Early warning system of natural hazards and decrease of climate impact from aviation

ALARM funded project

Hugues Brenot, Nicolas Theys, Erwin de Donder, Jeroen van Gent, Michel Van Roozendael
Dep. Atmospheric Reactive Gases
Royal Belgian Institute for Space Aeronomy (BIRA)
Brussels, Belgium

Manuel Soler, Javier Garcia-Heras, Alejandro Cervantes, Abolfazl Simorgh, Virginia Villaplana
Dep. Bioengineering and Aerospace Engineering
University Carlos III,
Madrid, Spain

Simone Dietmüller, Sigrun Matthes, Volker Grewe
Dep. Earth system modelling
German Aerospace Center (DLR)
Oberpfaffenhofen, Germany

Riccardo Biondi, Sandy Chkeir, Katerina Anesiadou
Dep. Geoscience
University of Padua
Padua, Italy

TimWinter, Adam Durant
SATAVIA
Cambridge, UK

Tanja Bolić[*], Francesco Urdih
SYMOPT, Trieste, Italy
[*]University of Westminster, London, UK

Lieven Clarisse
Dep. Spectroscopy, Quantum Chemistry and Atmospheric Remote Sensing
Free University of Brussels (ULB)
Brussels, Belgium

Pierre de Buyl, Nicolas Clerbaux,
Dep. Observations
Royal Meteorological Institute of Belgium (RMI)
Brussels, Belgium

Klaus Sievers
Klaus Sievers Aviation Weather (KSAW)
Lenggries, Germany

***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_2 conditions around a selection of few airports, on providing nowcasts and forecasts of risk conditions.**

Keywords-component: early warning, volcanic ash, SO_2, dust, smoke, space weather, severe weather, climatic hotspots, near real-time.

I. 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_2 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_2 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 radiation3 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

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

established as a priority for European Union (EU) to 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_2 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) data products from satellite and ground-based platforms/instruments (with delay of delivery from 10 min, to less than 4h) 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_2, 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. Subscription for receiving notifications can be proceeded on this link https://sacs.aeronomie.be/alert). 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 enabled 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.

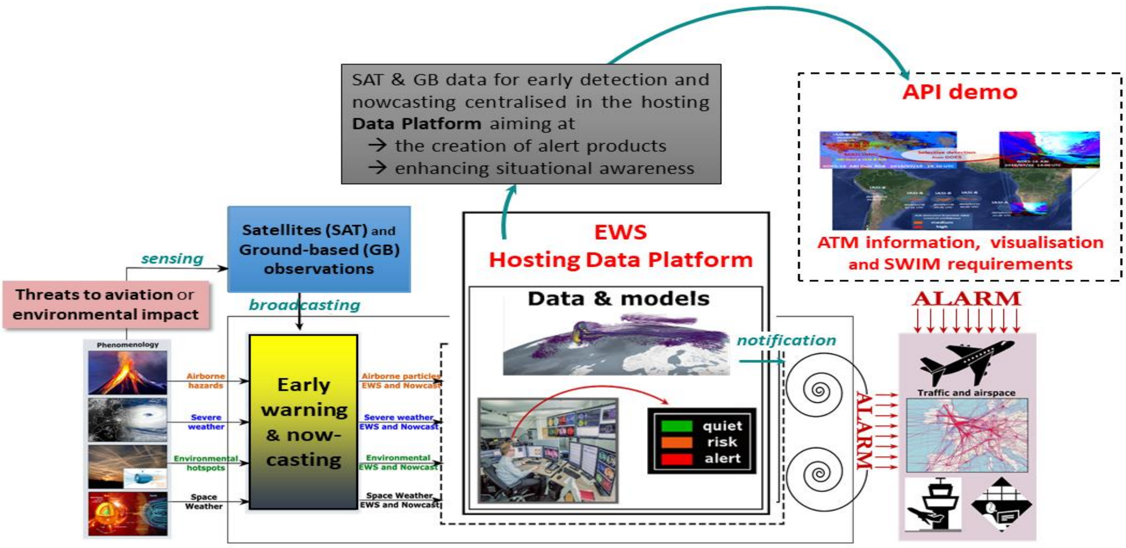


Figure 2: High level description of ALARM process.

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_2 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.

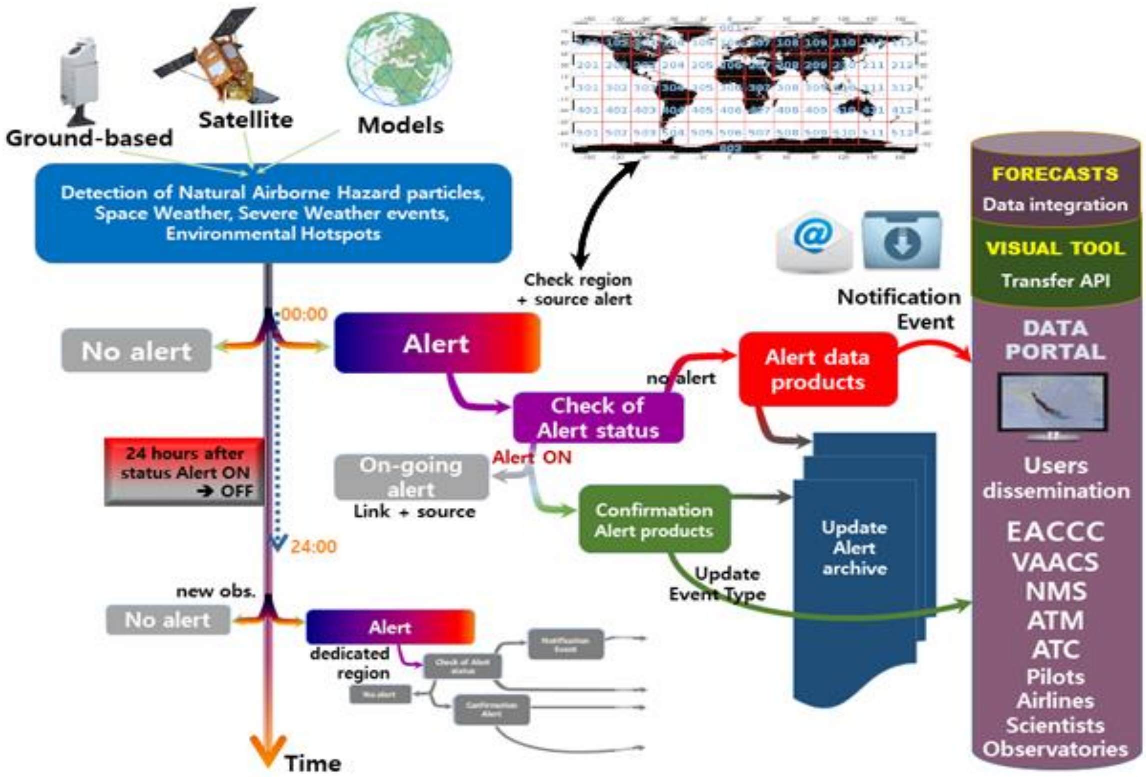


Figure 3: Technical process of ALARM system.

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_2 height information, improved SO_2 mass loading, SO_2 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 created (one notification per affected region). In case of exceptional SO_2/ash or dust concentration detected, such notification is sent to stakeholders (email) with relevant information (e.g., time, position and highest value detected) and a link to a dedicated webpage. To improve its capability of awareness, ALARM consortium has developed new algorithms for the selective detection of SO_2 and mineral dust (ash or desert dust) from geostationary satellite sensors (see Figure 9 with the detection of Saharan dust over Europe using SEVIRI instrument). The high temporal resolution of these instruments is a consequent added value. The SACS/ALARM 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_2 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_2 notification for Cumbre Vieja eruption in Autumn 2021 (Figure 4) contains information about the time of

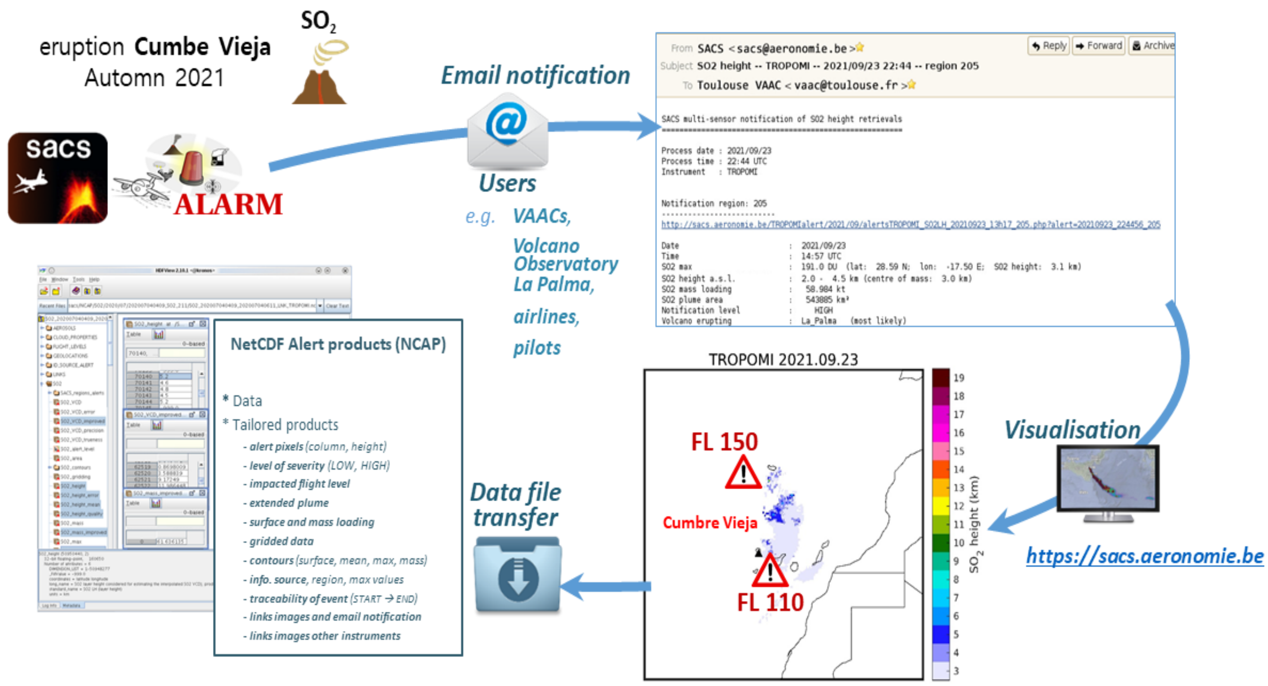


Figure 4: Example of chain of information provided by SACS/ALARM system.

observations, the lat/lon position and the value (in DU) of the highest alert pixel detected (in the dedicated SACS region), the SO_2 mass loading (in kt) of the data granule used to issue the alert, the size of SO_2 plume area (in km²), 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].

B. Alert and forecasts of SO_2 contamination at airports

ALARM system blends SO_2 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.

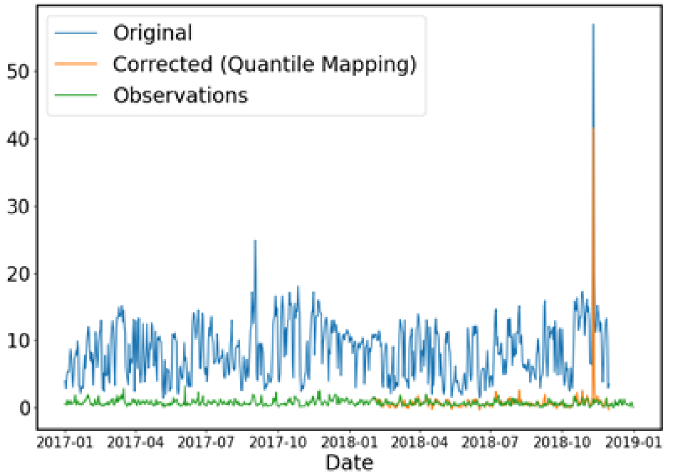


Figure 5: Example of SO2 warning at Birmingham Airport, Alabama. Modelled data, observations, and corrected model data are shown. Quantile mapping has been applied to the training data (days to correct from the previous years padded by 30 days on each side).

SO_2 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_2 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_2 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)

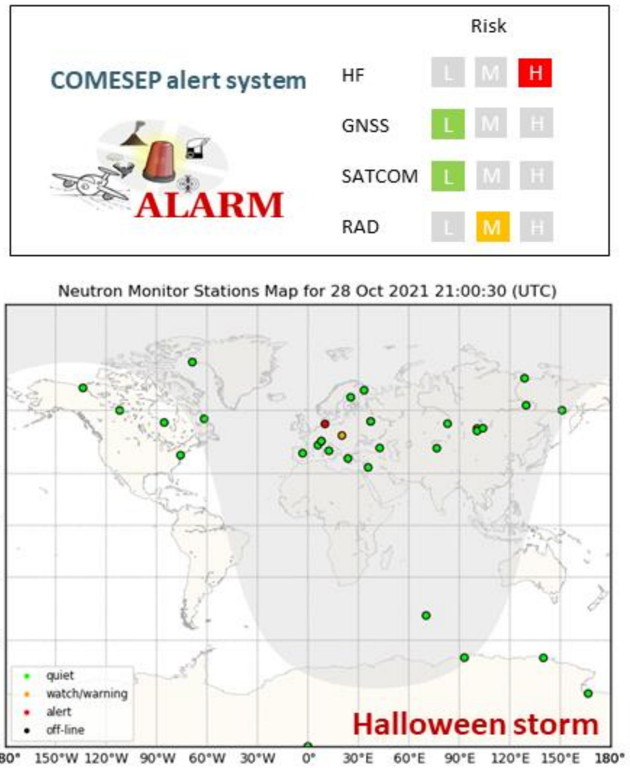


Figure 6: Example of Space Weather alert for the Halloween storm on 28 October 2021. Solar flare, proton event, and GLE (Ground Level Enhancements) event was observed. ALARM issued both warning for HF and RAD. GLE event seen on the Neutron Monitoring world maps.

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.

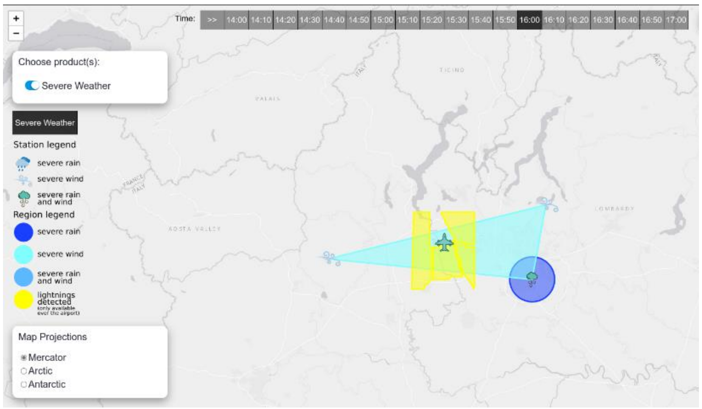


Figure 7: Example of Severe Weather alert around Malpensa airport at 16:00 UTC on the 29th of October 2018. Alerts of severe wind, rain and lightning are provided by ALARM system.

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 CO2 effects (i.e., NOx, 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

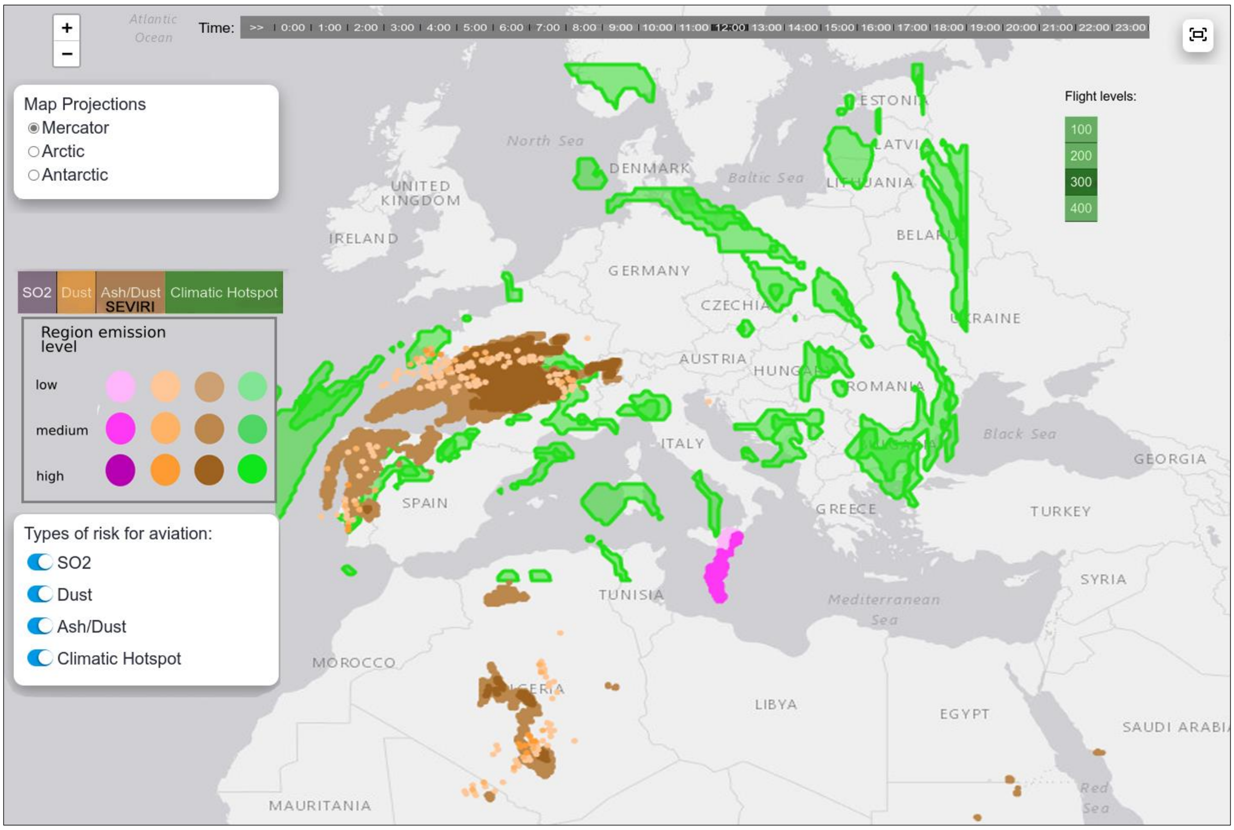


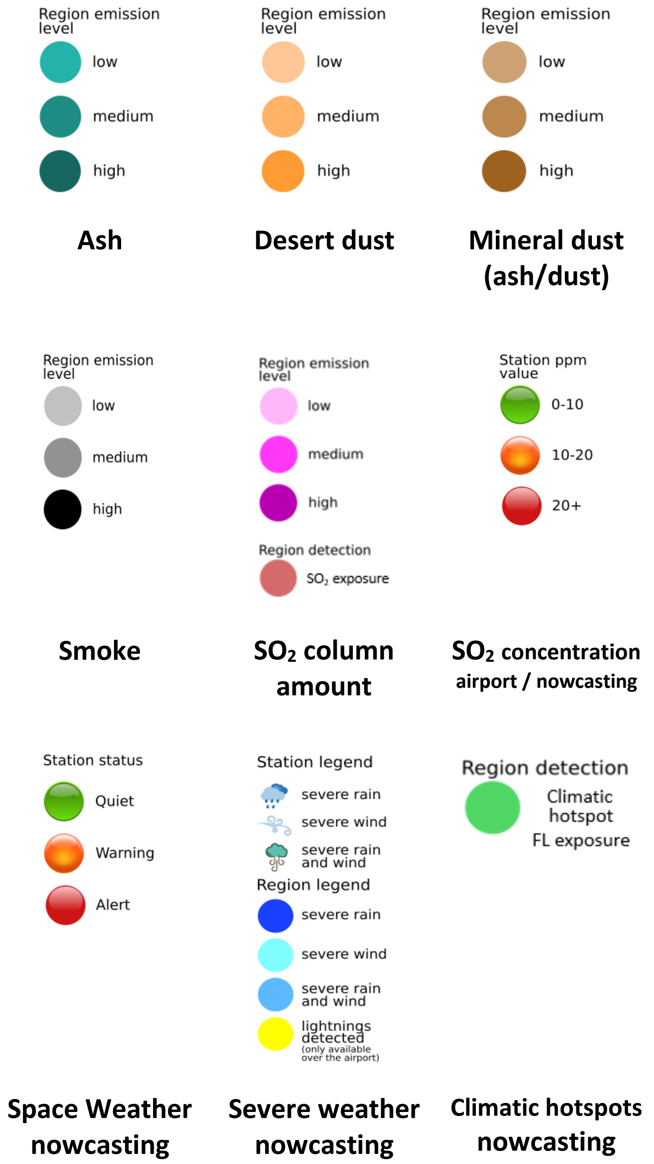
Figure 8: Illustration of 3 types of alert/risk for aviation on the 15th of March 2022 (SO2 from Etna, Saharan desert dust and environmental hotspots at FL300).

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 snapshots in Figure 7 and 8). Sets of several days related to the each types of alert are presented (SO_2, 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).

The list of hazard and associated legend available in this demo is the following:



In this web interface, the listed hazards are presented in subsets. For each hazard, level of severity has been defined with low, medium and high emission level. More details can be found in ALARM D6.2 [24]. There are many days with data available for three or more of them (e.g., see Figure 8 with the several risks taking place on 15 March 2022). Moreover, all these hazards detection areas often overlap, therefore it is very important to make the visualisation of each product as distinct as possible.

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 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_2**, **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_2 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.

The next step of ALARM consortium is to increase the maturity of our prototype warning system for future applications. First, with the use of robust detections and creations of alerts of natural hazards (e.g., severe weather, volcanic eruption or sandstorm), we plan to improve the accuracy and lead time of meteorological information provided to the aviation community by using artificial intelligence. Second, regarding the climatic hotspots and further research, the next objective is to develop remote sensing algorithms for the detection of contrails and aviation-induced cloudiness, with the aim of quantifying the radiative forcing of ice clouds based on remote sensing and radiative transfer methods. Then, the implementation of warnings and forecasts of environmental hotspots with quantification of climate impact could be provided to aviation stakeholders.

ACKNOWLEDGMENT

This research has been supported by the SESAR H2020 ALARM (grant no. 891467; https://www.sesarju.eu), the OPAS Engage-KTN (grant no. 783287; Thematic Challenge 3; https://engagektn.com), and the SESAR H2020 FlyATM4E (grant no. 891317) projects. This was a great opportunity to bring together research institution, universities and companies providing decision intelligence to aviation.

REFERENCES

[1] Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., 2007. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007. Secondary Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, 2007. C.U. Press, Cambridge, UK and New York, NY, USA.

[2] Daniel González-Arribas, Manuel Soler, Manuel Sanjurjo, Maryam Kamgarpour, and Juan Simarro. Robust aircraft trajectory planning under uncertain convective environments with optimal control and rapidly developing thunderstorms.. Aerospace Science and Technology. Volume 89, June 2019, Pages 445-459. https://doi.org/10.1016/j.ast.2019.03.051

[3] Daniel Hentzen, Daniel González-Arribas, Maryam Kamgarpour, and Manuel Soler. On Maximizing Safety in Stochastic Aircraft Trajectory Planning with Uncertain Thuderstorm Development. Aerospace Science and Technology. Volume 79, August 2018, Pages 543-553. https://doi.org/10.1016/j.ast.2018.06.006

[4] D. González-Arribas, Manuel Soler, and Manuel Sanjrujo. Robust Aircraft Trajectory Planning under Wind Uncertainty using Optimal Control. Journal of Guidance, Control, and Dynamics. Vol. 41, No. 3 (2018), pp. 673-688. http://arc.aiaa.org/doi/abs/10.2514/1.G002928.

[5] IATA: Press Release: Volcano Crisis Cost Airlines $1.7 Billion in Revenue – IATA Urges Measures to Mitigate Impact: http://www.iata.org/pressroom/pr/Pages/2010-04-21-01.aspx, 2010.

[6] Khaykin, S., Legras, B., Bucci, S., Sellitto, P., Isaksen, L., Tencé, F., Bekki, S., Bourassa, A., Rieger, L., Zawada, D., Jumelet, J., and Godin-Beekmann, S.: The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude, Commun. Earth Environ., 1, 22, https://doi.org/10.1038/s43247-020-00022-5, 2020.

[7] AlKheder, S. and AlKandari, A.: The impact of dust on Kuwait International Airport operations: a case study, Int. J. Environ. Sci. Technol., 17, 3467–3474, https://doi.org/10.1007/s13762-020-02710-3, 2020.

[8] Lekas, TH. I., G. Kallos, J. Kushta, S. Solomos, E. Mavromatidis (2011): Dust impact on aviation, 6th International Workshop on Sand/Dust Storms and Associated Dust fall, http://forecast.uoa.gr/Dust-wshop-pdf/Lekas.pdf, Athens, Greece, September 7-9, 2011.

[9] Guffanti, M., Casadevall, T. J., and Budding, K.: Encounters of air-craft with volcanic ash clouds: A compilation of known incidents, 1953–2009: U.S. Geological Data Series 545, ver. 1.0, 12p., plus 4 appendixes including the compliation database, Technical Report available at: http://pubs.usgs.gov/ds/545, 2010.

[10] Prata, A. J.: Satellite detection of hazardous volcanic clouds and the risk to global air traffic, Nat. Hazards, 51, 303–324, doi:10.1007/s11069-008-9273-z, 2009.

[11] Lilensten, J., Belehaki, A., Messerotti, M., Vainio, R., Watermann, J., & Poedts, S. (Eds.): Developing the scientific basis for monitoring, modelling and predicting space weather. COST Office, 2008.

[12] ALARM D2.1: Description of ALARM data platform, August 2021.

[13] Brenot, H.et al.: Support to Aviation Control Service (SACS): an online service for near-real-time satellite monitoring of volcanic plumes, Nat. Hazards Earth Syst. Sci., 14, 1099–1123, https://doi.org/10.5194/nhess-14-1099-2014, 2014.

[14] Brenot et al.: EUNADICS-AV early warning system dedicated to supporting aviation in the case of a crisis from natural airborne hazards and radionuclide clouds, Nat. Hazards Earth Syst. Sci., 21, 3367–3405, https://doi.org/10.5194/nhess-21-3367-2021, 2021.

[15] ALARM D2.2: Presentation of ALARM tailored products, October 2022.

[16] Chapter 7, Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond, Astrophysics and Space Science Library 444, DOI 10.1007/978-3-319-60051-2_7.

[17] The Operational Performance of the COMESEP SEPForecast Tool, M. Dierckxsens et al., Vol. 21, EGU2019-5426, 2019.

[18] ALARM D4.1: Extreme weather patterns report and risks map, May 2021.

[19] ALARM D4.2: Severe weather nowcasting and overshooting: algorithms and in-situ experiments, October 2022.

[20] van Manen, J. and Grewe, V., 2019: Algorithmic climate change functions for the use in eco-efficient flight planning. Transportation Research Part D: Transport and Environment,67, 388–405, doi:10.1016/j.trd.2018.12.016

[21] Yamashita, H., Yin, F., Grewe, V., Jöckel, P., Matthes, S., Kern, B., Dahlmann, K., and Frömming, C., 2021: Analysis of aircraft routing strategies for North Atlantic flights by using Airtraf 2.0, Aerospace,8(2), 1–19. doi:10.3390/aerospace8020033

[22] Yin, F., Grewe, V., Castino, F., Rao, P., Matthes, S., Dahlmann, K., Dietmüller, S., Frömming, C., Yamashita, H., Peter, P., Klingaman, E., Shine, K., Lührs, B., and Linke, F.: Predicting the climate impact of aviation for en-route emissions: The algorithmic climate change function submodel ACCF 1.0 of EMAC 2.53, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2022-220, in review, 2022.

[23] Frömming, C., Grewe, V., Brinkop, S., Jöckel, P., Haslerud, A., Rosanka, S., van Manen, J. and Matthes, S., 2021: Influence of the actual weather situation on non-CO2 aviation climate effects: The REACT4C Climate Change Functions. Atmospheric Chemistry and Physics, 21(11), 9151-9172.

[24] ALARM D6.2: Final information exchnage requirements for the ALARM, October 2022.