A census of deep volcanic eruptions in the tropics as observed by Himawari-8

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Definition: Deep eruptions are those that interact with the tropical tropopause layer (TTL), typically considered to lie between 14 and 18 km.
**Aims/workflow**

**What?**

Systematic survey of the Himawari-8 satellite characteristics of deep volcanic eruptions in the tropics

**Why?**

Deep eruptions potentially have significant aviation effects and/or climate impacts. Deep tropical eruptions are often 'ice rich' and so have 'non-classical' satellite signatures.

**Benefits**

- Fuller use of H8 imagery in operations, better situational awareness
- Improve understanding of eruption cloud dynamics and microphysics
- Improved dispersion model inputs and verification techniques

**How?**

1. Identify Cases
2. Make imagery
   - Volcanic Ash RGB (8.5 version)
   - True Colour RGB
   - SO2 RGB
   - Colour IR
   - Modified Natural Colour RGB
   - IR with BTD+
   - True Colour with BTD+
3. Identify Polygons
   - Half-hourly to hourly
4. Analyse Imagery
   - Eruption Height
   - Patterns
5. Characterize Lightning Activity (WWLLN)
   - See: [http://wwlln.net/USGS/Global/](http://wwlln.net/USGS/Global/)
6. Characterize thermodynamic and kinematic environments (ERA5)
Several events have multiple discrete eruptions or erupt continuously for extended periods

14 of 18 eruptions begin during the day

Varied Sample
• Different plume types
• Various eruption types
Polygons

Here: Ulawun 26 June 19

3 eruptions (blue, green, red) and stratospheric cloud (purple)

Subjectively and manually analysed (with powerpoint) relying primarily on VA RGB. Others used as needed

Pick vertices of polygons to separate and identify pixels inside the polygons

Count pixels and calculate area (using appropriate pixel-area conversion)
Finding UTLS Eruption Heights

Create UTLS reference profile for converting BT to height (with error bars)
2000-2021 IGRA2 radiosonde data, 17 stations, valid for W Pac/E Ind tropics (20N-20S)

Method to help identify the 'stratospheric warm spot' and estimate heights of 'undercooled' tops

Many heights reported by the VAACs, Smithsonian are severely underestimated

Eruption Areas

Eruption times vary from ~1 hour to >6 days

Rapid growth of cloud occurs in the first 1-3 hours
  Growth can continue after this time, but at a slower rate

Typical deep tropical eruptions have areas of $10^3$-$10^4$ km$^2$
  after 60 minutes

Area of volcanic cloud is proportional to a power of height
  'Eyeball' fit here is 3.4 power

Theoretically, the mass eruption rate is proportional to area
  raised to the 3/2 power (e.g. Bear-Crozier 2020)
  MER is a key parameter required for dispersion modelling

Hence, the cases suggest MER proportional to ~5$^{th}$ power of height
  Standard relationship is 4.15 power (Mastin et al 2009)
  More work needed
BTD+

Positive values of 13-15 BTD (10.2-12.4 um). This is a signature of small ice crystals and is the most prevalent signature of these eruptions.

Values of 7-12 K are fairly common everywhere, as are small areas of 15+ K, while many eruptions produce significant areas of 15+ K.

Presumably, this is ice that is 'seeded' by the ash acting as ice nuclei (e.g. Durant et al 2008). Very thin or sub-visible cirrus. 'Dark cirrus' on VA RGB.
Ice clouds

Typical values of peak BTD+ in stronger eruptions are ~25-30 K. Highest observed is 47 K. Peaks typically observed 3-9 hrs

Secondary peaks can occur as convection redevelops in regions of volcanic cloud
Also when areas advect downstream and interact with convection

Ice clouds can be $10^5$ km$^2$ or greater in area. In some cases they reside in the lower stratosphere

Stronger eruptions and/or those that are phreatomagmatic tend to have larger ice cloud areas…but not always

Given that these clouds are likely seeded from volcanic ash, do they represent an aviation hazard?
Lightning

Lightning occurrence is often suggested as a way to detect volcanic eruptions.

What do the events here indicate?

**No Lightning**
- manam1, sinabung1, manam3, sinabung2, Lewotolo, manam4

**Some lightning**
- Tinakula (15), manam2 (1), Ulawun2 (12)

**Moderate Lightning**
- Ulawun1 – peak rate 26 strokes/15 minutes

**High Lightning**
- Anak Krakatau (>300 strokes/15 minutes)
- Taal (> 100 strokes/15 minutes)
- Fukutoku (> 100 strokes/15 minutes for extended periods)
- Hunga Tonga1 (> 200 strokes/15 minutes)
- Hunga Tonga2 (> 700 strokes/15 minutes)
- Hunga Tonga3 (> 4200 strokes/15 minutes)

In the cases here, high lightning rates appear to be largely related to the phreatomagmatic nature of some eruptions. The relationship of lightning and water is very clear. It is not generally associated with eruptions and its ubiquity in tropics makes it challenging to use as a diagnostic.
Summary

Comprehensive survey of tropical volcanic eruptions that extend into the upper troposphere and stratosphere

Output/images from sensors like the AHI are extremely powerful, but can be better exploited in both operations and research

Analysis of multiple cases allows for the identification of common patterns in the images

- Develop insights into the dynamics and microphysics of volcanic clouds
- Provide better guidance and interpretation of these events

Additional work is needed to better formalize these patterns