P1.1-035

Air Quality Impact on the Sampling Possibilities of the International Monitoring System Radionuclide Stations

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INTRODUCTION AND MAIN RESULTS

The IMS radionuclide stations monitor low layers of atmosphere for radioactive particles through daily filtering of the ambient air with filters of high efficiency. As a backside of the designed capturing capability, poor air quality causes filter clogging and limits sampling effectiveness. The study analyses effect of external factors on sampling performance of particulate radionuclide stations in several world regions.

This presents indicative cases of the interrelation between the above factors and the performance of IMS radionuclide particulate stations during routine operation.

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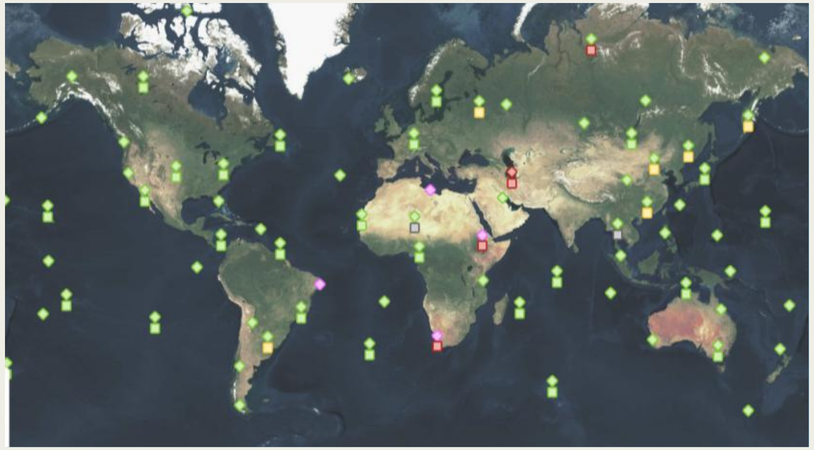
1. Introduction

The International Monitoring System (IMS) developed by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is a global system of monitoring stations, which spans the globe using more than 300 facilities distributed among four complementary technologies: seismic, hydroacoustic, infrasound and radionuclide.

IMS seismic stations monitor shockwaves through the ground; its hydroacoustic stations detect sound waves in the oceans; infrasound stations listen for ultra-low-frequency sound waves inaudible to the human ear; and radionuclide stations monitor the atmosphere for radioactive particles and gases from a nuclear explosion.

(IMS Stations map. Source: ctbto.org)



(IMS Radionuclide Stations map. Source: dotsx.ctbto.org)

Radionuclide technology is complementary to the three waveform technologies used in the CTBT verification regime, and the only one that can confirm whether an explosion detected and located by the others is indicative of a nuclear test.

The radionuclide network comprises 80 stations, of which more than 70 are certified, enables a continuous worldwide observation of aerosol samples of radionuclides. The network is supported by 16 radionuclide laboratories with expertise in environmental monitoring, providing independent additional analysis of IMS samples.

1.1 IMS RN Monitoring Stations

The 80 radionuclide stations sample air particulates to measure radioactivity; 40 of these also measure xenon gas levels. The equipment's technical specs, station distribution, and number were designed to detect nuclear explosions with a 90% probability within 14 days for a 1 kt detonation in the atmosphere or vented from underground or underwater.

Particulate stations cycle through 1-day collection, 1-day decay, and 1-day acquisition, while noble gas stations have 1-day collection and 1-day acquisition.

Each particulate station uses a high-volume air sampler (flow rate ≥500 m^3/h at standard conditions) and a HPGe detector system with at least 40% relative efficiency.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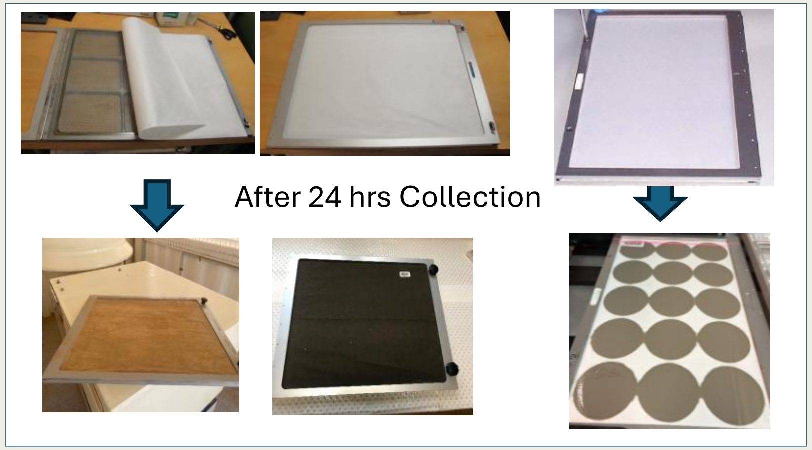
1.2 ATM Modelling



Air is forced through a filter, which designed to capture more than 80% of particles with a diameter larger than 0.2 μm that reach it.

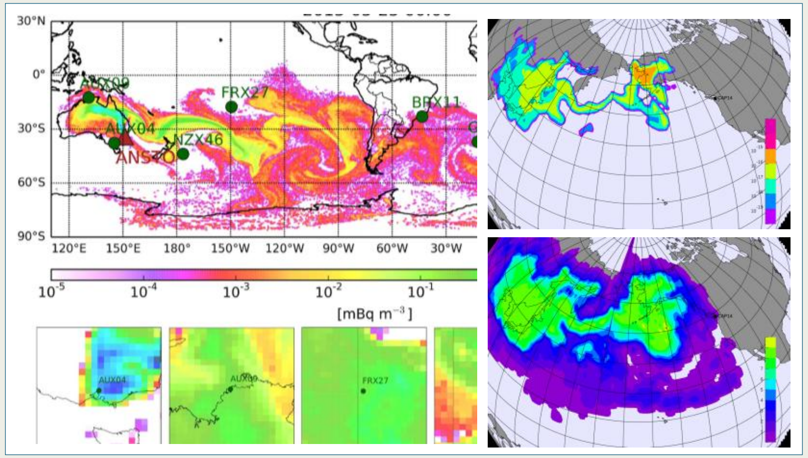
Although the filters of the manual radionuclide IMS stations are replaced daily, high efficiency of the filters has its downside as well: poor air quality can diminish sampling efficiency by decreasing the amount of ambient air pumped through the filter material, consequently impacting the analyzed totals volume of the sample and detection sensitivity.

Elevated levels of dust, smoke, or other particulates accelerate filter clogging, reducing the sampler's efficiency and potentially obscuring radionuclides.

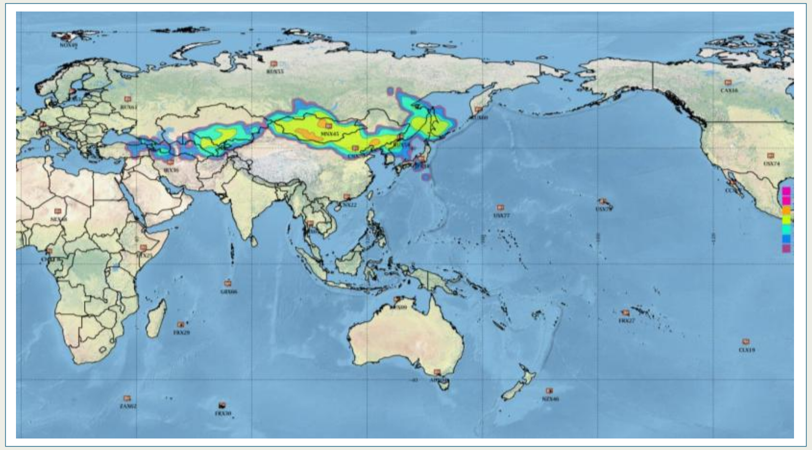
In case of the RN technology, the motions of the atmosphere govern the propagation of the signal. This makes it inherently impossible to locate an RN signal as precisely as a signal recorded by the waveform technologies.

To enhance IMS RN network detection possibilities, an advanced Atmospheric Transport Modelling (ATM) system is being installed at the IDC. This system facilitates the attribution of source locations for RN measurements in cases of treaty-relevant detections, providing a crucial geo-temporal location capability for the RN technology.

To identify the potential source of the CTBTO relevant



(WEB-GRAPE application for visualization of ATM. Source: webgrape.ctbto.org)



(IMS Radionuclide Stations map. Source: dotsx.ctbto.org)

radionuclides, the ATM model is used in backward mode. In the backward mode the potential source contributions for given receptors are determined based on simulations backward in time. To enable visualisation of the ATM outputs and identification of possible source areas of RN detections at IMS stations, the International Data Centre (IDC) has designed and developed the Web-connected graphics engine (Web-Grape) software.

Using global meteorological data and ATM, the three-dimensional travel paths of radionuclides can be traced from a measurement station back to their origin. This source region attribution identifies the release area that best matches the observations.

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1.3 What impacts efficiency of the sampling?

Over the past 10 years, several main factors have contributed to the increase in air pollution levels, including industrial emissions, transportation, wildfires, dust storms and agricultural activities. But how the air pollution is applicable to efficiency of sampling of the RN IMS stations? The factors above are a source of particles with sizes spanning five orders of magnitude from ~0.001 μm to > 10 μm in diameter.

Source Category	Approx. Global % of $PM_{2.5}$ Mass
Anthropogenic combustion (industry, energy, traffic, residential)	~50 – 60%
Natural mineral dust (desert/soil)	~15 – 20%
Wildfires / open biomass burning	~4 – 5%
(Other natural sources like sea salt, vegetation organics not detailed here)	Remainder (10–25%)

Approximate share of PM2.5 sources worldwide

The fine particulate matter (PM2.5) in the atmosphere considered as a critical pollutant due to its health impacts. Simultaneously, particles with diameter larger than 0.2 μm are collected by a filter of the RN IMS Stations with ≥ 80% probability by its design.

The relationship between filtration efficiency, particle size, and flow rate is complex. From a radioactivity measurement perspective, increasing sensitivity by using a larger sample volume may actually reduce sensitivity. This is because fine particles of interest can penetrate the filter, and higher flow rates can decrease efficiency by causing the filter to capture smaller particle sizes. Additionally, high humidity and rainfall can disrupt radionuclide dispersion patterns, making it more difficult for sampling stations to accurately determine the source and concentration of airborne particles.

The arrows on the graph below indicate an assumed direction of change with time, and width indicates relative fractions.

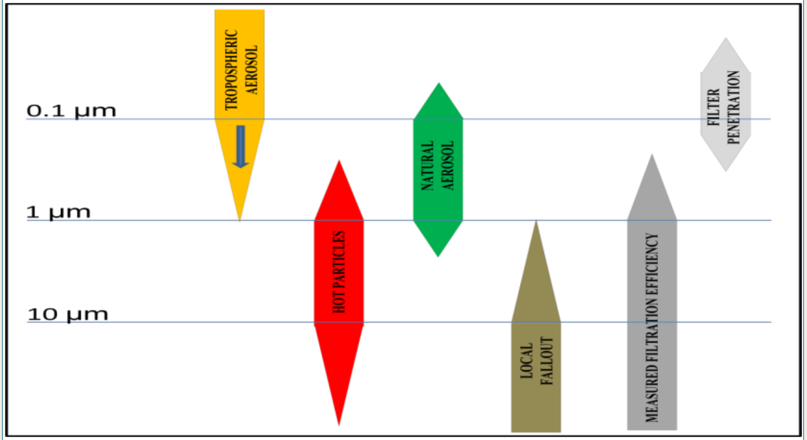
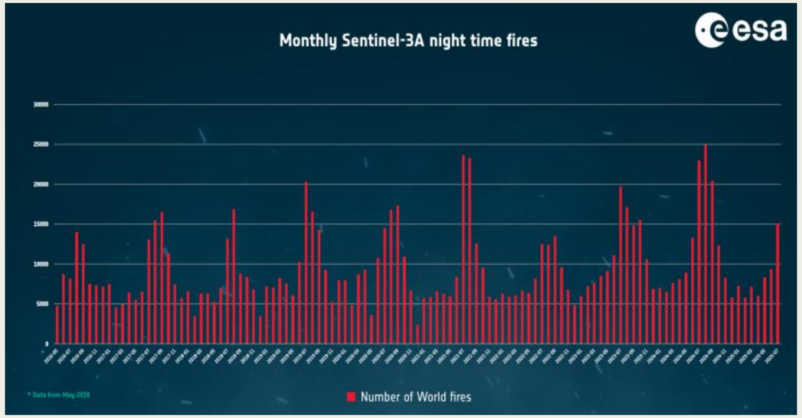


Illustration of the particles size corresponding to its origin

1.4 Accumulated filter aerosol load

Past years of operation, clearly demonstrated that the two main contributors to the accumulated filter aerosol load are the open biomass burning and natural mineral dust events.

While wildfires are a natural part of many ecosystems, scientists have warned that wildfires are becoming more frequent and more widespread (ESA).



From the sand and dust events side, their number is increasing globally, with a 31% rise in the number of people exposed to harmful dust levels between 2018–2022. This increase is linked to factors like drought, poor land management, and climate change, which together create a "perfect storm" for intensified dust activity worldwide (WMO).

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2. Applied Methods

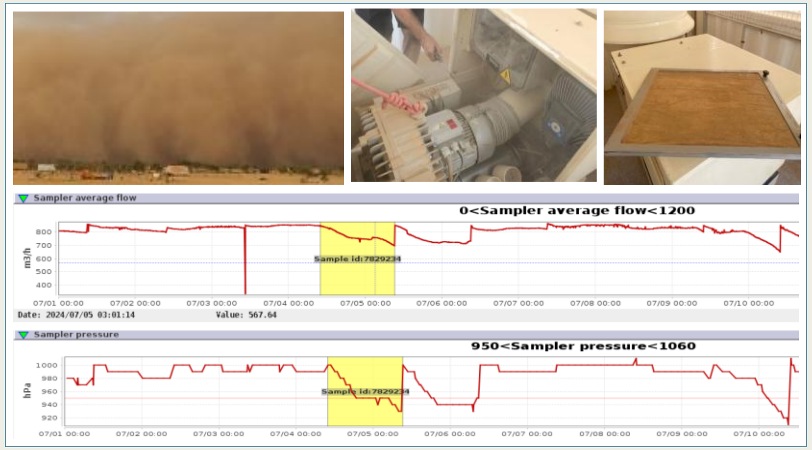
According to the minimum requirements for particulate monitoring system, the airflow of the sampler of any types of the systems should not be less than 500 m^3/h. The Collection time is 24 hours with allowed uncertainty up to 10% (CTBT/WGB/TL-11,17/18/Rev.7). Which turns into the minimum sampling time for the particulate RN stations as 21.6 hours (24 hours - 2.4 hours). For the purposes of the study only the spectra categorized by the IDC (having category within the Reviewed Radionuclide Report) were used. Therefore, the low limit of the sampling time is taken as 12 hours.
The total sampling volume and the average sampling flow (ASF) are related through the collection time as follows:

Total Sampling Volume/Sampling Time = ASF

According to the above, the boundaries for listing the samples chosen for the study are:

12 hours ≤ Sampling Time ≤ 21.6 hours
6000 m^{3*} ≤ Total Sampling Volume ≤ 10800 m^3

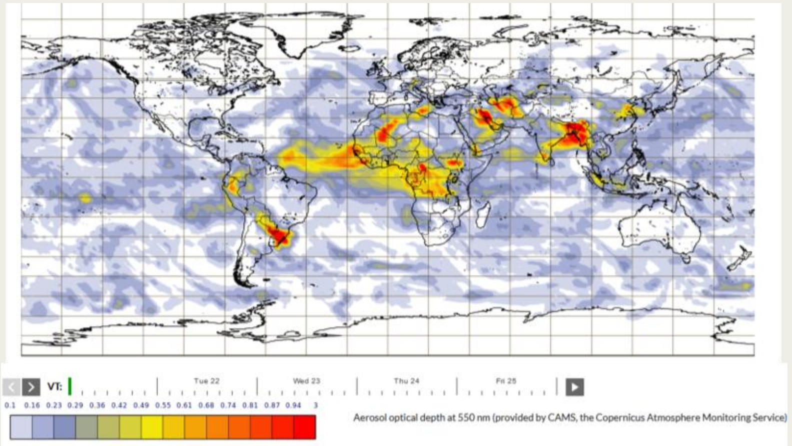
After the list of more than 11000 samples was identified, another round of screening was done to remove outliers where the reduced sampling volume was caused by unrelated reasons.



Immediate effect on the sampling flow and pressure, July 2024.

In order to compare the sampling volume of the unaffected samples against those experienced filter clogging, the average sampling flow of each particular station in normal conditions (for manual stations closer to 800 m^3 /h), and the average flow over one-year periods (2020-2024) were mapped.

It should be also mentioned that the clogged filter material does not only affect the results of the samples' measurement through the reduced volume of collected air, but also by influencing geometry of the end sample (i.e., its thickness) and introducing additional uncertainty of the debris collected by the filter. In case the filter container is not completely sealed due to non-standard geometric parameters of the compressed sample, the chain of custody established by the PTS should also be considered.



Aerosol optical depth at 550 nm (CAMS)

The specific sandstorms or wildfire events were linked to the series of affected samples using the CTBTO Web-Grape Internet Based Service (IBS) tool. The backward mode, which designed to identify possible sources of the treaty-relevant detections was used to match the list of the samples having the lowered sampling flow meanings to the known sources of PM1-PM10 matter (e.g. wildfires, desert areas, construction works, etc.) more precisely. The particles trajectory simulations were limited by 14 days.

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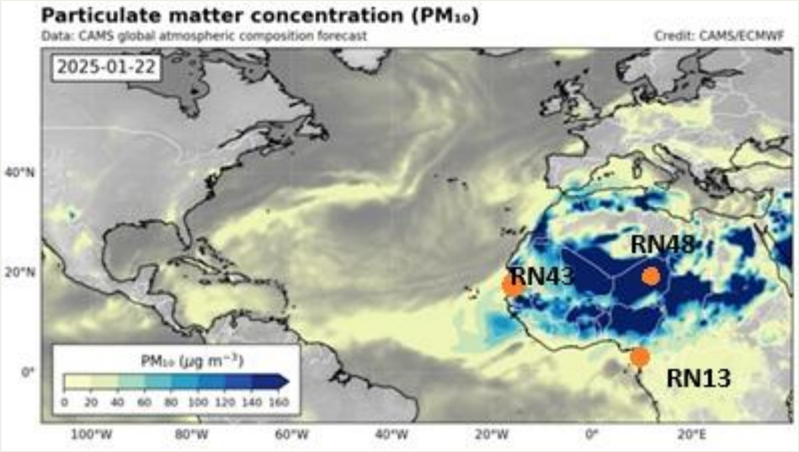
3. Collected Data

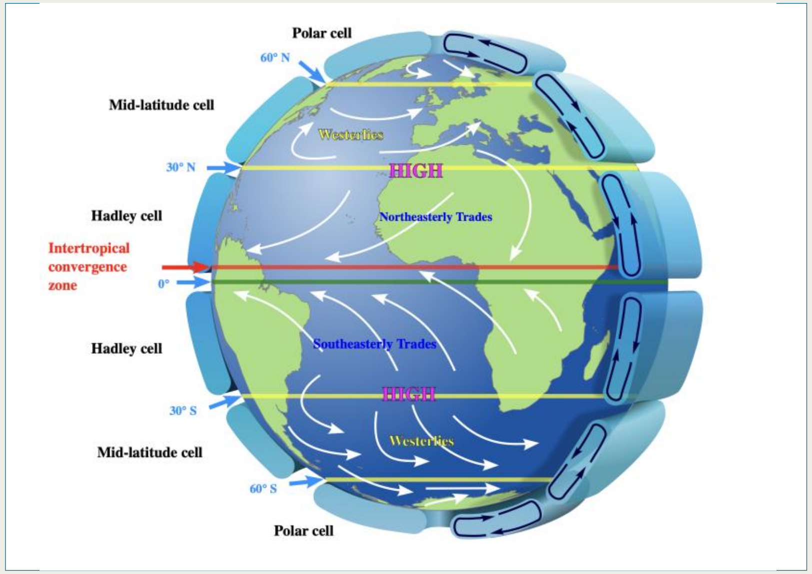
One of the examples of the sources of a natural origin affecting not only the sampling of the RN IMS stations but also having a significant impact on human health is Saharan dust releases. Strong winds, driven by the Saharan Air Layer (SAL), loft massive amounts of dust from North Africa and carry it across the Atlantic Ocean to regions like the Caribbean, Gulf Coast, and even Europe and South America.

The IMS Stations first met on the way of the sandstorms originated in Sahara desert are RN48 (Agadez, Niger) RN13 (Edea, Cameroon), RN40 (Kuwait city, Kuwait) and RN43 (Nouakchott, Mauritania).



CAMS global atmospheric composition forecast (CAMS/ECMF)

Due to its location within the intertropical convergence zone, RN13 experiences relatively lower effect from the Saharan dust releases.



The intertropical convergence zone (Astro EDU)

The number of the categorized samples, with the total sampling volume significantly decreased because of the filter clogging is less than 30 cases for the last 5 years (or approximately 1,6% of the total number of samples.

In contrast, the IMS stations RN48 and RN43 are on the main stream of SAL, directed from northern Africa over the Atlantic Ocean. The number of categorized samples from these stations which demonstrate decreased total sampling volume comparing to normal operation is as follows:

Station	2020	2021	2022	2023	2024
RN43 (P)	106	112	83	31	24
RN48 (P)	136	144	175	210	195
RN40 (P)	8	16	36	5*	6*

*RN40 recapitalized in 2023, installing a new RASA system

Similarly, the particulate stations RN21, RN45 and RN20 (more remote) which are located in the area of Gobi Desert, were strong winds carry a large dust plume over Mongolia and into China.

Station	2020	2021	2022	2023	2024
RN20 (P)	3	6	3	11	2
RN21 (P)	17	35	14	22	11
RN45 (P)	13	8	3	4	12

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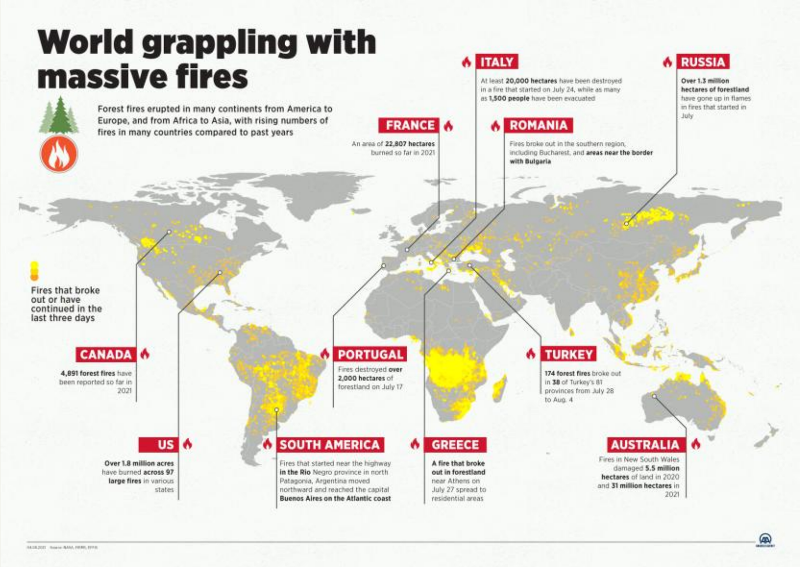
3. Collected Data (cont.)

Over the last five years a series of severe wildfires swiped across the globe.

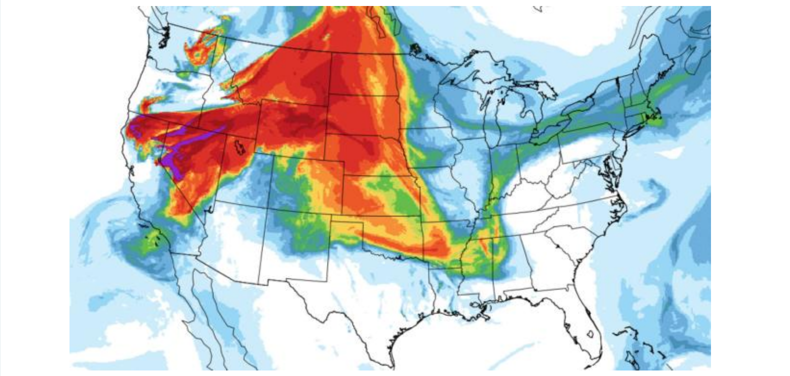


In North America, Canada experienced its worst wildfire season in 2023, burning 46 million acres and emitting nearly 2 billion tones of CO_2. The 2024 Jasper wildfire caused massive destruction, while the 2023 Maui fires in Hawaii caused billions in damages. In South America, Chile's 2024 wildfires destroyed thousands of buildings and caused multi-billion-dollar losses. Brazil also recorded unprecedented Amazon fires in 2023–2024, with activity nearly 850% higher than the previous year.

In Europe, Greece lost over 125,000 hectares to fires in 2023, Tenerife burned 15,000 hectares in its worst blaze in 40 years, and Madeira saw 5,100 hectares lost in 2024. In 2025, the EU faced its worst fire season on record, with over 1 million hectares burned. In Africa and Asia, while wildfires occurred, few reached the scale of declared natural disasters in this period. These events underline the escalating scale and frequency of wildfires globally. The wildfires / open biomass burning is one of the main contributors not only the CO2 emission, but also to PM2.5 pollution. As it was shown on a page 3, the filters of the IMS particulate stations are especially efficient for capturing fine (0.1 – 2.5 μm) and coarse (2.5 – 10 μm) particles.

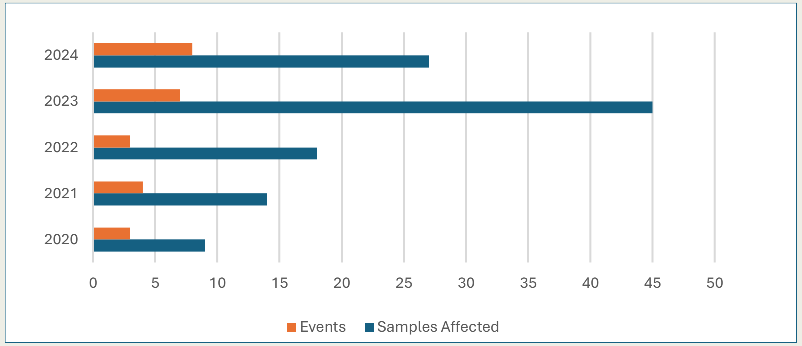
Wildfire intensity is growing - with larger areas burned, more frequent catastrophic events, and higher emissions. This is driven by a sum of factors as rising temperatures, prolonged droughts, land-use changes, climate feedback.

As the radionuclide IMS stations distributed evenly across the continents, the impact on the sampling rate can be identified for a wide range of geographical locations: Australia, Canada, Russia, United States and others.



Wildfires tracing across North America (NSCO)

The significance of the ash and smoke impact (excluding the cases when the operation of facilities was completely stopped) is illustrated by the graph below.



The visible trend is a complex result of interconnected producers of fine and coarse particles and yet require thorough study.

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4. Indicative Observations

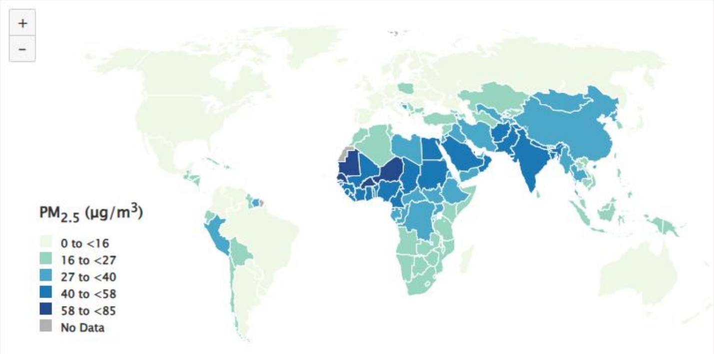
The International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) uses over 300 stations worldwide to detect signs of nuclear explosions. Among them, 80 radionuclide stations monitor radioactive particles in the atmosphere, with 40 also measuring xenon gas. These systems are designed for high sensitivity, but their performance can be compromised by environmental factors such as wildfires, desert dust, industrial emissions, and urban pollution.

Each particulate station forces air through high-efficiency filters, capturing over 80% of particles larger than 0.2 µm. While effective, these filters are vulnerable to clogging when air is saturated with fine particulate matter ($PM_{2.5}$ and PM_{10}). Clogging reduces airflow, lowers sampling volumes, and can obscure radionuclide signals. Over the past five years, more than 70 filter-clogging events were reported, averaging nearly 6 days per station where sampling volumes fell below required thresholds.

Each particulate station forces air through high-efficiency filters, capturing over 80% of particles larger than 0.2 µm. While effective, these filters are vulnerable to clogging when air is saturated with fine particulate matter ($PM_{2.5}$ and PM_{10}).

Clogging reduces airflow, lowers sampling volumes, and can obscure radionuclide signals.

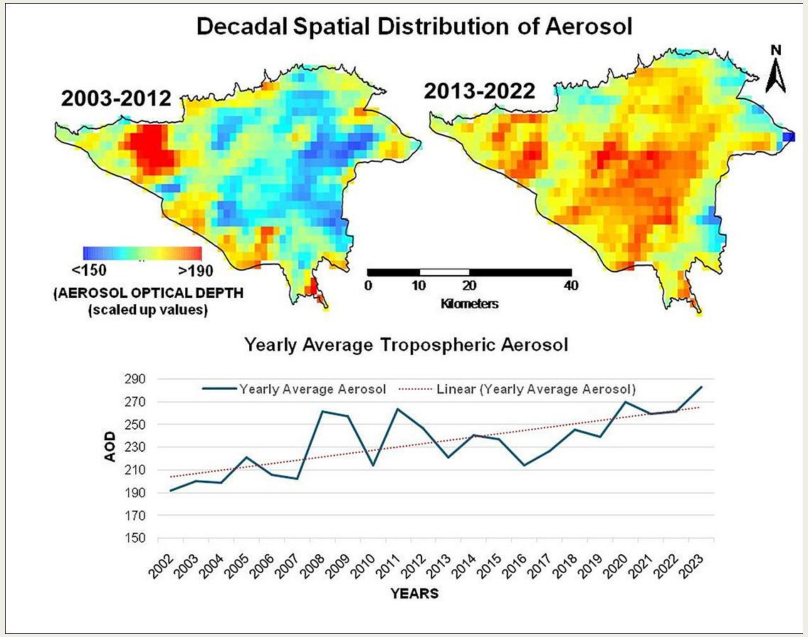
The growing intensity of wildfires is a documented global trend. Rising temperatures, prolonged droughts, land-use changes, and climate feedback loops have extended fire seasons and increased their severity. The implication for IMS operations is clear: as air quality events worsen, radionuclide sampling interruptions will become more frequent.



To mitigate these challenges, IMS employs Atmospheric Transport Modeling (ATM), enabling backward trajectory analysis to identify whether reduced sampling volumes align with known pollution events such as fires or dust storms. This allows better attribution of anomalies and ensures reliable treaty verification

In conclusion, while IMS radionuclide stations remain a cornerstone of nuclear test detection, their efficiency is increasingly influenced by global air quality trends.

Addressing filter clogging and improving sampling robustness in the face of climate-driven wildfire activity and desert dust transport will be critical to maintaining the integrity of the verification system.



Spatio-temporal modeling of PM2.5 risk mapping (Science Direct)

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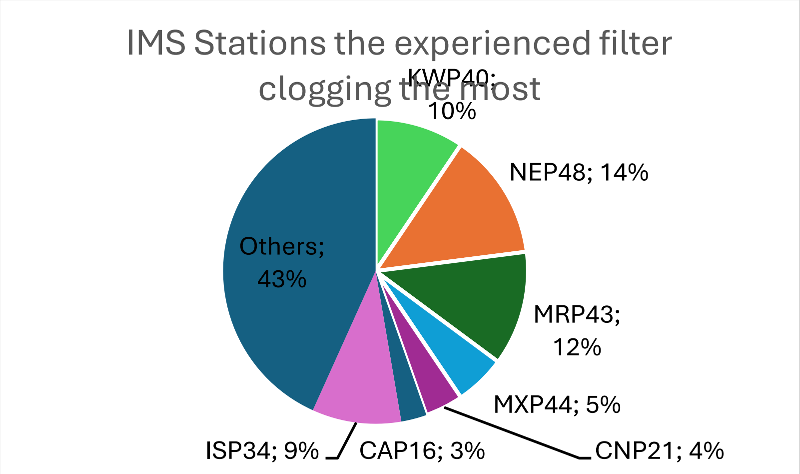
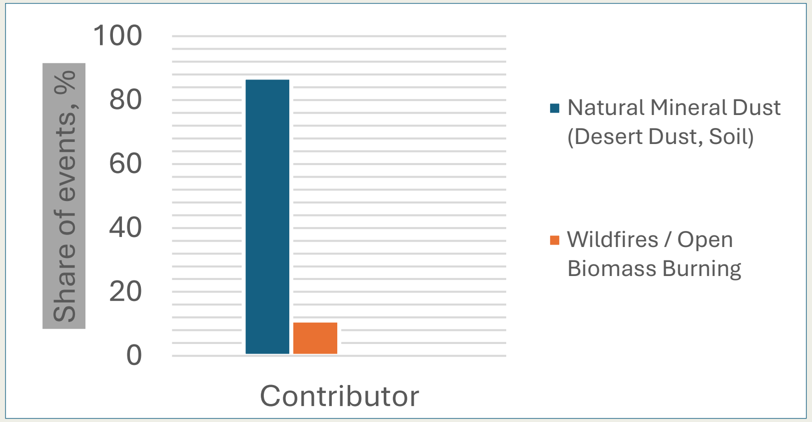
5. Conclusions

Over the last five years, more than 70 reports received from the Operators regarding significant impact of the filter clogging with an average of 5.94 days of the filters collected with lower flow rate per affected station.



It is important to note, that the relative number of events does not always reflect the number of affected samples. For example, CAP16 has not the biggest number of the identified event, at the same time, the station operation was stopped in August through October 2023 due to intensive forest fires in Yellowstone region.
Another example of the effect on sampling through filter clogging are seasonal dust storms over Reykjavik, which cause accumulation of significant amount of dust and on the filters of ISP34.

It is possible to approximately group the major factors of the air pollution based on global PM2.5 contributors as shown on page 3. At the same time, the statistics gathered throughout the work shows contradiction between the global PM2.5 share breakdown and the distribution of root causes of the filter clogging.



This is because PM2.5 levels don't directly match filter clogging because filters collect a controlled air sample, not all particles. PM2.5 is measured by mass in air (µg/m³), not how dirty the filter looks. Larger particles or humidity can clog filters without affecting PM2.5 readings. So, clogging isn't a reliable indicator of PM2.5 pollution and vise versa. At the same time, satellite imaginary is a great help in identifying filter clogging contributors using optical aerosols mapping.

In order to evaluate the impact of the air pollution on the performance of the IMS radionuclide stations, authors analysed more than 10000 samples to identify those affected by filter clogging and experiencing reduce of the total sampling volume. The data is analyzed using comparison of the sampling flow in normal conditions and under effect of studied event. The source regions of the filter clogging were visualized with a help of the CTBTO atmospheric transport modelling (ATM) web-Grape internet-based service (IBS).

The purpose of the work was to examine the main mechanisms by which air quality can affect the sampling capabilities of the IMS radioactive particle stations. In particular, it focuses on the effects of suspended particulates, noxious gases and weather conditions on the various stages of the monitoring process, from sample collection to laboratory analysis.

The topic becomes increasingly important due to growing air pollution caused by multiple reasons and requires further study and more comprehensive assessment of the dynamic over extended time periods.

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Note of thanks

The presentation includes only a brief overview of the study done on the important topic of the air quality impact on the sampling possibilities of the international monitoring system radionuclide stations. The comprehensive sets of the data, which were used for statistical analysis will be available in the related article, which is yet work in progress.

As a co-author, I would like to extend sincere gratitude to, Leslie Mercedes TCHEKOUNANG NJILA, for her generous and tireless contribution to the preparation of this presentation.

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