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+

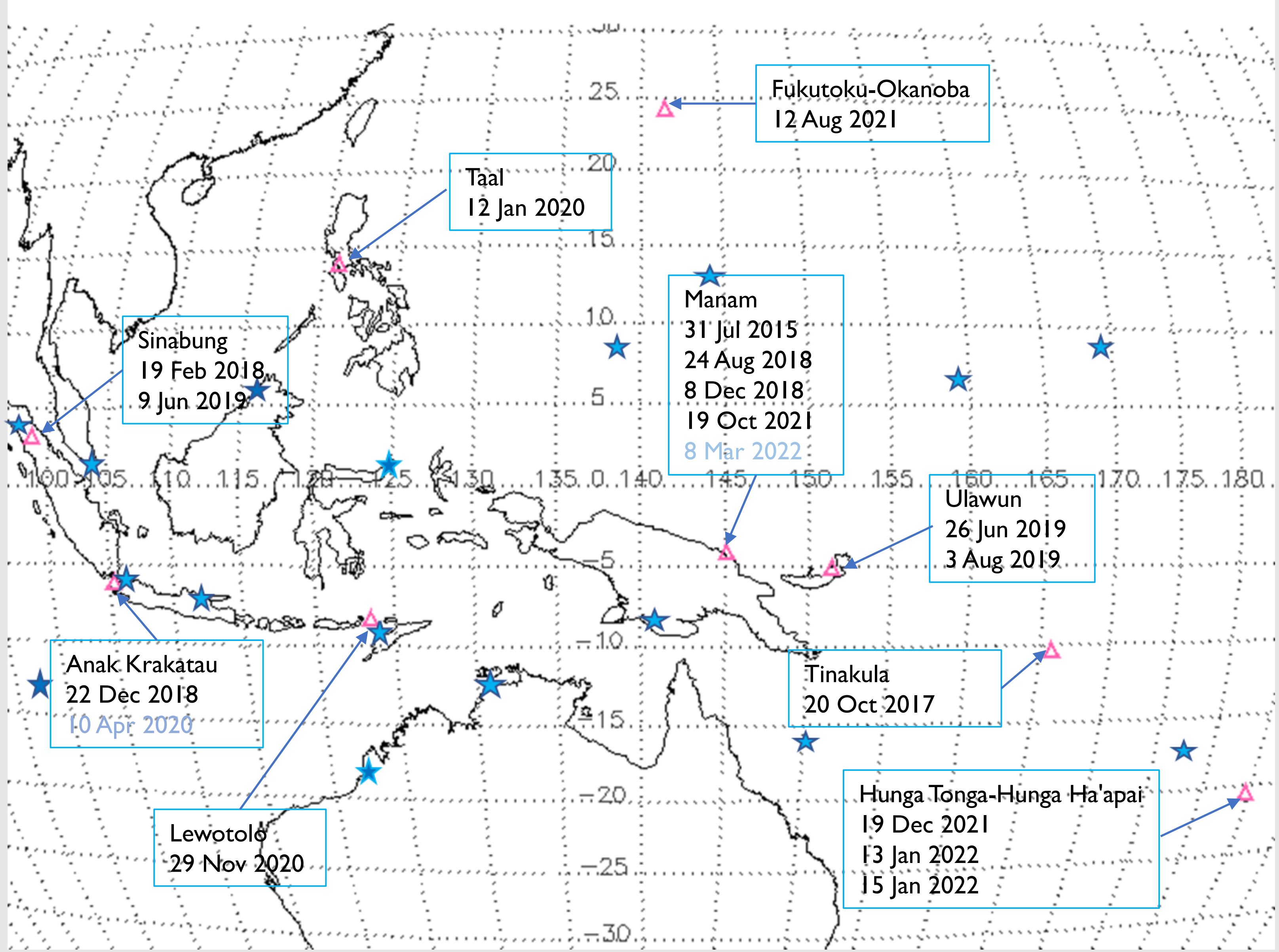
3. Identify Polygons
   - Half-hourly to hourly

4. Analyse Imagery
   - Eruption Height
   - Patterns

5. Characterize Lightning Activity (WWLLN)
   - See: http://wwlln.net/USGS/Global/

6. Characterize thermodynamic and kinematic environments (ERA5)

Frequency	
2015	1
2016	0
2017	1
2018	4
2019	3
2020	3
2021	3
2022	3
Total	18



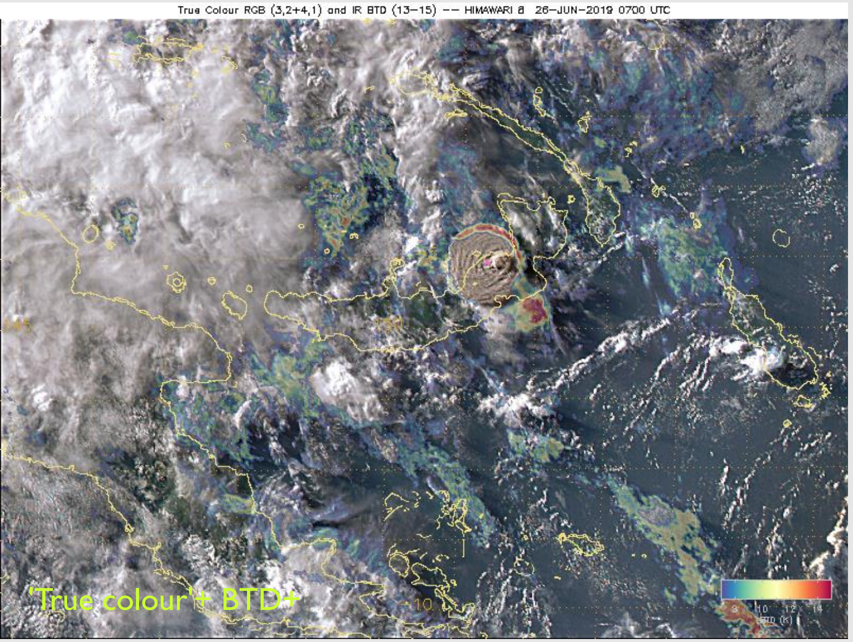
Several events have multiple discrete eruptions or erupt continuously for extended periods

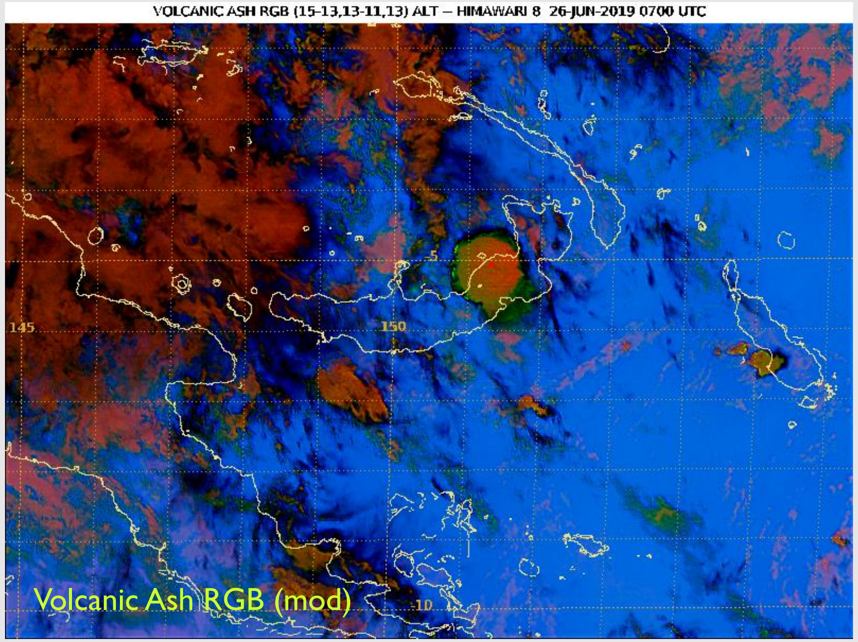
14 of 18 eruptions begin during the day

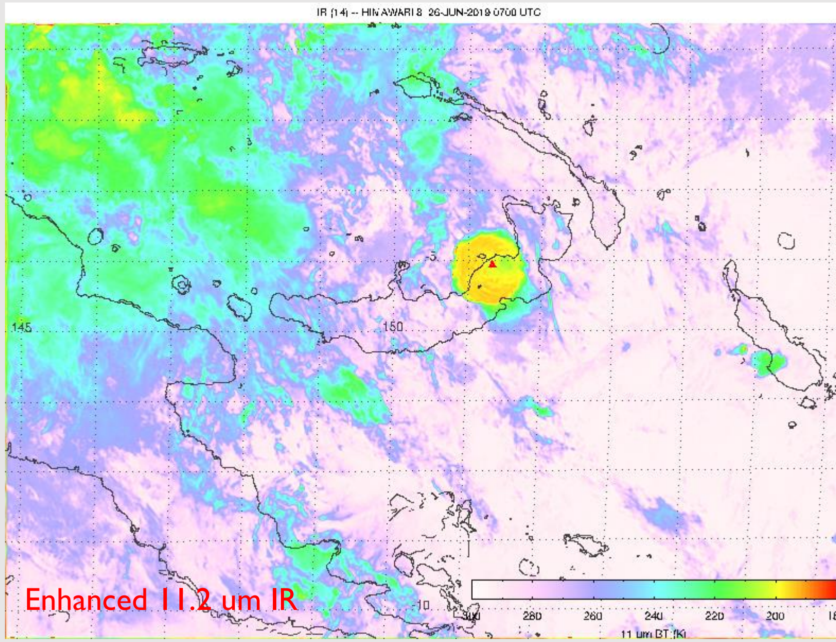
Varied Sample

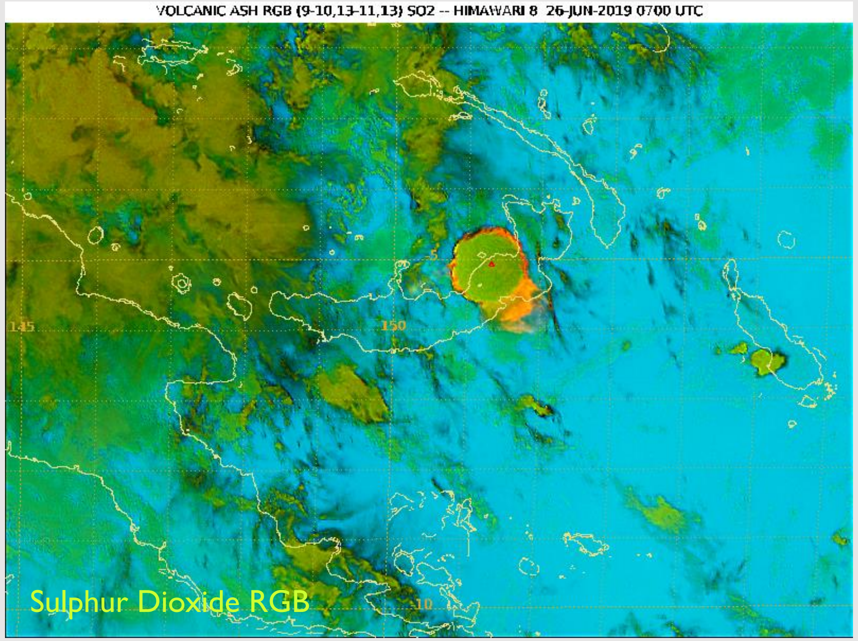
- Different plume types
- Various eruption types

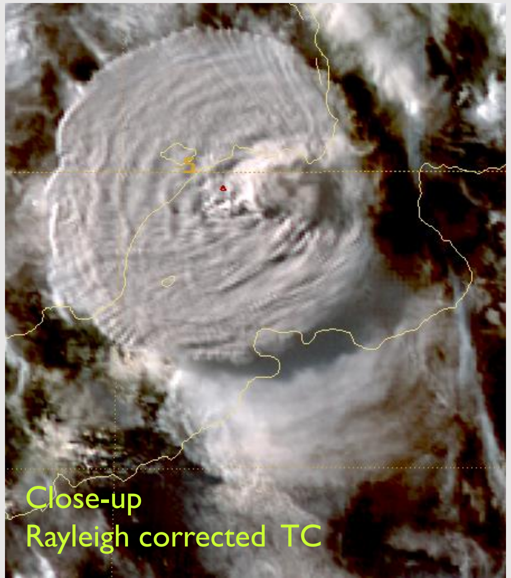
Ulawun, 26 Jun 2019, 0700 UTC











Polygons

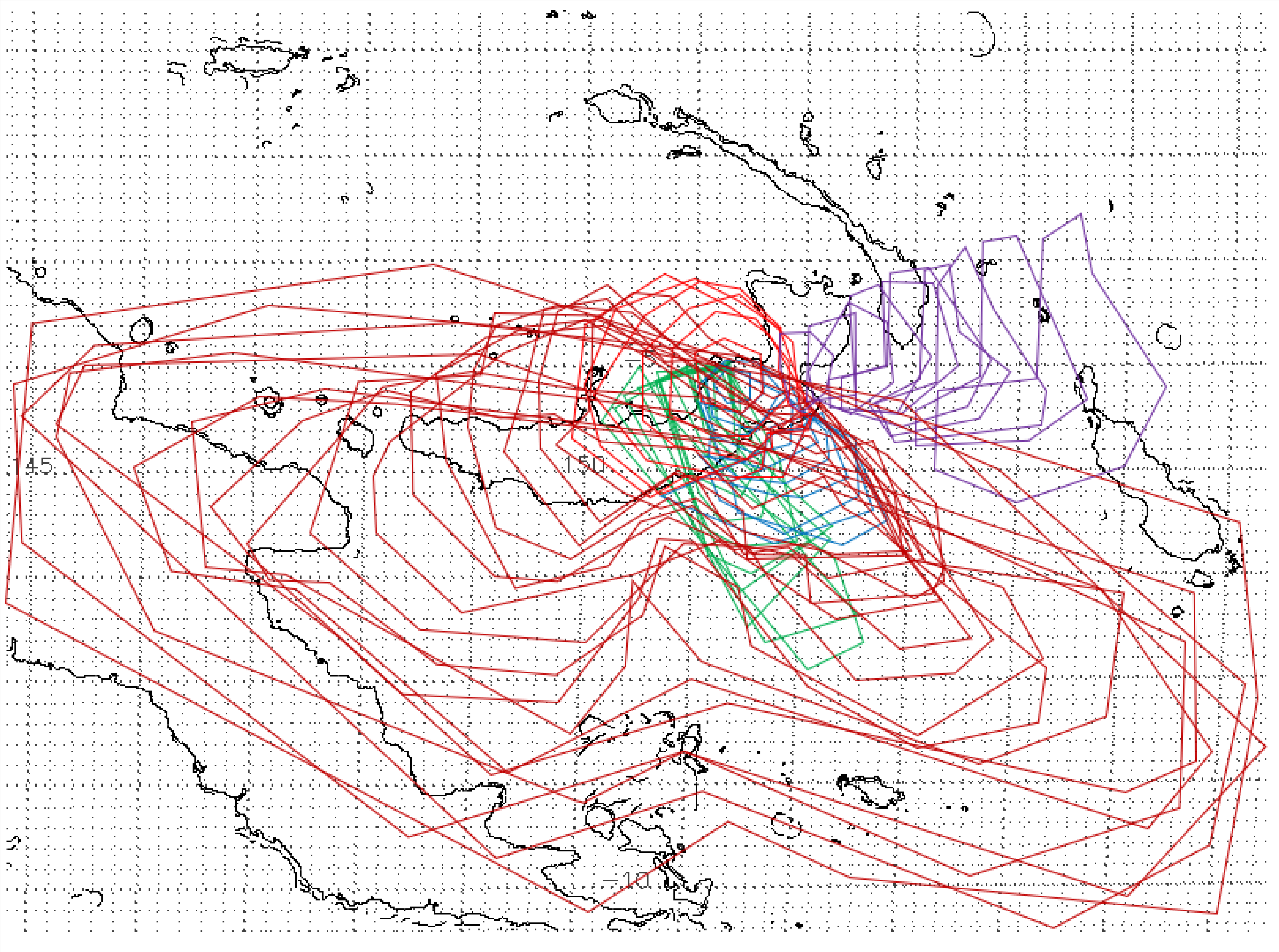
Here: Ulawun 26 June 19

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)



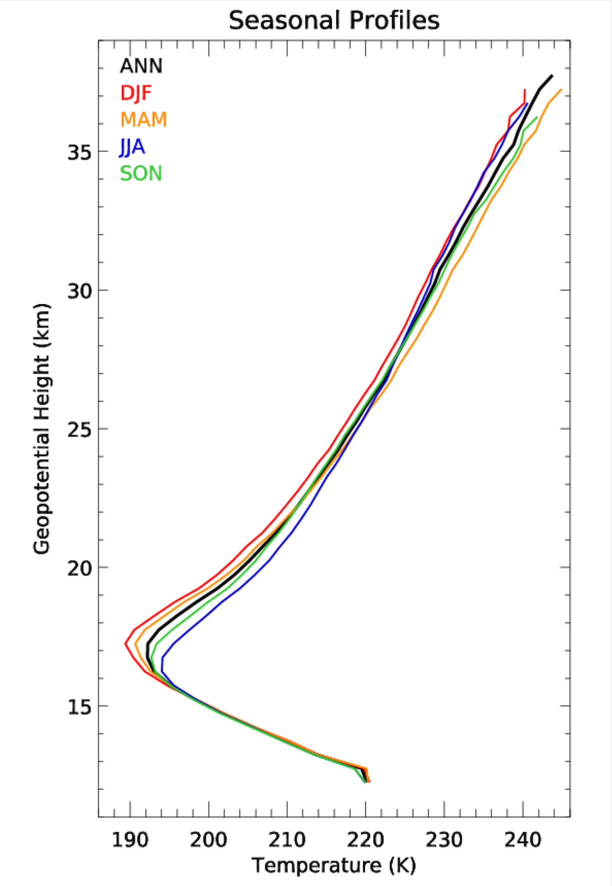
Finding UTLS Eruption Heights

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)

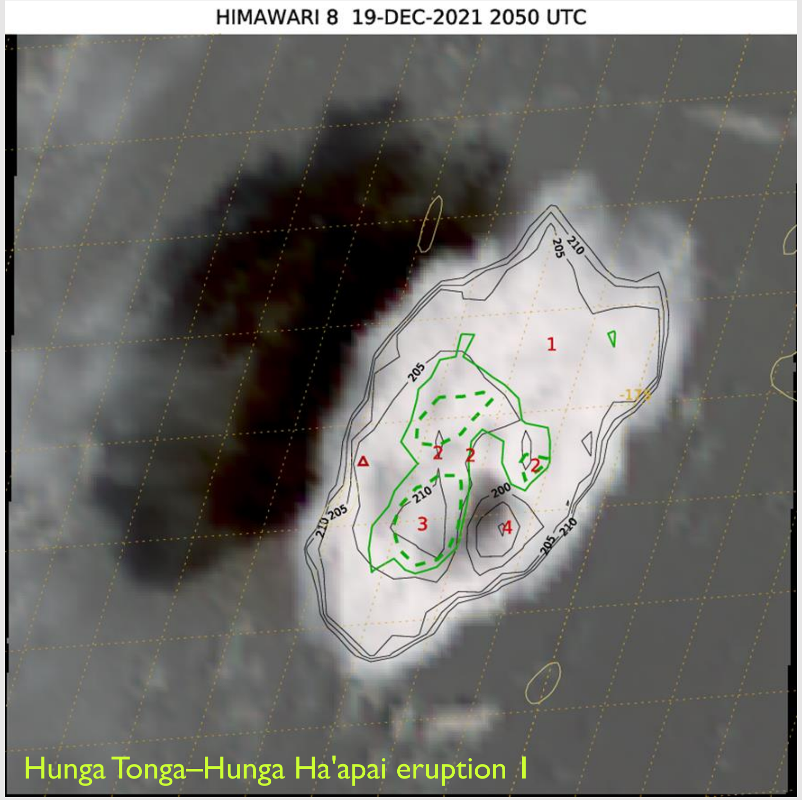
Method to help identify the 'stratospheric warm spot' and estimate heights of 'undercooled' tops

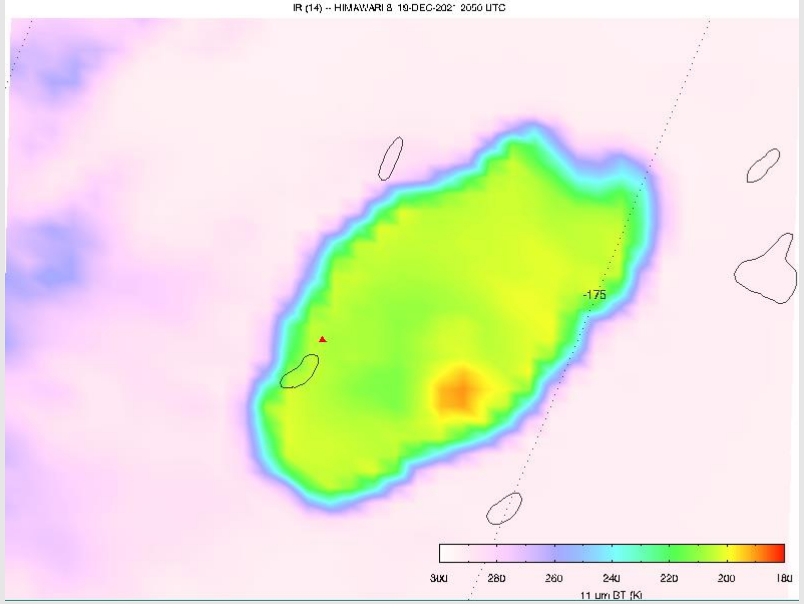
Many heights reported by the VAACs, Smithsonian are severely underestimated



Height (km)	DJF	MAM	JJA	SON	ANN	Ht Uncert (km)
13	217	217	216	216	217	±0.5
14	208	208	207	207	208	
15	200	200	200	200	200	
16	193	194	195	194	194	
17	190	191	194	193	192	±1.5
18	192	193	199	197	195	
19	197	198	203	201	200	
20	202	203	207	205	204	
22	209	211	212	210	211	±2.0
24	215	216	217	216	216	
26	219	221	221	220	220	
28	224	226	225	225	225	
30	227	230	228	229	228	
35	236	240	237	239	238	
40	246	250	247	249	248	±3.0
45	256	260	257	259	258	
50	266	270	267	269	268	
55	276	280	277	279	278	

See Lucas, C (2022): Determining the height of deep volcanic eruptions over the tropical western Pacific with Himawari-8. Submitted, *Journal of Southern Hemisphere Earth System Science*





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

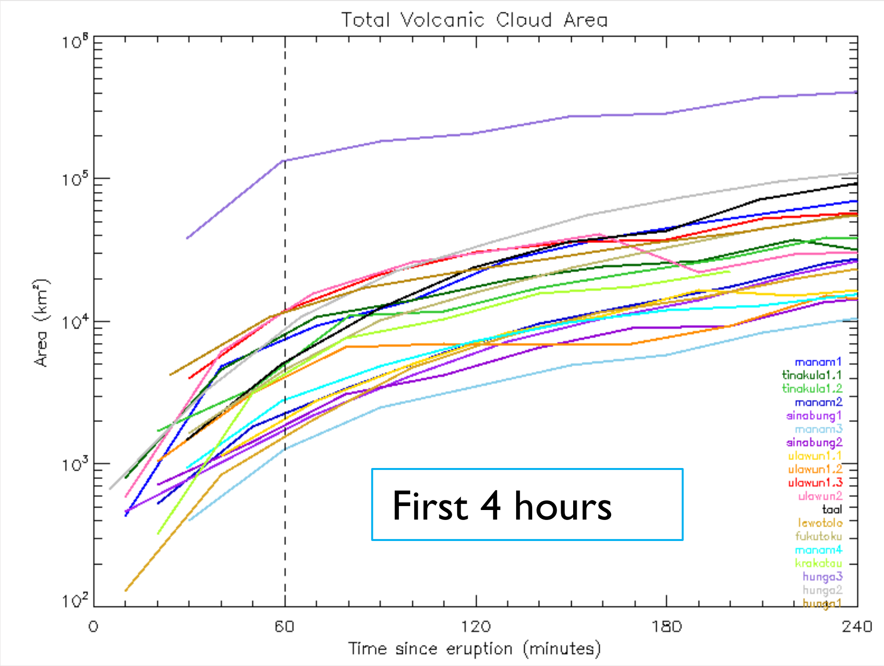
Theoretically, the *mass eruption rate* is proportional to area raised to the 3/2 power (e.g. Bear-Crozier 2020)

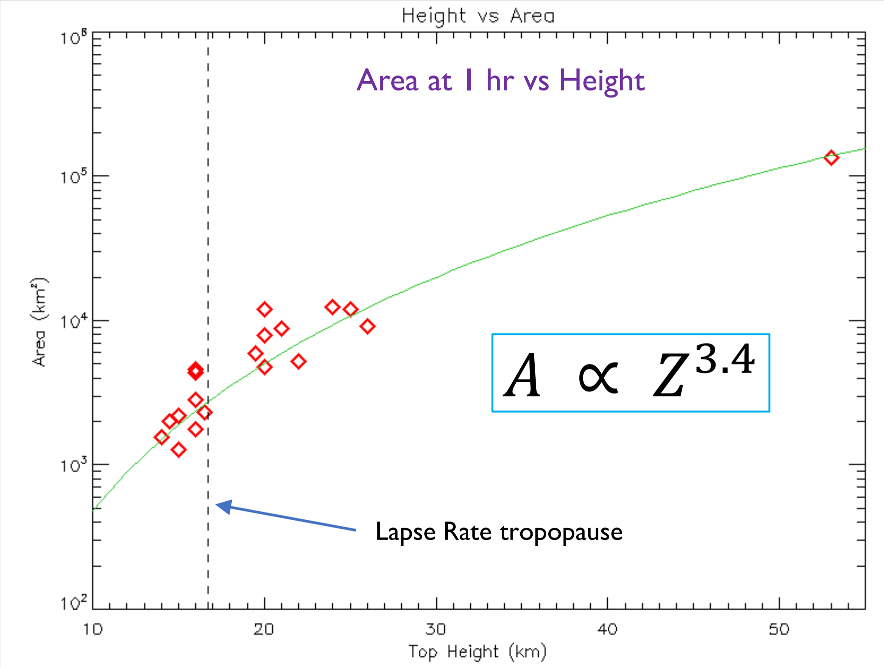
MER is a key parameter required for dispersion modelling

Hence, the cases suggest MER proportional to ~5th power of height

Standard relationship is 4.15 power (Mastin et al 2009)

More work needed



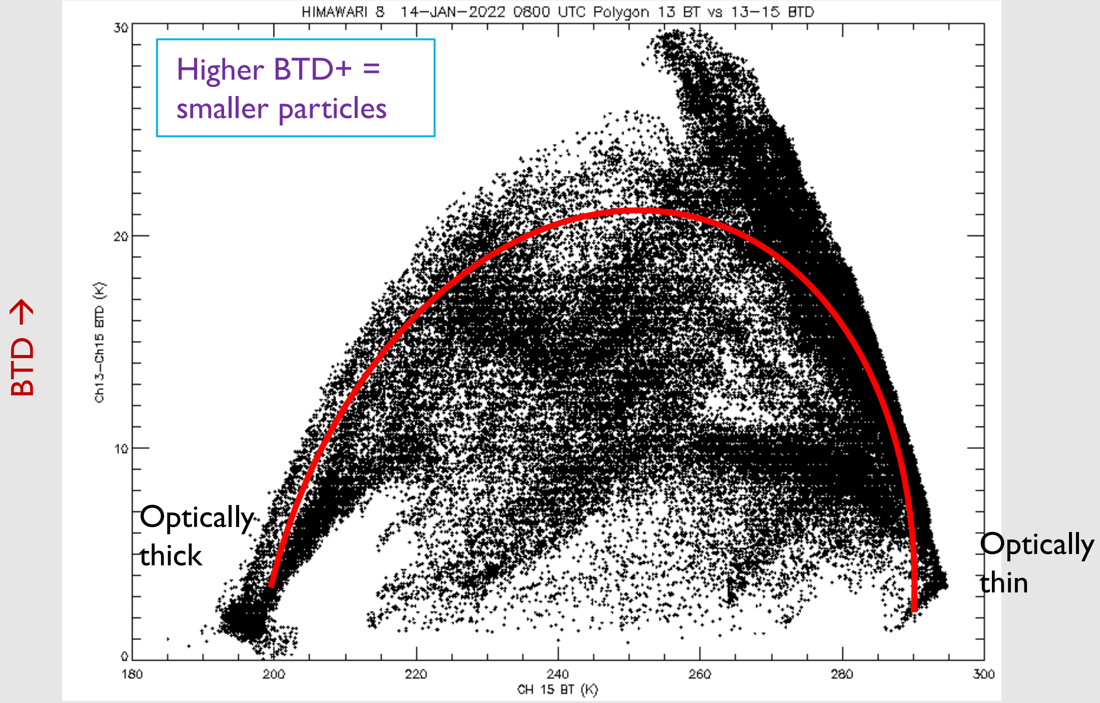


BTD+

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

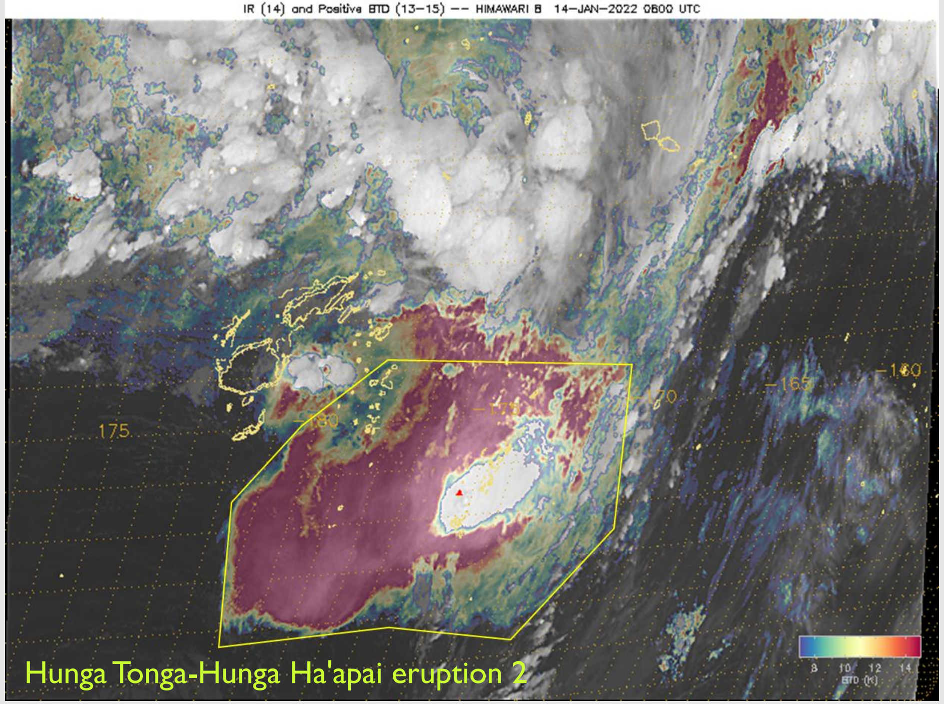
Values of 7-12 K are fairly common everywhere, as are small areas of 15+ K, while many eruptions produce significant areas of 15+ K

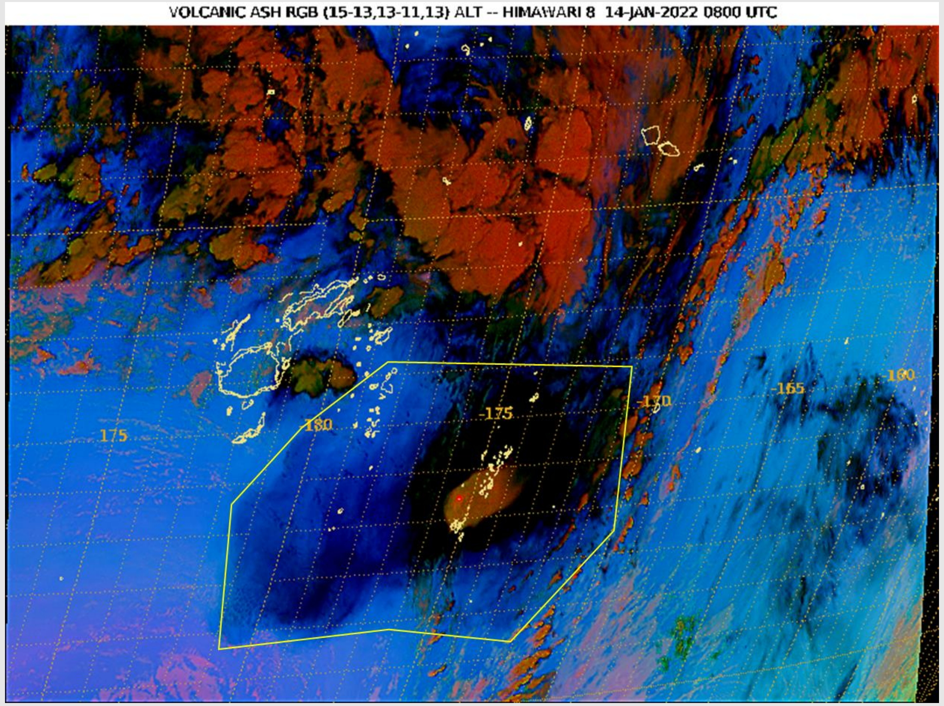
Presumably, this is ice that is 'seeded' by the ash acting as ice nuclei (e.g. Durant et al 2008). Very thin or sub-visible cirrus. 'Dark cirrus' on VA RGB



12.4 um BT

e.g. Rose et al (1995), Prata and Grant (2001)





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

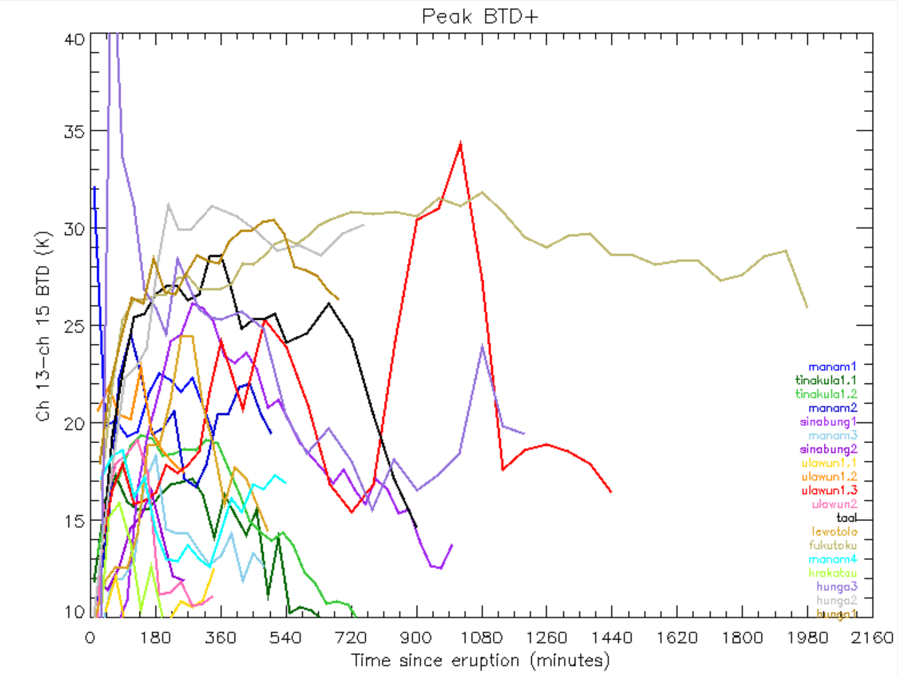
Secondary peaks can occur as convection redevelops in regions of volcanic cloud

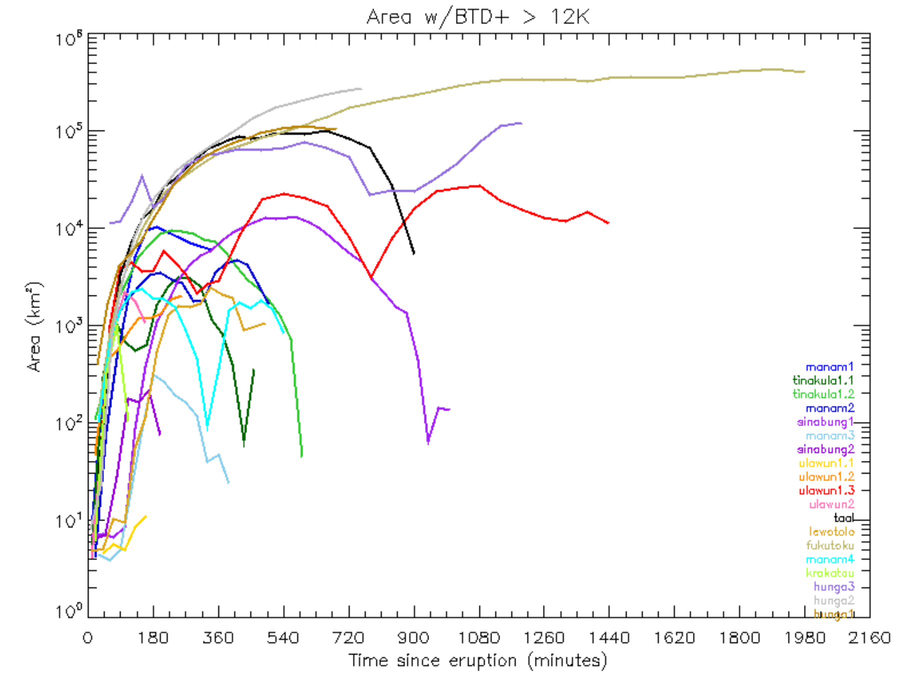
Also when areas advect downstream and interact with convection

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 the 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

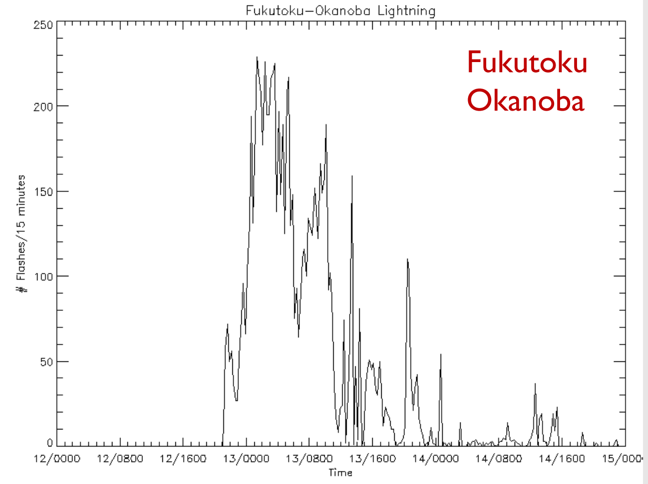
Tinakula (15), manam2 (1), Ulawun2 (12)

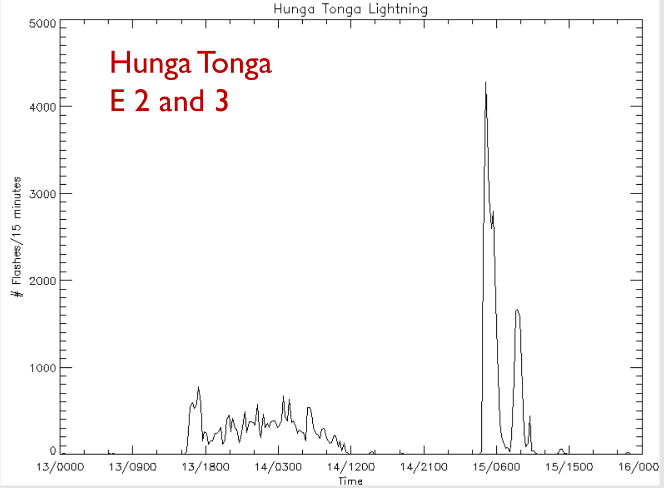
Moderate Lightning

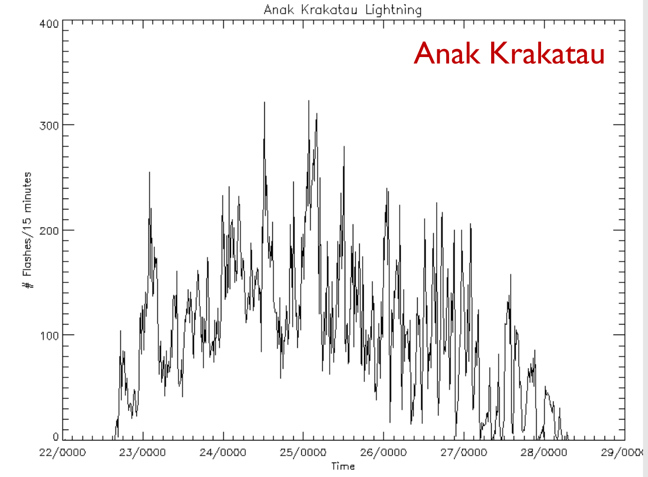
Ulawun1 – peak rate 26 strokes/15 minutes

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)







See Prata et al (2020) for discussion of this event

Lightning data taken from the WWLLN Volcano Monitor website, and is generally the lightning recorded within 20 km radius of volcano value, with exception of Hunga 3, as it grew very quickly

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