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METEOROLOGICAL SATELLITE PRODUCT DEVELOPMENT IN SUPPORT OF THE INTERNATIONAL AIRWAYS VOLCANO WATCH

Executive Summary

This working paper provides an overview of the international airways volcano watch (IAVW), a worldwide system overseen by the International Civil Aviation Organization (ICAO), the World Meteorological Organization (WMO) and partners comprising aeronautical, meteorological, volcanological, geological and other facilities and services with the objective to support continued safe and efficient aviation operations on the ground and in the air whenever and wherever volcanic eruptions are occurring and/or whenever and wherever volcanic ash clouds and gases are present in the atmosphere.

This working paper describes the evolving needs of the aviation user community (in particular a demand to transition from qualitative products to quantitative volcanic ash and gas information services over the next several years), the role of scientific and technological advancement (with a focus on satellite-based remote sensing), and the specific needs from the meteorological satellite provider community to enable the IAVW to evolve in line with meteorological capabilities and aeronautical requirements.

Action proposed: The CGMS agencies are invited to consider the following recommendations addressing meteorological satellite product development in support of the international airways volcano watch (IAVW):

- Ensure that the 'data overload' challenge is being addressed within volcanic cloud product development efforts.
- Prioritize development and operational transition of advanced capabilities – such as human expert-like volcanic cloud detection, automated cloud tracking, and more sophisticated ash/SO_2 characterization, which are needed to support the evolving IAVW – over incremental improvements to existing operational products.
- Coordinate product requirements for volcanic ash and SO_2 with ICAO's IAVW functional and performance requirements to enable integration into forthcoming amendments to ICAO Annex 3 – *Meteorological Service for International Air Navigation*[1].
- Ensure coordination between remote-sensing product development and operational modelling capabilities required for providing forecasts in accordance with ICAO's IAVW requirements.
- Recommend that geostationary satellite operators provide rapid scanning services (< 5 minutes) in support of VAAC operations when and where possible to ensure timely detection of new volcanic events.
- Recognize that no individual satellite sensor provides all of the needed measurement capabilities for volcanic cloud applications and, therefore, that a multi-sensor holistic approach is required to meet ICAO's evolving IAVW requirements (as concluded by a WMO Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) product inter-comparison effort).

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[1] ICAO Annex 3 is reproduced by WMO as Technical Regulations (WMO-No. 49), Volume II.

METEOROLOGICAL SATELLITE PRODUCT DEVELOPMENT IN SUPPORT OF THE INTERNATIONAL AIRWAYS VOLCANO WATCH

1 INTRODUCTION

The World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO), both specialized agencies of the United Nations, coordinate and collaborate with the support of their Members and other partners on the operation and development of the international airways volcano watch (IAVW).

The IAVW is a worldwide system comprising aeronautical, meteorological, volcanological, geological and other facilities and services with the objective to support continued safe and efficient aviation operations on the ground and in the air whenever and wherever volcanic eruptions are occurring and/or whenever and wherever volcanic ash clouds and gases are present in the atmosphere. Figure 1 illustrates the organization of the IAVW and the multiple entities involved.

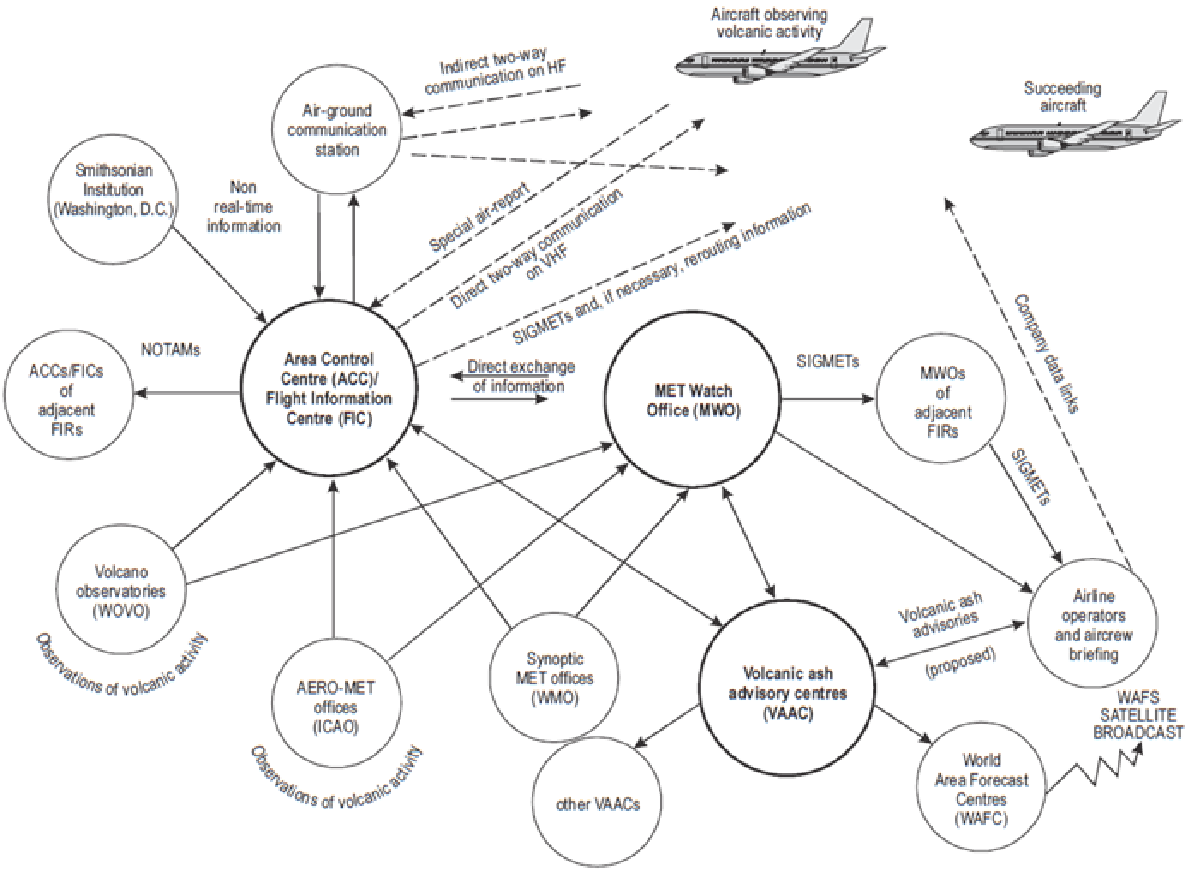

Figure 1. Organization of the international airways volcano watch (IAVW)
Source: ICAO

Volcanic eruptions are typically a daily occurrence in the volcanically-active regions of the world. Figure 2 illustrates the volcanically-active regions of the world over the Holocene period (the last 10 000 years). Volcanic ash cloud and gases emitted by active volcanoes or re-suspended volcanic ash from past eruptions present a hazard to aviation operations, not just proximal to the source but potentially also across large swathes of airspace, sometimes many hundreds or thousands of kilometres away, potentially extending the entire depth of troposphere and into the lower stratosphere.

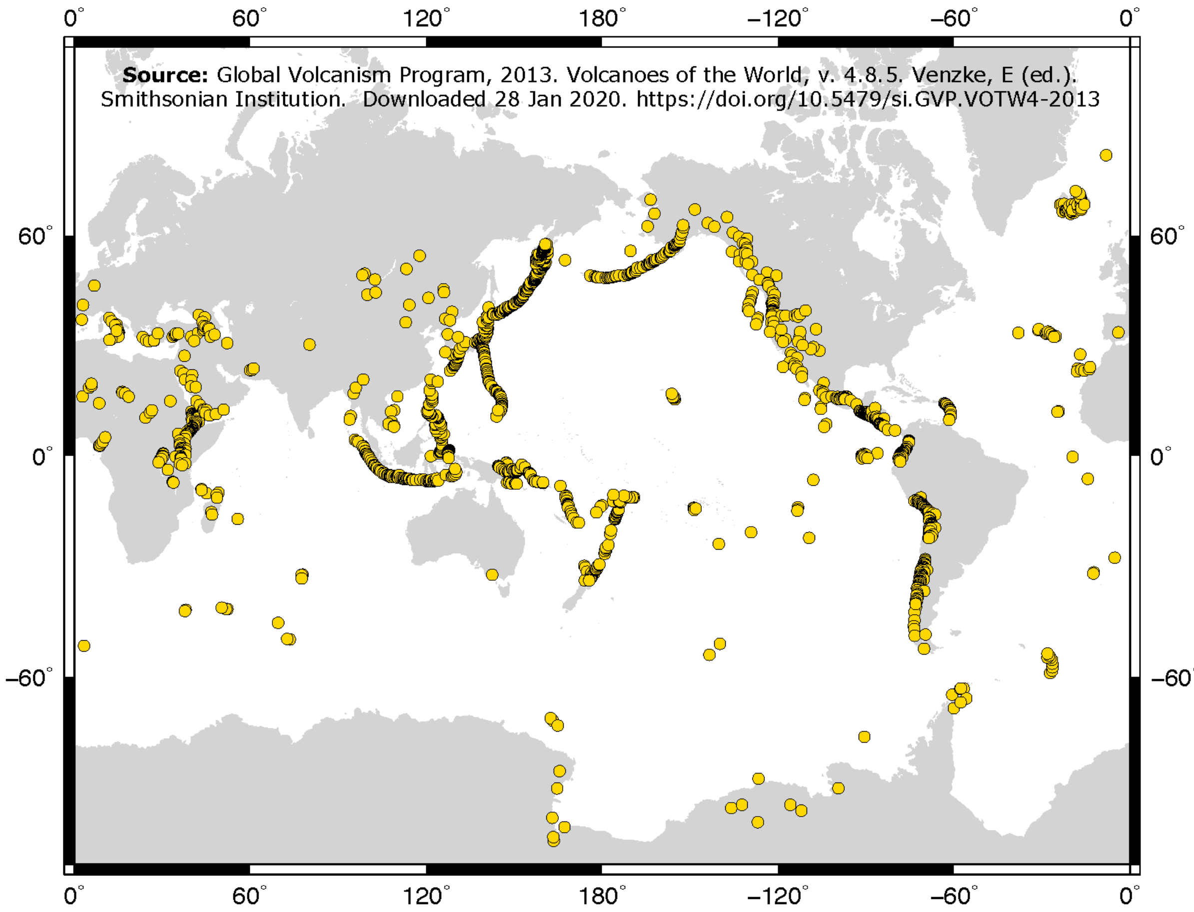

Figure 2. Volcanically-active regions of the world over the past 10 000 years
Source: See insert

Impact with an airframe or ingestion by an engine (or engines) of volcanic ash and gases can adversely affect the performance of an aircraft in flight in a number of ways including engine surge or stall/flame out, erosion of avionics and engine components, choking of filters and pipes, degradation of fuel performance, abrasion of windshields and other leading edges, and corrosion of metallic surfaces due to the presence of acid droplets. Figure 3 gives examples of the effect of volcanic ash deposition on engine and airframe components of a British Airways B747, flight BA009, following its encounter with volcanic ash emanating from an eruption of Mount Galunggung in Indonesia on 24 June 1982.

Figure 3. Damage to engine components (left) and abrasion of windshield (above) due to British Airways flight BA009 encountering volcanic ash over Indonesia in 1982

Source: Archive

Since the early 1980s, following serious incidents involving commercial aircraft encounters with volcanic ash, the international community, led by ICAO with the assistance of WMO and partner organizations including the International Union of Geodesy and Geophysics (IUGG), has made great progress in maturing the IAVW in line with the evolving service providers' capabilities and aviation users' needs. The advancement of science and technology has played a key role in the progress made and this will continue to be the case provided that emerging and foreseen future needs – for example, volcanic sulphur dioxide information services – are adequately identified.

International civil aviation is a global business. Any airspace could be impacted at any time, sometimes with little or no prior warning, by a volcanic eruption and the presence of volcanic ash clouds and gases in the atmosphere. International arrangements within the context of the IAVW are in place to ensure reliable, authoritative information is available to aviation users in advance of (whenever feasible) and during an event to enable them to make informed decisions, especially if their operations may be impacted. Figure 4 illustrates the areas of responsibility of nine ICAO-designated volcanic ash advisory centres within the framework of the IAVW.

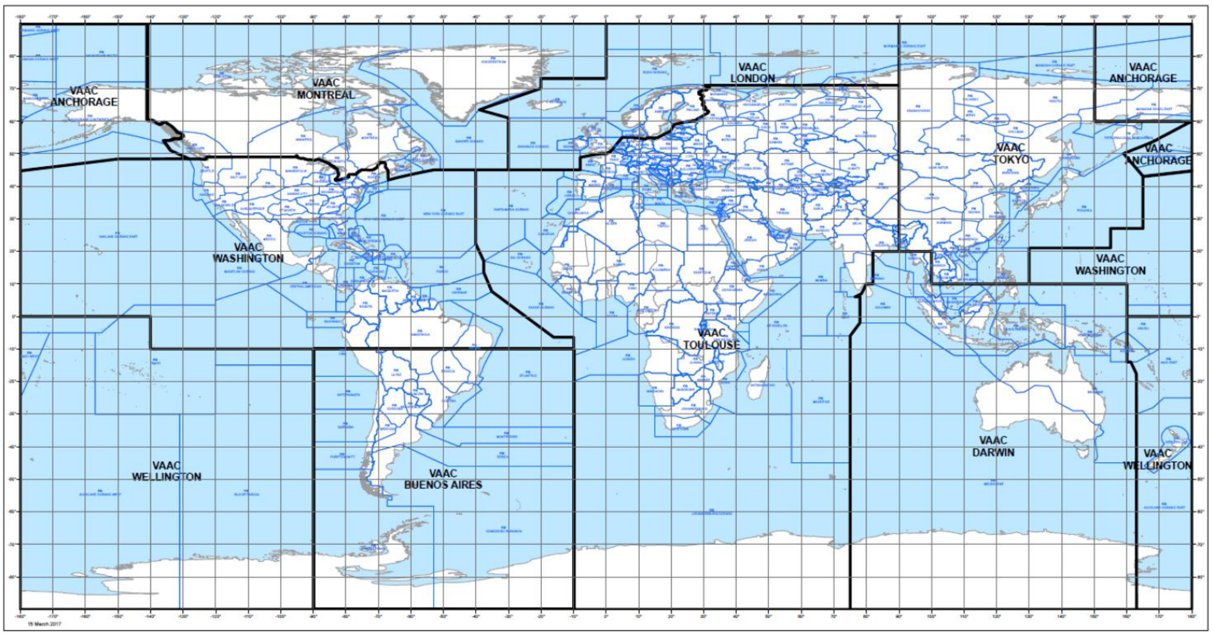

Figure 4. Areas of responsibility of nine ICAO-designated volcanic ash advisory centres (VAACs) within the framework of the IAVW (black) overlaying ICAO flight information regions (blue)

Source: ICAO

This working paper is intended to outline the evolving needs of the aviation user community for information on volcanic eruptions and the presence of volcanic ash in the atmosphere, the role of scientific and technological advancement, and the critical need for sophisticated products from the meteorological satellite community.

2 DISCUSSION

2.1 Evolving needs of the aviation user community

Aside from the prevailing coronavirus (COVID-19) pandemic that has resulted in a dramatic (likely temporary) decline in air traffic worldwide, generally speaking aviation has grown to in excess of 100,000 commercial flight operations daily, serving airports on each and every continent, across the developed and developing world (see Figure 5 for illustration of the 2018 network). This represents more than 4 billion passengers per year. These figures are projected to *double* by the end of the next decade subject, potentially, to the longer-term impact of COVID-19 or other such socio-economic global disruptor(s).

The demands placed upon airport and airspace utilization by such growth are significant if the aviation system (a system of systems) is to remain safe, efficient, economic, secure and environmentally friendly into the 2030s and beyond.

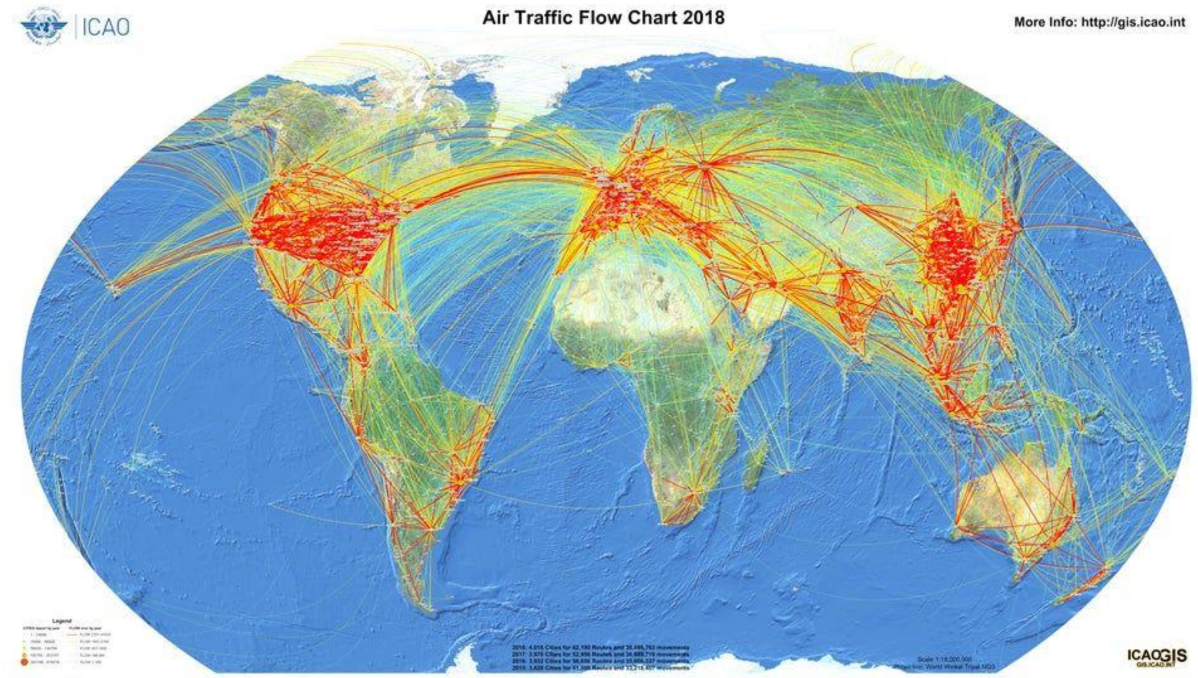

Figure 5. Global air traffic (2018)

Source: ICAO

Volcanic eruptions and the presence of volcanic ash clouds and gases in the atmosphere are typically a daily occurrence. Their direct or indirect impact on aviation operations however may vary depending on the area affected by the ash and volcanic gases, the flight operations area of interest, the duration of any exposure and so on.

Volcanic eruptions and the presence of volcanic ash clouds and gases in the atmosphere are just two of a multitude of hazards and other influencing factors that will be considered as part of an airline operator's safety risk assessment.

Notwithstanding that different airline operators may have different risk appetites, a common requirement is for decisions to be made based upon reliable, authoritative information on where volcanic eruptions are occurring (or are likely to occur) and where volcanic ash clouds and gases are present (or are likely to be present).

Traditionally, due to scientific and technological constraints or other influencing factors, the volcanic ash-related information made available to aviation users through the IAVW has almost exclusively been *qualitative*. However, over the past decade in particular, due to continued (continuing) aviation growth, advances in science and technology, an increased (increasing) understanding of the effects of volcanic ash and gas on aircraft and engine performance, and the necessary demands placed upon airline operators to conduct safety risk assessments, there has been an emerging demand for aeronautical meteorological service providers to provide *quantitative* volcanic ash-related information.

Knowledge of where, when and, importantly, *how much* volcanic ash and gas is present in the atmosphere following a volcanic eruption (and similarly for any re-suspended volcanic ash events) can and will play a key role in enabling airline operators to make better, more informed decisions taking into account their risk appetite. This may, in turn, yield more optimal use of airspace, help minimise risk factors and enable more efficient flight paths, which in turn will help reduce fuel burn and contribute to further minimising the environmental impact of aviation.

Similarly, knowledge of where, when and how much volcanic ash and gas is in the atmosphere is critical observational information that can be utilized by meteorological centres as part of their initialization and calibration of numerical weather prediction models and atmospheric transport and dispersion models.

2.2 Role of scientific and technological advancement

Advances in science and technology have played and will continue to play a key role in enabling the IAVW to transition from a *qualitative* world towards a *quantitative* world.

Since weather radar systems on board commercial aircraft cannot detect volcanic ash clouds – volcanic ash particles do not produce 'returns' or 'echoes' – and given that visual detection of volcanic ash clouds by flight crew may be difficult, especially in poor visibility or at night, several other methods are used to monitor volcanic ash clouds. These can be grouped as follows:

- ***Ground-based remote-sensing*** including lidar, ceilometers, Doppler radar, K-band and X-band radar, seismometers, infrasound detectors, webcams, particle counters and air quality monitoring stations.

- ***In-situ airborne observations*** including meteorological research aircraft, unmanned aerial vehicles (UAV) and drones, aerosol-sondes and airborne lidar.

- ***Satellite-based remote sensing*** including geostationary meteorological satellites (GMS) and polar-orbiting satellites.

The remainder of this paper will focus on the last grouping, namely satellite-based remote sensing. Meteorological satellites are the primary observational data source used for routine volcanic cloud detection, tracking and characterization.

To detect volcanic eruptions, particularly those at volcanoes that may lack ground-based or in-situ monitoring, forecasters regularly examine geostationary and/or polar-orbiting satellite images for clouds whose evolution, location and/or spectral properties are consistent with volcanic activity. Figure 6 illustrates the current coverage of routine geostationary satellite scanning domains along with the location of active or potentially active volcanoes.

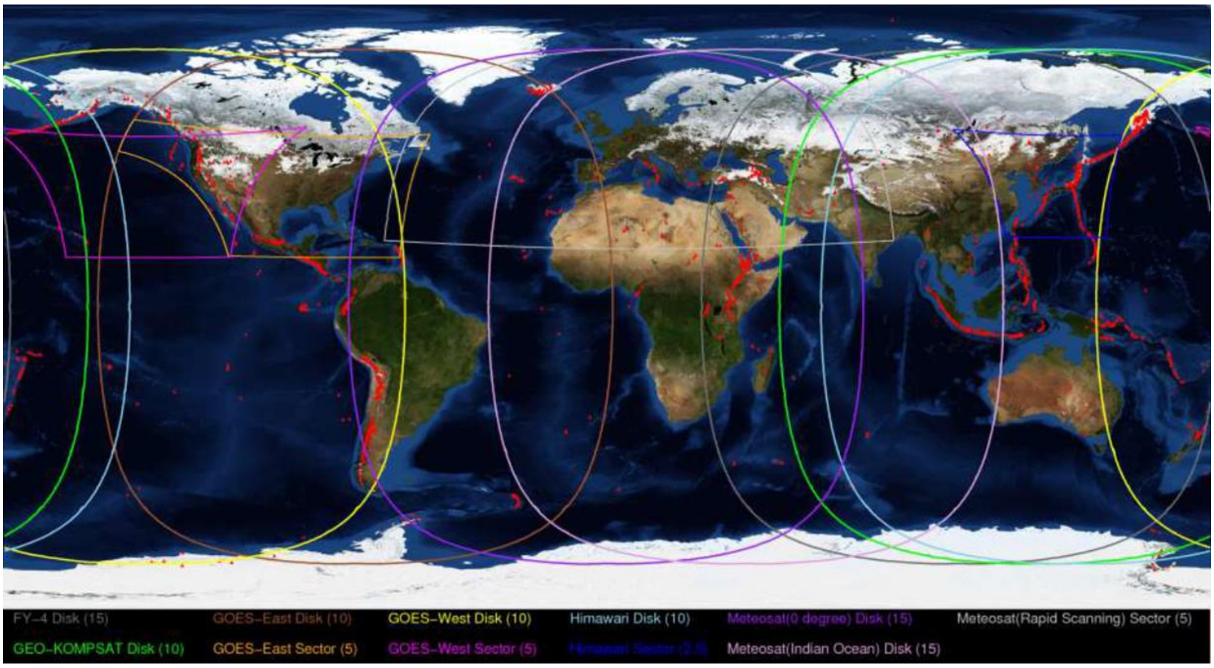

Figure 6. Current routine coverage of the geostationary satellite scanning domains overlaying active or potentially active volcanoes (red)

Manual examination of satellite imagery however, while a critical component of forecast operations, has important limitations. Satellite data volumes have increased significantly over the years (see Figure 7 as example) and it is challenging to manually examine every image, over every volcano, in near real-time. Clouds produced by volcanic eruptions are sometimes difficult to distinguish from meteorological clouds, and meteorological clouds may also obscure ash. As such, and particularly in the absence of eruption reports, clouds may occasionally travel undetected for hours, or may not be detected at all.

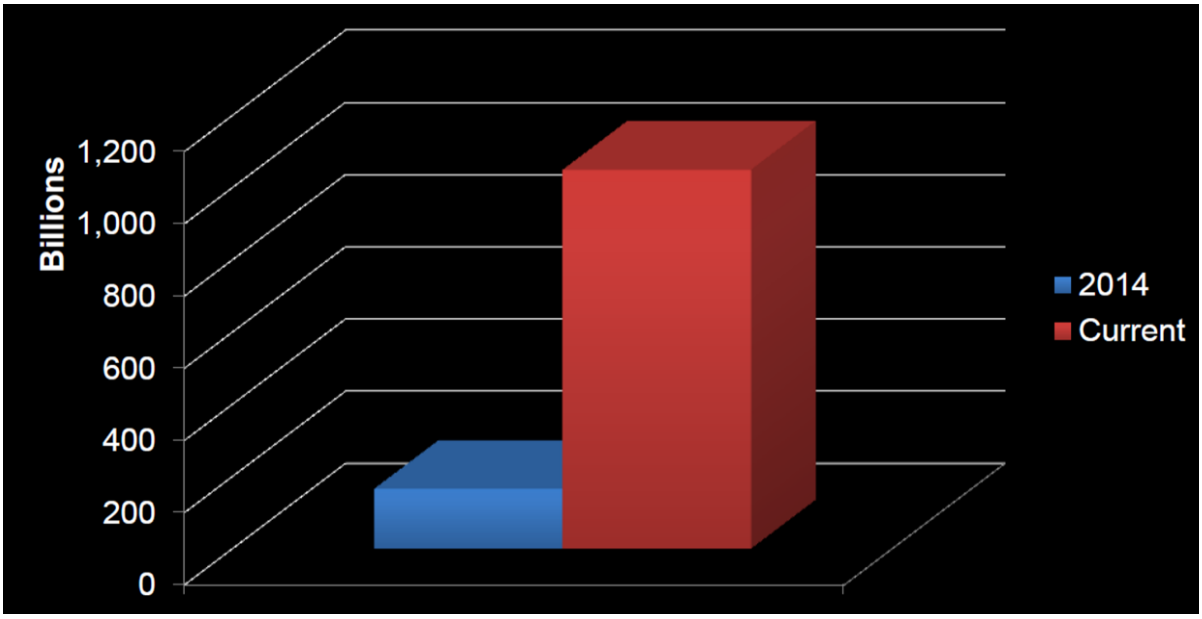

Figure 7. Daily meteorological satellite earth observation count. (Note, only includes satellites that are routinely utilized in operational meteorological applications.)

Fundamental limitations aside, meteorological satellite measurements are the primary observational tool utilized by forecasters, so recent improvements in meteorological satellite capabilities are extremely relevant to operational volcanic cloud monitoring. Compared to the previous generation of satellites, next generation satellites such as the latest GOES-series and Himawari-8 provide much more frequent imagery, with improved spatial detail, and better sampling of regions of the electromagnetic spectrum that are key for volcanic cloud detection and characterization.

Every volcanic ash advisory centre (VAAC) within the framework of the IAVW is now supported, at least in part, by a meteorological satellite that provides high quality images at least every 15 minutes. Several volcanic arcs are routinely imaged every few minutes. Next-generation satellite coverage and capabilities will continue to improve. Figure 8 gives conservative estimates of the minimum number of satellite images each VAAC would need to manually analyse each day in order to achieve complete eruption monitoring, illustrating the need for continued development and sustainment of alerting services.

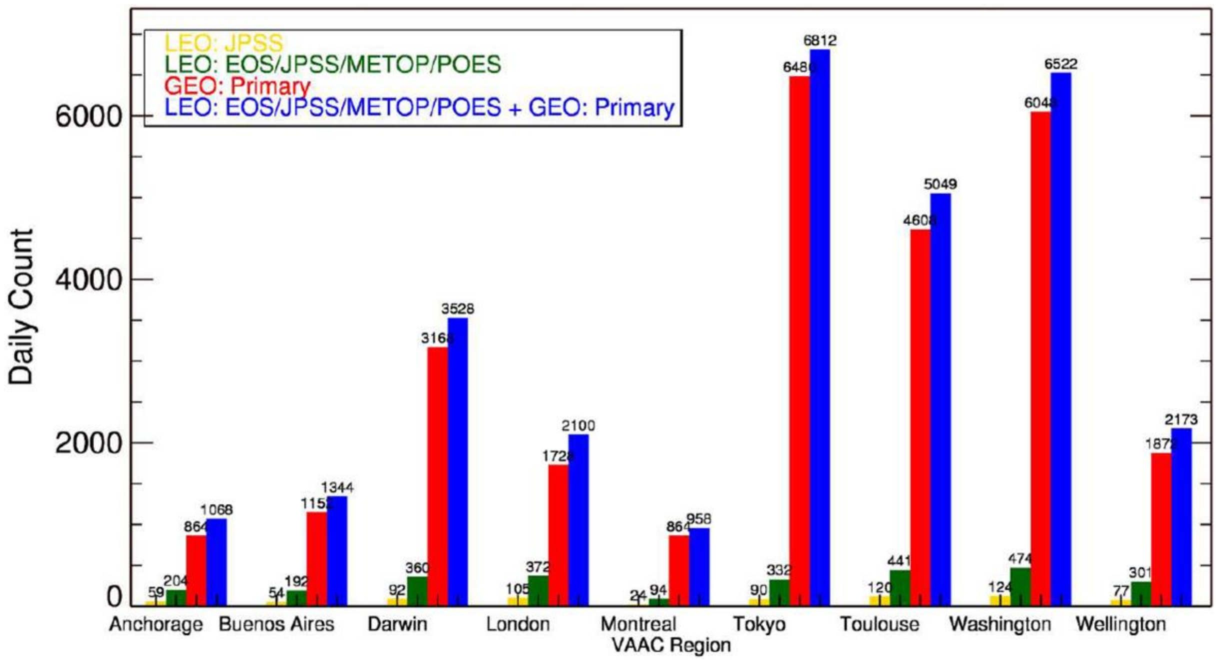

Figure 8. A conservative estimate of the number of daily satellite images pertinent to VAAC operations as a function of VAAC region

Since volcanic ash emissions can occur at any time of the day, VAAC forecasters rely heavily on thermal infrared imagery, which often allows clouds containing ash to be identified by knowledgeable analysts at all times of the day. During the daytime, VAAC forecasters supplement infrared imagery with satellite-based measurements of reflected sunlight at ultraviolet, visible and near-infrared wavelengths. Non-satellite data sources (e.g. webcams, volcano observatory reports, pilot reports, social media, etc.) are also utilized when available to build as complete a picture of the situation as is feasible in real time.

In addition to providing *qualitative* imagery, satellite data has *quantitative* value. Satellite measurements have been used to estimate the height of ash clouds, determine the horizontal extent of ash, and estimate the amount of ash present in each satellite pixel.

Quantitative ash cloud properties are largely derived from infrared satellite measurements, although reflected sunlight and microwave-based methods have also been prototyped. The infrared-based techniques, which can be utilized under a broad range of conditions at all times of the day, are most relevant to operations. Non-infrared based techniques provide valuable supplemental information.

2.3 Needs from the meteorological satellite provider community

In respect of satellite constellations, there is a continual growth in the number of meteorological and other environmental satellites with multispectral capabilities, and an associated significant expansion in the number of earth observations available on a daily basis that presented an information overload challenge for VAACs and others, as illustrated by Figures 6, 7 and 8 above.

While satellite data is the most common source of observation data utilized by the VAACs, the leveraging of additional data sources is important. Moreover, given the heterogeneous nature of satellite constellations and the enormous volumes of data, a complete reliance on manual analysis is already evidently impractical.

With regards to satellite-based remote-sensing in support of the IAVW, it is acknowledged that work is ongoing to:

- Improve the automated detection of new volcanic clouds and gases through, for example, the application of artificial intelligence (AI).

- Improve the initial and ongoing characterization of key parameters (height, loading, microphysics) across a broad range of conditions and uncertainty estimates.

- Automate, through AI, the tracking of volcanic clouds and gases in a manner that is consistent with human expert analysis.

- Support forecasting applications by the systematic provision of key volcanic cloud properties and associated uncertainty for automated dispersion modelling applications.

- Better integration of pertinent non-satellite based observational capabilities such as infrasound, lightning, lidar, radar and so on.

Additional research, development and testing is required to support the current and foreseen future changes within the IAVW brought about by a requirement (both an aeronautical requirement and a meteorological requirement) for *quantitative* volcanic ash cloud and gas information as outlined in the ICAO Roadmap for the IAVW in support of International Air Navigation (hereafter referred to as the 'IAVW Roadmap'). While awaiting validation from stakeholders, functional and performance requirements for quantitative volcanic ash information and forecasts have been drafted for inclusion into ICAO Annex 3 – *Meteorological Service for International Air Navigation* according to the following tentative schedule:

- *Amendment 80 to Annex 3 with intended applicability in November 2023*: Quantitative volcanic ash information to be provided by VAACs on best effort basis;

- *Amendment 81 to Annex 3 with intended applicability in November 2026:* Quantitative volcanic ash information to be designated a Recommended Practice for all VAACs; and

- *Amendment 82 to Annex 3 with intended applicability in November 2029:* Quantitative volcanic ash information to be designated Standard practice for all VAACs.

The IAVW Roadmap also calls for the development and provision of a sulphur dioxide (SO_2) information service and probabilistic guidance for volcanic ash and SO_2. The objectives outlined in the IAVW Roadmap *cannot* be achieved *without* meteorological satellite product development, in coordination with dispersion and numerical weather prediction model development and data fusion efforts.

Satellite products, currently operationally generated by CGMS agencies, provide estimates of ash height and column loading. Publically available CGMS agency products formally designated 'operational' do not provide the needed capabilities, with global coverage, including human expert-like ash detection, automated ash cloud tracking, and sufficient accuracy with regard to height and loading estimates. Fortunately, there are more robust capabilities being developed and tested, such as the VOLcanic Cloud Analysis Toolkit (VOLCAT) and Support to Aviation Control Services (SACS). CGMS agencies are asked to prioritize development of the needed capabilities over incremental improvements to existing operational products.

3 RECOMMENDATIONS FOR CONSIDERATION BY CGMS WORKING GROUP II: SATELLITE DATA AND PRODUCTS (WG II)

The CGMS agencies are invited to consider the following recommendations addressing meteorological satellite product development in support of the international airways volcano watch (IAVW):

- Ensure that the 'data overload' challenge is being addressed within volcanic cloud product development efforts.
- Prioritize development and transition to operations of advanced capabilities – such as human expert-like volcanic cloud detection, automated cloud tracking, and more sophisticated ash/SO_2 characterization, which are needed to support the evolving IAVW – over incremental improvements to existing operational products.
- Coordinate product requirements for volcanic ash and SO_2 with ICAO's IAVW functional and performance requirements to enable integration into forthcoming amendments to ICAO Annex 3 – *Meteorological Service for International Air Navigation*.
- Ensure coordination between remote-sensing product development and operational modelling capabilities required for providing forecasts in accordance with ICAO's IAVW requirements.
- Recommend that geostationary satellite operators provide rapid scanning services (< 5 minutes) in support of VAAC operations when and where possible to ensure timely detection of new volcanic events.
- Recognize that no individual satellite sensor provides all of the needed measurement capabilities for volcanic cloud applications and, therefore, that a multi-sensor holistic approach is required to meet ICAO's evolving IAVW requirements (as concluded by a WMO Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) product inter-comparison effort).

4 CONCLUSIONS/FUTURE CAPABILITY OUTLOOK

With the deployment of new satellite capabilities, there is always a significant time lag between initial deployment (launch and commissioning) and full utilization of the measurement capabilities. The time lag occurs because, although existing and accepted techniques can usually be implemented quickly with new data sources, longer-term data collection and scientific research are needed to develop more sophisticated practical applications, such as reliable *quantitative* tools for tracking and charactering volcanic ash clouds. There is also necessarily a significant amount of work to go from cutting edge research, the discernment of the correct way forward, and its implementation as a 24/7 process supported by procedures, training competencies, and operational technical support.

Qualitative volcanic cloud identification techniques are relatively mature from the research perspective, although improved techniques continue to be explored, but are still being implemented consistently by the VAACs worldwide, in combination with improved procedures for integrating satellite and other data and communicating insights.

Major future improvements in satellite products will largely be associated with *quantitative* applications, such as ash property mapping, eruption alerting, automated integration of satellite-derived products, and operational dispersion models.

Ash-cloud property mapping often consists of estimates of ash altitude, mass loading (i.e. mass of ash per unit area), and the effective grain size. The cloud altitude information is generally limited to the highest ash cloud layer in a given location. In addition, the estimated altitude will correspond to the cloud top for freshly erupted material and the middle of the cloud layer for dispersed ash. The ash mass loading is an estimate of the mass of ash integrated along a ray path through the cloud in a given satellite pixel. In order to convert the mass loading to mass concentration, an estimate of the geometric thickness of the ash layer is needed. The geometric thickness is generally unknown, so ash concentration is rarely derived from meteorological satellite data. The effective grain size product, which must be retrieved in tandem with mass loading, provides information that may be related to the residence time of ash in the atmosphere, but more research is needed to establish an operationally relevant relationship.

Given that many terabytes of meteorological satellite data are collected every day, automated volcanic eruption alerting has proven to be a useful complement to human expert analysis of satellite imagery. Further, several research studies have shown that the integration of high-quality satellite-derived information and dispersion models improves ash-cloud forecasts.

Computer algorithms that map ash-cloud properties must first accurately determine which satellite pixels actually contain volcanic ash. Automated volcanic ash detection is very challenging for the same reasons that human expert identification is sometimes difficult. The additional challenge is that computer algorithms struggle to replicate the feature identification skill of human experts, especially when the attributes of the feature of interest and background are highly variable, as is the case with volcanic clouds. Eruption alerting and dispersion modelling applications also require skilled automated ash detection. Transforming satellite measurements into estimates of ash cloud properties, such as altitude and loading, is also exceptionally challenging because the satellite measurements are influenced by so many factors, including background conditions (e.g. meteorological cloud cover, surface temperature, atmospheric moisture, etc.). Thus, while ash cloud property mapping was first introduced in the scientific literature in1994, such products have largely been used in research studies.

Usage of *quantitative* satellite products in VAAC operations has been very limited for various reasons. From a scientific perspective, high quality mapping of ash cloud properties, from eruption start until ash is no longer discernible in satellite imagery, has yet to be demonstrated across a broad range of conditions due to the aforementioned complexities. In addition, 24/7 support for the generation of satellite-derived volcanic ash products only recently began in a few meteorological and satellite agencies.

Transitioning satellite products from an experimental to an operational environment generally requires one year or more of effort. In addition, when *quantitative* satellite products are formally introduced to VAACs, sufficient time will be required for VAAC analysts to become proficient in using them for operational decision-making within a quality managed environment. In addition to the research timeline, all planning for future ICAO requirements should take these factors into account.

Given the above practical factors and the timeline of ICAO's new IAVW requirements, immediate prioritization of the development of information services and research-to-operations efforts that support the specific needs of the IAVW is absolutely critical. WMO and ICAO therefore kindly request the CGMS agencies to recognize and be responsive to the issues, challenges and recommendations identified in this paper.