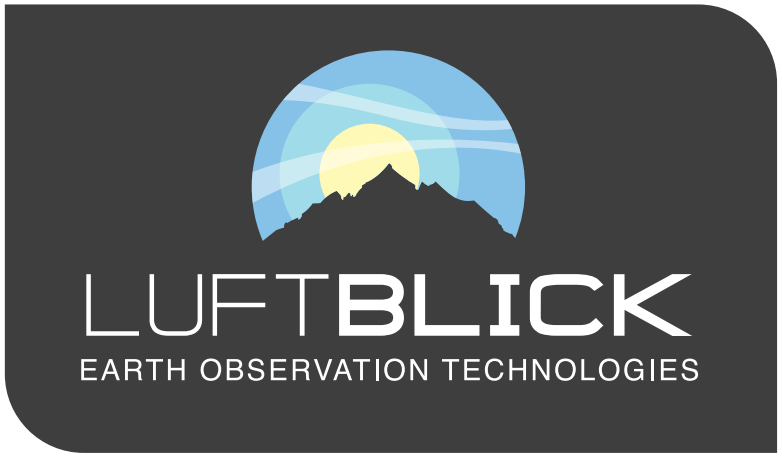

LuftBlick Report 2020004

Fiducial Reference Measurements for Air Quality

TN on PANDONIA Network representativeness

Version 3.0, 31st Dec 2022

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Contents

Document Change Record

Issue	Date	Section	Observations
0	29th Dec 2020	All	First version
0.1	30th Dec 2020	Updated landcover figures, added references	First version 0.1
1.0	31st Dec 2021	Updated landcover figure captions	First version 1.0
2.0	29th Dec 2021	Updated figures; first figures for SO_2 and HCHO, including related conclusions regarding these data products; appendix to explain used datasets	First version 2.0
3.0	31st Dec 2022	General revision, dropped landcover figures, included TROPOMI global average maps for NO_2, SO_2 and HCHO	First version 3.0

Acronyms and Abbreviations

CH_4	Methane
CO	Carbon monoxide
HCHO	Formaldehyde
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
O_3	Ozone
SO_2	Sulphur dioxide
ESA	European Space Agency
FRM4AQ	Fiducial Reference Measurements for Air Quality
NMVOC	Non-Methane Volatile Organic Compounds
PGN	Pandonia Global Network
SCD	Slant column density
$StratNO_2$	Stratospheric nitrogen dioxide
TN	Technical note
TotHCHO	Total column formaldehyde
$TotNO_2$	Total column nitrogen dioxide
$TotO_3$	Total column ozone
$TotSO_2$	Total column sulphur dioxide
$TropNO_2$	Tropospheric nitrogen dioxide
VOC	Volatile Organic Compound
VOC	Volatile Organic Compounds

1 Introduction

This report is deliverable 6 (D6) of the ESA project "Fiducial Reference Measurements for Air Quality" (FRM4AQ) [1, 2]. It is a technical note (TN) giving an overview about the representativeness of the Pandonia Global Network (PGN) instruments in terms of satellite validation of total column O_3, NO_2, SO_2 and HCHO. This will include a characterization of instrument locations in terms of temporal and spatial variability of target species and a regional, continental and global representativeness of the network.

1.1 Applicable Documents

[1] Fiducial Reference Measurements for Air Quality [Proposal], LuftBlick Proposal 201805DEV, Issue 1, 2018.

[2] Fiducial Reference Measurements for Air Quality [Contract and Statement of Work], ESA Contract No. 4000125841/18/I-NS, 2018.

1.2 Reference Documents

[3] Tropomi data products. URL http://www.tropomi.eu/data-products/.

[4] T. Fehr. Sentinel-5 Precursor - Scientific Validation Implementation Plan, 2016. URL https://sentinel.esa.int/documents/247904/2474724/Sentinel-5P-Science-Validation-Implementation-Plan.

[5] K.-P. Heue, K.-U. Eichmann, and P. Valks. TROPOMI/S5P ATBD of tropospheric ozone data products, 2020. URL https://sentinel.esa.int/documents/247904/2476257/Sentinel-5P-ATBD-TROPOMI-Tropospheric-Ozone.

[6] J.-C. Lambert and A. Keppens. Quarterly Validation Report of the Copernicus Sentinel-5 Precursor Operational Data Products 08: April 2018 – August 2020, 2020. URL https://mpc-vdaf.tropomi.eu/ProjectDir/reports/pdf/S5P-MPC-IASB-ROCVR-08.01.01-20200921_FINAL.pdf.

[7] N. Theys, C. Lerot, M. van Roozendael, I. de Smedt, and H. Yu. S5P/TROPOMI SO2 ATBD, 2020. URL https://sentinels.copernicus.eu/documents/247904/2476257/Sentinel-5P-ATBD-SO2-TROPOMI.

1.3 Current PGN locations

An overview figure about the official and non-official PGN stations (status 30th Nov 2022) is shown in Fig.1. At a first glance it is apparent that the USA and Central Europe are well represented, as well as East Asia. This is a result of the increasing preparation for the upcoming geostationary satellite missions Sentinel-4, TEMPO and GEMS (already in orbit).

Furthermore, the northern hemisphere is better represented than the southern hemisphere. Gaps are present in South America, Africa and from Russia down to the Middle East and India. The coverage of PGN sites with respect to latitude is shown in Fig.2. The majority of instruments is located between 30°N and 50°N.

1.4 Validation requirements

Species of interest for Sentinel-5P validation are, amongst others, O_3, NO_2, SO_2 and HCHO. For O_3 and NO_2 the tropospheric and stratospheric columns are of specific interest and for SO_2, regions with significant pollution and enhanced SO_2 due to eruptive volcanoes are situations to be looked at for validation. HCHO is strongly driven by natural cycles but on top of that, anthropogenic activities play an important role as well. For TROPOMI validation, other species like CO or CH_4 are of interest, too, but they are not taken into account in this representativeness study since these species are not retrieved by Pandora. In deliverable 4 of this project, a schedule is outlined which retrieval products can be expected when. Since the four gases O_3, NO_2, SO_2 and HCHO are already operational data products of the PGN or are in their final testing stages, they are the examined data products in this study.

In the following, specific validation requirements are identified for the respective products, and table 1 gives an overview about the requirements for the individual data products.
One could arrange the validation requirements into spatial, temporal and special requirements. Temporal validation requirements, like long time series or diurnal and seasonal cycles are typically fulfilled within the PGN anyway, since, except for campaigns, Pandoras are installed on a long-term basis at their locations, doing measurements throughout the year with covering the daily cycle of the measured species.

In summary, for stratospheric gases, a good coverage of all latitudes throughout the seasons is needed. But there are special requirements as well, for example the coverage of the O_3 hole. Air mass factor (AMF) calculation is the largest source of uncertainty in NO2 and HCHO satellite retrievals in situations with enhanced trace gas concentrations in the lower troposphere. This means that different latitudes with enhanced and variable column abundances should be covered for the validation of these products. SO_2 needs to be validated at strongly polluted regions or near volcanoes. In the following, the gases of interest are listed with an individual description about the validation requirements ([3, 4, 5, 6]).

Figure 1: PGN stations overview.

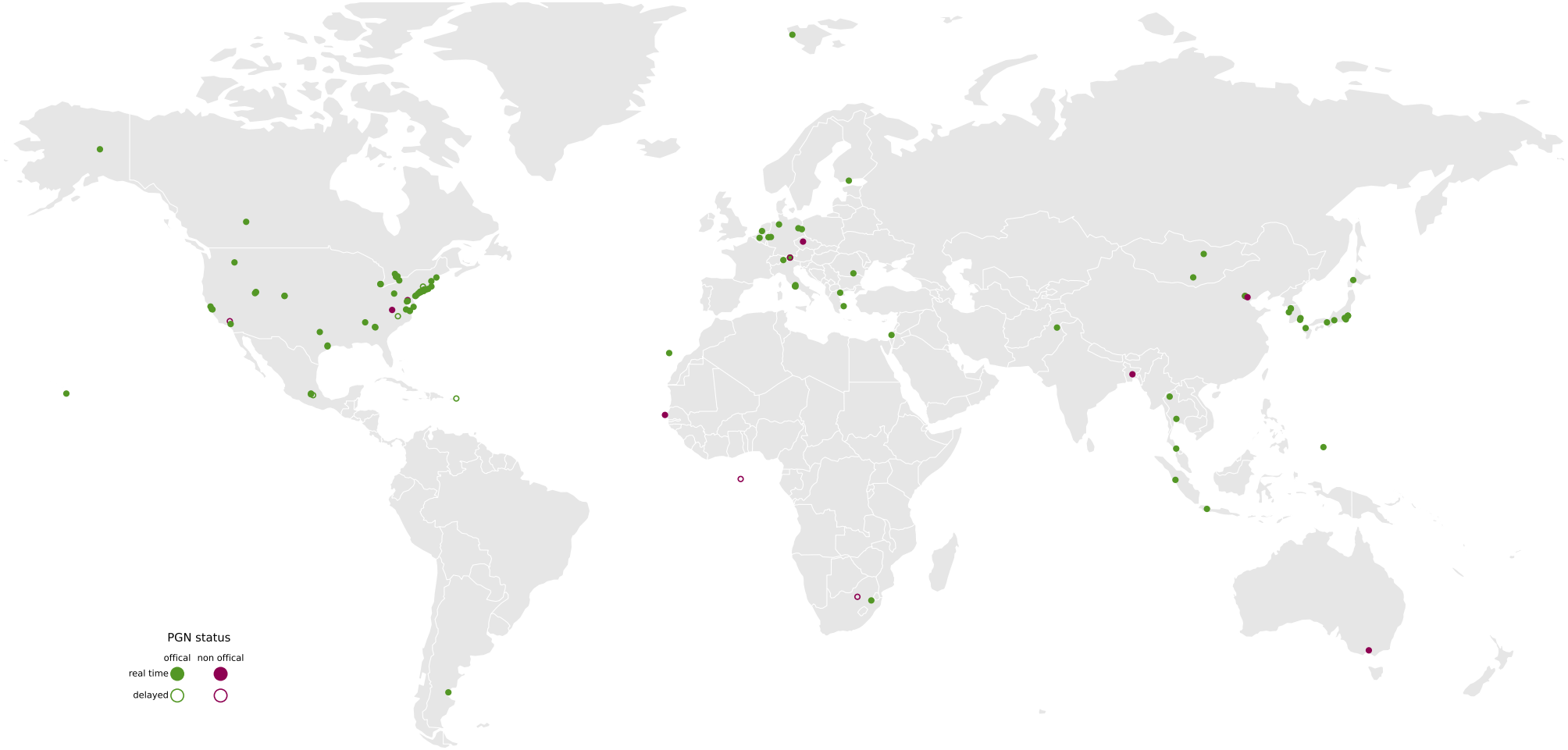


Table 1: TROPOMI validation requirements for species retrieved by Pandora

Product	**Validation requirement**
$TotO_3$	Global scale validation Measurement representativeness 10km x 10km Long time series Covering all season Tropics O_3 hole conditions
$TropNO_2$ $TotNO_2$	Zonal bands for $StratNO_2$ Polluted conditions (anthropogenic) Presence of natural emissions (e.g. biomass burning) Clean conditions Partly cloudy conditions Information about diurnal cycle Near arctic vortex Horizontal gradients on the order of satellite pixel Validation collocated with aerosol profile information
$TotSO_2$	Global covering degassing and eruptive volcanoes. Regions with significant SO_2 pollution Long time series Covering all seasons
TotHCHO	Validation in the tropics Validation in temperate forests and boreal forests Sub-urban environment Urban areas Global validation Validation of the seasonal and diurnal cycle Long-term validation

2 Distribution of stations and target species

2.1 O_3

The highest proportion of atmospheric O_3 is formed by chemical cycles in the stratosphere involving oxygen molecules and UV radiation. The global (spatial) distribution of stratospheric O_3 is mainly determined by the so called Brewer-Dobson circulation, leading in general to a lower column density around the tropics and a maximum at mid- to high latitudes, with a seasonally varying component.

For the validation of stratospheric O_3, a good coverage of all latitudes is important. In addition, special regions of interest are the high latitudes, in particular the antarctic region, where the so called Ozone hole appears every year ([4]) as a result of (photo)chemical reactions involving, in particular, chlorofluorocarbons from anthropogenic emissions.

Tropospheric O_3 is mainly driven by photochemical reaction cycles, involving NOx, CO, CH_4 and VOCs. This can lead to high O_3 amounts near the surface, especially in summer and in regions with intense UV radiation. So for the tropospheric O_3 validation, polluted regions in the tropics are very interesting, especially in regions with large emissions from natural and anthropogenic sources ([5]).

Fig.2 shows the distribution of official PGN instruments in latitudinal bands. Very clearly, the majority of PGN stations are located around 30° and 50° in the northern hemisphere.

In order to improve the validation range regarding O_3, the focus for new PGN sites would be the tropics and the southern hemisphere to fill the gaps in the latitude bands. For validating stratospheric O_3, remote sites would be preferable. More urban sites in the tropics would be valuable for tropospheric O_3 validations due to the presence of precursors from pollution and biomass burning.

2.2 NO_2

NO_2 is an important trace gas as an indication of anthropogenic and natural combustion and plays a key role in various (photo)chemical processes in the atmosphere, both the troposphere and the stratosphere. For the latter, clean background stations are used for validation being either at high elevations above the polluted boundary layer or at high latitudes. A global coverage of background validation locations is of advantage due to the different stratospheric amount of NO_2 for different latitudes. For the validation of tropospheric NO_2, highly polluted regions and also areas with high variability like (sub-)urban locations are important. Finally, regions with high natural emissions like biomass burning are interesting.

Fig.3 shows the global average NO_2 distribution (total column density) measured from TROPOMI. Included are all PGN stations, both official and unofficial. Background stations are highlighted by Pandora ID and station name.

With respect to NO_2 it looks like the network covers all major types of conditions. Background stations cover a wide range of latitudes from the southern hemisphere to the arctic region. All other sites range from sub-urban locations (e.g. GreenbeltMD, BoulderCO, Innsbruck), urban locations (Rome-SAP, OldFieldNY) to extremely polluted sites like Seoul-SNU or Beijing.

For improving air quality monitoring / satellite validation, the focus for new sites could be bigger cities in northern India and China but also the growing metropolitan areas in Africa, such as Kinshasa (Kongo), Lagos (Nigeria) or Nairobi (Kenya).

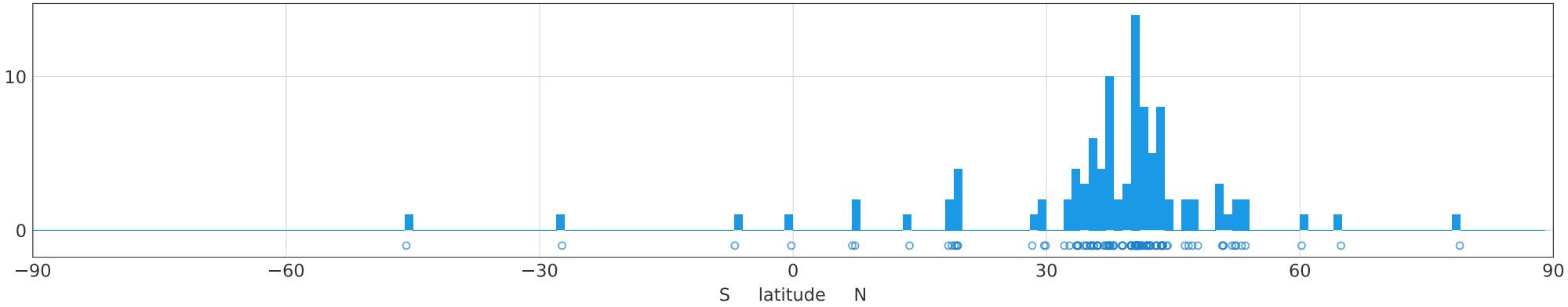
2.3 SO_2

Global SO_2 sources are both anthropogenic (coal power plants, mines, oil industry) and natural (volcanoes). Highest concentrations are mostly found in the troposphere and have a high spatial variation which poses a challenge for validation. Except for polluted hotspots, typically the SO_2 column densities are below the detection limit of the satellite (between 0.3DU and 0.5DU SCD, see [7]).

In special events, during exceptional volcanic eruptions, high SO_2 concentrations are emitted into the stratosphere where spatially more homogeneous layers may be transported over intercontinental distances and be detectable for several months.

The global SO_2 distribution (from -51°S to 72°N latitude) is shown in Fig.4. Data source for volcano locations is the Global Volcanism Program and only volcanoes

Figure 2: Latitudinal coverage of the official PGN stations. Distribution of site latitude in 1° bins, open circles for each instrument below.



which had a documented eruption in the past 500 years are shown. Regarding anthropogenic emissions, it is interesting to note the difference to the NO_2 distribution in Fig.3.

So most PGN sites are located in low SO_2 environments but some interesting sites for SO_2 validation are highlighted. Mauna Loa, Izana, Altzomoni and Bandung are situated in close vicinity to (potentially) active volcanoes and periods with particularly high SO_2 concentrations may be found in the data sets.

Wakkerstroom in South Africa (and Potchefstroom, unoffical site) is situated near coal power plants and, depending on wind conditions, often shows high SO_2 concentrations.

So for improving validation opportunities, possible future sites could be located around the industrial areas on the Persian Gulf or in northeastern India in the area of the large coal power plants. Otherwise, sites close to continuously active (degassing) volcanoes or fumaroles are always potentially interesting. Most prominently in Europe, this would be the area around Etna or Stromboli.

2.4 HCHO

HCHO plays a key part in atmospheric chemistry and its pathways into the atmosphere are manifold and include oxidation of VOCs, higher NMVOCs and CH_4 ([3], [6]). Emissions are both natural (biogenic emissions and biomass burning) and anthropogenic (industrial).

An overview over the global average HCHO distribution is shown in Fig.5, which again also includes the PGN locations. Elevated HCHO concentrations are notably observed in the tropical forest regions resulting mainly from biogenic emissions and (seasonal) biomass burning. On the other hand, mainly industrial emissions lead to the exceptional concentrations in India and China.

So regarding the validation of HCHO, only few stations are located in high concentration areas (e.g. Islamabad, Pan73) and considerable gaps in the current PGN exist with respect to these regions. Most specifically, central Africa, the Amazon region in South America, India and China would be valuable locations.

Figure 3: Global average NO2 distribution from TROPOMI. Data courtesy I.de Smedt, BIRA. PGN stations are shown as blue circles, background stations are indicated by instrument ID and name.

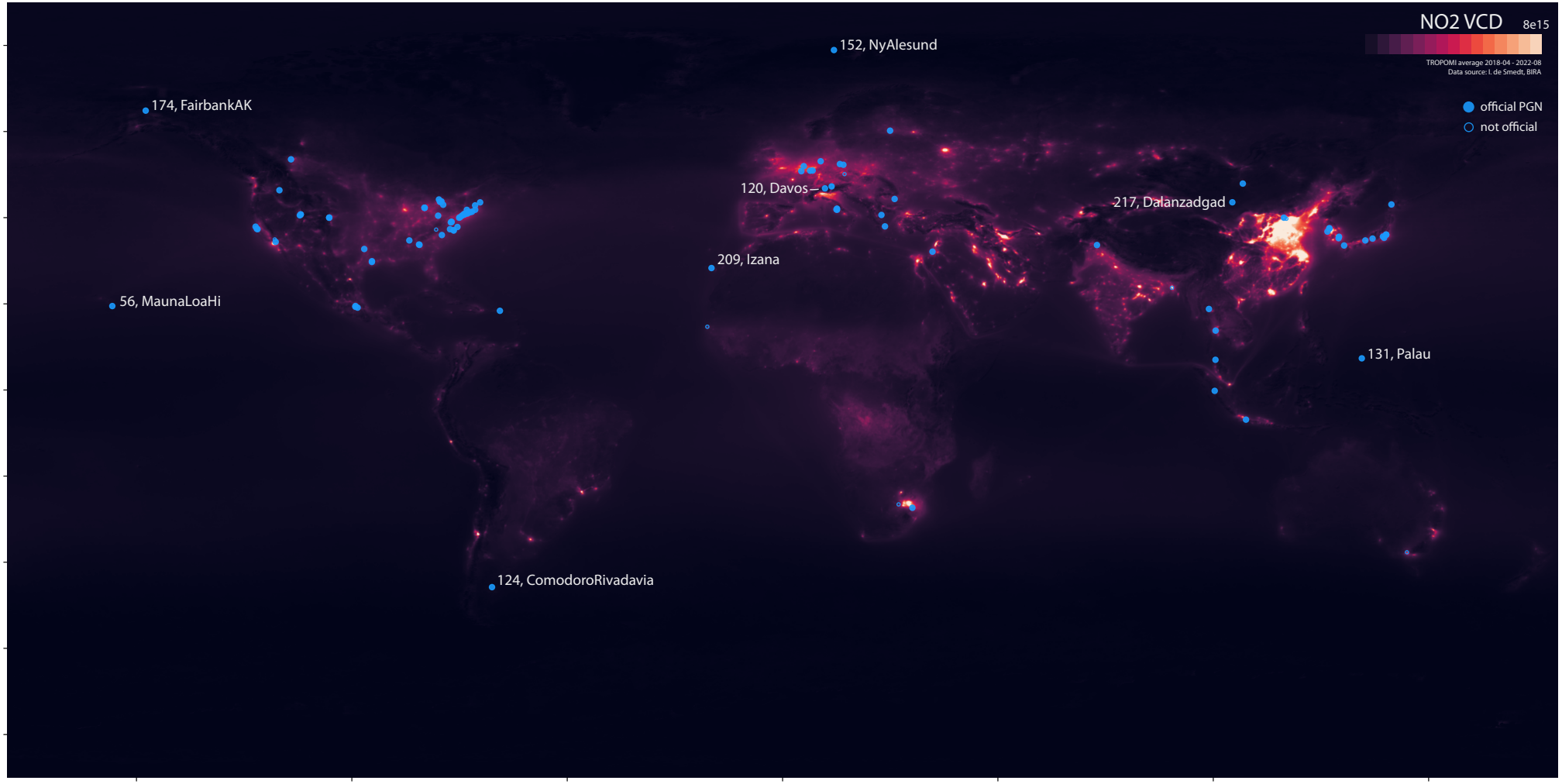


Figure 4: Global average SO2 distribution from TROPOMI. Data courtesy N.Theys, BIRA. Also shown are PGN locations and volcanoes.

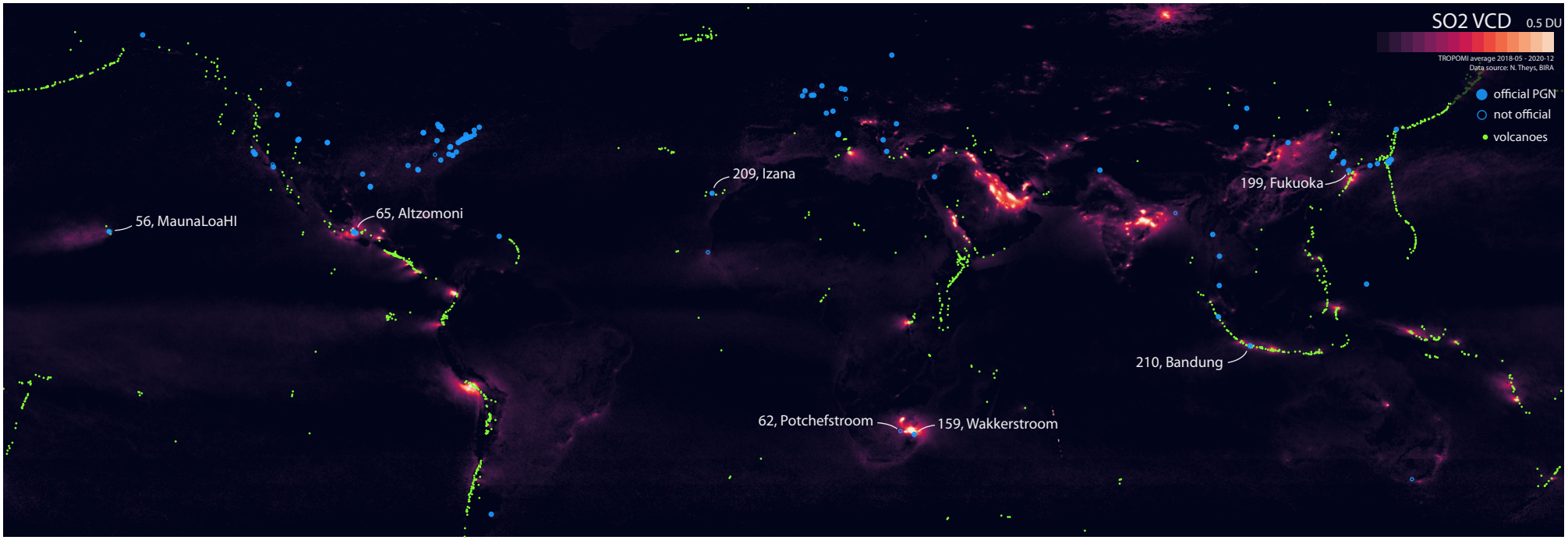
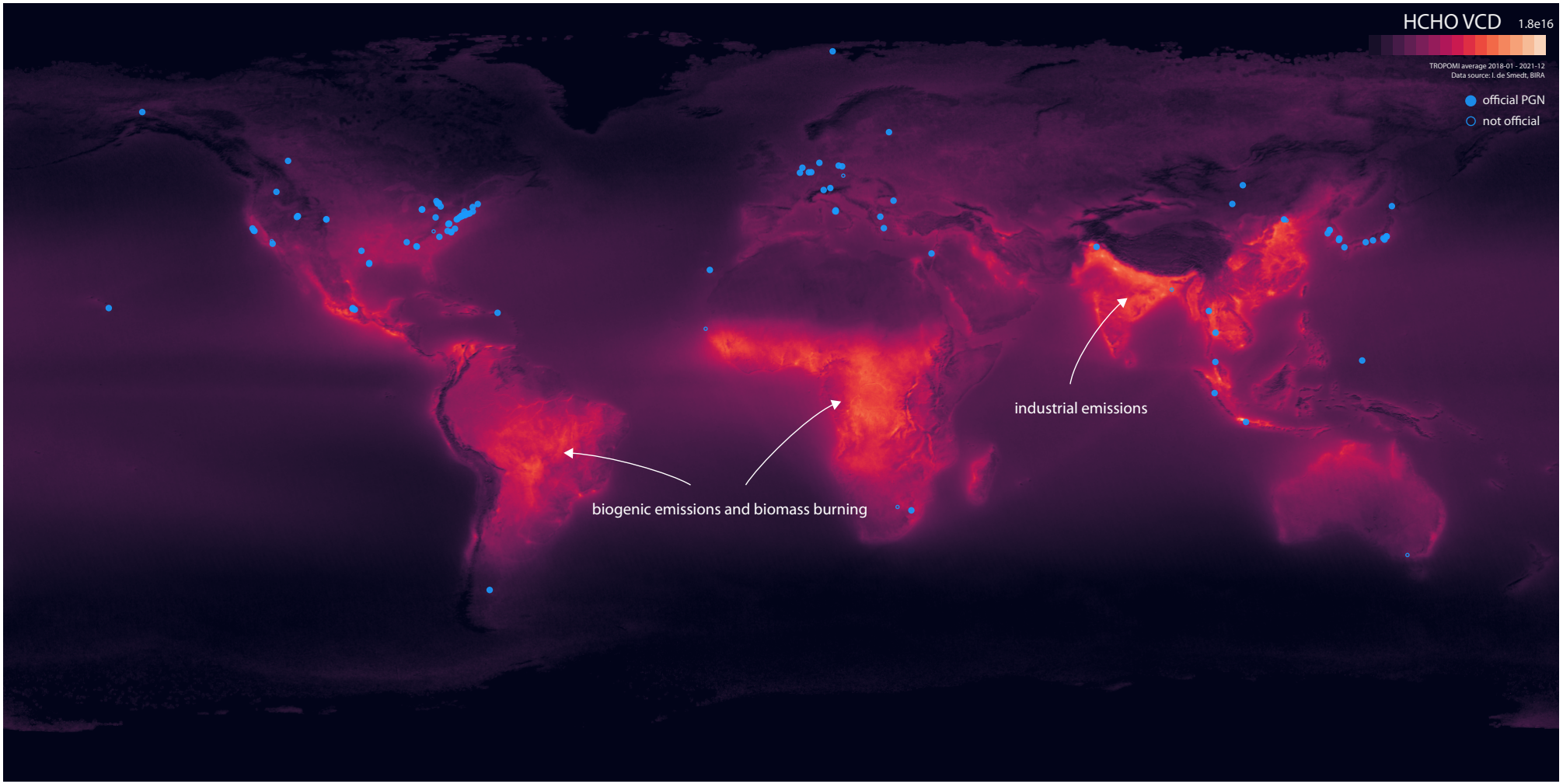


Figure 5: Global average HCHO distribution from TROPOMI. Data courtesy I.de Smedt, BIRA



3 Summary

In the past year, again the number of official PGN instruments has increased substantially, from 90 to 131. However, it becomes evident, and to no surprise, that most new instruments are deployed for the dedicated support of the geostationary satellite missions Sentinel-4, TEMPO and GEMS over Europe, North America and Southeast Asia, respectively.

Hence large regions remain uncovered by PGN network sites for monitoring air quality or atmospheric trace gases in general and validating Low Earth Orbiting (LEO) satellite missions, such as TROPOMI.

A particularly interesting region is central Africa. Metropolitan areas in Africa feature one the highest grow rates, the population of e.g. Kinshasa (Kongo) and Lagos (Nigeria) have exceeded 15 million in 2022. Besides air quality (NO_2 and tropospheric O_3), the tropical region also has dense vegetation, i.e. intense biogenic emissions and seasonal biomass burning (HCHO) that would be valuable to monitor / validate. Also these latitudes are interesting for stratospheric O_3 measurements. In fact, South America and the Amazon region feature similar conditions, however without the high population densities and growth.

Furthermore, there are gaps for sites to be filled in the regions of the world's highest anthropogenic emissions. Northern India and China would be locations to measure NO_2 and HCHO, while for SO_2, the Persian Gulf region would be the most interesting.

Finally, the high latitudes are among the suggested sites because of the regions' high sensitiveness to climate and atmospheric changes, stratospheric ozone depletion have been one of the most prominent examples.

Table 2 gives suggestions for possible future PGN stations for the species of interest.

Table 2: Suggestions for future Pandora locations. Listed areas are currently underrepresented and of interest.

Product	General suggestion	Detailed suggestion
O_3	Tropics: polluted and remote areas Latitudes above 60°	Central Africa South America Arctic region and Antarctica
NO_2	Tropics: polluted and remote areas Cities with latitude above 60° Remote stations in the temperate zones	Central Africa South America Southeast Asia Cities in Canada, Scandinavia Mountain stations (e.g. Jungfraujoch, Zugspitze)
SO_2	Strongly polluted areas near mines, oil and coal industry Areas with active volcanoes	north east India Persian Gulf region Mt. Etna
HCHO	Tropics, Industrial areas in Asia	Central Africa Amazon region India eastern China

Figure 6: Regions currently underrepresented by PGN sites.