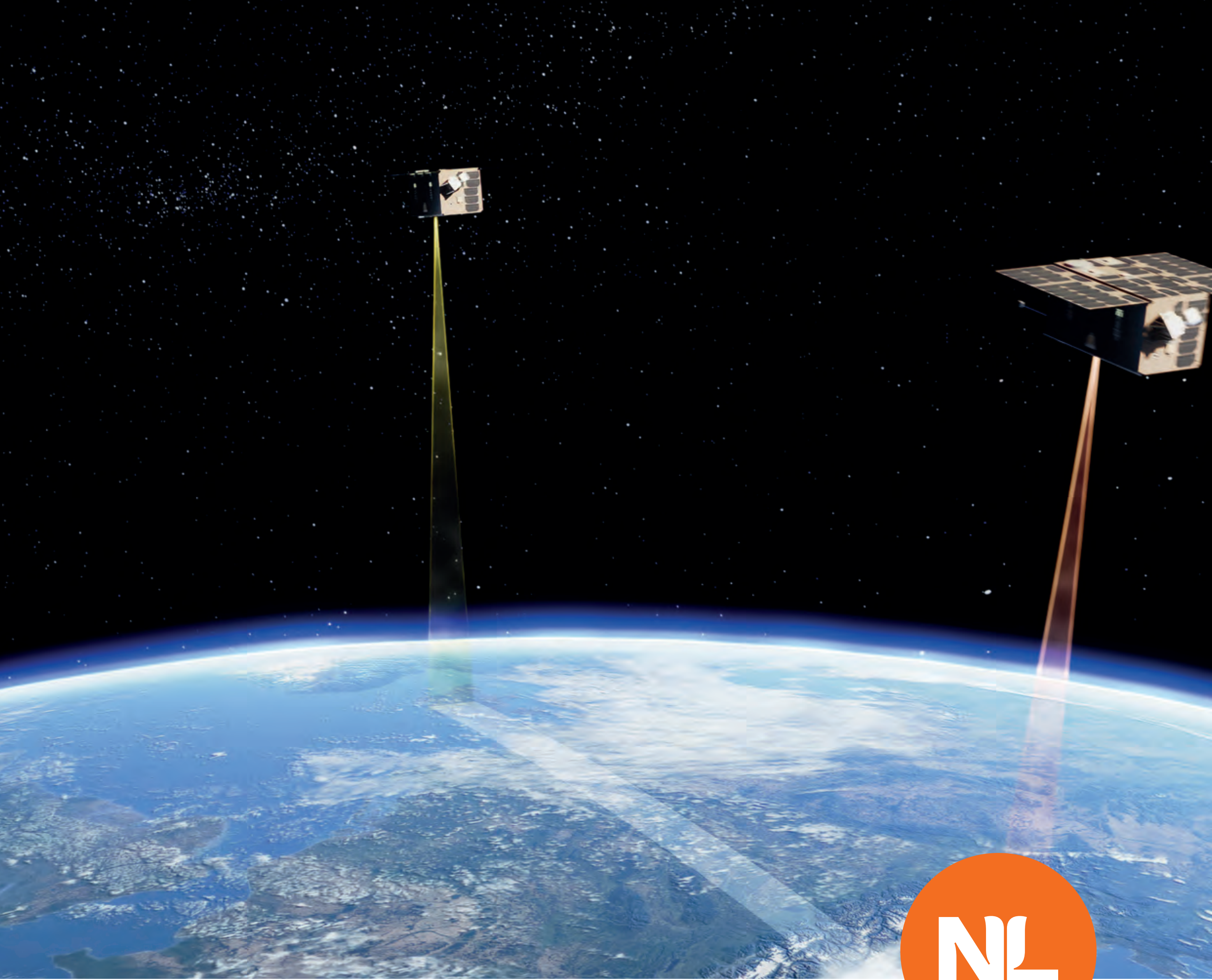

Space & Climate collaboration United States of America and the Netherlands

White Paper

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Content

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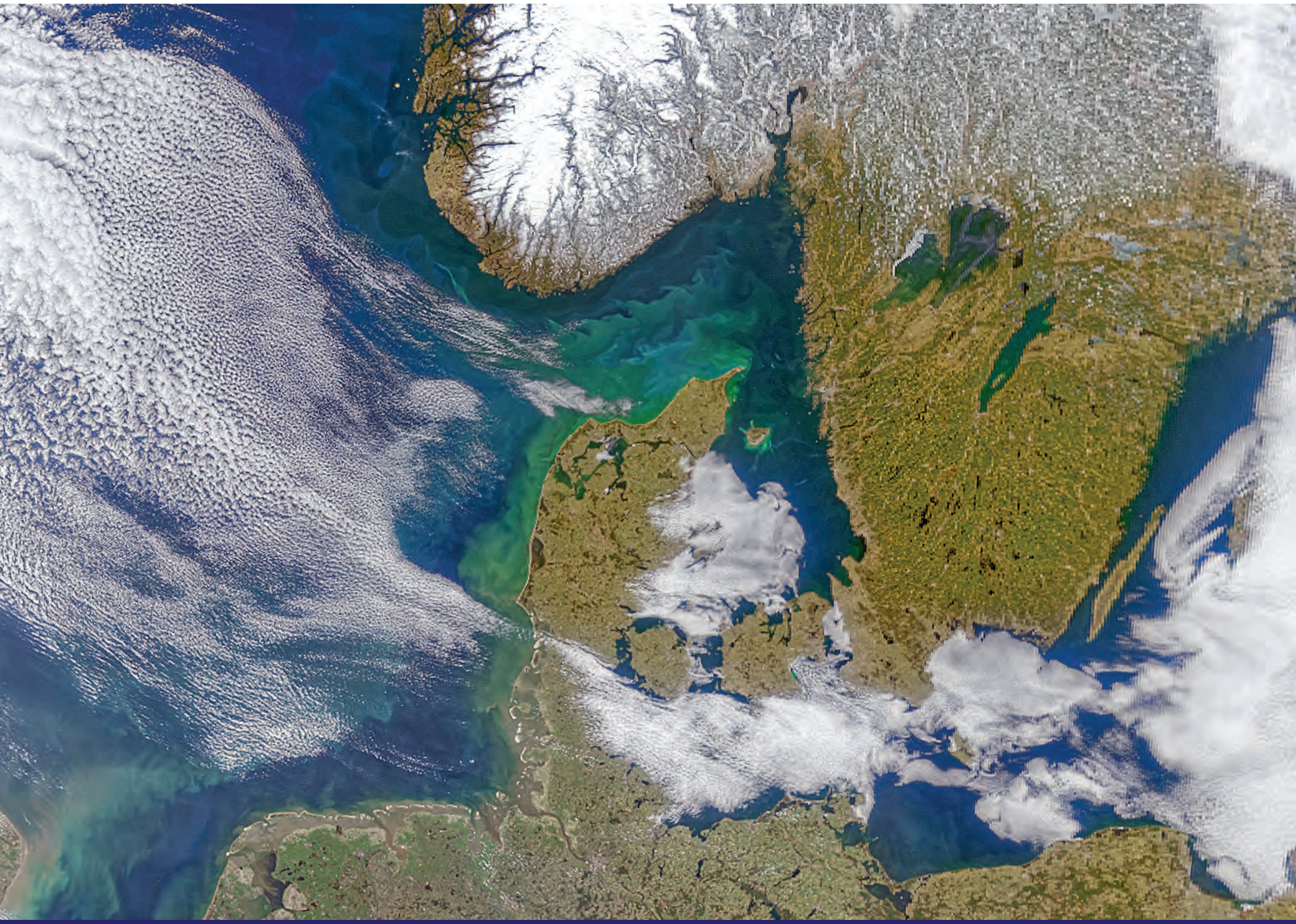
Executive summary

Scientists from the United States and the Netherlands have identified opportunities to explore avenues to further enhance the US-NL partnership, in the fields of clouds and aerosols, greenhouse gases and reactive gases. In total 10 cross cutting topics between these fields have been identified that will benefit from collaborative research. The subject matter experts have made recommendations, that can be summarized in the following three categories:

1. Joint development of satellite missions and sub-orbital campaigns, including the follow on for OMI/TROPOMI and SPEXone, and the study of reactive nitrogen.
2. Joint research to reduce biases in satellite data, by improving methods and algorithms, calibration and validation studies, as well using the satellite data to enhance our knowledge on air quality, climate and biodiversity.
3. Organizing scientific workshops and exchanging students and scientists, to exchange ideas and to build the US-NL partnership for the future.

For all the recommendations clear actions, as well as next steps have been identified.

This whitepaper will be presented to the leadership of the organizations with which the authors are affiliated in early March 2025. During this meeting, next steps on the recommendations will be discussed.



Introduction

In the 21st century, there have been dramatic increases in greenhouse gas levels, a significant deterioration of global air quality, a measurable loss of biodiversity, and notable climate changes. Satellite remote sensing has played a crucial role in observing these changes, enhancing our understanding of their drivers, and catalyzing actions to address them.

Recognizing the importance of these space-based observations, the international community has expanded their quantity and diversity, incorporating new capabilities to measure from local scales (e.g., meters) to global scales (e.g., thousands of kilometers) and encompassing a wider range of geophysical quantities. As members of the international community, the Netherlands and the United States have played leading roles in the development and deployment of these satellite instruments. Through long-standing scientific partnerships, such as OMI on EOS Aura and SPEXone on PACE, and scientific exchange, they have significantly advanced this field.

During a two-day workshop, scientists from the United States and the Netherlands discussed and identified opportunities in the fields of clouds and aerosols, greenhouse gases and reactive gases, to explore avenues to further enhance thee US-NL partnership. This whitepaper summarizes the main outcomes of this workshop, exploring paths to build and strengthen this relationship, and identifying gaps and opportunities in the current Earth Observation system from space. Subject matter experts from both The Netherlands and the United States have made recommendations that advance collaboration in specific disciplinary areas and identified critical cross-cutting themes. These recommendations are made in the personal and independent capacity of the scientists.The international community faces policy tipping points in 2030 and 2050 that require a detailed roadmap to distill complex measurements into well-characterized, actionable and timely information.

This whitepaper is intended to be ambitious by laying out a far-reaching vision on what needs to be done from national and global perspectives. It provides actionable recommendations and suggestions for the continuation of this fruitful international collaboration.

Following this introduction, the identified cross-cutting themes are described, followed by the specific recommendations and actions on aerosols & clouds, greenhouse gases and reactive gases.

The three themes explained

Aerosols & Clouds

Two missions with a focus on monitoring clouds, aerosols, and their radiative effects were launched in 2024: the PACE mission (NASA) carrying the Dutch SPEXone instrument and the EarthCARE mission (ESA/JAXA) with a Dutch instrument contribution and data and science leadership. These satellites succeed the heritage CloudSAT and CALIPSO missions and will be followed by the planned AOS mission. SPEXone on PACE provides multi-angle polarimetric observations with unprecedented accuracy and spectral sampling. EarthCARE carries high-performance radar and lidar instruments. U.S.-Netherlands collaboration can further refine multi-sensor data integration, deepening insights into the climate impacts of aerosols and clouds as well as air quality impacting human health.

Greenhouse Gases

The US and the Netherlands have long-standing collaborations in observing greenhouse gases methane (CH_4) and carbon dioxide (CO_2) and the pollutant carbon monoxide (CO) from space. Over the last decade, there has been a substantial increase in the use of satellite GHG observations - especially NASA OCO-2, TROPOMI on Copernicus Sentinel-5P, and JAXA GOSAT - to quantify global and regional fluxes. New observations from high-resolution instruments designed to observe methane (such as the recently launched Carbon Mapper and MethaneSAT mission and future TANGO mission) and imaging spectrometers such as the NASA EMIT instrument are used to quantify facility-scale GHG emissions. Progress is needed in linking GHG datasets together and to translate those into information for decision makers. In addition, deeper insights into GHG emissions and air quality and their interactions are needed to improve climate projections.

Reactive Gases

The Ozone Monitoring Instrument (OMI), a joint project between the Netherlands and the United States, exemplifies successful international cooperation in space-based atmospheric research. Launched in 2004 on NASA's Aura satellite, OMI continues to provide crucial data on reactive gases such as nitrogen dioxide, sulfur dioxide and formaldehyde, contributing significantly to our understanding of air quality, ozone depletion, and climate change. Recent developments include higher spatial resolution data (TROPOMI, CO2M, CHAPS) and hourly observations using geostationary satellites (GEMS, TEMPO, Sentinel-4, IRS), enabling new research and application areas.

Cross-cutting topics

I. TROPOMI / SPEXone follow on

Build on the successful collaboration between the United States and the Netherlands by the EOS Aura and PACE missions to fulfil the needs for continued observations of trace gases, clouds, and aerosols.

The Netherlands has contributed the OMI and SPEXone instruments to NASA's Aura and PACE missions, while NASA has supported TROPOMI through data mirroring, algorithms, and calibration activities. Planning is underway in the U.S. for the NEON observing system to replace JPSS, and a PACE/OCI follow-on instrument. TROPOMI and a SPEXone follow on can be strong contributions to these missions.

Actions:

a. To address the future of the afternoon LEO orbit for atmospheric composition in a CEOS activity.
b. Investigate the possibilities for atmospheric composition and aerosol polarimeter observations within the NOAA NEON program, including with the use of the PACI/OCI follow on and the second generation SPEXone instrument.

II. Integrating data in models

We have to advance our models to maximize the use of our satellite observations.

Understanding greenhouse gases, air quality, and climate drivers requires further development of Earth System models informed by high-fidelity observations. Advances in data assimilation and inverse modeling enhance predictions by allowing observations to directly inform emissions, initial and boundary conditions, as well as model parameters. Collaboration is crucial for developing observation operators, fast hyperspectral radiative transfer tools, addressing biases, and managing data latency to optimize the Earth current and future observing system models.

Actions:

a. Development and exchange of observation operators for present instruments, e.g., SPEXone, TROPOMI and CrIS, and near-term instruments, e.g., TANGO, to assess information impact in an OSSE framework.
b. Coordinate comparisons against independent data to assess potential biases.
c. Coordinate delivery mechanisms--leveraging success with TROPOMI--to insure timely availability of US and Dutch data.

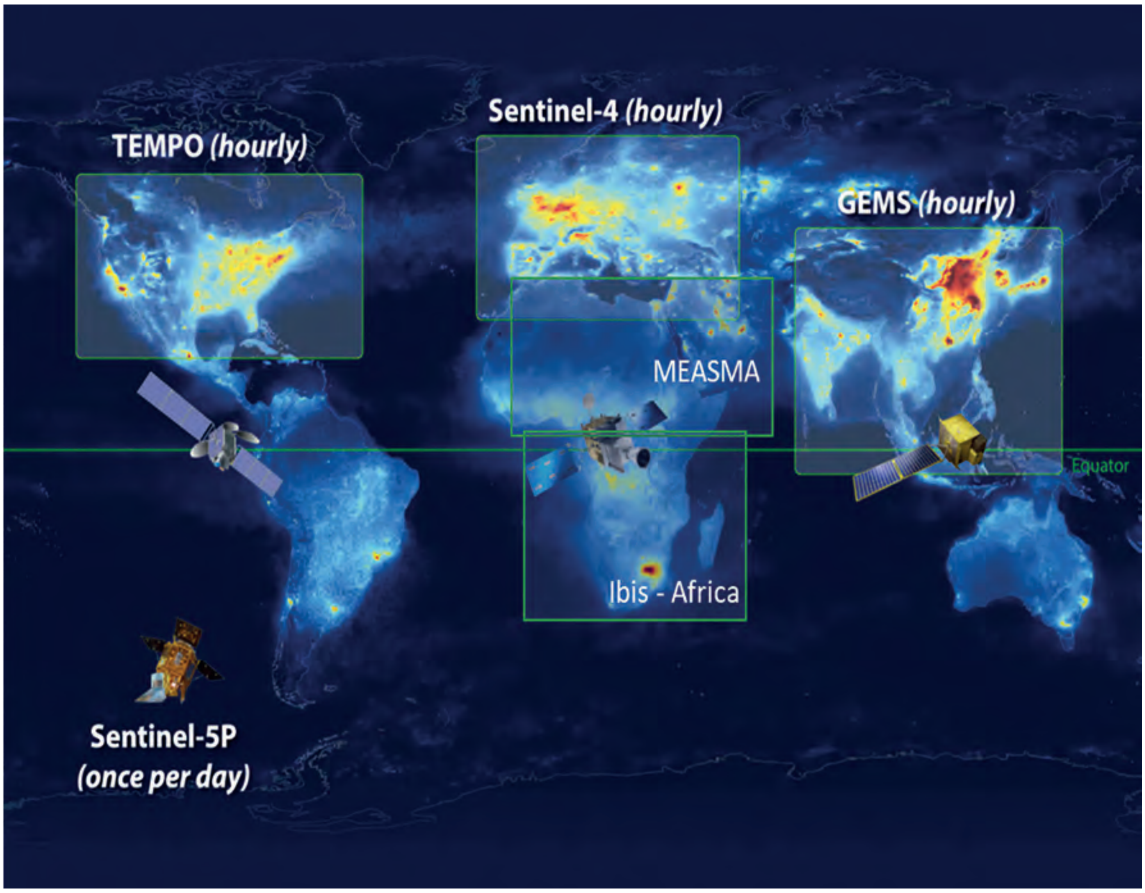
III. Global South

Diurnal satellite observations of trace gases and aerosols can be a game changer for Africa and South America, as the ground-based observations are very sparse.

In the coming decades it is expected that largest demographic changes will occur in the Global South and specifically in Africa, causing large environmental threats on air quality, biodiversity and climate change. In the United States there are initiatives for expanding the CEOS air quality constellation with geostationary observations over Africa and South America. In the Netherlands there are initiatives for capacity building in Africa, mostly in the framework of WMO and ESA programmes.

Actions:

a. For the United States and The Netherlands to contribute to the planned CEOS whitepaper on satellite observations for air quality and climate over the global south.
b. To consider the possibility for CHAPS to fly in an inclined orbit, to optimize observations over lower latitudes, including the global south.
c. To discuss possible interest in Europe for an Earth observation mission from the Lagrange 1 point.



IV. U.S. Participation in the TANGO mission

Collaboration between The Netherlands and the U.S. is expected to significantly enhance TANGO's scientific impact.

TANGO, a small-satellite mission under ESA's SCOUT program led by Dutch scientists and industry, aims to quantify CO_2 and CH_4 emissions and utilize co-aligned NO_2 observations. It will complement the global constellation of greenhouse gas monitoring satellites, including U.S. contributions like EMIT, Carbon Mapper, and MethaneSat.

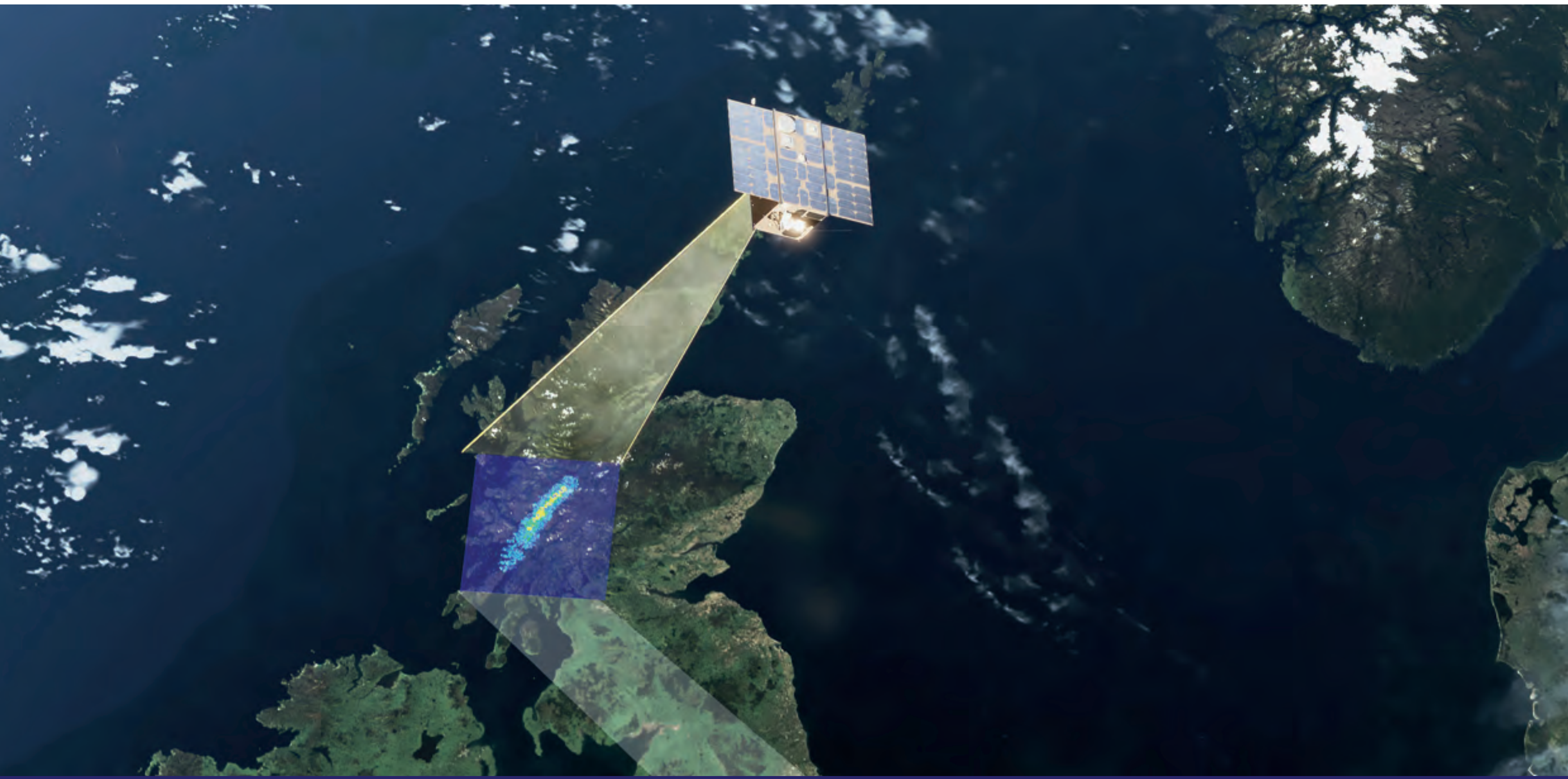
Actions:

a. To identify sub-orbital mission organized in the U.S. that can contribute to the calibration and validation activities of TANGO, for example airborne campaigns that include CO_2 /CH_4/NO_2 remote sensing observations, as well as controlled release experiments.

b. The potential satellite deployment of the CHAPS instrument has a synergy with the TANGO NO_2 instrument. It is recommended that the CHAPS and TANGO science teams collaborate on algorithms, data processing and calibration and validation activities.

c. To investigate potential synergies and complementary aspects of TANGO and NASA's Carbon-I mission selected as earth system explorers program candidate by NASA. Both missions have the objective to map carbon dioxide (CO_2) and methane (CH_4) emissions globally but differ in spatial resolution, spectral ranges, and the use of the NO_2 trace gas as a plume proxy.

d. Further US involvement in TANGO to promote the uptake of the TANGO data and integration with other instruments. This would, for example, include a US contribution to the TANGO science team, which could help optimize impact of TANGO in conjunction with US assets (e.g., OCO-3, EMIT, TEMPO) through OSSE studies.



V. Sub-orbital observations

Sub-orbital observations from ground or aircraft are essential to validate and supplement satellite products and to demonstrate new technology.

Sub-orbital campaigns benefit from diverse expertise and instruments, with Dutch and U.S. collaboration key to aligning efforts with satellite missions. Leveraging existing airborne tools like SPEX- airborne, Spectrolite and CHAPS-D, and ensuring compatibility with U.S. research aircraft is essential. Maintaining and adapting validation and calibration sites in both countries will further enhance these efforts.

VI. CEOS is vehicle for accomplishing

The U.S. and The Netherlands are anticipated to strengthen their future scientific collaboration within the CEOS context.

Actions:

a. Initiate studies between the different CEOS space agencies to intercompare algorithms for retrieving atmospheric pollutants, greenhouse gases, and aerosol and cloud properties, including new mission ideas (like ESA's, NITROSAT, Earth Explorer Mission).
b. Stimulate activities to improve and harmonize algorithms.
c. Intercomparison and harmonization of satellite data products to improve our understanding of long-term trends. This includes the assessment of systematic biases in the different data products.
d. Support more global validation sites to increase the number air quality and greenhouse gas observations available for calibration and validation.
e. With a growing time series of methane observations from space, provided by a similarly growing number of instruments (GOSAT(-2), TROPOMI, GOSAT-GW, Sentinel-5, CO2M), there is a need and opportunity to assess both natural and anthropogenic long-term methane trends. Considering their expertise and experience, the US and Netherlands are in a good position to spearhead such an activity. We recommend an activity of the Netherlands and the US with CEOS to assess the satellite-based capability to understand these long-term methane trends.

VII. Development and continuity of products from different instruments

U.S.-Netherlands collaboration can further refine multi-sensor data integration for radar-lidar missions, deepening insights into the climate impacts of aerosols and clouds.

CloudSAT, CALIPSO, EarthCARE, and AOS missions focus on monitoring clouds, aerosols, polar stratospheric clouds, and their radiative effects. These missions advance radar-lidar synergy and unified retrieval approaches to improve data consistency and enhance understanding of cloud-aerosol interactions. U.S.-Netherlands collaboration can further refine multi-sensor data integration, deepening insights into the climate impacts of aerosols and clouds.

Actions:

a. Coordinate collaborations between ATLID retrieval improvements (e.g. on aerosols, clouds and PSCs) and assisting in creating/improving EarthCARE products to enable the creation of continuous/climate cross instrument datasets.

b. Coordinate (statistical) comparisons between the EarthCARE and Calipso-CloudSAT retrievals against independent datasets (i.e. ground based sites, campaigns, Aeolus L2 retrievals) to assess potential biases.

c. Potential synergies of TIR and SWIR sensors that could improve retrievals of CO and methane profiles. For example, Sentinel-5P TROPOMI combined with CRIS for methane or Sentinel-5 with IASI-NG for free tropospheric methane. We therefore recommend the to support the development of synergistic green-house products (e.g., SO_2, H_2O, CO and Methane) combining multiple sensors (e.g., UV + NIR+ SWIR + TIR).

VIII. Stratosphere

Several surprises in recent years have shown that the stratosphere is not a solved problem and that continuous observations of its composition are essential.

The expected end of the MLS data record in 2026 will signifcantly reduce observation capabilities for the stratosphere, which remains critical for studying volcanic effects, biomass burning, climate-ozone interactions, and potential climate interventions. Observations of trace gases, aerosols, and stratospheric clouds are essential. EarthCARE provides information on aerosols and stratospheric clouds, and both in in the U.S. (STRIVE) and in Europe (CAIRT) missions for the stratospheric composition are studied in Phase A. Scientists from the U.S. and the Netherlands plan to collaborate on stratospheric composition research.

Actions:

Directors of KNMI and NCAR to discuss possible collaborations including the stratosphere research.

IX. Wildfires and Biomass Burning

There is an urgent need for improved satellite data, modeling, and information systems on the emissions from wildfires/biomass burning that have an alarmingly increasing impact on climate and human health.

Understanding wildfire processes is crucial for prevention, mitigation, improving climate predictions, as well as regarding poorly understood fire-induced weather effects and aerosol-cloud interactions. Climate feedbacks from biomass burning on the carbon budget and radiation balance remain uncertain but are critical for assessing future climate impacts.

Actions

a. To jointly study the use of the planned NASA Carbon-I mission (if selected) carbon monoxide data for the wildfire/biomass science case. combined with e.g. TROPOMI and MOPITT. Carbon-I will allow observations of CO, CH_4 and CO_2 right at the source of the fire. Knowledge of CH_4/CO and CO_2/CO ratio directly at the fire, will allow us to constrain both long-lived gases with, e.g. TROPOMI CO much better.

b. To jointly study the development of next generation instrument for carbon monoxide observations at high spatial resolution (300 m) 'TANGO-CO'.

X. Building Scientific Networks between US and Dutch Scientists

Advances and excellence of joint 'space & climate'- science between US and NL builds on close relations between scientists promoted with the exchange of students and scientists.

Actions:

a. Bring together students and early career scientists in events organized on either side of the Atlantic for example; summer schools (such as organized by Dutch EO community), 'hackaton' activities, scientific workshops and, international exchange of interns at e.g. NASA/NCAR or SRON/KNMI/TNO. These activities would be aimed at educating a new generation of scientists and building working relations and to jointly develop methods, tools and concepts for future research and space missions.

b. Early career scientists can benefit from extended visits working with teams on the other side of the Atlantic. For example, on the integration of satellite data in models of the intercomparison of data, models, or methods. Funding for such an exchange would be advisable. For example, the NASA Postdoctoral Program (NPP) offers opportunities.

c. Experienced scientists can act as advisor for missions or as co-Investigator. This requires funding from host organization such as the NASA Earth Science US Participating Investigator program. A similar grant is also advised for the Netherlands.

Aerosols & Clouds

The United States of America and The Netherlands have a long history of collaboration on the observation of clouds and aerosols and the role that they play in the Earth's Climate.

One current example is the recently launched NASA PACE mission, which has a contributed instrument (SPEXone) from a consortium of entities in the Netherlands. PACE's mission is to extend the data record and provide new observations of the Earth's ocean, land surface, clouds and aerosols. Also recently launched is ESA's EarthCARE mission, devoted to the observation and study of clouds and aerosols. These missions have different, but highly complementary, capabilities. The value of this can be realized with continuing strong bilateral relationship for which we have several specific recommendations.

1. **Promote the use of Dutch technology for US missions.**
   Based on expertise gained from, e.g. SPEXone, TROPOMI, the Netherlands keeps developing technology to advance aerosol and cloud satellite instruments. Development is driven by requirements to (better) observe essential aerosol and cloud observables, e.g. with better resolution, information content and/or accuracy. We recommend to keep informing each other on mission requirements and technology development to promote compatibility.

2. **Promote use of SPEXone and EarthCARE data for model validation, calibration and data assimilation in models.**
   Many cloud and aerosol observation products from these missions are new, and their appropriate use in models requires careful consideration and study. Challenges include ensuring data transparency and interoperability in a cloud computing environment and integration of diverse scientific communities.
   We recommend to establish lasting joint efforts with funded programs to encourage collaboration, data accessibility and use. We propose to identify systemic barriers, such as agency data restriction and code sharing policies, terminology variation, and institutional norms.

3. **Establish a PACE-EarthCARE synergy project.**
   The complementary characteristics of the missions, and regular coincident simultaneous observations means there is potential for synergistic use of the datasets. Synergy could be explored in three ways:
   1. (cross) validation of data products, and sharing of validation resources,
   2. unique science that can be performed with synergistic observations, and
   3. exploration guiding the design of future missions, such as AOS.

   We propose to establish a funded PACE-EarthCARE synergy project and encourage further collaboration, such as through 'Hackathons' like PACE's August Hackweek.

4. **Establish a funded bi-lateral aerosol algorithm intercomparison project.**
   Algorithm development has been a core enabling aspect for the use of multi-angle polarimeters (such as SPEXone) in aerosol remote sensing. Currently, multiple algorithms exist and are being implemented for the PACE mission. Understanding the impacts of these differences requires careful consideration.

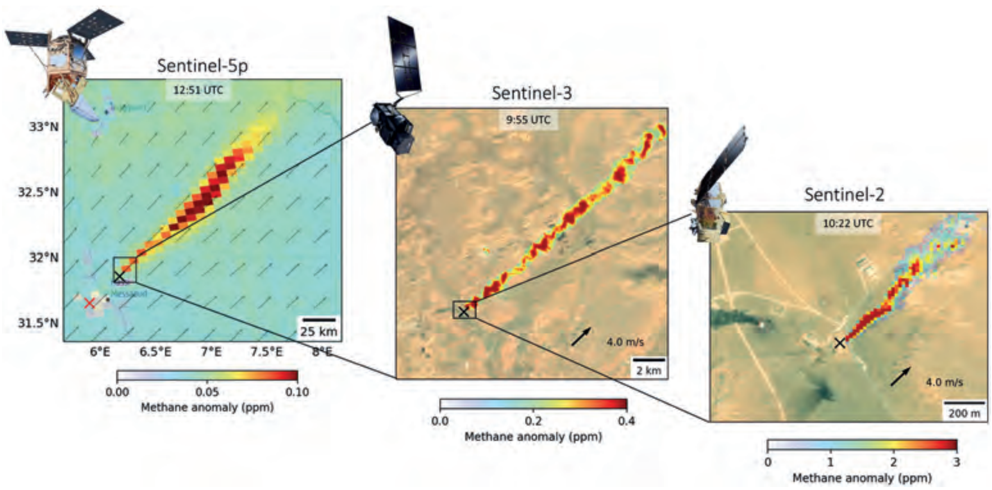
5. **Collaborate on sub-orbital field campaigns dedicated to observation of aerosols, clouds and their radiative impacts.**
   While institutions in both the US and the Netherlands are frequently involved in sub-orbital field campaigns, they are often planned and implemented independently. We encourage earlier cooperation on field campaigns and to make efforts to raise awareness of upcoming events. Barriers to sharing of data and analysis should be minimized.

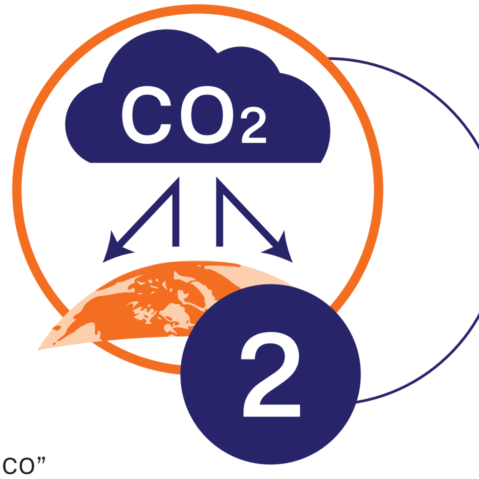
Greenhouse Gases

The US and the Netherlands have a long track record of collaboration when it comes to observing greenhouse gases, featuring both institutional as well as individual engagements. Satellite GHG observations are provided by flux mappers like NASA OCO-2, TROPOMI on Copernicus Sentinel-5P, and JAXA GOSAT, and high-resolution instruments like Carbon Mapper, MethaneSAT, NASA EMIT and the future TANGO mission focused at point-source emissions.

The scientific and societal landscape is changing rapidly with increasing demands on these data and the models that assimilate them. In particular, long-term GHG emission trends depend on linking multiple satellite datasets together. Greenhouse gases are integral to air quality and climate projections with emission scenarios looking at air quality and climate co-benefits. To fully assess the impacts, integration of AQ observations is needed. In addition, substantial challenges remain in how to translate the information provided by GHG observations into inventories used by decision makers. In order to address these issues and leverage the unique Dutch and US expertise, the following recommendations are proposed.

1. **Collaboration on validation and intercomparison of methane and CO_2 point source emission estimates from near-term satellite instruments (CO2M)/TANGO/EMIT/TANAGER/Carbon-I/MethaneSAT/Carbon Mapper.**
   With increased interest from stakeholders, providing confidence in satellite-based emission estimates is vital. The SRON-led MEDUSA ESA project aims to provide the comparison and (till the extent possible) validation of satellite-based methane hot spot products. Meanwhile, NIST is spearheading a linked US effort on standardization and best practices. We propose sustained and enhanced engagement (including as follow-up to MEDUSA) between the Netherlands (SRON) and GHG Center (which includes NIST, NOAA, NASA, and EPA) about additional activities on validation and intercomparison of near-term future point source methane and CO_2 satellite data products (e.g., TANGO, Carbon-I).





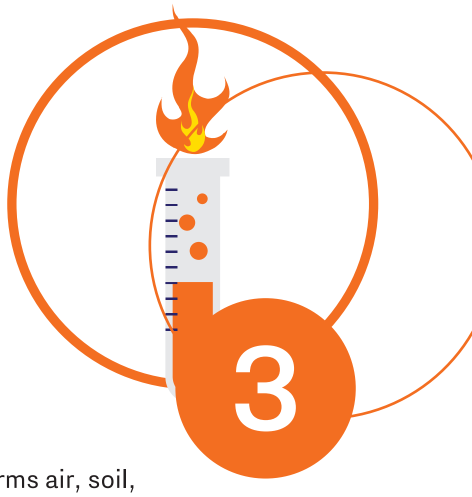
2. **Develop CO measurements at high spatial resolution (~300m).**
   The tentative Carbon-I (JPL) mission is under evaluation at NASA and would provide Carbon Monoxide data at 300m resolution, opening up new possibilities for understanding emissions from combustion in the urban environment, industrial sources, and fires (This also links to cross-cutting topic 9 on improved information on wildfires and biomass burning). SRONscientists are named as collaborators on Carbon-I. "TANGO-CO" is a concept in the Netherlands that would provide similar observations.
   If Carbon-I is selected, we propose to request Dutch science involvement on investigating the potential of high-resolution CO observations and use of the observations and development of a parallel instrument in the Netherlands (TANGO-CO).

3. **Methane Inventory assessment and development using or constrained by remote sensing.**
   A central point of work related to greenhouse gas emissions is to answer the question "*how do we use observations of both point and area sources to improve bottom-up inventories (including UNFCCC inventories)*". This question is also urgent for the Global Methane Pledge as goals are set for 2030. A IGAC-GEIA working group has been established to provide guidance on answering this question and developing a consensus approach. Several related efforts are ongoing in both countries, both at the area scale and the point-source-emission scale. We propose to support joint efforts contributing towards the IGAC-GEIA methane working group's goal on providing best practices on the incorporation of top-down estimates into bottom-up inventories.

4. **The synergetic use of GHG and AQ measurements to infer emission estimates for point sources and area sources.**
   Sources often emit multiple species (e.g., co-emission of CO_2, NO_x and/or SO_2) but quantification of emission using EO data generally focuses on a single species. As these emissions are not independent, combination of multiple species could provide valuable constraints and information on the activity causing emissions. We propose to identify collaborations on the combination of satellite-based GHG and AQ measurements to estimate emissions from point and area sources, e.g. by combining observations from different instruments.

5. **Identify and develop enabling technology concepts (like immersed gratings for TROPOMI) currently at low TRL, that could support a future greenhouse gas constellation by boosting the performance to cost ratio.**
   For example, photonic crystals that allow for spectrometers that are 10 times smaller or type-2-superlattice / quantum-well infrared detectors that remove the need for cryogenic cooling.

Reactive Gases



The U.S. and The Netherlands have a long-term collaboration on research of reactive gases, for example in the OMI and TROPOMI satellite missions, as well as in data use of other missions. While several aspects of the collaboration are already discussed as part of the cross-cutting themes, there is also the ambition to collaborate on the nitrogen cycle and the hydrogen economy.

The nitrogen cycle disruption, largely from agricultural fertilizer use, harms air, soil, water, biodiversity, and climate. Reducing reactive nitrogen (NH_3 + NO_x) emissions offers environmental benefits, but current ground-based monitoring is inadequate. Researchers from the Netherlands and the U.S. aim to enhance collaboration on emission inversion and remote sensing of reactive nitrogen through current and future satellite and sub-orbital missions.

The hydrogen economy could impact the environment through unintended emissions like molecular hydrogen and ammonia, leading to increased stratospheric water vapor, cooling, and ozone depletion. Researchers in the U.S. and the Netherlands are studying these effects and propose a dedicated workshop to enhance collaboration.

1. **Develop a satellite mission for studying the nitrogen cycle.**
   ESA has studied such a concept for the Nitrosat Earth Explorer. To assess the feasibility of significant international contributions in NASA Earth Venture calls, to develop a satellite mission dedicated to reactive nitrogen observations.

2. **To investigate possibilities for sub-orbital campaigns to study the nitrogen cycle.**
   To check if the airborne remote sensing instrument available at NASA (HYTES and CrIS Airborne Simulator) have sufficient sensitivity for NH_3, and to check future deployment possibilities.

3. **To interact with the SBG (Surface Biology and Geology) mission for the capabilities for NH_3 and/or NO_2 observations.**

4. **Host a workshop with current leading inversion/assimilation techniques experts within the nitrogen field**, to exchange ideas/current methodologies / explore cooperation for the science case of a future ammonia instrument.

5. **To organize a workshop with energy, atmospheric and climate experts from the United States and The Netherlands on the hydrogen economy,** to explore further collaboration.

Colofon

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