estimates (H6), vertical profile estimates of aerosols and precursor measurements. This is also a good example of the potential conversion of abstract products (AOD) to a more user-friendly product (PM-concentrations, CC0), which is desired by (potential) end-users as explained in section 3.1.1.

Measurements over the arctic region
A natural source or natural origin of interest for further research is the melting of permafrost. More measurements of CO_2 and CH_4 are desired. To achieve this with a satellite, a geostationary satellite would be optimal, requiring an active instrument technique. The downside is that active instruments usually have a lower footprint, but still the added value of these measurements would be considerable (CC2).

Greenhouse horticulture emissions
A specific anthropogenic source in the Netherlands on which more research is necessary, is greenhouse horticulture. The emission from these sources has been investigated previously with satellite measurements, but these attempts were without success and therefore interest remains (H3).

User needs within the Climate Change domain

CO_2

- Expansion in surface-station measurements
- Remote sensing of permafrost emission
- Measurements of emissions over greenhouse horticulture

CH_4

- Expansion in ground-station measurements
- Remote sensing of permafrost emission

N_2O

- Expansion in ground-station measurements

Aerosols

- High spatial resolution ground-station measurements of SO_2, NH_3 and $PM_{2.5}$ emissions
- Increased knowledge on interaction with clouds, including rainfall data

3.2.2 *Human health studies*

Regarding the atmospheric constituents affecting health, multiple user needs have been identified during the interviews and these are listed below.

Ship emissions

Multiple interviewees mentioned ship emissions (e.g., NO_x and SO_2) as being a knowledge gap. Emissions from ships are largely based on emission factors, with inherent uncertainties and only a few auxiliary data sources are available (H4). An improved assessment of ship emissions is interesting and one of the user needs. To achieve this with satellite instruments, the aforementioned improvements in spatial resolution are required (H0, H3, H4).

SVHC and VOC emissions

Regarding satellite instruments, there are still some components not yet available. Multiple interviewees expressed their interest in satellite measurements of Substances of Very High Concern (SVHC; such as carcinogenic substances) and VOC (H0, H3, H4). To some extent this interest is based on the anxiety regarding these substances, and the fear of missing leaks because measurements are lacking (H4). A potential solution may be the monitoring of co-emitted species with satellite instruments (H6), but research on this would be needed. Interest in co-emitted substances is also applicable to PM, to improve PM estimations and source attributions (H5).

User needs within the Human Health domain

NO_2	Measure shipping emissions
PM	More research on co-emitted ratio's to deduce VOC and PM emissions
Others	Measurements of SVHC and VOC

3.2.3 *Environmental studies*

Regarding the atmospheric constituents affecting the natural environment directly, multiple user needs have been identified during the interviews.

Interpretation and validation of ammonia observations

For this domain, most attention went to the fluxes of nitrogen containing components (e.g., NH_3). Regarding NH_3 there are some additional steps needed, among these are improvements in temporal and spatial resolution, but external factors are deemed to be more important at this moment. The integration between ground station measurements and satellites is considered the highest priority. The satellite instruments have a limited sensitivity for NH_3 close to the surface. This, in combination with the limited availability of surface measurement stations, makes interpretation of retrievals challenging (E1). The expansion of the ground stations is therefore a key factor (H6). Then, to obtain relevant information from the surface measurements and satellite retrievals, a high resolution assimilation model is needed (E1). In this model, there should be special attention for the flux estimate of NH_3, since this is more complex than for other components. The flux depends on external factors, such as temperature and acidity (pH). These external factors need to be taken into account in bottom-up emission estimates, to optimize the comparison with top-down estimates. Another way to deal with this complexity would be a model in which the flow of nitrogen holding components are tracked through a farmer-system and emissions are estimated (E0).

Ammonia emissions over sea

Emissions of ammonia close to the Dutch coastline are important to monitor, because of the vulnerability of the dunes' ecosystem. Observations of algae may help in assessing the ammonia emissions over sea, relevant for the 'Natura 2000' areas (H3).

User needs within the Environmental studies domain

NH_3

- Surface measurements of NH_3 and expansion of the ground stations.
- Measurements of external factors affecting NH_3-flux (e.g. temp, pH).
- Monitor N-flows for agricultural sources
- Monitor algae, to estimate NH_3 emissions over sea

3.2.4 *Inventory Reports*

All of the anthropogenic emitted components of GHGs are captured in the National Inventory Report (NIR) and multiple shortcomings have been identified during the interviews for these components.

Distinction between natural and anthropogenic emissions

The main concern for people working on emission inventory reports is the distinction between anthropogenic and natural emissions (H1, IR0) and the uncertainty of natural emissions (e.g. CH_4) (IR0). For example, the natural emissions from trees (isoprene), lightning (NO_x), wetlands (CH_4) and peatlands (CO_2) are highly uncertain. As stated in the previous section, the same applies to NH_3 where emission-distinction is especially relevant within the Netherlands due to the nitrogen-crisis (H3). To improve the distinction between the natural and anthropogenic sources, a higher spatial resolution of the satellites is needed. This can help overcome this problem, since source attribution would be easier (H1, IR4).

Model infrastructure
For this domain, the model infrastructure is very important, to enable bottom-up emission estimate validation with top-down techniques (IR0). The question remains whether authorities will invest money in this, as long as top-down validations are not a part of legislation.

User needs within the Inventory Reports domain
CO_2
- Investment in IM techniques, but NIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

CH_4
- Investment in IM techniques, but NIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

N_2O
- Investment in IM techniques, but NIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

PM
- Investment in IM techniques, but IIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

NO_2
- Investment in IM techniques, but IIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

NH_3
- Investment in IM techniques, but IIR validation not obliged by EU
- Improved distinction between natural and anthropogenic emissions within satellite products

4 Discussion

In literature, limitations of satellite observations within different domains have been identified. In general, these limitations are expressed in quantitative terms and refer to satellite mission or instrument requirements. During the interviews many of these requirements were pinpointed as well, supplemented by more practical challenges and needs. In the next sections, these outcomes are put into a broader perspective and, if possible, connected to the literature. We start with the practical challenges and needs, since these seem to be widely shared by the interviewees, and hold the most promise to really make a difference.

4.1 Practical challenges and needs

Many of the interviewees acknowledge the importance of technical progress and instrument development. Nevertheless, to make use of satellite data (products), potential users face many practical challenges. It seems clear that in these practical challenges the most quick wins can be found and that a more optimal and also wider use of satellite data can be achieved in particular by *removing or reducing practical obstacles*. Without eliminating these obstacles, the user group is likely to remain the same, since potential users largely lack the resources, knowledge and support to access satellite data products.

An important way to reduce obstacles, seems to be to facilitate collaboration across different organizations. A bright example, mentioned by one of the interviewees, is the upcoming collaboration '*satellietmetingen en ensemble modellering*' in the 'Nationaal Kennisprogramma Stikstof' (NKS) between TNO, RIVM, Wageningen University & Research (WUR), KNMI, Institute of Environmental Sciences (CML) and the Ministry of Agriculture, Nature and Food Quality (LNV). The collaboration is aimed at investigating the potential added value of satellite data in estimating nitrogen fluxes (e.g. NH_3) and indicates a step towards expansion of the user group of satellite data. These types of collaboration can bridge many of the practical obstacles identified. It offers access to the satellite community and their tools, and members of this community are granted resources to convert data to products. At the same time it is an example of how a governmental institution like LNV is applying a data-driven workflow and has formulated a research question in which satellite data is clearly involved. However, if increasing the use of satellite data by individual parties is an objective, there are still practical challenges left (e.g. increase of user friendliness, central database). Moreover, this example of collaboration is largely driven by the recommendations by the Advisory Board 'Meten en Berekenen' (Hordijk et al., 2020), which means that it is not necessarily the result of an internal paradigm shift and the collaboration may have a limited lifespan. Nevertheless, the fact that the recommendation is leading to such a collaboration shows the attainability of wider collaboration.

For other challenges, possible solutions also seem to be available. For example, a number of data services are in place, but these are not known to all potential users, or they do not fulfill their need. Also inventory reports are available on the VERIFY portal[2] and the data used is published[3] (ETC/CME, 2021). Satellite data from the Copernicus network may be downloaded from the "Copernicus Open Access Hub"[4]. For NASA data there is a webservice for raw data available as well[5]. However, at the same time this demonstrates the fragmentation of data-services and for some of these services significant processing has to be done to achieve desired data products. Combining different data-sets in one central database has not been done yet, to our knowledge.

Lastly, more communication, education, and outreach activities, which also enlarge the knowledge on existing services and tools, could perhaps help to close the gap between the existing satellite community and potential users including policy makers.

4.2 Technical requirements and needs

4.2.1 Improvements in spatial and temporal resolution

In the literature, requirements on both the temporal and the spatial resolution of satellite data have been identified. The constraints on these differ, depending on the purpose of the research in which satellite data is used. During the interviews, almost all interviewees across the different domains mentioned a need for higher spatial and temporal resolution. For many potential satellite data users it was difficult to quantify these needs. However, by combining the literature review and interviews, some quantifications can be formulated.

For climate change research, CO_2, CH_4, N_2O and aerosols are the most relevant components. For CO_2 future satellite missions are planned. The needed spatial resolution to resolve individual sources is high. The components dilute after emission and the expected enhancement in signal for column densities depends on the spatial resolution and wind speeds (Sierk et al., 2021). For example, Pan et al. (2021) found a maximum signal of 5.3% of a 13 Mt CO_2 year^{-1} emitter, using a hypothetical 1 x 1 km^2 satellite resolution in a Gaussian plume model. For a 10 x 10 km^2 resolution, the maximum signal was only 0.5%. Satellite instruments should have a spatial resolution similar to the size of an individual factory or power plant site. Using a similar plume model, Jacob et al. (2016) estimated a single pass detection limit of 0.24 t h^{-1} CH_4 for the GHGSat instrument, allowing it to detect methane point sources due to its spatial resolution of 50 x 50 m^2. For the CarbonSat instrument this would be 0.8 t h^{-1}, due to the 2 x 2 km^2 spatial resolution. Thus, the spatial resolution needed is strongly dependent on the desired threshold for source detection.

For human health studies, emissions of components should be known on a fine scale as well. According to the interviewees, spatial resolution of satellite instruments should therefore be on sub-urban scale, 2 x 2 km^2, 1 x 1 km^2 or even 100 x 100 m^2. This is in line with literature, since 10 x 10 km^2 was likely to be too coarse to capture the spatial heterogeneity

[2] http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/
[3] https://essd.copernicus.org/articles/13/2363/2021/essd-13-2363-2021-assets.html
[4] https://scihub.copernicus.eu/twiki/do/view/SciHubWebPortal/WebHome#dias-box?TWIKISID=31422c54d2784abdfc8c01d161946685
[5] https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MOD04_L2/2021/010/

and local sources of NO_2. According to Timmermans et al. (2019) even 7 x 7 km^2 is not representative for heterogeneous locations. Nevertheless, Beirle et al. (2019) showed the ability of the TROPOMI satellite with corresponding resolution of 3.5 × 7 km^2, to estimate points emissions with a lower detection limit of 0.03 kg/s NO_x under ideal conditions. To detect smaller sources, the proposed Nitro-Sat resolution would be 500 x 500 m^2, required for differentiation of main point sources in a single overpass (Coheur et al., 2021). Considering aerosols, no direct resolution requirements were mentioned, since attention should first be paid to aerosol characterisation and source attribution.

Besides the nitrogen emissions, the occurrence and emissions of forest fires are relevant within environmental research, but this was not elaborated on during the interviews. In the literature the spatial resolution required was found to be 0.25 - 3 km.

For national inventory reports, interviewees were not able to quantify their needs regarding the spatial resolution. In literature, a required spatial resolution of 2 x 2 km^2 for CO_2 and CH_4 is mentioned, needed to half the emission errors for urban areas/large powerplants.

4.2.2 *Instrument sensitivity*

A third point of technical feedback mentioned was the desire for higher sensitivity for components close to the surface and consequently a lower detection limit. A higher sensitivity and lower detection limit would allow detection of point sources within the Netherlands (CC2). According to some interviewees the sensitivity also refers to the sensitivity close to the surface (E0), for example for NH_3 (E1). An increase in the sensitivity for SO_2 would be needed to improve the assessment of aerosol emissions (CC0) and the same needs apply for methane (H6) and N_2O (H1, E0). These needs have not been quantified during the interviews. Similar as for the spatial resolution, desired sensitivities are dependent on the strength of the emission source to be captured and closely related to the precision of instruments. For example, the assumed instrument precision used by Jacob et al. (2016) was 5%, resulting in the thresholds mentioned in 4.2.1. For NO_x the sensitivity of TROPOMI is 10^{15} mol cm^{-2} yielding a detection limit of 0.03 kg/s NO_x in the study of Beirle et al. (2019).

4.2.3 *Aerosol properties*

Considering aerosols, multiple issues were identified in both literature and the interviews. These were i) source attribution of aerosols, ii) cloud interactions and iii) aerosol composition characterisation. Probable solutions were identified as well, namely the launch of the MAIA or SPEXone instruments. These instruments are both using a multi-angular polarimeter, which is one of the most promising techniques to measure aerosol properties (Dubovik et al., 2019). The technique already proved its worth with the POLDER instrument (now no longer in orbit) (Parol et al., 2004). In addition to the multi-angular polarimeter, measurements on clouds are needed. These can be combined within the PACE mission (where SPEXone is part of), where HARP and OCI will measure clouds, yielding the opportunity to study aerosol-cloud interactions and allow for distinction between these two (Van Amerongen et al., 2019). The PACE mission is expected to initiate in 2023. Remaining user needs would be the combination with LIDAR observations and spectrometer instruments to measure precursors.

4.2.4 Natural sources

The importance of distinction between natural and anthropogenic emissions has been mentioned by multiple interviewees and was also identified in the literature review. The uncertainty in natural fluxes is high and more research on this is important (e.g. nitrogen emissions from soils or lightening and methane emissions from permafrost). Satellite observations may help, especially if spatial and temporal resolutions increase, enabling better source attribution. For nitrogen emissions, Nitro-Sat is aiming to improve our knowledge on emissions from e.g. farm sites. For methane emission monitoring over permafrost or the arctic region, active instrumentation is needed. The downside is the inherent lower footprint of these instruments, and therefore a combination with an instrument with larger footprint is interesting.

4.2.5 Presence of clouds

Not all points of concern found in literature, were mentioned during the interviews. The presence of clouds was only mentioned once during the interviews as being a constraining factor for satellite retrievals. Further remarks on clouds were with respect to their interaction with aerosols. Nevertheless, it would be beneficial to be less limited by the presence of clouds, since these decrease the number of usable retrievals. According to the literature this issue might be overcome by using active instrumentation, increased measurement swaths or by letting satellites fly in an elliptical orbit. Alternatively, the launch of a constellation of satellites or measuring with a higher resolution could help, since more pixels would be considered cloud-free.

4.3 Satellite data in a broader perspective

In the literature and during the interviews, the importance of surface station measurements was pointed out. To a large extend, these observations are and will be needed to validate satellite retrievals and perform bias corrections. This applies to GHGs, but also to aerosols. Surface measurements also help in analysing the correlation between satellite column retrievals and surface concentrations. A specific need mentioned by some interviewees was the expansion of ground stations measuring GHGs. Furthermore, observations on the vertical profile of components are of added value to improve satellite retrievals, as indicated in the literature review. The retrieval algorithms are under constant development, yielding improved data products with the same input data (satellite measurements). According to an interviewee, four retrieval algorithms are available for the MODIS instrument. This indicates the importance of additional data-sets and of computational development regarding satellite retrievals. Interviewees recognized this importance, pointing to the importance of data-assimilation (on a fine scale), atmospheric modelling, artificial intelligence-developments and ground station measurements. Resources to develop these techniques should be available in the future, with more and more data becoming available from multiple satellite missions.

5 Conclusion

The RIVM inquired into the needs and wishes of (potential) satellite data users with regard to emissions. The enquiry consisted of, first, a literature study, followed by interviews with 24 (potential) users, with a broad range of backgrounds and knowledge levels on the use of satellite data. The interviewees are working in different domains: climate change studies, human health studies, environmental studies, and inventory reports. Due to the extensive lists of interviewees and their wide-ranging employers, a comprehensive overview is formulated. The literature study was used as input for the interviews and the outcomes of both are combined in the resulting lists of needs and wishes.

Most remarkable outcome of the inquiry is the list of practical challenges that the interviewees came up with. There is a widely felt need for more and wider collaboration, building a more open community, and more emphasis on ways to increase the application of data, make the data more visible and user friendly. The interviewees give many suggestions to address these challenges and it is clear that the quick wins and opportunities to enlarge the group of satellite data users are mostly found in this part of the enquiry.

Below, we list the needs and wishes that were identified, grouped in three categories: practical challenges regarding data usage, technical needs and requirements regarding satellite data or modelling, and scientific needs and interests. The practical challenges are mostly applicable across domains, the technical and scientific needs are partly component specific. During the interviews, not all technical needs could be expressed in quantitative terms. We used literature as a complementary source.

Practical challenges and needs:

- **P1** Allocate more resources to data-analysis and to the conversion of data into useable (end)products.
- **P2** Integrate a *multidisciplinary* approach in satellite mission-plans Facilitate *collaboration* across institutes for example by building a (national) community or network. NSO could play a role in the coordination.
- **P3** Increase accessibility of the satellite community for new organizations and institutions.
- **P4** Ensure *consistency and continuity* by use of *standard classifications* within satellite products and by harmonizing different products
- **P5** Build a coordinated and *central database,* including ground-measurements of various components
- **P6** Improve user friendliness and visibility of satellite data (products).
- **P7** A shift in policy; *(re)formulate policy questions* such that satellites come into view to be used, switch to a more *data-driven* workflow or mindset

Technical needs and requirements:

- **T1** Increased temporal resolution of satellite data with geostationary satellites.
- **T2** Increased spatial resolution of satellite data, to the order of 1 x 1 km^2.
- **T3** Increased sensitivity (detection limit) for several components, including methane and ammonia.
- **T4** Optimisation of retrieval algorithms, considering the ongoing computational developments.
- **T5** Increased instrument sensitivity to the atmospheric boundary layer, for example by combining SWIR and TIR measurements.
- **T6** Improved sensitivity over sea, less depending on sun glint.
- **T7** Improved sensitivity over clouds, with active instrumentation or increased satellite footprints, higher resolution or flying an elliptical orbit. Alternatively, a constellation of satellites could be launched, combining the high resolution of active instruments with a larger swath of other instruments.
- **T8** Improved distinction between anthropogenic and natural sources for aerosols, for example by increasing spatial resolution. This is also a need for other components, since uncertainties for natural sources are high (e.g. NO_x from lightning).
- **T9** More research on cloud-aerosol interactions, including rainfall observations.
- **T10** Improved aerosol characterisation and composition measurements, for example with multangular polarimeter instruments.
- **T11** More ground-station measurements of GHGs, SO_2, NH_3 and $PM_{2.5}$ concentrations, partly to validate and calibrate satellite retrievals. Expansion should include observation stations over sea.
- **T12** More research on the relation between ground-based measurements and satellites observations of the vertical profile of pollutants. This can also improve satellite retrievals themselves. For example with the aid of LIDAR observations.
- **T13** Near real-time availability of data-products.

Scientific needs and interests:

- **S1** Improved bi-directional parameterization in retrieval algorithms for dry deposition for ammonia, probably with the aid of Nitro-Sat. Furthermore, high resolution assimilation models should be available and external factors influencing the NH_3 flux should be measured (e.g. temp, pH).
- **S2** Satellite measurements of greenhouse horticulture emissions.
- **S3** Satellite measurements of shipping emissions and platform activities.
- **S4** Remote sensing of permafrost melt and resulting methane emissions with active instrumentation and investigate the natural carbon sources (and sinks).
- **S5** Over sea measurements of algae to improve ammonia emissions estimates.
- **S6** More research on co-emitted ratio’s to deduce PM, VOC and SVHC emissions, since direct observations are not yet available.
- **S7** Investment in IM techniques, where use of satellite data will become more important.

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