Timelines of plume characteristics of the Hunga Tonga-Hunga Ha'apai eruption sequence from 19 December 2021 to 16 January 2022: Himawari-8 observations

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Preface:

Hunga Tonga-Hunga Ha'apai eruption on 15 January 2022 recorded as one of the most explosive submarine eruptions in modern times.

Abstract:

The 15 January 2022 shallow water eruption of Hunga Tonga-Hunga Ha'apai (HTHH) volcano was remarkable, in part, because it produced the highest plume observed in the advanced satellite era. The Himawari-8 geostationary satellite captured this HTHH eruption well and provides a unique opportunity to track the evolution (plume and umbrella cloud height) of a large volcanic eruption through time. The 15 January 2022 eruption was preceded by eruptions in late December 2021 and 13 January 2022, for which we have also assessed plume characteristics. In addition to umbrella cloud height, we use Himawari-8 data to determine the radial expansion of the umbrella clouds and volumetric flow rates (VFR).

The altitude of umbrella clouds preceding 15 January 2022 reached ~16-18 km, crossing into the stratosphere. On the day of the large climactic eruption (15 January 2022), the umbrella clouds attained a height close to 31 km. We observed two powerful explosive eruptions on 15 January at an interval of four hours, indicated by the minimum 11.2μm brightness temperature occurring at 04:10 UTC (172 K) and 08:10 UTC (174 K). On 15 January 2022, beyond 05:30 UTC, the strong westward propagation of upper umbrella (U_B) clouds at ~31 km enabled the visibility of lower umbrella (U_A) clouds at ~18 km. We find that U_A is mainly dominant with ash, whereas U_B is dominant with thick ice clouds based on brightness temperature difference analysis. The satellite-derived VFR for 15 January 2022 is around 5.00 x 10^{11} m^3s^{-1}, nearly two orders of magnitude higher than that estimated on 19 December 2021 and 13 January 2022 eruptions.

Main Text

On 15 January 2022, at 04:00 UTC, the shallow water Hunga Tonga-Hunga Ha'apai (referred as, "HTHH") (175.38°W, 20.57°S) volcano, constituted one of the century's most explosive submarine eruptions to our knowledge. The ashfall, tsunamis, and shock waves produced by the eruption severely affected the Kingdom of Tonga and surrounding regions[1]. Shock waves produced by the HTHH eruption circled multiple times around the globe[2] and the overshooting region of the plume reached around 55-58 km[3,4]. The quantification of the plume height and umbrella cloud height (height of dominant level of radial spreading of umbrella clouds) is essential for understanding the physical processes associated with this explosive eruption and linking plume behavior with other data sets (e.g., seismic, atmospheric, infrasound, hydroacoustic, lightning). We use the Himawari-8 geostationary satellite[5] (full disk data at 10-min interval) to track the timelines of grid-averaged brightness temperatures of the umbrella clouds measured at the wavelength of 11.2μm (BT_{avg}), which we then convert to cloud height, over 19 Dec 2021–16 Jan 2022. We also use minimum brightness temperatures at 11.2μm (BT_{min}) to determine when plume overshoot occurs. Because the 15 January 2022 HTHH eruption occurred after an approximately month-long period of eruptive activity that started on 19 December 2021, an assessment of this full eruptive sequence is critical for understanding why the preceding HTHH submarine eruptions were not as explosive. We also measure the radial expansion of umbrella clouds as a function of time to calculate volumetric flow rate (VFR, in the atmosphere) for three distinct eruptions during this period. These volumetric flow rates include ash but may be dominated by the volumes of water and gas in the plumes.

a. Initial eruption on 19 Dec 2021

The recent eruptive phase of HTHH began on 19 Dec 2021 at 20:40 with the creation of a water and ash-rich plume that rose to an altitude of ~17 km (crossing above mean tropopause height at ~16 km; Figure 1e; violet shaded region). This initial eruption subsided on 20 Dec 2021 between 04:30-05:00 UTC, as inferred from the pulsed brightness temperature at 11.2μm ($BT_{11.2\mu m}$) emanating from the center of the volcano. Umbrella clouds from this event laterally spread in the northeastward direction, due to prevailing westerly (eastward) wind in the upper troposphere (as seen from ERA5), covering an area of around 22 thousand square km within the first 150 min (Figure 1g). Using the umbrella cloud area over the first 150 minutes of the eruption on 19 Dec 2021, and assuming spreading at the level of neutral buoyancy[6,7], the VFR was found to be ~3.91 x 10^9 m^3s^{-1} (Figure 1g).

We use the brightness temperature difference between thermal infrared bands at 11.2µm and 12.4 µm ($BTD_{11.2\text{-}12.4\mu m}$) to assess the plume's composition. On 19 Dec 2021 at 22:50 UTC, $BTD_{11.2\text{-}12.4\mu m}$ is negative for the umbrella clouds spreading in the north-east direction, implying the presence of an ash-dominant plume. But at the edge of the umbrella clouds, the near zero value of $BTD_{11.2\text{-}12.4\mu m}$ indicates the prevailing thick ice clouds ($BT_{11.2\mu m}$ at ~230K).

Between 20th and 31st Dec 2021, we observe intermittent fluctuations in $BT_{11.2\mu m}$ around the volcano (within an area of about 3000 km^2) indicative of lower intensity sporadic eruptions. During this period, the plumes moved towards the northeast and the averaged plume top heights within grid-box varied between 8 and 12 km. The presence of meteorological clouds during 01-12 Jan 2022 hindered clear observations of brightness temperature changes related to volcanic activity. However, we do not see evidence for eruptions that surpassed the different meteorological clouds during this time. The ground-based observations would be more useful to assess the weak and sporadic volcanic activity during 01-12 Jan 2022.

b. Major eruption on 13 Jan 2022

With the clearing of the meteorological clouds, we could use Himawari-8 to observe a major eruption on 13 Jan 2022. We see the major surge and fluctuations in BT_{min} between 13 Jan 2022 at 15:30 UTC and 14 Jan 2022 at 14:50 UTC, where its minimum value reaches around 174.5 K at 23:30 UTC (Figure 1f; light-blue shaded region). The plume spreads in the north-eastward direction following the upper tropospheric eastward moving wind, and the umbrella clouds covered an area of about 30 thousand square km within the first 150 min (Figure 1g). The altitude of umbrella clouds reached ~18.5 km, crossing the tropopause height (Figure 1f; light-blue shaded region). For the initial 150 min of eruption on 13 Jan 2022, our estimation of VFR was found to be ~5.13 x $10^9 m^3 s^{-1}$. The VFR on 13 Jan 2022 is almost 30% higher than the corresponding value on 19 Dec 2021.

c. Climactic eruption on 15 Jan 2022

The climactic stage of the eruption began on 15 January 2022, at 04:00 UTC, was observed in 11.2μm brightness temperature (Figure 1f; orange shaded region). This timing of the initial eruption at 04:00 UTC was also confirmed with the true color imagery. Within forty minutes (for instance, at 04:50 UTC, Fig. 1c), the umbrella cloud had expanded around the volcano in a near-circular pattern. We find that the umbrella cloud had an initial height of ~31.5 km, which is less than the overshoot height around 55-58 km[3,4] [sky-blue dot in Fig. 1f]. The average umbrella cloud height declines to ~18 km over a period of ~11 hours (Fig. 1f). As stated above, plume overshoot can be identified using BT_{min} values. For example, the BT_{min} value at eruption initiation (04:00 UTC) was 172K, which is colder than any point in the atmosphere (Figure 1g,f). We identify a second instance of plume overshoot between 08:10-08:30 UTC as shown by a second dip in BT_{min} and that we confirm with GOES data (indicated by the grey line in the orange shaded region in Figure 1f). We interpret the second overshoot to indicate a second eruptive pulse.

Two umbrella-clouds

We identify a second lower-altitude (~18.5 km, 1-1.5 km above the tropopause) umbrella cloud that becomes visible at 05:30 UTC as the upper umbrella cloud moves westward, presumably due to advection by stratospheric winds (Figure 1d). The lower umbrella cloud, U_A, has a distinct brightness temperature relative to the upper umbrella cloud: U_A ($BT < 210$ K) and U_B ($215K < BT < 235K$) (Figure 1d; indicated by two contour labels). This is further established based on the probability distribution function (PDF) of $BT_{11.2\mu m}$ on 15 Jan 2022 at 08:40 UTC in Figure 1j, which shows the two peaks at around 210 K and 220K, representing the umbrella clouds U_A and U_B.

On 15 Jan 2022, between 04:10-04:30 UTC, we observed that significant ash is present in the initial plume based on the negative value of $BTD_{11.2\text{-}12.4\mu m}$. As time progresses, $BTD_{11.2\text{-}12.4\mu m}$ of the upper and westward spreading umbrella cloud (U_B) evolves to be near-zero or slightly positive indicating a thick ice dominant U_B. However, the eastward umbrella (U_A), especially near the edge, has a negative value indicating the ash dominance. The U_B covered an area of about 175 thousand square km within the initial 150 min (Figure 1i).

The satellite-based VFR for the upper umbrella cloud, U_B (contour levels between 215 and 235 K), is estimated to be 5.00 x $10^{11}\,m^3s^{-1}$ for the initial 50 min of eruption. Note that the model fit to the data is poor, which brings into question the assumption of gravitationally driven spread at the level of neutral buoyancy. Still, the VFR on 15 Jan 2022 is around two orders of magnitude higher than the corresponding VFR on 19 Dec 2021 and 13 Jan 2022.

Concluding remarks:

The 15 January 2022 eruption of HTHH was preceded by approximately a month of volcanic activity including two eruptions that produced stratospheric plumes. The major findings are summarized below:

1. The initial eruption occurred on 19 Dec at around 20:40 UTC for about 9 hours until 20 Dec 2021 between 04:30-05:00 UTC; the umbrella clouds reached an altitude of ~17 km and crossed into the stratosphere. The satellite-based VFR for the Dec 19 event is ~3.91 x $10^9 m^3s^{-1}$. Between Dec 20 and 31 Dec 2021, we find the production of weak plumes that reached 8-12 km. During 01-12 Jan 2022, we did not observe volcanic plumes. However, meteorological clouds may have hindered the ability to interpret small plumes.

2. A major eruption occurred on 13 Jan 2022 at 15:30 UTC and where the minimum value of $BT_{11.2\mu m}$ reached approximately 174 K. The umbrella clouds reached an altitude of ~17.5-18.5 km (above tropopause height). The VFR attained a value of ~5.1 x $10^9 m^3s^{-1}$.

3. On 15 Jan 2022 at 04:00 UTC, we observe the large climactic eruption. The altitude of umbrella clouds was stratospheric in nature, attaining an altitude around ~31 km. The satellite-derived VFR for 15 Jan 2022 is 5.00 x 10^{11} m^3s^{-1}, nearly two orders of magnitude higher than that estimated on 19 Dec 2021 and 13 Jan 2022 eruptions. We observe a second eruptive pulse at ~08:10 UTC, four hours after the start of the eruption, that produces plume overshoot. This is inferred from the coldest $BT_{11.2\mu m}$ occurring at ~08:10 UTC with a value of 174 K.

4. We identify two distinct umbrella clouds within the 15 Jan 2022 plume. The upper cloud, U_B, is at an altitude of ~31 km. The lower cloud, U_A, spreads approximately at the level of the tropopause (~18 km) and only becomes visible at 05:30 UTC as the upper umbrella cloud is advected westward, presumably due to the easterly wind in the stratosphere near 30 hPa. We find that U_A is mainly composed of ash as indicated by negative value $BTD_{11.2\text{-}12.4\mu m}$, whereas U_B is composed of thick ice clouds as revealed from near-zero or a slightly positive value of $BTD_{11.2\text{-}12.4\mu m}$.

Results on the timelines of overshooting volcanic plumes (based on BT_{min}) and umbrella heights (based on BT_{avg}) during HTHH eruption suggest that the high spatial and temporal resolution satellite data play an important role in advancing our understanding of eruption history and their implementation in plume modeling. Observations reveal two explosive eruptions observed on 15 Jan 2022 at the interval of four hours – an aspect of the eruption sequence not yet recognized. These observations lead to the fundamental question about what causes multiple eruptive pulses, a topic warrants investigation. In this context, a future direction could be comparing the occurrence of these two strong explosive eruptions against other data sets (e.g., seismic). During the eruption, we also find the formation of two distinct umbrella clouds, a lower one dominated by ash that spreads at the tropopause, and an upper cloud that is dominated by ice (as inferred from $BTD_{11.2\text{-}12.4\mu m}$). An idealized simulation of this submarine eruption using a plume dynamic model[8,9] might help in understanding the series of processes controlling the dynamics of thick ice-rich and ash-rich umbrella clouds with an overshooting plume height at ~58 km[3,4].

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Author contributions:

AG analyzed the data and developed it with RB, KEF and TM. AG, RB, KEF, TM contributed to conceptual development of this work. KEF, RB, TM supervised this research. KEF and RB obtained NASA funding. AG drafted the original manuscript. The manuscript was reviewed and edited by KEF, TM and RB.

Competing interests: Authors declare that they have no competing interests.

Data and materials availability:

The Himawari-8 data used in this study are available in public domain and it can be also obtained from https://registry.opendata.aws/noaa-himawari/. Two supplementary movies of $BT_{11.2\mu m}$ and $BTD_{11.2\text{-}12.4\mu m}$ and .csv related to Figures 1e,f (BTmin, BTavg, Plume/Umbrella height) can be accessed using this link https://zenodo.org/record/6331115#collapseCitations.

Figure:

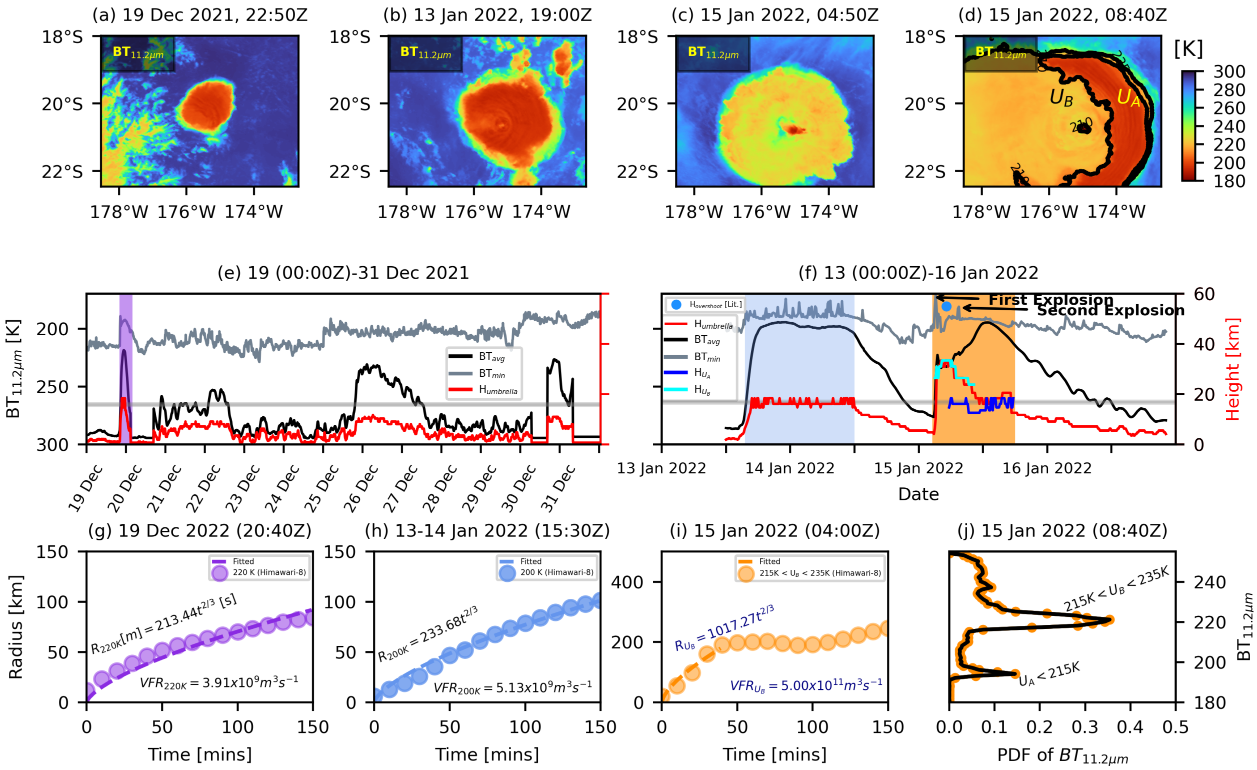

Figure 1: Upper panels: (a) Himawari-8 observed brightness temperature at 11.2 microns (BT11.2μm) centered around Hunga Tonga-Hunga Ha'apai (HTHH) (175.38°W, 20.57°S) submarine volcano on 19 December (Dec) 2021 at 22:50 UTC. Panel (b), (c) and (d) are similar to panel (a) but for 13 January (Jan) 2022 at 19:00 UTC, 15 Jan 2022 at 04:50 UTC, 15 Jan 2022 at 08:40 UTC, respectively. The colorbar represents the brightness temperature measured in Kelvin [K].

Middle panels: (e) the black line (BT_{avg}) indicates the timelines of the domain averaged (174.953°W–175.842°W; 20.6005°S–20.247°S) $BT_{11.2\mu m}$. The redline ($H_{umbrella}$) indicates the satellite-derived umbrella height based on the BT_{avg} value and ERA5 data above. The grey line represents the minimum $BT_{11.2\mu m}$ (BT_{min}) covering 400 by 300 pixels centered over HTHH volcano during 19-31 Dec 2021. The light grey horizontal bar around ~16 km is for the mean tropopause height during 19-31 Dec 2021 estimated using ERA5. (f) The black, red, and grey lines represent the same quantities as in panel e. The blue and cyan lines indicate contour U_A and contour U_B umbrella heights (depicted in panel d) for the eruption on 15 January 2022. The contour U_A is outlined for $BT_{11.2\mu m} < 215K$, and contour U_B is outlined for $BT_{11.2\mu m} < 215K$ and $BT_{11.2\mu m} > 235K$. Skyblue dot indicates the overshooting plume height as shown by preprints online[3,4]. The light grey horizontal bar line is again the same as (e). Both the first and second explosions on 15 January at the interval of four hours are highlighted by the black arrows (represented by the coldest $BT_{11.2\mu m}$ value).

Bottom panels: (g) on 19 December 2021 (initial eruption starts around 20:40 UTC), the radial change of umbrella height as a function of the initial 150 minutes is described by violet dots (representing the highlighted violet shaded region in panel e). The dashed brown line in panel (g) indicates the polynomial fitting for the initial 150 min contour labeled at 220K. The R (in meter) and t (in sec) relations and volumetric flow rate (VFR) values are described by the inset text at different $BT_{11.2\mu m}$ contour level. (h) Same as (g) but for light sky-blue shaded regions in panel (f) depicting the 13-14 January 2021 eruption time (starting around 15:30 UTC). In this case, the polynomial fitting is performed for the 200K $BT_{11.2\mu m}$ value. The R and VFR represent the same as in (g). (i) Same as (g) but for an orange shaded region in panel (f) of the greatest explosive eruption on 15 January 2022 starting at 04:00 UTC. (j) The probability distribution function of $BT_{11.2\mu m}$ on 15 January 2022 at 08:40 UTC, when two umbrella clouds are quite distinctly appearing (as seen in Fig. 1d).

Materials and Methods

Umbrella Cloud heights

We use atmospheric window channels (11.2µm and 12.4µm) observations from Himawari-8 geostationary satellite to determine the average altitude of HTHH plumes and umbrella clouds from 19 Dec 2021 to 16 Jan 2022 (red lines in Fig. 1e and 1f). We take domain average (174.953°W–175.842°W; 20.6005°S–20.247°S, ~3000 km^2 centered over HTHH) brightness temperature at 11.2µm (BT_{avg}) and convert the BT_{avg} into the height based ERA5 data[10]. This method allows us to determine the altitude of the cloud tops associated with volcano eruption provided that the averaging domain is devoid of meteorological clouds contamination as it can influence the BT_{avg} values.

For some overpasses of CALIPSO datasets[11], we also compare the plume height estimations with observations from space-borne active sensors to validate our method and results (Figure not shown).

To identify when plume overshoot happens, we estimate the minimum BT11.2µm (BT_{min}) values within a domain of 400 x 300 pixels enclosing the vent site. Each pixel of full disk Himawari-8 data has a 2 km resolution. In this BT_{min} analysis, the cold pixels indicate that a portion of the plume rose higher and are consistent with the occurrence of overshoot (grey line in Figure 1e,f).

Differentiating U_A and U_B

We identified two umbrella clouds on 15 Jan 2022 using brightness temperature contour levels fixed at $BT_{11.2\mu m}$< 215 K (tropospheric umbrella; U_A) and 215K < $BT_{11.2\mu m}$ < 235K (stratospheric umbrella; U_B) within a domain of 400 x 300 pixels. We also evaluate the normalized probability distribution function (PDF) of $BT_{11.2\mu m}$ as a function of time for the above domain to characterize the peak $BT_{11.2\mu m}$ for U_A and U_B. If PDF is zero for the condition of U_A, then it is likely that U_B is dominant (as observed from cyan color in Fig. 1f) and vice-versa. Two peaks in Fig. 1j depict two umbrella clouds at 08:40 UTC on 15 Jan 2022. Estimation of umbrella clouds in this fashion is useful to characterize the composition of plumes. Based on $BTD_{11.2\text{-}12.4\mu m}$ estimation, we show above that the U_A is mostly ash rich (especially near the edge) and U_B is dominant with thick ice clouds.

Volumetric Flow Rate Estimates

We use a 3D distribution of brightness temperature data to assign each pixel value with a unique index of zero and nonzero value for a given threshold condition of brightness temperature, and we then apply histogram to estimate the time-series of areal extents of umbrella clouds. The threshold condition of brightness temperature is given based on the maximum PDF of $BT_{11.2\mu m}$. The time-series of areal extents (A) of umbrella clouds is then converted into radial extent (R), using $R = \sqrt{A/\pi}$ as the umbrella was elongated in one direction (eastward on 19 Dec 2021 and westward during other three events) due to prevailing wind in the upper troposphere and stratosphere. For estimating volumetric flow rate (VFR), we use the parameterization equation[6,12] $R = \left(3\lambda QN/2\pi\right)^{1/3} t^{2/3}$ (where λ is a constant that is approximately 0.2, Q is the volume flux and *N* is the brunt-Vaisala frequency, and *t* is time) to fit with our measurements of spherical-equivalent plume top radius through time for the initial 50-150 min (Figure 1g-h). Also, the brunt Vaisala frequency (N) is taken as 0.026 near tropopause and 0.022 at around 30 km in the stratospheric region as evaluated using ERA5 reanalysis data.