

Volcanic eruptions & volcanic ash in the atmosphere

WMO Aviation Meteorology training seminar 2022

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This commentary accompanies the recorded power-point presentations.

Welcome to these sessions on volcanic eruptions and volcanic ash in the atmosphere, which are part of the WMO Aviation Meteorology training seminar of 2022.

In preparing these sessions I acknowledge the course notes of my colleagues Ciaran Doolin and Ashlee Parkes from the Meteorological Service of New Zealand Ltd, on which these sessions are based.

Outline of topics 1 to 8 to be covered in these sessions on volcanic ash.

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- 1. Introduction to VA – history, world volcanoes, volcanic groups, eruption column**
 - 2. Hazards to aviation of VA – drifting ash cloud, composition of particles (Mt Ruapehu ash demo), jet engine effects, windscreen abrasion, on-ground effects**
 - 3. Effects on airspace in your region, ash concentration**

In the first session we will start with some definitions and history, the distribution of world volcanoes, how they can be grouped, and the structure of eruption columns.

Let's start. There are many aspects to severe volcanic eruptions, and they have their own hazards, but for this seminar we are concerned with volcanic ash that enters the atmosphere. Ash has severe effects on aircraft, but more generally it can affect air quality for the general population and if it accumulates on farm-land it can have beneficial or toxic effects.

The first time that major attention was given to the effects of ash on aircraft was in 1980 with the eruption of Mt St Helens in Washington state, USA. Then, two years later, probably the most documented case for aviation was that of a British Airways Boeing 747 that was severely impacted by ash from an eruption in Indonesia.

Here is a summary of some of the significant eruptions of the past 40 years or so. The New Zealand eruption in the mid-1990s was very significant for my country, New Zealand, and we will look at a demonstration a little later of what the ash from that eruption looks like.

Inside the Earth we have the outermost solid crust and upper part of the mantle, and beneath that are layers of solid and liquid material. The outermost layer is divided into so-called plates, and it's when the liquid is forced up through gaps in the plates that we have an eruption.

This map shows the worldwide distribution of volcanoes. There are many of them and they are concentrated in certain zones. Three quarters of the volcanoes lie along the so-called "Ring of Fire" which surrounds much of the Pacific ocean.

We can divide volcanoes into three main types. First are the "shield" volcanoes which have very hot magma but little dissolved gas, whether it be carbon dioxide, water vapour or sulphur dioxide. These eruptions tend to flow out with less ash production. The second type of volcano is "cone" or "strato-volcanoes" where the temperatures are not so hot and there is a moderate amount of gas. These eruptions tend to be flowing with moderate explosions. The third type is "caldera" or "super volcanoes" where the magma is at a lower temperature but there is a lot of gas. These eruptions are very explosive.

The eruption column can be divided into sections. First, we have the gas and solid material that's propelled upwards immediately above the volcano. Then there is the umbrella region that spreads out from the volcano. In this photo of the 2010 eruption of Eyjafjallajökull in Iceland, upper winds have sheared the umbrella across to the right of the image. That sheared ash has become a downwind plume, and that has spread the region of ash fall well across the right-hand side of the photo and beyond.

What are the hazards to aviation of volcanic ash?

Ash is made up of sharp, hard particles ranging from fine powder to particles of a few millimetres in diameter. Here is a video of ash that I saved from the eruption of Mount Ruapehu in New Zealand in 1995. As I play the video, observe the Ash escaping from the bottle – it looks like smoke, but it is actually composed of very small, hard particles of rock. Perhaps you can imagine the effect of an aircraft flying through a cloud composed of this.

If an aircraft flies through ash, it will wear away at moving parts, and may melt inside the engine causing a total failure of that engine, leading to so-called "flame-out". Any forward-facing surface on the aircraft is likely to be scratched, and this is particularly hazardous on the windscreen because it will reduce visibility. The photograph is of an aircraft windscreen that was damaged in the 1989 eruption of Mount Redoubt in Alaska. If you look closely at the glass, you will see that it has been significantly obscured on the right-hand side where most of the abrasion occurred. Small particles of ash can also affect sensors on the aircraft, impacting their performance.

Other hazards include sulphur dioxide that can react with water to produce corrosive sulphuric acid. On the ground, any ash accumulation can be whipped up by the wind and become just as hazardous as encounters in flight, particularly because aircraft would fly through it during take-off and landing.

Can volcanic ash affect airspaces that are long distances from any volcanoes?
Unfortunately, the answer is 'Yes'.

When volcanic ash enters the upper atmosphere, winds can carry it for thousands of kilometres. A prominent example is the Cordón-Caulle eruption of Chile in 2011 & 2012, when the Ash completely encircled the Southern Hemisphere. Things to consider when monitoring and predicting the transport of ash are the upper wind profile, the

magnitude and duration of the eruption itself, how quickly the ash will fall out of the cloud, and the prospects of precipitation speeding up the removal of ash from the air.

The eruption of the Eyjafjallajökull volcano caused massive disruption to air travel across Europe in 2010. Since then there has been research on the effects of ash concentration on aircraft in flight, showing that aircraft can tolerate small amounts of ash although this exposure may lead to a shorter engine life. The research showed that aircraft can tolerate flying for one second in a concentration of 14.4 grams of ash per cubic metre, equivalent to flying for two hours in a concentration of 2 milligrams of mass per cubic metre. Currently, in 2022, Volcanic Ash Advisory Centres do not factor in ash concentration, but there is a plan to do so in the future.

So far, we have focused on major eruptions, but we should note that there are many small eruptions that may eject only gas or a small ash plume. Such minor events have limited impact on aviation operations.

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- 4. *VA meteorological products – VA SIGMET, the nine VA Advisory Centres, VAA, Pilot reports, TAF, Metar***
 - 5. *Volcano observatory products – VONA, VAB***

Volcanic ash meteorological products include the Volcanic Ash SIGMET, Volcanic Ash Advisories (VAA), Terminal Aerodrome Forecasts (TAF) and Meteorological Aerodrome Reports (METAR).

A volcanic ash SIGMET is valid for six hours rather than the standard four hours for most other types of SIGMET. They include the volcano name and location, whether they are for observed or forecast events including the height and extent of the ash, and they have a forecast of the position of the Ash at the end of the SIGMET validity period.

It's important that, after an eruption has been confirmed, the initial SIGMET gets issued as soon as possible. This is to give early notice to all aircraft that may be affected. In New Zealand, for example, the Civil Aviation Authority expects the initial SIGMET to be issued within five minutes of confirmation of an eruption, and a full SIGMET to be issued within 35 minutes of receipt of a VONA (we'll look at VONA a little later). A final volcanic ash SIGMET is cancelled when ash is no longer observed on clear satellite imagery or when it's been 24 hours since the last indication of ash.

Here is an example of an initial volcanic ash SIGMET issued by the Wellington Volcanic Ash Advisory Centre for an eruption of Whakaari-White Island just off the northeast coast of New Zealand, and the subsequent full volcanic ash SIGMET for the same event. Note the extra detail in the full SIGMET, including all the latitudes and longitudes of the boundary of the ash cloud.

There are nine Volcanic Ash Advisory Centres around the world. They look after these air-spaces and are based in London (UK), Toulouse (France), Tokyo (Japan), Darwin (Australia), Anchorage (Alaska), Montreal (Canada), Washington (USA), Wellington (New Zealand), and Buenos Aires (Argentina).

The Volcanic Ash Advisory is valid for six hours. It has more information than a SIGMET, including the forecast position of ash every six hours up to 18 hours into the future. The Volcanic Ash Graphic is just the VAA in graphical form. As for the SIGMET, timeliness is important – the initial VAA is sent quickly and gives only the current observed location of the ash. A full VAA also gives the forecast locations of the ash. In New Zealand, the Civil Aviation Authority expects the initial advisory to be issued within 10 minutes of confirmation of an eruption, and the full advisory to be issued within 30 minutes of the VONA. Note that Volcanic Ash Advisory Centre areas of responsibility often differ from Flight Information Regions (FIR), so issuing offices must communicate to ensure consistency. An advisory has the same cancellation criteria as a volcanic ash SIGMET.

Here is an example of an initial Volcanic Ash Advisory and the associated Volcanic Ash Graphic, again for an eruption of Whakaari-White Island in New Zealand. Every volcano in the world has a unique number, and in this case the number is 241040. Note that the “FCST VA CLD” (forecast volcanic ash cloud) is stated as “NOT AVBL” (not available) in this initial product.

Here is an example of a full volcanic ash advisory and associated graphic. The full advisory has extra detail of the forecast location of the ash in six-hour time steps. It also has a remark (RMK) stating that the ash emission was weak, and was visible on webcam and satellite imagery.

The remark usually states how the ash was identified, the type of emission, and how the height and movement of the ash was forecast.

Here are examples of VAA remarks when the ash was clearly visible. There are a number of abbreviations used in this slide, and the link at the bottom is to an online list of abbreviations, so you can find out what each abbreviation means.

Here are examples of remarks when ash was not clearly visible. So it was not so easy to discern the ash from satellite imagery or other data sources.

If volcanic ash falls onto an aerodrome, then the Terminal Aerodrome Forecast (TAF) includes a mention of the ash. Likewise, a Meteorological Aerodrome Report (METAR) mentions ash if the ash falls within 8 km of the aerodrome or, if it is within 16 km of the aerodrome, as a VC or “vicinity” phenomenon. Any distant ash can be reported as a remark (RMK).

Here are real examples of TAFs which include volcanic ash associated with visibility reductions. The stations here are Gisborne Airport (NZGS) and Rotorua Airport (NZRO), both on the North Island of New Zealand. These METAR also include ash associated with visibility reductions. NZTG is Tauranga Airport on the North Island of New Zealand.

The VONA (Volcano Observatory Notice for Aviation) and Volcano Alert Bulletin are issued by volcanic observatories rather than meteorological offices...

... they describe the state of unrest of the volcano and potential hazards. The VONA uses a four-colour system, ranging from Green where there is little activity, through to Red where an eruption is imminent, with significant ash likely, or an eruption is underway. A Volcano Alert Bulletin describes the geological state of the volcano.

Here is an example of a VONA for Whakaari-White Island in New Zealand, and...

... here is another example, which includes a photo, for an eruption in the Ha'apai region of Tonga in the southwest Pacific.

This is an example of a Volcano Alert Bulletin issued by the Vanuatu Meteorology and Geohazards Department in the southwest Pacific. I'll leave you to read the contents at your convenience.

6. Responding to VAA, with examples of how you deal with VA in your agency
7. VA monitoring – manual observations, satellite imagery (including RGB, SO2 products), soundings, upper wind data, webcams

Responding to volcanic ash advisories.

How do you deal with volcanic ash within your agency? We look forward to receiving your feedback for discussion at the live seminar.

Volcanic ash monitoring. There are many ways in which meteorological offices can monitor ash – there are pilot reports and other manual observations, satellite imageries, upper wind data and soundings, webcams, and lightning sensors. Let's have a closer look at these.

A pilot report (PIREP) reports any ash to air-traffic control or comes in by phone or email from airlines. Meteorological offices must always review pilot reports and check the latest forecasts against them for forecast accuracy.

Here is an example of a real PIREP from Aoba in Vanuatu (in the southwest Pacific), and another example from Whakaari-White Island in New Zealand. Note that not all such reports need to be of significant eruptions – some may be minor.

Satellite imagery is a great tool for detecting and monitoring volcanic ash. However, when there is meteorological cloud composed of liquid water or ice, monitoring becomes difficult – ash clouds are often thin, so they show up better on visible imagery than InfraRed. Thankfully, modern satellites allow techniques to be used based on multi-spectral imagery, for example true-colour imagery which allows us to distinguish between ash (which will usually appear brown) and steam (which will appear white or grey), noting of course that imagery at these visible wavelengths is only available when there is daylight.

Here is an example of a conventional visible image from the Mount Ruapehu (New Zealand) eruption in 1996, when an ash plume was swept to the north-northeast in a strong southwesterly flow. On the right is the infrared image several hours later, which still has some evidence of the plume although it is less clear.

This is an example of a true-colour RGB (Red-Green-Blue) image for an eruption at Aoba, Vanuatu in 2018. Here, three narrow bands in the visible part of the

electromagnetic spectrum have been combined to make the final imagery look like the “true” colours that we would see with our own eyes if we were looking at Aoba from above. The volcanic ash streaming to the east (highlighted) is brown, whereas the meteorological cloud everywhere else is either white or grey because it’s composed of only liquid water or ice crystals.

The Himawari-8 satellite of the Japan Meteorological Agency uses the 12.4 and 10.4 μm bands in the InfraRed part of the electromagnetic spectrum, plus the 8.6 μm SO_2 (sulphur dioxide)-detection band, to create an ash and dust RGB product. Other satellites may replace the 8.6 μm with the 3.9 μm band in the near-InfraRed. These bands are carefully combined in red, blue and green to give us a rich source of information about what the satellite is sensing.

The three colours can be interpreted as follows: a strong red or magenta (which is a reddish purple) or orange colouring indicates ash. Any bright green indicates sulphur dioxide. And any yellow means a mixture of ash and sulphur dioxide.

In this loop of ash RGB images from an eruption at Aoba, Vanuatu in 2018, we see an initial plume of bright green (indicating sulphur dioxide) and patches of orange drifting eastwards away from the volcano. At another time in the loop a redder plume appears near the volcano, indicating more concentrated ash.

This slide illustrates the schemes used with different satellites. On the left is an example like we saw in the previous slide for the Aoba eruption. On the right is the image at the same time, but using the slightly different scheme of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

The National Oceanic and Atmospheric Administration (NOAA) and Cooperative Institute for Meteorological Satellite Studies (CIMSS) have collaborated to create a volcanic ash monitoring website that combines imagery from geostationary and polar-orbiting satellites around the world. You can visit this website at the link shown.

Following an eruption, the ash cloud will be transported away by the winds in the area. This transport can be modelled by computer, and one such modelling system is the “HYSPLIT”. This model uses NWP (numerical weather prediction) winds and details of the eruption to predict the future location of the ash cloud.

Aircraft winds, and observed and modelled upper-air soundings in the area of the volcano are useful for short-term forecasting of the speed and direction of the ash cloud.

Webcams allow us to view an eruption remotely, as in this photo from Aoba, Vanuatu.

Lightning networks may also be useful in monitoring explosive eruptions where colliding particles create electrical discharges. Note, though, that eruptions with flowing lava, such as from the shield volcanoes that we defined earlier, will not produce lightning.

8. Tongan eruption case study (15 January 2022)

Let's have a look at a recent eruption that occurred in Tonga in the southwest Pacific in January 2022.

On the right is a close-up map of the islands of Tonga, and the red circle shows where this particular eruption occurred.

Some facts about the main eruption of the Hunga Tonga – Hunga Ha'apai eruption on 15 January. It happened just after 0400 UTC, and it was an underwater eruption where sea-water entered a reservoir of magma and generated a very explosive reaction. In this case the eruption column formed within minutes and reached a height of 58 km. There was a lot of water vapour emitted but not much sulphur dioxide. The umbrella region reached a height of 30 km, so in the stratosphere. It was a particularly explosive eruption, and the shockwave propagated around the Earth – if you search in YouTube you will find video clips related to this event. The shockwave generated a sonic boom sound-wave, and there was intense lightning. People on Pacific Islands observed the sea retreating soon after the eruption, then a tsunami hit. After 12 hours, nearby islands got a hundred millimetres or 10 cm of ash on the ground.

During this major event, the Tonga Meteorological Services continued their operations and communicated with the Volcanic Ash Advisory Centre in Wellington by satellite phone. After the eruption, high-level ash was blown westwards by the upper winds onto northern Australia and beyond, and this was well handled by the Darwin and Wellington Volcanic Ash Advisory Centres working together to ensure consistent warnings. They also communicated with the Toulouse Volcanic Ash Advisory Centre for the ash that drifted further west onto the Indian Ocean. Pilot reports advised that the ash was suspended above their flight levels, so above Flight Level 400. Here is a link to a very good talk on this eruption given by the Australian VLab Regional Focus Group in February 2022.

This is a loop of InfraRed imagery from the Himawari-8 satellite of the Japan Meteorological Agency, taken two days before the major eruption. Here I have chosen a monochrome image, recognising that different countries will use different colour enhancements, so to maintain a consistent understanding of the imagery I have chosen a common monochrome setting. We see the eruption occurring near the start of the loop and, in the InfraRed, although the image shows the ash cloud rapidly developing, towards the end of the loop the ash cloud looks fairly similar to convective meteorological cloud to the north.

This is the same type of imagery but two days later, the date of the main eruption. Here we see an extremely violent initial eruption and we can see the shockwave extending rapidly outwards as concentric circles. I will let this run a few times so you can view this dramatic sequence of images.

This is a true-colour RGB loop of the major eruption. Here we see extra detail and we get a sense of the explosive nature of the Tonga eruption. Because the image is within visible wavelengths of electromagnetic radiation, when the sun sets the image becomes dark towards the end of the loop.

The shockwave from the eruption propagated around the entire Earth, and the link on this slide is to a specially constructed animation of satellite images that show the shockwave propagating all the way around the planet.

The month before the main eruption there was minor activity at Hunga Tonga – Hunga Ha’apai. This is an initial Volcanic Ash Advisory issued on 19 December for a plume of smoke and steam generated by the volcano.

This is the initial Volcanic Ash Advisory for the main eruption on 15 January. We have the date-time group, showing that the message went out at 04:39 UTC. The volcano was Hunga Tonga – Hunga Ha’apai , and its volcano number is 243040. The eruption details state that it was a new eruption seen in satellite imagery, and the extent of the observed ash cloud is given, but there is no mention of forecast position of the ash at this early stage of the event. More information is to follow.

This is the full Volcanic Ash Advisory issued at 05:19 UTC for the same volcano but with much more detail. It contains the observed location of the ash cloud and the forecast positions, which I have summarised for our purposes here.

This is the Volcanic Ash SIGMET issued at 05:21 UTC for the eruption, and the associated graphical SIGMET for the “NZZO” oceanic Flight Information Region.