Advances in Remote Sensing and In-situ Monitoring of Volcanic Ash and Other Gases

VAAC BP/7 and VASAG/9 conjoint session

Washington DC, USA, 21 and 22 November 2019

Item: 6.1
Presented by: M. Pavolonis and M. Hort
Outline

• Satellite constellation update

• Satellite based workflow development in support of current and future IAVW needs: Advances and challenges

• In-situ observation update
Outline

• Satellite constellation update

• Satellite based workflow development in support of current and future IAVW needs: Advances and challenges

• In-situ observation update
Additional Environmental Satellites

Current:
- CMA FY3
- ESA Sentinel
- EUMETSAT MetOp
- NASA A-Train
- NASA/NOAA DSCVR
- NASA ISS
- NASA Terra
- NOAA POES
- USGS/NASA Landsat

Future:
- Additional ESA Sentinel Satellites
- EUMETSAT EPS (Imaging, UV, and sounding)
- EUMETSAT MTG (Imaging, UV, and sounding)
- KMA GEO-KOMPSAT-2B (GEO UV)
- NASA NISAR (INSAR)
- NASA TEMPO (GEO UV)
- EarthCARE
- Many cubesats???

Google acronyms for more information and see WMO OSCAR tool (https://www.wmo-sat.info/oscar/spacecapabilities)
Daily Earth Observation Count – Meteorological Satellites

Only includes satellites that are routinely utilized in operational meteorological applications!
Data Overload Challenge: VAACs

Daily Satellite Imagery Refresh by VAAC Region

Illustrates the need for continued development and sustainment of alerting services
Outline

• Satellite constellation update

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Goal: Development of an Automated Remote Sensing Workflow in Support of IAVW

1. Detect new volcanic cloud

2. Initial characterization

3. Tracking

4. Characterization over time

5. Utilize results of 1-4 to support forecasting applications
State of Workflow Development

1). Detect new volcanic cloud

Goal: automated results that are consistent with human expert analysis (e.g. artificial intelligence - AI)

Recent Advances:
• Advances in satellite measurement capabilities have resulted in earlier detection of new volcanic clouds
• NOAA VOLcanic Cloud Analysis Toolkit (VOLCAT) v3 detection skill (including volcano attribution) is approaching human capabilities, although human experts will always add value
• Hyperspectral measurements, from low earth orbit satellites, can detect new SO$_2$ emissions with exceptional skill (e.g. Support to Aviation Control Service – SACS)
State of Workflow Development

2). Initial and/or instantaneous characterization
4). Characterization over time

Goal: consistent retrieval of key parameters (height, loading, microphysics) across a broad range of conditions and uncertainty estimates – *more specific performance targets need to be established*

Recent Advances:
• Hyperspectral (UV and infrared) based characterization of SO$_2$ (height, loading, and uncertainty) has continued to mature (NASA, ESA, SACS, NOAA, academia, etc.). SO$_2$ products will generally be more accurate than ash products (higher signal-to-noise). TROPOMI products and recent research on infrared based retrievals show good promise for operational applications (including high loading scenarios).
• Improvements to ash cloud properties have largely been incremental (e.g. improved time continuity within NOAA VOLCAT).
# Major Sources of Uncertainty: Ash Cloud Characterization

<table>
<thead>
<tr>
<th>Condition</th>
<th>Minor</th>
<th>Significant</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underlying cloud layer(s)</td>
<td>X</td>
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<tr>
<td>Overlying cloud layer(s)</td>
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<tr>
<td>Underlying complex land surface</td>
<td>X</td>
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<tr>
<td>Measurement artifacts</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Mixture of ash and hydrometeors</td>
<td></td>
<td></td>
<td>X</td>
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<tr>
<td>Opaque cloud</td>
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</table>

Other sources of uncertainty (e.g. microphysical assumptions) exist, but, from a practical standpoint, these need the most attention.
State of Workflow Development

3). Tracking

**Goal:** automated tracking of volcanic clouds in a manner that is consistent with human expert analysis (also requires AI)

**Recent Advances:**
- Advances in satellite measurement capabilities have resulted in improved tracking of volcanic clouds (volcanic clouds are often tracked longer compared to legacy satellites)
- VOLCAT v3 utilizes a feature tracking algorithm that improves the consistency of ash identification from start to “dissipation” (dissipation = difficult to identify in satellite imagery)
- Automated SO$_2$ time series generation capabilities are being developed under a collaborative project lead by NOAA
5). Support forecasting applications

**Goal:** systematic provision of key volcanic cloud properties and associated uncertainty for automated dispersion modeling applications (inversion modeling, data insertion, trajectories, eruption source parameter estimation, and verification)

**Recent Advances:**
- Continued development of techniques for integrating satellite products into the dispersion modeling workflow (all major players)
- VOLCAT v3 alerts are automatically triggering HYSPLIT trajectories on an experimental basis
- With some additional development, VOLCAT v3 umbrella cloud time series can be used for ESP estimation
- See dispersion modeling briefing
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• In-situ observation update
In Situ Update

• Operational resource or used by operational staff
• UK Met Office:
  – Aircraft: Operational MOCCA and other research aircraft
  – Aerosol-sonds – research devices
• Argentina - Particle counters
• Few – air quality monitoring stations
In Situ Update

• Some examples do exist, however:
  – Very limited operational use of in-situ observations
  – Research activity also limited
• Clear value as part of an integrated observing network
• Wider interest and in-situ aerosol and SO$_2$ observations does exist
• Questions:
  – Does the above summary an accurate reflection?
  – If so, then why and how can we make better use of existing resources an/or develop new capabilities?
In Situ Research Examples

• UAV
  – Miniaturisation of instruments for UAV deployment
  – Exeter University/Met Office
  – Sun photometer, POPS (Printed Optical Particle Spectrometer)
  – Focus is on aerosol in general

• Various networks of surface instruments – e.g. GAW (~530 stations)

• SSiRC (Stratospheric Sulphur and its Role in Climate) – KLAsh measured stratospheric plume from Mt. Kelud

• Field Campaigns
Ground-based Remote Sensing

- **Lidar**
  - UK only country with operational network
    - 10 Raman lidars with depolarisation
    - 10 Sun-photometers
    - Currently the network provides only imagery to the VAAC in near real time (15 min)
    - Particle typing (via lidar ratio + particle linear depolarisation ratio)
    - Separate mass estimates for volcanic ash and other particles
  - Operational use of research lidar
    - ?
- **Webcams**
- **Radar**
- **Mix of NMS and SVO resources**
Ground-based Remote Sensing: Ceilometers

VAACs
- Operationally used UK, New Zealand, Argentina

Composition
- Example: ECMWF
  - Focus is aerosol in general
  - Event based experiments: wildfires and Saharan dust
  - Being used in data assimilation
  - Driving discussion on operational use of such instruments.
Ground-based Remote Sensing and in-situ: Servicio Meteorológico Nacional

**PIDDEF - SAVER-NET network**

<table>
<thead>
<tr>
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<td>8</td>
<td>R</td>
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<td>Solar photometers (Cimel)</td>
<td>7</td>
<td>O</td>
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<td>Differential optic absorption Spectrometer DOAS (LuftBlick)</td>
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**Local Instruments**

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POC: Soledad Osores
Key Points (1)

• Satellite data are the most common source of observational data utilized by VAACs, but continued leveraging of additional data sources (e.g. ground-based, aircraft, UAVs, etc.) is important.

• Satellite measurement capabilities will continue to advance, but the constellation will remain heterogeneous.

• Given the enormous satellite data volume, complete reliance on manual analysis is impractical (complementary role for automated tools).

• The satellite-based workflow, required to support changes to the IAVW (e.g. quantitative VAA), needs additional research, development, and testing. From a global, frequent time refresh, perspective, the NOAA VOLCAT is furthest along, but does not yet sufficiently support the entire workflow.

• The satellite workflow should allow for integration of non-satellite observational sources (infrasound, lightning, lidar, radar, etc.)
Key Points (2)

• Operational capabilities always lag advances demonstrated in the literature, as operational applications demand additional science and software development to address practical issues (timeliness, measurement artifacts, performance over a broader range of environmental conditions, etc.).

• The interests of the research community and the IAVW could be better aligned (e.g. not enough research into accounting for influence of hydrometeors on ash cloud property retrievals)

• Meteorological and space agencies generate products in response to user requirements. Development of specific satellite product requirements for the “next generation” IAVW is critical. Without requirements, there is a significant risk that needed capabilities will go undeveloped and/or unimplemented in operations.

• Higher-level outreach to agencies that operate VAACs is needed (risk of IAVW needs being under prioritization in agencies with a large mission scope).
— END —

(supplemental material follows)
The VA lidar – sun-photometer network

Operational network
• 10 Raman lidars with depolarisation
• 10 Sun-photometers

Currently the network provides only imagery to the VAAC in near real time (15 min)
• Particle typing (via lidar ratio + particle linear depolarisation ratio)
• Separate mass estimates for volcanic ash and other particles

Future plans for data
Raman + depolarisation

- Particle typing (via lidar ratio + particle linear depolarisation ratio)

- Separate mass estimates for volcanic ash and other particles (such as $\text{SO}_4^{2-}$ droplets)

- High quality depolarisation measurements are difficult!!

- Calibration is challenging

Currently the network provides imagery only to the VAAC in near real time (15 min)
Web app for VAAC meteorologists (demo only!)
Use of remote sensing in Europe

E-PROFILE Ceilometers network
Experiment with wild fires and Saharan dust layer

Lidars
Use in data assimilation

Activities are driving discussion on operational nature of such instruments.
PIDDEF - SAVER-NET network

The network is a fusion of two Projects: PIDDEF 31554/11 and Science and technology Research Partnership for Sustainable Development Program (SATREPS).

The SAVER-NET project expanded the network in collaboration with Argentina, Chile and Japan.

The aim of the network:
- Development of a network of monitoring of aerosols with a near real-time response
- Determination of the main properties of aerosols (source, area of origin, type, transportation and seasonal variations)
- Improvement of the current system of O3 capacity monitoring and UV irradiation
- Analysis of the variations of the O3 hole and the study of its impact on the radiation UV in the middle altitudes of the South American region

It is in a research and development stage.

LIDAR’s are part of the Latin American LIDAR network (LALINET)
In situ and remote sensors for volcanic ash detection

- **PIDDEF - SAVER-NE**

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LIDAR

Characteristics

• “Conventional” Lidar: (λe for 355nm, 532nm and 1064nm + λd for 355nm and 532m) – 5 signals
  o Aeroparque, Buenos Aires
  o Comodoro Rivadavia, Chubut
  o Neuquén, Neuquén
  o Río Gallegos, Santa Cruz
  o Tucumán, Tucumán

• “Raman” Lidar: (λe for 355nm, 532nm and 1064nm + λr for 387nm, 408nm and 607nm) – 6 signals
  o Bariloche, Río Negro

• High Resolution Spectral Lidar: (λe for 355nm, 532nm and 1064nm + λr for 387nm, 408nm + λd for 355nm and 532m + λHSR for 532nm) – 8 signals

Products

• Attenuated backscattering coefficient (Raman, Elastic y HSRL)
• Range corrected Raman scattering (Raman y HSRL)
• Range corrected HSR Rayleigh scattering (HSRL)
• Volume depolarización ratio (Elastic y HSRL)
• Sphere extinction coefficient (Elastic y HSRL)
• Dust extinction coefficient (Elastic y HSRL)
Sun photometers

Types of Measurements
1. Direct measurement
2. Almucantar
3. Main Plan
At different wavelengths

Products:
• Optical aerosol thickness (AOD or AOT)
• Size distribution
• Angstrom coefficient
• Refractive index
• Single scattering albedo

http://aeronet.gsfc.nasa.gov/

Aerosol Robotic Network
Particle Counters

Characteristics:

Continuously record of dust and particle employing a light scattering technique

Products:
- Total Suspended Particle
- PM10
- PM2,5
- PM1
Differential optic absorption Spectrometer (DOAS)

Products:
• Total and tropospheric ozone column (O3)
• Total and tropospheric nitrogen dioxide (NO2) column
• Aerosol optical thickness (AOD) in the UV and visible ranges
• The possibility of adding other products such as sulfur dioxide (SO2), deormaldehyde (CH2O), and water vapor (H2O) columns

http://pandonia.net/
Meteorological Radars

Scanning strategy

Bariloche Radar
- C-band
- 44 active volcanoes in the scanning area

Neuquén Radar
- C-band
- 41 active volcanoes in the scanning area