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Supplementary Materials for

The January 2022 eruption of Hunga Tonga-Hunga Ha'apai volcano reached the mesosphere

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Materials and Methods

Satellite data

In this study we use data from three geostationary satellites, GOES-17, Himawari-8 and GK-2A. Data was downloaded via the open APIs listed in the paper acknowledgements and processed using version 0.33.1 of the Satpy tool *(30)*. We converted the satellite data for each 10-minute timestep into both "true color" imagery that merges information from images taken at multiple wavelengths to mimic what the human eye would see and into single-wavelength images at the highest possible spatial resolution (band 3 for all satellites). These images were radiometrically calibrated from digital counts into radiance using the calibration coefficients supplied in the raw data files. We did not perform any atmospheric correction to these images, so they are affected by Rayleigh and aerosol scattering as well as gaseous absorption. This is not problematic for our study as we are not reliant upon the radiance values themselves, only upon feature matching between images. We consider that applying atmospheric correction would not add value, especially as the volcanic plume was at high altitude and hence, unlike clouds in the lower troposphere, relatively unaffected by scattering and absorption processes.

For the temperature-based estimates of plume altitude we generated temperature images for Himawari-8's channel 13, which is centered at 10.3 micron, and converted from digital number to brightness temperature using the default operator-supplied calibration, not the alternative GSICS calibration. Himawari-8 was chosen as it is located closest to the volcano and hence minimizes parallax-induced distortion and effects due to atmospheric absorption and scattering along the signal path length.

Selection of points for altitude calculation

Using the satellite imagery described in the previous section we manually identified a series of points within the plume that were readily identifiable across all three satellites. These were often prominent features such as cloud edges, bright spots – usually the tops of the highest clouds – and dark spots denoting troughs or shadows in the cloud tops. We also attempted automatic feature detection using a machine learning framework, but found that this performed poorly, most likely due to the significant intra-satellite image distortion introduced by the satellites viewing the plume from very different geometries meaning that shadows and highlights were often visible to one satellite but not the others. In addition to the tri-satellite feature matching, we also focused on the 04:30 UTC images from GK-2A and Himawari-8 to select a larger number of common points between these two satellites to map cloud topography. We excluded GOES-17 from this portion of the analysis as it viewed the plume from the opposite direction, which limited the number of high-quality matches that were possible. The tri- and dual-satellite feature positions and estimated altitudes are given in Tables S2 and S3 respectively.

Parallax based height estimation

To estimate the height of the volcanic plume at each manually selected feature we use well-established methods based on the parallax between observed and actual plume position. In the simplest model, the difference between these two positions is a function of only the angle at which the satellite views the plume and the altitude of the plume itself, meaning simple trigonometric identities can be used to find the actual position if the observed position is known, or vice versa. However, geostationary satellite images the field of view is very large, and the curvature of the Earth must also be considered. Furthermore, each satellite uses its own definition of the Earth's shape (polar and equatorial radii) when generating its imagery data. We therefore use a cartesian coordinate system to perform the parallax correction with a predefined plume altitude as follows:

1) Retrieve satellite longitude, latitude, and altitude from the raw data. Also retrieve the Earth model (WGS84 or GRS80) used by the satellite and the two Earth radii.
2) Convert satellite position and feature position into cartesian coordinates for the Earth model used by each satellite.
3) Determine the position along a line from observed position to satellite position at which the line's altitude is equal to the plume altitude. This is the parallax-corrected location of the plume.
4) Convert the parallax-corrected position from Cartesian coordinates to geographic coordinates.

This approach requires the plume altitude, which is unknown. But we do know the observed position from multiple satellites and can therefore iterate of a range of altitudes, computing the parallax-corrected position for each satellite. The true altitude of the plume will be that at which the difference between the parallax corrected locations found from each satellite is minimized.

However, the above assumes that the satellites perfectly observe plume location and that the manual point selection has no inaccuracies. There is an uncertainty due to the pixel spacing of the instrument – we cannot locate features with precision better than the pixel spacing, and other factors such as noise and instrument jitter also affect location accuracy. Furthermore, the eruption examined here was very energetic and evolved rapidly. Although all three satellites have very similar ten-minute scan patterns there are small differences in the time at which they

observed the eruption – on the order of seconds – and this also adds uncertainty to the position. These factors are unknown so cannot be explicitly quantified as an uncertainty on our height estimate. Instead, we apply random Gaussian noise with standard deviation of 0.018 degrees (approx. 1.5km) to each of our observed plume positions and repeat the iterative altitude estimation process 2e6 times. The variation in retrieved altitude from this repetitive process can give us an indication of the altitude uncertainty and these values are also given in tables S2 and S3. The tri-satellite analysis produces consistently lower variation (~0.6km) compared to the dual-satellite analysis at 04:30 (~2.2km), which in part is likely due to the selection of clearer matchup points in the tri-satellite analysis, thus minimizing input position uncertainty, and in part due to the inclusion of GOES-17 on the opposite side of the volcano and thus providing a much greater separation between the observed position seen by the satellites.
The code used in the height estimation process outputs multiple variables: The actual plume latitude and longitude averaged across all two million repetitions of the estimation process for each observation, the mean retrieved altitude, the mean distance between closest observations for each satellite and the standard deviations of heights and distances. The mean height, however, is not necessarily representative of the actual height, and therefore we also chose to output the height estimated by a subset of the 100 closest repetitions of the code. This threshold and approach were decided upon by comparison of estimated altitude and actual altitude (derived using the temperature method described below) for clouds visible in pre-eruption images. We output the average height estimated by these 100 closest points, the standard deviation in these heights and the average distance between intra-satellite parallax corrected position. For the figures and manuscript text we use the heights derived from the closest 100 points, but all output information is given in the supplementary tables.

Temperature based height estimation

In addition to the approaches described above, we also estimated plume height from the Himawari-8 temperature measurements made at 10.3μm. This band was chosen as it is a 'window' channel, does not overlap any strong absorption features and thereby provides an accurate temperature estimate of the object being observed. Most existing temperature-based height retrievals are designed to operate in the troposphere and therefore do not produce accurate results for such high plumes as generated by the Hunga-Tonga eruption. We therefore wrote our own very simple height retrieval that compares an observed cloud temperature to the temperature profile provided by the ECMWF operational analysis at 00z (approx. 4 hours prior to the eruption) and selects the altitude at which the ECMWF temperature is closest to the cloud temperature. Some portions of the plume in the stratosphere are significantly colder than the surrounding air (known as 'undercooling') and therefore do not correspond to any point on the ECMWF profile. For these points we assumed that they cool at a constant lapse rate of -6.5K/km relative to the tropopause temperature of 191.7K (at 90.9hPa, 17.3km altitude). This lapse rate assumption is based on our analysis of undercooling of overshooting tops from severe storms and may not be valid for this eruption but is the best estimate available.
To generate the statistics shown in figure 3 we extracted altitude estimates only for pixels associated with the plume itself. We did this by first masking out all pixels warmer than 250K, as very few plume pixels displayed such warm temperatures, and these were in the central – very high altitude – plume core where the ECMWF temperature profile is likely to be unrepresentative. The remaining pixels warmer than 250K were all associated with clear sky or

very low cloud unrelated to the eruption. Therefore, this temperature threshold enabled us to select only plume pixels and convective cloud pixels. Next, we used the *scipy* and *scikit-image* python libraries to erode the binary mask of pixel temperatures (removing speckle), fill small holes and then segment the resulting binary in labelled zones of low temperature pixels. Finally, we selected the labelled region that overlapped the location of the volcano and designated this as the volcanic plume. This approach failed for the first two timesteps (04:10 and 04:20 UTC) after the eruption due to insufficient development of the plume but was successful thereafter.

Stereoscopic vision height estimation

For the stereoscopic altitudes presented in Fig 3 we generated a digital elevation model (DEM) for each ten-minute timestep in the satellite data of the eruption from point clouds of the ash plume by using the commercial Agisoft Metashape software *(31)*. We used the high-resolution visible channel (at 0.6µm) for each of the three satellites. As Metashape is incompatible with the geostationary projection of the original data we resampled the Level-1 images onto a near-sided perspective projection with the same height and projection center as the original data. Subsequently, the images had to be georeferenced again in Metashape with the use of ground control points that we manually placed in each image on recognizable coastal features on the full disk images for each satellite. We assumed that the ground control points do not change between timesteps, which is a reasonable assumption given that satellite jitter and other factors have been corrected for in the original data.

The ground heights were approximated at zero meters above the GRS80 ellipsoid for simplification of the process, although this will introduce a small bias in the resulting altitudes. Initially this resulted in large projection errors as the near-sided perspective projection didn't account for the oblateness of the GRS80 ellipsoid, this could however be minimized by enabling the B1 (affinity) distortion correction in Metashape which flattened the images in the latitude axis to reintroduce the oblateness. The resulting alignment showed positional errors of ~2000m for markers in the Vicinity of Tonga. The final point cloud was calculated at 4 points per square kilometer and a DEM was generated at 1km resolution in equirectangular projection.

Lastly, we used the plume identification method described in the previous section to extract only those altitudes associated with the plume itself and we derived the altitude statistics shown in Fig 3 from these identifications.

This approach has considerable uncertainty compared to the manual identification of features used for the parallax correction method but allows analysis of the full plume rather than a subset of features. We compared the two methods and found that this stereoscopic approach produces altitudes up to 2.2km higher and 1.6km lower than the parallax method. Nevertheless, within these bounds the altitudes match well, and thus we have confidence in the timeseries of altitudes shown by this method being an accurate description of the trends in plume height.

Satellite name	GOES-17 *(32)*	Himawari-8 *(33)*	GK-2A *(34)*
Sensor name	ABI	AHI	AMI
Nominal longitude	137.2ºW	140.7ºE	128.2ºE
Scanning frequency	10 minutes*	10 minutes	10 minutes
0.455µm		1	
0.47µm	1		1
0.51µm		1	1
0.64µm	0.5	0.5	0.5
0.86µm	1	1	1
1.38µm	2		2
1.61µm	1	2	1
2.26µm	2		2
3.9µm	2	2	2
6.15µm	2		
6.25µm		2	2
7.0µm	2	2	2
7.4µm	2	2	2
8.5µm	2		
8.6µm		2	2
9.6µm		2	2
9.7µm	2		
10.3µm	2		
10.4µm	x	2	2
11.2µm	2	2	2
12.3µm	2	2	
12.4µm			2
13.3µm	2	2	2
*GOES-17 enabled a 1-minute 'rapid scan' mode at 07:05 UTC			

Table S1. Summary of the satellites used in this study. The satellite position listed is the nominal position, and some drift from this is both normal and expected. Our parallax calculations use the actual instantaneous position rather than the nominal position. The scanning frequency is identical for all three satellites, we did not use the 1-minute GOES-17 data as this introduces inconsistencies when comparing across sensors. The wavelengths given in the table represent the central wavelength and the values given for each wavelength row are the nominal pixel spacing at the subsatellite point. For the location of the Hunga-Tonga volcano, actual pixel spacing will be wider than this. Blank boxes represent wavelengths not available for a given instrument.