

# Early warning system of natural hazards and decrease of climat impact from aviation

ALARM funded project

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**Abstract**— Aviation safety can be jeopardised by multiple hazards arising from natural phenomena, e.g., severe weather, aerosols/gases from natural hazard, and space weather. Furthermore, there are the anthropogenic emissions and climate impact of aviation that could be reduced. To mitigate such risk and/or to decrease climate impact, tactical decision-making processes could be enhanced through the development of multi-hazard monitoring and Early Warning System (EWS). With this objective in mind, ALARM consortium has implemented alert products (i.e., observations, detection and data access in near real-time) and tailored product (notifications, flight level — FL contamination, risk area, and visualization of emission/risk level) related to Natural Airborne Hazard (NAH, i.e., volcanic, dust and smoke clouds) and environmental hotspots. New selective detection, nowcasting and forecasts of such risks for aviation have been implemented as part of ALARM prototype EWS. This system has two functionalities. One is to provide alerts on a global coverage using remote sensing from satellites and models (focus on

NAH, space weather activity and environmental hotspots). A second focuses on detecting severe weather and exceptional SO<sub>2</sub> conditions around a selection of few airports, on providing nowcasts and forecasts of risk conditions.

**Keywords-component:** *early warning, volcanic ash, SO<sub>2</sub>, dust, smoke, space weather, severe weather, climatic hotspots.*

## I. INTRODUCTION AND MOTIVATION

Hazardous clouds can very often be a considerable threat to human society for the life, health and properties of a population, especially for aviation. Such threats requires Air Traffic Flow Management (ATFM) which needs well-implemented process exhibiting good collaboration between all involved stakeholders. Timely estimate of capacity shortfalls (typically

driven by potentially unsafe situations) enables the Network Manager (NM) to consider a portfolio of capacity management solutions to address imbalances with minimal impact on the network. However, vulnerabilities always exist when dealing tactically with disturbances that are difficult to foresee strategically (especially those due to atmospheric behaviour). Thus, tactical decision-making processes could be enhanced through the **development of multi-hazard monitoring and Early Warning System**, including the following phenomena (as a main goal of ALARM project and illustrated in Figure 1):

- **Severe weather conditions** create major challenges for the ATM system. Flying through a thunderstorm entails multiple risks (strong turbulence, wind shear, downbursts, icing, lightning and hail). Low predictive capability of these events has led to an abundance of regulations being issued on short notice. With climate change on the rise, the weather is expected to have a larger impact on aviation [1]. In the last year alone, the frequency of storms, winds and rainfall has not only increased [2][3][4], they have become more intense wreaking havoc on the ATM network.
- **Aerosols / gases from natural hazards**, i.e., fire smokes, desert dust or volcanic ash and SO<sub>2</sub> plumes. They are not so frequent as severe weather; however, their effects can be extremely disruptive [5]. Dense smoke clouds from wildfire and dust/sea salt loaded areas in low altitude drastically reduce visibility, they are also associated with very strong winds that affect aircraft in flight [6][7]. The engine ingestion of dust / smoke / sea salt aerosols can also induce severe damages (erosion, corrosion, pitot-static tube blockage, engine flame out in flight) [8]. Volcanic ash and SO<sub>2</sub> gases are also major hazards, causing windscreen abrasions, reduction of visibility, damage to aircraft instrumentation and systems, hot corrosion (when sulphate's coat inside/outside engine surfaces) that calls for extra maintenance, and most importantly

stalling of engines due to the melting ash [9][10]. A significant difficulty in mitigating impact of ash/dust/smoke clouds on aviation is that these fine aerosol particles can rapidly be transported over long distances (>1000 km), often not along the forecasted path of the cloud. The use of space-based instruments enables the continuous, global monitoring of natural airborne hazard in an effective, economical and risk-free way.

- **Space weather** can be defined as “The physical and phenomenological state of the natural space environment, including the Sun and the interplanetary and planetary environments” [11], which refers to natural perturbations from the sun / space that can influence performance / reliability of space-borne, ground-based or airborne systems, is understudied as aviation hazard. Space weather events follow a 11-year cycle with a ~4 year period of minimum solar activity with severity and probability of occurrences being quite low (unfortunately not equal to zero), followed by a period of ~7 year high activity or solar maximum. The immediate and delayed effects on aviation include: the disruption of radio / satellite communication (jeopardising VHF, HF and datalink communications, also those of Remotely Piloted Aircraft Systems – RPAS); the degradation of navigation systems, e.g., GNSS based procedures and magnetic compasses; increased radiation exposure to crew and passenger and higher risk for radiation-induced failures of on-board systems.
- **Aviation-induced climate change** due to emissions of greenhouse gases or their precursors is not being considered today in ATM decision-making. Facing the continuing expansion of air traffic (expected to double by 2040), the goal of developing eco-efficient aviation becomes increasingly challenging. It should be established as a priority for European Union (EU) to



Figure 1: Motivation and risk/impact for aviation targeted by ALARM project ([www.alarm-project.eu](http://www.alarm-project.eu)).

achieve the goals of the Paris Agreement, among others, to limit the increase of temperature of the planet to 1.5°C in the XXI century. ALARM integrates existing assessments obtained by previous studies to mitigate the climatic impact of aviation. Should ATM be taking into consideration the environment in its decision-making (e.g., issuing regulations due to environmental hotspots as different cities in Europe are enforcing road traffic restrictions due to over pollution), alert systems capable of anticipating potential environmental hotspots would become paramount in the future.

The implementation of an EWS requires some technical considerations for providing relevant information to stakeholders. Section II describes the mechanism of ALARM system. Section III presents example of alert products developed by ALARM for the 4 types of risks. Section III gives an overview of ALARM visualisation dashboard and section IV the conclusions and perspectives.

## II. MECHANISM OF ALARM SYSTEM

### A. ALARM system description

The structure and the choice of the data products harvested by the facilities of ALARM Data Platform (DP) and considered in the ALARM EWS, relies on the user requirements and risk assessments [12]. Four types of threats and environmental impact to aviation are addressed by ALARM (i.e., Natural Hazard and Airport SO<sub>2</sub> Contamination, Space Weather events, Severe Weather events, and Environmental Hotspots).

Sensing of data observations and alerts from external service is downloaded by ALARM harvesting facilities (hosted by BIRA). Nowcasting model outputs are also provided by ALARM partners (UC3M, DLR, Uni. Padova and SATAVIA) to feed ALARM DP and its EWS.

Figure 2 shows the block action of ALARM system. An illustration of the processing chain, from retrievals to triggering of alarms, notifications and transfer alert data products (used by the API demo implemented by SYMOPT partner) is shown.

Near real-time (NRT) Products from satellite and ground-based platforms/instruments are provided by ALARM partners and external data sources, collected by ALARM data harvesting facility, and transferred to the EWS. The automated EWS (including Routine data products) applies its own mechanisms to issue Alerts. This is an extension of the SACS/EUNADICS-AV system to other kinds of alerts and instruments [13][14]. ALARM system also considers inputs from existing systems, like OPAS Engage-KTN service (<https://engagektn.com>), NASA-FIRMS (<https://firms.modaps.eosdis.nasa.gov>) and CAMS (<https://atmosphere.copernicus.eu>). For transmitting Notifications, ALARM EWS is based on the detection of volcanic ash/SO<sub>2</sub>, sand/dust storms, fire plumes, space weather, severe weather and environmental hotspots alerts. Specific notifications, associated to the creation of events is sent to ALARM partners and key users. The event type implemented, alert data products, charts and links to dataset collections, is available via https/ftp and accessible for the API demo (see section IV). As illustrated Figure 2, stakeholders get notifications and access to alert data products directly from ALARM DP, information can also be shown via the API.

According to the Technology Readiness Level (TRL) of alert developed by ALARM EWS [15], the access to NRT observations is proceeded using SACS web interface (<https://sacs.aeronomie.be>). Some observations are public but the access to alerts and events is restricted to VAACs, MWOs, NMs, volcanic observatories, and research collaborators, as these are considered pre-decisional products. Two levels of accessibility (public and restricted) can be implemented in the API demo.

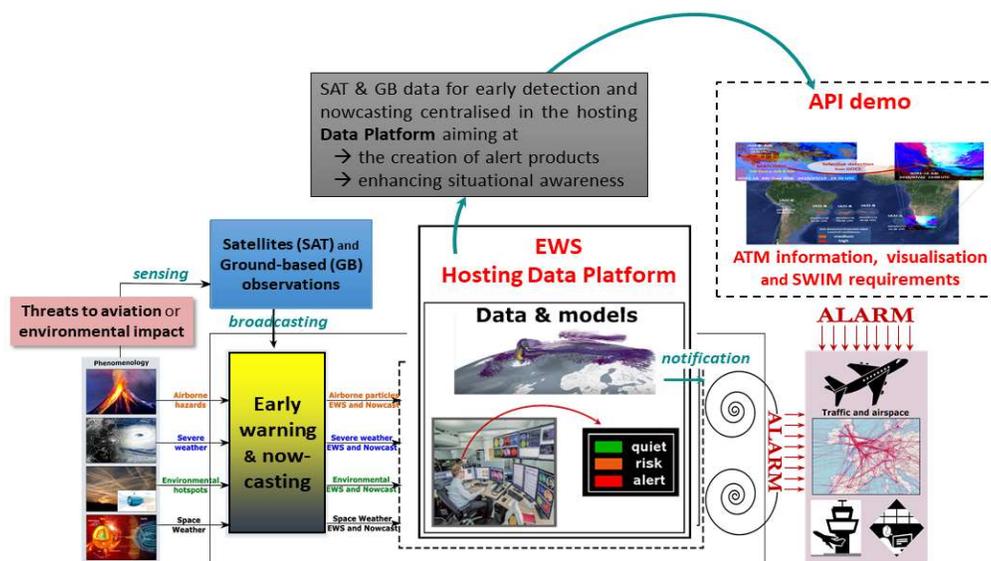


Figure 2: High level description of ALARM process.

### B. Chain process of ALARM EWS

Figure 3 presents the chain process of ALARM multi-sensors warning system. The implementation of alert notifications and the creation of alert data products requires a two steps approach:

1. A proper establishment of warnings criteria for the different sensors (satellite, ground-based or model outputs) and the different types of alerts (i.e., issued from the detection of volcanic, sand/dust storms or fire plumes, airport SO<sub>2</sub> contamination, space weather events regarding exposure to increased levels of radiation during flight, severe weather situations such as deep convection and extreme weather, and environmental hotspots potentially contributing to global warming in a large extent). Particular attention is given to the avoidance of false notifications (e.g., due to noise or retrieval failures) or overly frequent/redundant notifications (caused by highly dispersed plumes). Alerts criteria with threshold are used for each satellite and ground-based product, each model outputs. This includes the name of the quantity products, the type of instruments and the platform for satellite sensors or the type of model, the criteria of Alerts and the limitation. The alerts criteria are established based on test data and/or model outputs by ALARM partners [15].
2. Combining the information from the products in one multi-sensors system (hosting DP). The EWS relies on pre-defined geographical regions (see Figure 3) and

notify the start of an Event Type to parties of interest as soon as a new airborne hazard plume is detected. If within a period of 24 hours (to few hours, depending on the type of hazard), a plume (or hazardous cloud) is detected again in the same region (for the same quantity product) no new notification is generated (to avoid sending redundant information).

The description of the successive processes, related to steps 1 and 2 as described above, is the following:

1) The first step is the **analysis of the data using the alert criteria**. This takes place as soon as the EWS harvests new observations. After the detection of airborne emission from a natural hazard and the start of an **Event Type**, there are potentially multiple warnings generated by the system. For this reason, it has been decided to consider a set of world regions of 30° by 30° plus two polar regions poleward of 75° in latitude. Figure 3 shows the locations (and associated name/number) of the 62 regions of the EWS system. As soon as a notification is issued, the related region is flagged ‘ON’.

2) The second step is to check the “warning status” of this region. If there is no on-going notification for this region (meaning no notification in the past 24 hours), the warning status can possibly become ON. The system compares the time of observations with the processing time. If the delay is less than 8 hours, the **Notification** is issued. **Alert data products** are generated and transmitted to the Event archive of ALARM DP. If the “warning status” is already ON (**on-going Event**), there is no notification issued but an **update** of the Event Type and DP archive is proceeded.

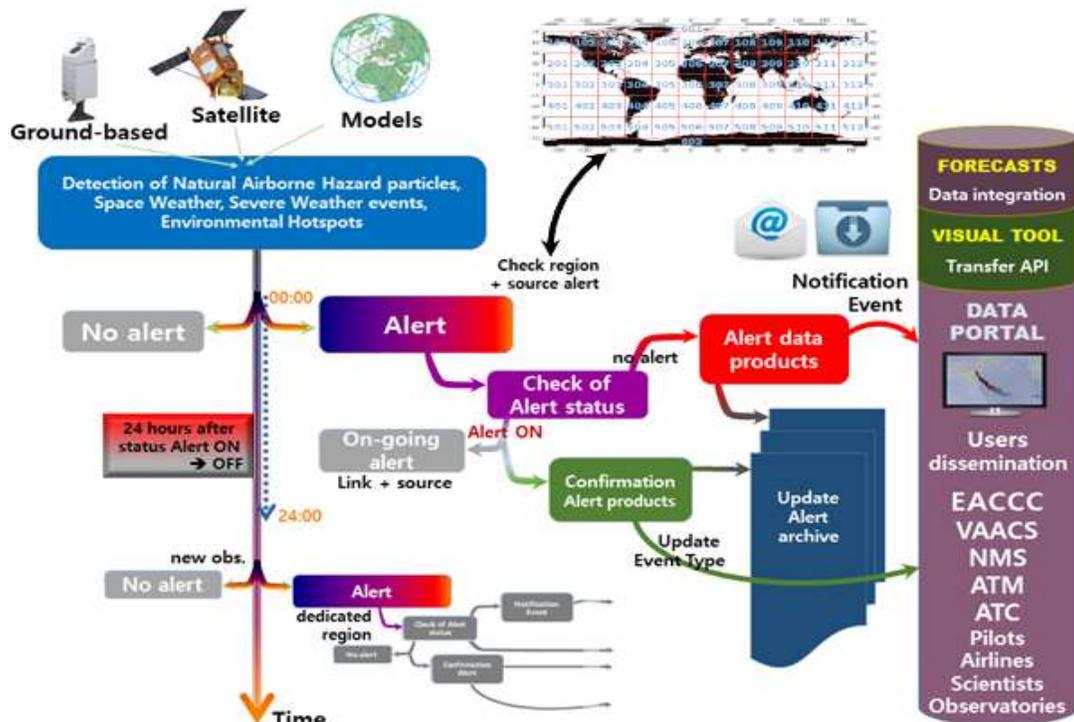


Figure 3: Technical process of ALARM system.

This set-up enables to provide timely information to the users and also to avoid issuing too many notifications (maximum one notification per region and per 24 hours).

For each alert/event issued by ALARM EWS, the associated event type is created/updated, and the alert archive is completed. Three types of alert products delivered by SACS/ALARM system:



NRT imaging on a dedicated web interface



Email notifications (with key information and link to dedicated tailored images)



Creation of homogenised alert data products (SO<sub>2</sub> height information, improved SO<sub>2</sub> mass loading, SO<sub>2</sub> contamination of the flight level, identification of source, and links to images)

The Routine data products, based on NRT products from 8 satellite hyperspectral sensors (i.e., OMI, OMPS, GOME-2B, GOME-2C, TROPOMI in the UV-vis, and AIRS, IASI-A, IASI-B in the IR range) related to the detection of volcanic eruptions, sandstorms or smoke from wildfires, and can be consulted and monitored through the SACS/ALARM web interface. The currently operational SACS website (<https://sacs.aeronomie.be>) is a self-contained system that allows the consultation of NRT satellite data and provided alerts to subscribed users in case of detection of elevated amounts or concentration of volcanic emissions. At the moment, all the NRT observations linked to ALARM EWS relies on the current SACS web interface.

### III. EXAMPLES OF AVIATION TAILORED PRODUCTS

#### A. Alert of Natural Airborne Hazard

Currently email notifications from SACS/ALARM EWS for public or governmental users take only place after volcanic and dust cloud hazards detection. Data products are collected by SACS/ALARM data harvesting facility and transferred in NRT for analysis by our EWS. The automated EWS applies specific mechanisms to issue selective detection (extension of the SACS system to other kinds of alerts and instruments) but also consider inputs from existing systems, like NASA-FIRMS and VONA messages. In case of the detection of a Natural Airborne Hazard (NAH) in a specific SACS region, a notification is sent internally to ALARM partners (one notification per affected region). In case of exceptional SO<sub>2</sub>/ash or dust concentration detected, a notification is sent to stakeholders (email) with relevant information (e.g., time, position and highest value detected) and a link to a dedicated webpage. The SACS system has currently about 300 users (from the VAACs, NMS, scientific institutions, airlines, pilots, other ATM institutions, and other public users). On the alert webpage, images of volcanic observations (e.g., ash, SO<sub>2</sub> vertical column and layer height if available for the instrument in alert, or dust optical thickness) are shown. Additional links to other images are provided (i.e., links to interpolated plot and google earth file). The example of TROPOMI SO<sub>2</sub> notification for Cumbre Vieja eruption in Autumn 2021 (Figure 4) contains information about the time of observations, the lat/lon position and the value (in DU) of the highest alert pixel detected (in the dedicated SACS region), the SO<sub>2</sub> mass loading (in kt) of the data granule used to issue the alert, the size of SO<sub>2</sub> plume area (in km<sup>2</sup>), the notification level (LOW or HIGH), the name of the most likely volcano source of emission (if identified), and the link to the alert data product created by SACS/ALARM EWS [12][15].

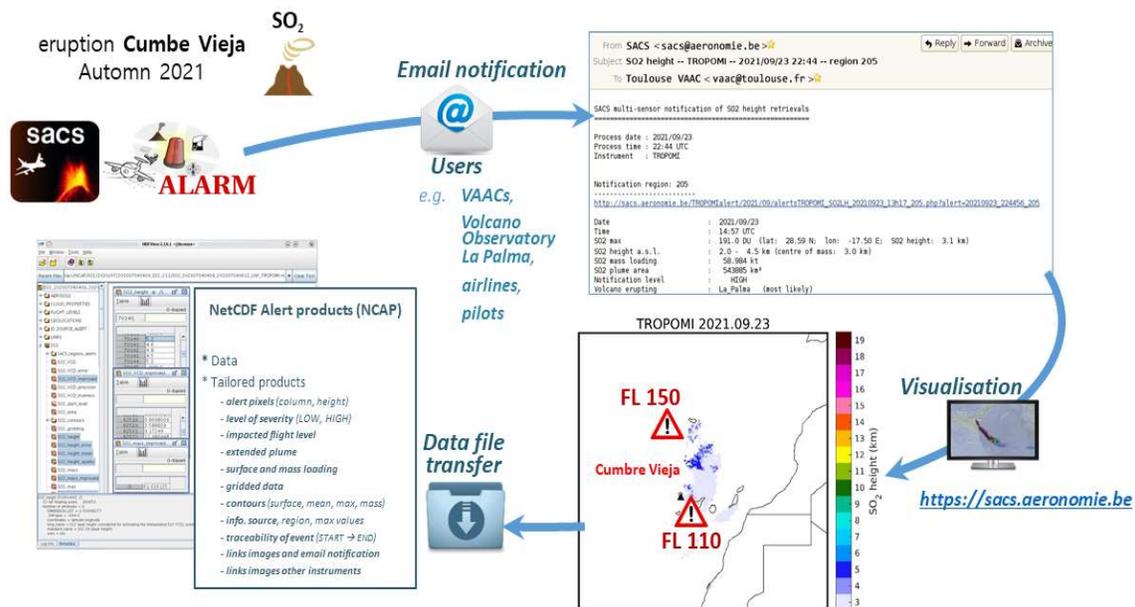


Figure 4: Example of chain of information provided by SACS/ALARM system.

### B. Alert and forecasts of SO<sub>2</sub> contamination at airports

ALARM system blends SO<sub>2</sub> observational data with hindcast data in order to obtain a bias correction metric used to build an alarm forecast system for airports. Note that hindcast (archive of forecasts with the operational condition), initially introduced in oceanography and meteorology, is a way of testing a mathematical model; researchers enter known or closely estimated inputs for past events into the model to see how well the output matches the known results.

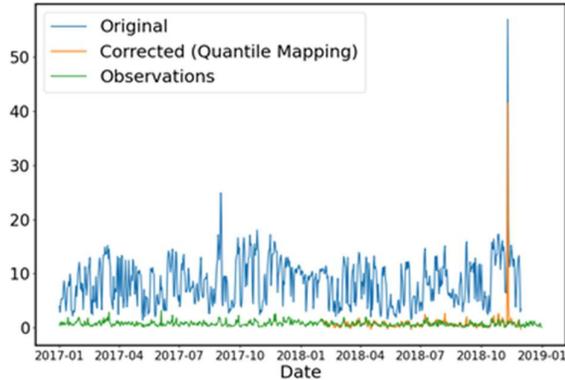


Figure 5: Example of SO<sub>2</sub> warning at Birmingham Airport, Alabama. Modelled data, observations, and corrected model data are shown. Quantile mapping has been applied to the training data (days to correct from the previous years padded by 30 days on each side).

SO<sub>2</sub> data from 2017 to present time (up to ~2130 stations in US, Europe, China, and India) has been analysed. All the stations fall into different categories. (i.e., Urban, semi urban, rural etc.). For the locations (latitude/longitude) of the observational stations ALARM system extracts the associate SO<sub>2</sub> model hindcast data (CAM data). It is important to identify the bias of this model data in comparison to the observational sites in order to identify how well the model data is fit for purpose when used as an alarm forecast system. Based on the calculated biases ALARM system implements a bias correction metric. Various bias correction techniques has been implemented and tested, including mean bias correction, median bias correction and quantile bias mapping. Depending on the region a different bias correction method may need to be chosen. ALARM applies the defined bias correction metric for 3 airports within the regions mentioned and obtained alert of SO<sub>2</sub> contamination.

### C. Alert of Space Weather event

In answer to the risk of Space Weather to aviation, ALARM creates, on the basis of some of the PECASUS radiation products, a standardised 3D alert product from which a simple three colour message (green for a quiet situation, orange for a risk and red for an alert) is generated in real-time within the ALARM system (Figure 6; Halloween storm at 21:00 UTC on 28 October 2021).

ALARM system for Space Weather is using BIRA COMESEP alert system (Coronal Mass Ejections and Solar Energetic Particles – SEP), based on data and model. It provides SEP forecast to issue a warning on an increased risk for high frequency (HF) disruption and for enhanced radiation exposure

with impact on the radiation dose and avionics [16][17]. ALARM generated automatically alerts/warnings table for geomagnetic and radiation storms with risk indicator (low, moderate, high) for impact on HF, GNSS, SATCOM and Increased Radiation exposure at flight altitude using:

- COMESEP alert system
- GOES16 proton flux data
- HESPERIA UMASEP-500 system
- Neutron Monitor data (NM)

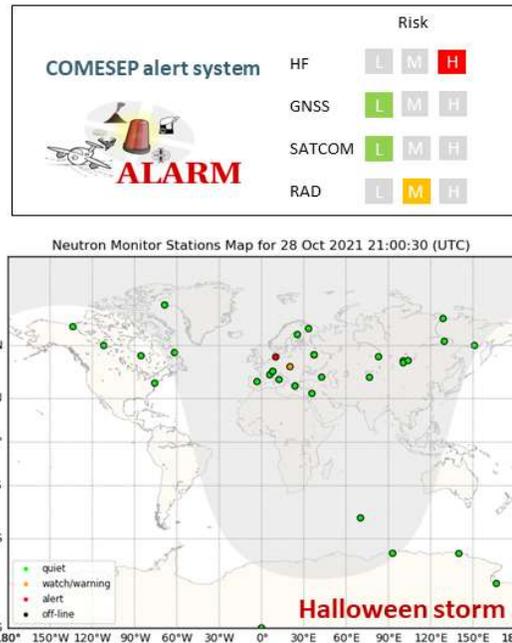


Figure 6: Example of Space Weather alert fro the Halloween storm on 28 October 2021. Solar flare, proton event, and GLE (Ground Level Enhancements) event was observed. ALARM issued both warning for HF and RAD. GLE event seen on the Neutron Monitoring world maps.

### D. Alert of Severe Weather event

Alert of Severe weather is obtained by using machine learning algorithms specifically developed according to the parameter of interest.

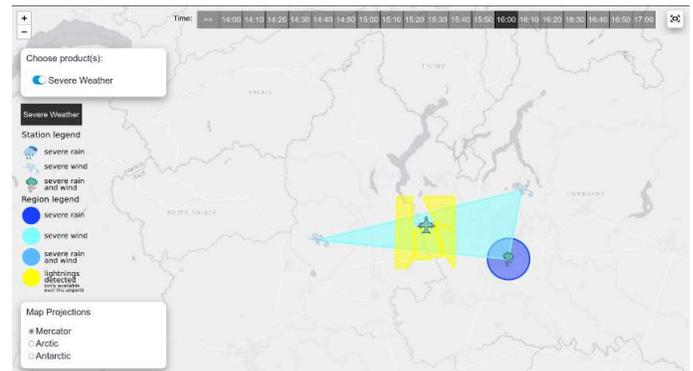


Figure 7: Example of Severe Weather alert around Malpensa airport at 16:00 UTC on the 29<sup>th</sup> of October 2018. Alerts of severe wind, rain and lightning are provided by ALARM system.

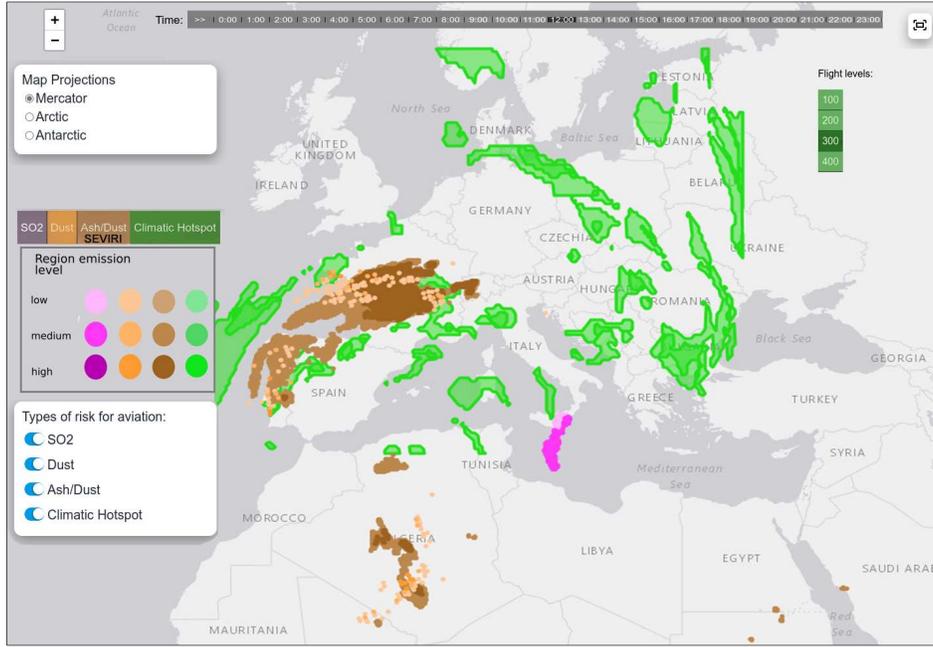


Figure 8: Example of 4 types of risk for aviation on the 15<sup>th</sup> of March 2022. Severe Weather alert at around Malpensa airport on 29 October 2018. Alerts of severe wind, rain and lightning are provided by ALARM system.

We work in two different hotspots accurately chosen [18]: Milano Malpensa and Brussels Zaventem. We nowcast three different parameters: lightning, wind speed and accumulate rain. The algorithm receives in input data from weather stations, GNSS receivers, radars, lightning detectors, radiosondes and radio occultations and provides in output the nowcasting of lightning (in binary format) and the wind speed and rain absolute values. The output of the algorithms [19] are finally combined to map the ATM sectors very likely affected by extreme weather in the next 60 minutes. Severe Weather alerts are presented in Figure 7, as part of the section IV about the visualisation demo.

#### E. Alert of Climatic Hotspots

The experimental approach to obtain the detection for the Met product Environmental Hotspots is based on state of state of the art prototype algorithmic climate change functions aCCFs [20][21][22], which describe the temporal and spatial climate impact of non CO<sub>2</sub> effects (i.e., NO<sub>x</sub>, contrail, water vapour). Based on these aCCFs, volumes of airspace that are very sensitive to aviation emissions are identified. These climate sensitive regions are termed as environmental hotspots. Treating that information as harmful and integrating it within a state-of-the-art alert system is surely a ground-breaking concept within ALARM. These aCCFs can be calculated using metrological input data, e.g., from numerical weather forecast, thus a warning on possible high climate impact regions can be generated. The generation of these Environmental Hotspots uses statistical analysis to dynamically derive thresholds to define an area as Environmental Hotspot. To evaluate our results, a systematical analysis of the characteristic aCCF

patterns over the European airspace is done based on high resolution ERA5 reanalysis data. The aCCF dependency on season, cruise altitude and synoptical condition is investigated in detail. Moreover the structure and magnitude of the patterns will be verified by comparing them with current scientific literature [23]. Environmental Hotspots alerts are presented in Figure 8, as part of the section IV about the visualisation demo.

#### IV. VISUALISATION DEMO

A demonstration of ALARM API visualisation dashboard has been implemented in the final stage of ALARM project (see snapshot in Figure 7 and 8). Sets of several days related to the each types of alert are presented (SO<sub>2</sub>, ash, dust, smoke, space weather, severe weather, climatic hotspots). This demo of ALARM alert products is publicly available on the following link (<http://alarm.aeronomie.be>).

#### V. CONCLUSIONS AND PERSPECTIVES

ALARM project develops a **prototype global multi-hazard monitoring** and Early Warning System (EWS). Such early warning refers in this context to alert of an existing hazard in an early stage. A global multi-hazard monitoring means NRT and continuous global Earth observations from satellite, with the objective to generate prompt alerts of natural hazards affecting ATM and to provide information for enhancing situational awareness and providing resilience in crisis. NRT data (with delay of delivery from 10 min, to less than 4h) and tailored products from ground-based and satellite systems, are used to feed models capable of detecting (creation of alert products) and predicting (nowcasting/forecasting) the risk/displacement of:

a) particles in suspension and gas derived from natural hazards (**volcanic ash and SO<sub>2</sub>, dust clouds from sandstorms, and smoke from forest fire**); b) **severe weather situations** such as deep convection and extreme weather; c) **space weather** regarding exposure to increased levels of radiation during flight; d) **environmental hotspots** potentially contributing to global warming in a large extent.

ALARM EWS provides alert information for the stakeholders about the threat to aviation in three different manners:

1) early warning (geolocation, altitude and level of severity – quantification if available – of the observed hazard;

2) for nowcasting [up to 2h] of SO<sub>2</sub> contamination at ground level and detection of deep convection / wind shear around airports;

3) forecasting [from 2h to 48h] of severe weather evolution and identification of risk area, at different flight levels, with increased climatic impact.

The list of all ALARM alert products is publicly available [15], as well as the demo of ALARM visualisation dashboard. Figure 7 and 8 illustrate the interest for the stakeholders. Specifically, the use of such tailored alert is a way to enhance situational awareness of all stakeholders in case of multiple hazard crisis by facilitating the transfer of required relevant information to end-users, presenting such information in a user-friendly manner to ATM stakeholders. In summary, anticipating severe hazards and fostering better decision-making.

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