Tools and dispersion models
For Observing, and Forecasting Volcanic Ash

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A variety of tools exist for evaluating and predicting the presence and dispersion of volcanic ash so as to ensure the safety of aircraft crews and passengers. These tools include both in situ and remote sensing instruments as well as numerical models.

Before a volcanic event occurs, you should be familiar with your regional Interagency Operating Plan for Volcanic Ash Events. These plans detail interagency protocols and response procedures in case of a volcanic event. You can find some of these documents at this web site: http://www.ofcm.gov/homepage/text/pubs.htm

In case of volcanic unrest or eruption in or near your forecast area, it is vitally important that you remain in close communication with the Volcano Observatory responsible for the volcano. Volcanic eruptions can be detected by ground-based monitoring instruments, pilots, web cams if available, or observed on satellite imagery. It is important to coordinate with all the agencies mentioned in your region’s operating plan to ensure consistent and helpful warning information.
Volcanic eruptions create numerous natural hazards and many of the world’s active volcanoes threaten the aviation community.

Wind-driven ash (tephra) threatens far larger areas than any other volcanic hazard.

Ash can also aggregate into large particles that fall quickly and cause tremendous harm to life at the surface.

Volcanic clouds can be tracked using radar and satellite microwave sensors.

Noxious gases from eruptions are monitored not only by air chemistry sensors, such as OMI and TOMS, but also by geostationary satellites.

Since 2003, the Atmospheric Infrared Sounder (AIRS) has provided images of volcanic sulphur dioxide and aerosols.
Satellite Monitoring

Satellite imagery can help you detect and follow volcanic ash at all levels of the atmosphere over wide geographical areas.

Geostationary satellites have the advantage of orbiting over the same location above the Earth's surface at all times. This position allows for continuous monitoring and rapid updates of an ash cloud to determine the areal extent of the plume and its temporal evolution.

However, the resolution of the imagery decreases with increasing latitude as the viewing angle of satellite increases. In addition, there is a parallax error with increasing latitude and height of the eruptive plume, which will cause the plume to appear displaced from its actual geographic location in the direction away from the satellite.
Polar orbiting imagery provides high resolution data with better coverage over high latitudes than seen over the equatorial regions of the Earth. However, the observations are not as frequent as with geostationary satellites covering the same region.

Similar to geostationary satellites, parallax errors can also occur with polar orbiting imagery towards the edge of the scan. Polar orbiting satellites used for monitoring volcanoes include those from NOAA, NASA (Terra and Aqua), EUMETSAT (MetOp series), and China (FY-1 and -3 series).
Identifying Presence of Ash
(use of satellite imagery)

- Methods for exploiting different features of data collected from satellite detectors sensitive to various wavelengths have been developed to better evaluate the presence of volcanic ash.

- Each type of satellite gives a unique observation of the plume and different processing techniques of the data allow forecasters to focus on specific aspects of volcanic ash. We will utilize these data to help identify the presence of volcanic ash, and predict the height and extent of dispersion of volcanic ash.

- Ash clouds can be seen on visible satellite imagery, especially when the plume is moving over darker features below, such as ocean surfaces or dark vegetation.

Visible Image

Soufriere Hills volcano eruption, February 2010.
Review the image on the right panel and select the location where volcanic ash may be present.

- The correct answer is D.
- The ash cloud has moved over the water and can be discerned from the more opaque cloud cover.
- In regions of cloud cover or more reflective surfaces, ash will be more difficult to detect depending on the water content of the plume. The less water vapor in the plume, the less reflective it becomes and therefore more difficult to identify in visible imagery.
Thermal Infrared Channel

• Single band (3.0 – 14 µm) infrared imagery can be used in the evaluation of volcanic eruptions.
• As illustrated by the animation, shortly after the eruption, the cold-topped ash cloud can be found on the thermal IR image loop. As the ash cloud begins to thin, it becomes more difficult to distinguish from thin cirrus clouds, and contamination from the surface and lower level features such as clouds can mask the ash.
• When using single channel infrared imagery, detection of volcanic ash can be a challenge since clouds can have the same brightness temperature as the ash plume. This can, for example, result in misinterpreting high clouds as ash.
False Color Imagery

• Processing imagery with false color helps highlight features of interest. False color or RGB (red, green, blue) products take measurements from different channels and combine them into one product, allowing simultaneous analysis of more than one channel.

• As can be seen from the image above, the colors provide more discernible information than gray scale images in the application of detecting and interpreting volcanic ash. In this example, the volcanic cloud is blue from the thermal infrared channel and the yellow hot spot from the volcano appears from input from the visible and shortwave infrared channels.

• These images become available several hours after an eruption. Thus, they will be more useful to forecasters further away from the erupting volcano.
Split Window Technique

• One of the most common methods of detecting volcanic ash has been the use of differences in the brightness temperature in two longwave IR channels (10 and 12 micron infrared channels), also known as the split window technique. Keep in mind that IR observations are available day and night, which makes continuous monitoring possible.

• On GOES 12-15 satellites the 12-micron channel has been replaced by the 13.3 micron carbon dioxide channel for cloud height determination. Thus, the split window imagery will not be available until the GOES-R series of satellites becomes operational. However, this imagery is still available from polar orbiting satellites.
Use of multi-channel imagery:

- 10.7 um - 12.0 um temperature difference
- 8.5 um - 10.7 um temperature difference
- 3.9 um - 10.7 um radiance/temperature difference
- 3.9/10.7/12.0 um combined product

- Emissivity of silicate particles is higher at 12.0 um than at 10.7 um
- Emissivity of water/ice particles is lower at 12.0 um than at 10.7 um

...... therefore

- In standard vis and IR, volcanic ash clouds can resemble water-bearing clouds.
- Volcanic ash clouds with a high concentration of silicate particles exhibit optical properties in the IR (8-13 um) that can be used to discriminate them from normal water/ice clouds.

Take a temperature difference

\[ BT_{12.0\,\text{um}} - BT_{10.7\,\text{um}} = \text{positive for ash/dust} \]

\[ BT_{12.0\,\text{um}} - BT_{10.7\,\text{um}} = \text{negative for ice/water cloud} \]
10.7μm-12.0μm product

A 10.7 micron image showing the ash plume (outlined in yellow) from an Oct 21, 1997 eruption of the Soufriere Hills Volcano on Montserrat.
The volcano had erupted 6.5 hours earlier (during daylight hours). The plume is still quite distinct but it is hard to distinguish from the high clouds.

The 10.7 μm - 12.0 μm brightness temp difference shows the main portion of the volcanic ash plume distinguished by large negative differences.
The image on the left is a band 4 image, and shows how difficult it is to distinguish the volcanic cloud. The image on the right is a band 4-5 difference image, and shows the volcanic cloud clearly.
Challenges in using the 10.7-12.0 um difference product

• For optically thick plumes, when water and ice are mixed with the volcanic debris, the ‘ash’ signal may be confused.

• Low ash concentrations can be difficult to detect.
3.9-10.7 μm product

Removes the emitted signal and therefore enhances the reflected signal.

On the 3.9 μm image, notice that the plume is hard to detect.

However, on the reflectivity product, the 3.9 μm - 10.7 μm difference, the plume is readily distinguished.

Since the radiation detected by the 3.9 micron channel is a combination of reflected and emitted radiation, the thermal infrared is used to remove the emitted radiation from the 3.9 micron signal, leaving the reflected solar radiation.
3.9/10.7/12.0 μm combined product

In order to remove as much background information as possible and show only the ash plume, a 3-channel product using the 3.9 μm, 10.7 μm and 12.0 μm imagery has been created (a combination of the previous 2 methods).

(Ellrod et al. 2001)

\[ B = C + m [T(12.0) - T(10.7)] + [T(3.9) - T(10.7)] \]

- \( B \) = output brightness value
- \( C \) = constant = 60 (determined empirically)
- \( M \) = scaling factor = 10 (determined empirically)
- \( T \) = brightness temperature at (wavelength)
Bezymianny Ash Cloud - 25 Feb 99 - GOES-10 Multispectral
NOAA/NESDIS/ORA/G. Ellrod
Sulfur Dioxide Product

- Sulfur dioxide can appear in high concentrations in the vicinity of some volcanic eruptions. Early on in an eruption, the presence of sulfur dioxide can be helpful in identifying locations of high-altitude eruptions. It can also be used to detect low-altitude eruptions where more conventional tools such as the split window technique do not show the presence of ash.
- Sulfur dioxide also stays in the atmosphere longer than volcanic ash. Forecasters use this product to follow up on a pilot report of sulfur smell in a location or at a time when an eruption is not expected. If the sulfur dioxide is centered over a volcano, a call to the Volcano Observatory can confirm whether or not the volcano is active.
- This image was taken by the OMI sensor on the NASA Aura satellite just after the eruption began from the Soufriere Hills volcano on the island of Montserrat.
- Instruments available on some polar orbiting and geostationary satellites are helping forecasters detect sulfur dioxide. These data are used to evaluate the areal coverage of the plume and can help track the progression and expansion of the ash cloud. GOES sounder channels can also be used to evaluate sulfur dioxide concentrations.
On an evening shift you are briefed by the Volcano Observatory that a volcanic eruption is expected upstream from your forecast area. You receive a report from a pilot stating that there is a sulfur smell in the cockpit. The crew is very concerned that there may be volcanic ash in their flight path. Which of the following products would you reference to diagnose the presence of volcanic ash? (Select all that apply.)

- a) Visible satellite imagery
- b) Thermal infrared imagery
- c) Shortwave infrared imagery
- d) Split window difference imagery
- e) Sulfur Dioxide Product

The correct answers are c), d), and e).

Since you are working an evening shift, visible imagery is not available. Thermal infrared imagery may be helpful when a deep plume of ash is present, but may not be the best product to use. The shortwave infrared imagery may often show hot spots indicating the location of the erupting volcano, and the split window difference imagery detects ash that might not be obvious on thermal infrared imagery alone.

The sulfur dioxide product will help confirm the presence of the gas and be compared with the ash plume location. Keep in mind that sulfur dioxide can reach higher altitudes than the ash particulate, so it may be subject to different winds and be transported in a different direction.

Therefore, just because the crew is smelling sulfur, doesn't mean that the ash plume will also be in the same location. They will still be interested in the details of the presence and location of the ash so that they can avoid it. This will be another opportunity for you to coordinate with your nearest Volcano Observatory.
Beyond detecting the presence of volcanic ash, we can use satellite data to determine other information of importance to aviation operations. The height of the plume, the direction of its movement and the size of the eruption are of interest in evaluating the possible hazards to aviation.

Remember, you may be the first one to detect the volcanic eruption, so it is crucial that you communicate with all the agencies mentioned in your operational plan. Your first call should be to the appropriate Volcano Observatory to confirm or deny any pilot reports of a volcanic eruption.
Plume Spread

• Let’s take a look at how forecasters use satellite data and integrate it with other forecasting and analysis tools to monitor and predict volcanic ash dispersion once an eruption has occurred and the Volcanic Ash Advisory Center (VAAC) has issued a Volcanic Ash Advisory (VAA).

• Actions will differ depending on the proximity of the forecast area (near and distant) to the eruption. We will focus on actions taken by a forecaster regardless of proximity to the eruption. A brief discussion of the actions taken near an eruption will be added where appropriate.
• While the products and forecast priorities will vary depending on each case, the following steps will help you generate a volcanic ash forecast and alert your customers to any potential dangers:

• Evaluate/Confirm the height of the eruption plume
  – Review VAAC (and METWATCH office) products about the eruption
  – Review satellite imagery and radar data
  – Review pilot reports
  – Contact the relevant Volcano Observatory listed in your regional plan

• Determine the direction of plume drift (movement in different directions at different heights)
  – Review satellite and radar data
  – Review HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) output
  – Review upstream wind observations
  – Review forecast winds

• As you are working through these tasks to generate a product in the vicinity of an erupting volcano, it is vital that you remain in communication with the Volcano Observatory responsible for that area, and VAACs, Meteorological Watch Offices, and other forecast offices responsible for warning products in the area covered by ash.
The height of the ash cloud is an important factor in determining hazardous regions for aviation operations. Also, dispersion and trajectory models use the height of the plume as an input. A variety of observed data can be used and combined to determine the height of the plume. These include satellite data, radar, pilot reports, and model output from trajectory models.

The first step in the forecast process is to review the Volcanic Ash Advisory (VAA) issued by the VAAC and any additional information provided by the Aviation Weather Center in their volcanic ash SIGMET. Remember to consult with the local Volcano Observatory. Below is an example of a VAA issued for the hypothetical eruption of Mammoth Mountain.
Question

- You are the forecaster on duty in the area of a hypothetical eruption of a volcanic Mountain. What inquiries would you make? (Select all that apply.)

- a) How large is the eruption?
- b) In which direction is the plume moving?
- c) How far into the atmosphere has it reached?
- d) What time did the eruption begin?
- All of the choices are correct.

Answers to these questions will enable you to refine your forecast and issue appropriate warnings for your forecast area. Be sure to coordinate with adjacent offices to ensure that you provide consistent information to customers.

In addition to working with the appropriate Volcanic Observatory, you can call the nearest CWSU office to review any incoming pilot reports and coordinate the issuance of any aviation or public advisories. Refer to your regional interagency operations plan for contact information. As you can see, it is important to begin developing your relationship with these offices so that collaboration with them is easy and effective during an event. You may even consider developing a checklist with the appropriate steps for a volcanic event.
Satellite and Radar

- After you have become familiar with the VAAC advisory, you are ready to review some of the satellite data that is available. The brightness temperature of the top of the plume, if opaque, can be measured using satellite imagery and compared to rawinsonde data to estimate the height in the atmosphere to which that temperature corresponds.

- This method assumes that the temperature of the ash plume measured from satellite really corresponds to the atmospheric temperature at that level and that the plume top corresponds to the coldest part of the plume. If the ash plume has reached into the stratosphere, its top will appear warmer and could be mistaken for a cloud at a lower tropospheric height. For this reason it is important to look at all available data, radar observations, pilot reports, and dispersion model output to help assign an ash cloud height.
Question

- Based on this NOAA-18 infrared image from a Mt. Redoubt eruption, what is the temperature of the coldest tops of the ash plume? (Select the best answer.)
  
  a) -35°C  
  b) -45°C  
  c) -55°C  
  d) -65°C  

- The correct answer is c), -55°C.  
- The red color in the center of the plume is the coldest temperature which is lower than -50°C but slightly warmer than -60°C. Remember that operationally, you may be able to use the cursor readout to determine the pixel temperature.
Question

Use the rawinsonde plot of the atmospheric temperature and winds with height for Anchorage to help determine the height of the ash plume. (Select the best answer.)

- a) 9 km
- b) 11 km
- c) 13 km
- d) 16 km

The correct answer is d), 16km.

From the rawinsonde data, -55°C appears near 9 km. This level is also near the height of the tropopause. You might expect that this level would logically be where the top of the ash cloud would be observed.

However, in this case, the plume actually rose to 16 km. Looking more closely at the sounding, you can see there are several levels where the temperature is near -55°C. To further refine your estimate of which level corresponds to the top of the ash cloud, you need to investigate the wind profile. Since the plume has moved east of the volcano’s location, and the winds above 13 km are from the west, then the plume must be located where the temperature is -55°C above 13 km, which is 16 km.
• A word of caution, volcanic ash clouds downstream of an eruption tend to become progressively semi-transparent rather than opaque, and can be contaminated by nearby clouds and a warmer surface below. This results in an overestimate of the ash cloud temperature and thus an underestimate of the actual plume height.

• The trajectory of the ash cloud can also be evaluated on satellite imagery and numerical model output to help pinpoint the plume's height. Satellite observed plume motions can be compared with the altitude where the winds from either rawinsonde data or model soundings appear to match.

• Radar data may also be used to find the top of the ash cloud.
Question
Which of the following tools are useful in determining the height of ash plume when used with satellite imagery? (Select all that apply.)

- a) rawinsonde data
- b) model sounding data
- c) pilot reports
- d) surface observations

- The correct answers are a), b), and c).

- Rawinsonde data and pilot reports can be combined with satellite imagery to determine the height of an ash plume. Model-derived sounding data could also be useful. Surface observations generally do not include observations of the tops of clouds or ash plumes. Remember that collaboration with the local Volcano Observatory will provide you with the most up-to-date information about an eruption.
Spread/Plume Drift

- The direction the plume is moving can be observed by animating consecutive geostationary satellite images and watching the expansion of the ash cloud.
- Also, once the height of the plume is known, wind field forecasts and trajectory models can be used to determine where the plume can be expected to move.
- Keep in mind that ash plumes that reach high into the atmosphere are subject to parallax error, especially at high latitudes on geostationary imagery and in regions away from the satellite sub-point with polar orbiting satellites. These errors can lead to incorrect placement of the plume and analysis of plume drift.
Upstream Wind Obs

• Wind and temperature observations provided by rawinsondes and aircraft aid in the analysis of the height and direction of transport of the volcanic ash plume. Upstream data indicates what direction the plume will travel and when or if it will reach your location.

• Also, the direction of the winds at different heights above the ground can be used to predict how the plume will move initially at specific levels. Data near the location of the plume can be used to determine the height of the plume. Note that incoming pilot reports depend on the location and perspective of the pilot, and as such they may or may not represent the reality of the situation.

• Let’s go to a hypothetical eruption at Mammoth Mountain. The location of nearby upper air stations have been added.

Which upper air station (image, above) would best represent the conditions surrounding the volcano? (Select the best answer.)

a) Oakland, CA (OAK)
b) Reno, NV (REV)
c) Elko, NV (LKN)
d) Salt Lake City, UT (SLC)

The correct answer is b), Reno. This station is closest to the location of Mammoth Mountain, and is on the same side of the Sierra Nevada Mountain range.
Question

- Based on the Reno, NV sounding from 12 UTC on 6 January, at what level would you expect the fastest transport of ash, and toward which direction will it travel?
  - The correct answer is **FL250 to 390** with movement of the plume toward the **west**.
- The strongest winds in the sounding are seen in the layer between 20,000 and 35,000 feet coming from the east, so we would expect to see the strongest transport in this layer toward the west.
- In addition to rawinsonde data, sounder data from satellites and AMDAR data can provide higher temporal resolution of the vertical profile of the atmosphere.
Forecast Winds

• Gridded forecast data will give you a comprehensive view of the three-dimensional wind field based on observed and numerical weather prediction forecast data. These wind fields can be used to evaluate the evolution and transport of the ash cloud and are input into dispersion models.

• Locations near the volcano may not have rawindsonde sites nearby. However, soundings derived from model data can give estimates of the vertical characteristics of the wind field.
**HYSLPIT Output**

- The HYSLPIT (Hybrid Single Particle Lagrangian Integrated Trajectory) trajectory and dispersion model can be run using the volcanic ash version of the model available through: [http://ready.arl.noaa.gov/READYVolcAsh.php](http://ready.arl.noaa.gov/READYVolcAsh.php). This model has been designated as the primary model to be run by the NWS for volcanic plume dispersion forecasts. The version of the model on the site above was developed specifically for volcanic ash events.

- A list of volcanoes provides the details on location and summit. You can select a volcano and then add details about the eruption including the date and time, duration and the height of the ash cloud. There is an option to reduce the amount of ash displayed which is intended for situations where a great deal of water vapor is present in the plume and the displayed ash cloud does not represent the actual presence of ash. This feature is also used when the ash cloud produced by the model is much larger than the one observed on satellite imagery.

- Running the trajectory model will provide estimates of the direction and timing of spread of the plume over time. The data input to the model includes the time and duration of the eruption, the location of the volcano, a sounding representing the vertical temperature and wind fields and/or a numerical model forecast file. Using this information, the HYSLPIT model predicts the evolution of the location, transport, and concentration of the ash cloud over time.

- Weather data can be input either as numerical weather prediction model output or observed sounding data. These model data are archived for two days and can be helpful for modeling longer-term eruptions.

- Output from the HYSLPIT model can be displayed directly from the website, and can be saved in a variety of formats, including that which can be displayed via Google Earth. The output is a trajectory of the visual ash cloud, and can be plotted at levels of interest to the aviation community.
Other trajectory/dispersion models

• The Puff model is also used by The Alaska Volcano Observatory (AVO) and the Anchorage Volcanic Ash Advisory Center (AAWU VAAC) to monitor and assess volcanoes and eruptions. The AVO in Fairbanks runs WebPuff automatically to generate Puff model runs every six hours for all currently active volcanoes. This may be your first stop for model data in case of a volcanic eruption in your area.

• CANERM is the Canadian Emergency Response Model that has been adapted to model volcanic ash and is used operationally by the Volcanic Ash Advisory Center (VAAC) in Montreal to help predict the track of volcanic ash clouds that affect Canadian air space.

• The Numerical Atmospheric-dispersion Modelling Environment (NAME) is used by the United Kingdom Meteorological Service (UK Met Office) in the London VAAC to model the dispersion of volcanic ash.
Future products

- New products are being developed as part of the GOES-R proving ground that help map the height as well as other properties of the ash cloud. This example is from eruption of Eyjafjallajökull Volcano in southern Iceland in April of 2010.
- The four panel display shows various characteristics of the ash plume. The top left panel shows an RGB image used to show where volcanic ash is present.
- The upper right panel is a quantitative depiction of ash loading, which is analogous to ash concentration.
- The lower left panel gives an estimate of the height of the ash cloud. In addition to the contoured values, a maximum height is recorded at the top of the panel.
- The lower right panel contains the ash effective radius, which can be correlated to the residence time of the particles in the ash cloud.
Pilot Reports and Webcams

- Pilot reports, when available, provide data directly from the flight path and with other methods can help determine the height as well as the vertical extent of the ash plume. Working with the local CWSU office to analyze the pilot reports may be an effective way to review all the incoming data and issue a product.
- In addition, if one is available, you can view a live video stream from a webcam and get a better sense of the conditions at the volcano. This is an image from Mt. Redoubt’s webcam taken on August 12, 2011:
Issue Products

- The release of a Volcanic Ash Advisory (VAA) or a Volcanic Ash Graphic (VAG) from a Volcanic Ash Advisory Center triggers the necessity for forecasters to take action.
- The Ocean Prediction Center (OPC) and the Aviation Weather Center provide large scale forecasts and warnings to alert marine and aviation customers to volcanic ash events. The Center Weather Service Units provide information to the National Airspace System traffic flow managers. The Weather Forecast Office forecasters alert their county warning area (CWA) through marine and volcanic ash fall forecasts and warnings. Meteorological Watch Offices work on a larger scale in their area of responsibility to warn aviation operators of volcanic ash incidents. There are four Meteorological Watch Offices in the United States to support tasks jointly defined by the International Civil Aviation Organization, the World Meteorological Organization and various U.S. government agencies.

The signal from the observed feature travels a longer distance through the atmosphere and interacts with its constituents before reaching the satellite. Also, the features that can be detected are limited by the instrumentation it carries, which varies by satellite. Geostationary satellites positioned around the globe include the GOES satellites that cover the Western Hemisphere, METEOSAT that covers Europe and Africa, MTSAT over Asia and Australia, INSAT over India, and FY-2 and FY-4 that cover China and adjacent regions of Asia.