Remote hydroacoustic-infrasonic detection and characterization of Anak Krakatau eruptive activity leading to, during, and following the December 2018 flank collapse and tsunami

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Abstract

A climactic eruption phase on December 22, 2018, triggered the collapse of the southwest flank and summit of Anak Krakatau stratovolcano, generating a tsunami which struck the coastlines of Sumatra and Java. We employ a selection of remote moored hydroacoustic (H08S, 3307 km; H01W, 3720 km) and infrasonic (IS06, 1156 km; IS07, 3475 km; IS52, 3638 km) stations of the International Monitoring System (IMS) to investigate eruptive activity preceding, during, and after the climactic eruption phase. We observe 6 months of co-eruptive intermittent infrasound at IS06 and powerful infrasound from the climactic eruption on IS06 and IS52. The climactic eruption phase was not detected hydroacoustically, but we observe a ~12-day swarm of hydroacoustic signals beginning 24 days before the flank collapse event that we attribute to sustained submarine eruptive activity at Anak Krakatau. We perform hydroacoustic waveform and envelope multiplet analysis to assess event similarity during the hydroacoustic swarm. Hydroacoustic waveforms are not well-correlated, but envelopes with a main pulse duration of ~20-s are correlated, with 88.7% of 247 events grouping into two multiplets using a threshold correlation coefficient of 0.75. The repetitive envelopes indicate a repetitive impulsive volcanic process, either underwater submarine explosions or volcanic earthquakes in the solid Earth coupled to the water column from the Sunda Shelf. This study further underscores the potential of remote acoustic technology for detecting and characterizing eruptions at submarine or partially submerged volcanoes.

Keywords Anak Krakatau · Infrasound · Hydroacoustics · Submarine eruption · Explosive volcanism

Introduction

Anak Krakatau (Child of Krakatau) is a highly active basaltic to dacitic stratovolcano located on the rim of the caldera formed by the 1883 paroxysmal eruption of Krakatau in the Sunda Strait of Indonesia (Fig. 1; Camus et al. 1987; Stehn 1929). Anak Krakatau is a partially submerged volcano, defined here as a volcano which rises from the seafloor, with some part of the upper volcanic edifice that has emerged above the sea surface as an island. A new eruptive phase

began on June 18, 2018, followed by 6 months of intermittent explosive eruption activity (Global Volcanism Program 2019). The eruption peaked on December 22, 2018, with a period of intense eruption triggering a flank collapse and a powerful tsunami in the Sunda Strait (Global Volcanism Program 2019; Grilli et al. 2019). As the eruption included a period of intense Strombolian activity, a tsunamigenic flank collapse, and ~19 days of Surtseyan eruption activity, this new eruptive phase is an opportunity to investigate an eruption using both remote infrasound and remote hydroacoustic technology. Prior to this event, infrasound from a shallow submarine explosive eruption had rarely been reported (e.g., Global Volcanism Program 2004; Green et al. 2013; Lyons et al. 2020) and volcanic flank collapses are rare events which have few recordings in the geophysical record (e.g., Kanamori and Given 1982; Eissler and Kanamori 1987; Green and Neuberg 2005; Watts et al. 2012).

Regarding terminology, the Smithsonian Global Volcanism Program (GVP) bulletin (Global Volcanism Program

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Fig. 1 The location of Anak Krakatau volcano (red triangle) in the Sunda Strait, Indonesia, and IMS infrasound and hydroacoustic stations. Infrasound stations are shown as squares, and hydroacoustic stations are shown as circles; filled symbols are stations used in this study. On the azimuthal map, the open black triangles show locations of potentially active subaerial volcanoes, and the open blue triangles show locations of submarine volcanoes (Global Volcanism Program

2013). The bathymetry map was created using the ETOPO1 1 Arc-Minute Global Relief Model (Amante & Eakins, 2009). The inset satellite map uses a visual-band image from the Sentinel-2 satellite, taken at the start of the new eruptive phase on June 19, 2018 (modified Copernicus Sentinel Data 2019). IMS: International Monitoring System

2019) and existing literature to date refer variously to the December 2018 Krakatau collapse event as a flank collapse (Williams et al. 2019; Perttu et al. 2020) or sector collapse (Walter et al. 2019). According to the definition of Scott et al. (2001), a flank collapse is smaller and does not include the summit, whereas a sector collapse is larger and includes the summit. Although the Krakatau collapse included the summit and is therefore a sector collapse according to the definition of Scott et al. (2001), we use the term flank collapse here to be consistent with the GVP reports and the majority of literature on this event to date.

Volcanoes produce seismo-acoustic waves through a variety of processes and are powerful sources of atmospheric infrasound with frequencies from ~ 0.01 to 20 Hz (Johnson et al. 2004; Fee and Matoza 2013; Matoza et al. 2019). Infrasound can propagate for thousands of kilometers in atmospheric ducts between Earth's surface and upper atmosphere, enabling long-range infrasound signal detection (Liszka 1974; Georges and Beasley 1977; Sutherland and Bass 2004; Campus and Christie 2010; Christie and Campus

2010). Infrasound technology has emerged in recent years as a useful tool to detect and locate volcanic eruptions at local to remote distances (Dabrowa et al. 2011; Matoza et al. 2011a, 2017, 2019). Similarly, hydroacoustic signals can propagate for thousands of kilometers with low attenuation in the ocean water column especially in the Sound Fixing and Ranging (SOFAR) channel waveguide (Ewing and Worzel 1948; Johnson and Norris 1968; Talandier and Okal 2001). The SOFAR waveguide allows hydroacoustic propagation exclusively by refraction, with minimal signal power loss through reflections at the sea surface or seafloor (Jensen et al. 2011). Hydroacoustic signals from a volcanic eruption were first detected in 1952 (submarine Myojin volcano; Dietz and Sheehy 1954), and other volcanic eruptions have been detected at hydrophone stations up to $\sim 15,800$ km from the volcanic source (Metz et al. 2016). This remote hydroacoustic and infrasonic detectability has the potential to aid substantially in volcanic hazard monitoring, as explosive eruptions at remote subaerial, submarine, and partially submerged volcanoes can pose numerous hazards to local

populations, shipping, and aircraft (Przedpelski and Casadevall 1991; Spence et al. 2005; Masson et al. 2006; Schneider et al. 2020).

We present analyses using data from infrasonic and hydroacoustic stations of the global International Monitoring System (IMS). The IMS network was constructed as a component of the verification regime of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) to detect explosions anywhere on Earth (Marty 2019). Infrasonic and hydroacoustic stations of the IMS have been used to characterize and provide chronologies of eruptions, both subaerial (e.g., Dabrowa et al. 2011; Fee et al. 2010; Matoza et al. 2011a, 2018) and submarine (e.g., Green et al. 2013; Metz et al. 2016; Tepp et al. 2019).

Here we compile infrasound and hydroacoustic data from the start of the new eruptive phase at Anak Krakatau in June 2018 through the end of the Surtseyan eruption in January 2019 and place these signals in context with the eruption chronology. We investigate infrasound and hydroacoustic signals from 7 months prior to the December 2018 flank collapse, as well as the flank collapse event and subsequent Surtseyan activity, to provide a longer temporal context for these observations in complement to recent publications on this event (Grilli et al. 2019; Williams et al. 2019; Walter et al. 2019; Paris et al. 2020; Perttu et al. 2020; Ye et al. 2020).

Eruptive history

The Krakatau volcanic complex is the result of arc volcanism caused by subduction of the Australian plate beneath the Sunda plate, and crustal thinning caused by the extensional faulting and rifting of the Sunda Strait (Dahren et al. 2011). The 1883 eruption culminated in a sequence of large magmatically driven explosions that generated catastrophic pyroclastic flows and a tsunami in the Sunda Strait (Self and Rampino 1981), which are estimated to have killed over 36,000 people (Auken et al. 2013). The 1883 tsunami mechanism is uncertain; pyroclastic flows entering the ocean (Self and Rampino 1981) or violent submarine explosions (Yokoyama 1981) have been proposed as the source. The eruption destroyed most of the volcanic edifice, forming a partially submarine caldera. Anak Krakatau began forming as a cone on the northeast rim of the caldera during an eruption in 1927, emerging above sea level in 1928 (Stehn 1929). The volcano has erupted frequently, with at least 40 recorded episodes of Strombolian to Vulcanian style eruptive activity characterized by ash plumes, explosions, incandescent ejecta, and lava flows (Global Volcanism Program 2019). A submarine eruption on the volcano's south flank was observed by eyewitnesses on April 11, 1972 (Global Volcanism Program 1972), and lava domes were reported in 2011, 2012, and 2017 (Global Volcanism Program 2011,

2012, 2017). Since 1928, the volcano has been growing predominantly toward the southwest, toward the center of the 1883 caldera (Deplus et al. 1995), making the southwest part of the edifice particularly unstable. By October 2018, the cone of Anak Krakatau had grown to a height of 338 m above sea level (Global Volcanism Program 2019).

New eruptive phase chronology

After a 15-month period of quiescence, a new eruptive phase began on June 18, 2018, characterized by an increase in seismic activity (Global Volcanism Program 2018). Ash plumes and explosions from the volcano were first observed on June 21, 2018, followed by the first incandescence on July 1, 2018 (Global Volcanism Program 2018). Lava flows reached the sea on September 22, 2018, and frequent explosions, ash plumes, and incandescent material were observed from July through December of 2018. On December 22, 2018, a period of intense Strombolian activity began, characterized by explosions, lava fountaining, ballistics, and a sustained ash column. At ~13:55 UTC, the southwest side and summit of the volcano collapsed into the ocean resulting in a tsunami which impacted the coastlines of Banten and Lampung (Walter et al. 2019; Perttu et al. 2020). The tsunami was first detected on tide gauges at 14:28 UTC and traveled up to 330 m inland with a maximum surveyed runup of 13.5 m, resulting in 437 deaths and > 30,000 injuries (Muhari et al. 2019). Estimates by Ye et al. (2020) indicate that the flank collapse slide volume was small ($< \sim 0.2 \text{ km}^3$) and did not produce short-period seismic waves strong enough to trigger a warning from the existing Indonesian tsunami warning system. As a result of the flank collapse, the vent was submerged in seawater, and eruptive activity transitioned to sustained Surtseyan activity. This Surtseyan activity, base surges, and a sustained ash plume were observed from December 23, 2018 through January 9, 2019, when a rim of tephra formed around the vent, forming a crater lake (Global Volcanism Program 2019). The eruption has continued to the time of writing (April 2021).

Observations

Data

We search infrasound data from the three closest IMS infrasound stations to Anak Krakatau for volcanic eruption signals: IS06 (Cocos Islands; 1,156 km), IS07 (Warramunga, Western Australia; 3,475 km), and IS52 (Chagos Archipelago, British Indian Ocean Territory; 3,638 km) (Fig. 1). IS06 and IS07 are 8-element arrays, station IS52 is a 7-element array. Each station has a total ~1–2 km aperture across array elements, spatial pipe filters on each array element (sensor)

to reduce wind noise, and a sampling frequency of 20 Hz (Marty 2019).

We also analyze hydroacoustic data from two Indian Ocean IMS hydrophone stations: H08 (Chagos Archipelago; 3307 km) and H01W (Cape Leeuwin, Western Australia; 3720 km) (Fig. 1). H08 is constructed of 2 triplet arrays, but only the southern triplet (H08S) is used here due to lack of data availability for the northern triplet (H08N) at the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC). H01W consists of one triplet array. The triplets at each station are moored at the approximate depth of the SOFAR channel at each location (~ 1 km average depth at H01W, and ~ 1.4 km average depth at H08S) to intercept long-distance hydroacoustic signals, with a horizontal sensor spacing of ~ 2 km and a sampling rate of 250 Hz (Lawrence 2004).

Array processing

We perform array processing for infrasound and hydroacoustic data from June 5, 2018, through January 31, 2019 (Fig. 2) using the Progressive Multi-Channel Correlation (PMCC) method (Cansi 1995; Le Pichon et al. 2010), which uses time-domain correlation to measure signal delays between array elements, detect coherent signals, and estimate wavefront parameters (backazimuth, apparent velocity) for a set of filter bandpasses. The PMCC algorithm identifies coherent acoustic signals propagating across subsets of 3 sensors (triplet subarrays) in the array, and consistency in estimated wavefront parameters between progressive subarrays results in a detection logged as a “pixel” (a correlated

Fig. 2 PMCC summary detections for infrasound and hydroacoustic stations from June 5, 2018, to January 31, 2019. Horizontal dashed black lines indicate the back-azimuth of Anak Krakatau, and vertical solid black lines indicate the major flank collapse event on December 22, 2018 at $\sim 13:55$ UTC. Blue-outlined region in **a** shows the extent of **b**. The blue shaded region in **b** shows the length of the hydroacoustic swarm at H08S with a similar back-azimuth to Krakatau. The blue shaded regions of H08S and IS06 indicate the signal timeframes from which hydroacoustic and infrasound events were picked to investigate waveform similarity in Figs. 8 and 9. **c** The H01W plot shows detections that overlap with the H08S swarm. **d** IS06, the closest

IMS station, shows intermittent signal arriving from the back-azimuth direction of Anak Krakatau from July to December, 2018 (see Fig. 3 for detail), followed by powerful detections during the main eruption sequence from December 22, 2018, to January 9, 2019, with the end of Surtseyan activity. **e** IS07 does not show continuous detections from the direction of the volcano. **f** The detections at IS52 are dominated by microbarom clutter (e.g., Matoza et al. 2011b, 2013; Williams et al. 2020), but magnifying the plot to the time of the main eruption reveals co-eruptive signal beneath the clutter (see Fig. 4). PMCC: Progressive Multi-Channel Correlation; IMS: International Monitoring System

and for the hydroacoustic stations, we used 40 frequency bands log-spaced from 0.01 to 120 Hz with window lengths ranging from 30 to 400 s.

Beginning December 22, 2018, IS06 records 19 days of powerful, nearly continuous infrasound associated with the main

Fig. 4 **a** Comparison of PMCC summary infrasound detections. The back-azimuth of Anak Krakatau is indicated on each panel with a gray dashed line, and the time of the flank collapse at ~13:55 on December 22, 2018, is indicated by a vertical red-dashed line. Eruptive activity at Anak Krakatau is detected infrasonically at IS06 and IS52. Krakatau detections at IS52 are partially obscured by microbarom clutter, but the histogram of detections for the time range of the plot shows a significant peak in detections near the direction of the volcano. Blue lines on the histograms indicate the median back-azimuth of all detections in each panel. **b** Detection cross-bearings for infrasound stations IS06 and IS52 where coherent eruptive detections are observed, calculated using the median back-azimuth of detections at each station during the eruption period. The great circle paths at

the median back-azimuth directions are indicated with solid teal lines. Anak Krakatau is indicated by a red triangle. The back-azimuth intersection of the cross-bearings is 128 km from true. **c** Comparison of PMCC summary hydroacoustic detections, parsing only detections with mean frequencies of 1–15 Hz to reduce ocean clutter (background hydroacoustic signals). The main eruption and flank collapse were not detected hydroacoustically, but H08S and H01W detect a 12-day hydroacoustic swarm ending 12 days before the main eruption began. Blue lines on the histograms indicate median back-azimuth of detections of suspected volcanic activity (black rectangle). **d** Detection cross-bearings for H08S and H01W hydroacoustic swarm. The back-azimuth intersection of the cross-bearings is 100 km from true. PMCC: Progressive Multi-Channel Correlation

eruption phase (intense Strombolian activity followed by the flank collapse, tsunamis, and the onset of Surtseyan activity; Fig. 4). The waveform and spectrograms presented are for a time-delay beamformer implemented by Matoza et al. (2007), which is used to delay and stack the signals from the elements of the array and reduce incoherent noise. Using PMCC bulletin (i.e., summary) detections at IS06, we identify a period of weak, higher-frequency (3.0 Hz average) activity at Anak Krakatau lasting for ~89 h, followed by the onset of high-amplitude Strombolian activity on December 22, 2018, beginning

at ~05:17 UTC, which increased in intensity until ~07:41 UTC (Figs. 4 and 5). The flank collapse occurred at ~13:55 UTC (Walter et al. 2019; Perttu et al. 2020), and was recorded at station IS06 (Fig. 5). The flank collapse signal lasts ~6 min and appears on the beamformed spectrogram as three ~2 min duration higher frequency pulses with frequency content in the 0.1–4 Hz range. The first and third pulses are of lower amplitude, but the middle pulse is a powerful ~70-s duration, high-amplitude (4.5 Pa) signal. The detail of the flank collapse waveform is shown on Fig. 5c.

Fig. 5 Infrasound station IS06, Cocos Islands (1156 km range) waveforms and spectrograms for a 10-day period, from December 19–29, 2018, including the beginning of the climactic eruption phase and flank collapse on December 22, 2018, followed by signals from December 22–29, 2018, that we attribute to Surtseyan activity, base surges, and ash plumes based on eyewitness observations at the volcano reported by the Smithsonian’s Global Volcanism Program (2019). Panel **a** shows the 0.01–4 Hz bandpass filtered and beamformed waveform, and panel **b** shows the 1.5–4 Hz bandpass filtered and beamformed waveform. Solid red circles indicate when

coherent eruptive signal was detected by PMCC as arriving from $\pm 3^\circ$ of the Anak Krakatau back-azimuth. Panel **c** shows the beamformed spectrogram for the 10-day timespan. Panel **d** shows the detail of the flank collapse signal, bandpass filtered from 0.1 to 4 Hz. Panels **e** and **f** show spectral details for the high-power signals from pre-collapse eruption and flank collapse, and the Surtseyan activity, respectively. We observe a notch in the frequency spectrum from ~ 0.7 – 1.0 Hz at IS06, particularly during the intense pre-collapse Strombolian eruption (panel **e**). PMCC: Progressive Multi-Channel Correlation

Immediately after the flank collapse, we observe an overall drop in frequency content. The average frequency of PMCC summary detections from the time of the flank collapse until the end of Surtseyan activity on January 9, 2019, is 1.3 Hz, though detections fluctuate between periods of higher and lower frequencies.

Though microbarom “clutter” (correlated signals other than the signals of interest; Landès et al. 2012; Matoza et al. 2013) dominates the detections at IS52, a notable increase in the number of detections arriving from the back-azimuth of Anak Krakatau shows that IS52 captured sustained infrasound from the main eruption sequence (Fig. 4). A band of detections with stable back-azimuth and mean frequency of 0.86 Hz is present within this clutter that arrives from $\sim 5^\circ$ clockwise of the true back-azimuth of the volcano, which we interpret as a volcanic signal with a typical azimuth deviation caused by atmospheric

cross-wind effects. Detections from both IS06 and IS52 record intermittent higher frequency (0.5–5 Hz) pulses during the Surtseyan eruption period. The first infrasound attributed to Anak Krakatau at IS52 is recorded ~ 26 h after the start of intense Strombolian activity, a delay likely caused by low signal-to-noise ratio (SNR) at IS52 (compare with Fig. 4 of Matoza et al. 2018).

Station IS07 did not record continuous, coherent infrasound attributable to Anak Krakatau during the June 2018 to January 2019 period (Figs. 2, 4). Since infrasound propagation is strengthened when atmospheric winds are directed along the same direction as the wave propagation (especially stratospheric winds for long-range infrasound), and inhibited by wind in the opposite direction (de Groot-Hedlin et al. 2010; Mutschlecner and Whitaker 2010), wind conditions presumably precluded the signal reaching station IS07.

Hydroacoustic

The hydroacoustic PMCC detections at H08S do not show continuous detections from the direction of Anak Krakatau during the main eruption sequence, possibly due to low SNR caused by interference from a marine seismic survey (Rose 2020). However, detection results show a 12-day swarm of nearly continuous hydroacoustic signal arriving at H08S from the Anak Krakatau back-azimuth beginning 24 days before the flank collapse and tsunami, from November 29 through December 11, 2018 (Figs. 2, 4). This hydroacoustic swarm arrives from a back-azimuth that is densely populated with other short-duration detections (which we interpret as signals from Java Trench earthquake events and anthropogenic noise) but the swarm is distinguishable from these based on its extended duration. Hydroacoustic waveforms and spectrograms corresponding to these detections show discrete, impulsive signals with frequency content of ~ 3 –40 Hz (Fig. 6). We also observe consistent hydroacoustic detections at H01W, from November 30 through December 4, 2018 (Fig. 4), which overlap with the swarm observed at H08S. We compare the swarm at H08S with activity at IS06 on Fig. 7, which shows that the hydroacoustic detections overlap with explosive eruption activity at Anak Krakatau in the weeks prior to the main eruption and flank collapse event.

In addition to interpreted volcanic signals, H08S and H01W detections include strong bands of detections in the

respective back-azimuth directions of the southern Indian Ocean (see Fig. 2, panel a). These detections are consistent with iceberg cracking and calving in the southern Indian Ocean found by Evers et al. (2013), which used satellite observations and hydroacoustic data from the same two IMS stations to monitor iceberg breakup.

Waveform and envelope similarity analysis

Waveform similarity (multiplet) analysis has been used for seismic data at subaerial volcanoes to identify stable low-frequency earthquake sources (e.g., Green and Neuberg 2006; Matoza and Chouet 2010; Petersen 2007; Stephens and Chouet 2001) and with acoustic data at submarine volcanoes to classify generation mechanisms of hydroacoustic events (Green et al. 2013). Highly repetitive events which exhibit strongly correlated waveforms indicate a repetitive, stable, non-destructive source, with the energy propagating along an almost identical path to reach the sensor. Events for which the waveforms gradually evolve over time reflect a changing source-time function, source geometry, or source location (Stephens and Chouet 2001). We apply a method similar to Green and Neuberg (2006) and Green et al. (2013) to the hydroacoustic signals from Anak Krakatau to investigate waveform and envelope similarity and resolve whether physical eruption processes may be linked to systematic changes in the waveform and envelope shapes produced.

Fig. 6 **a, b** Hydroacoustic waveform and **c** spectrogram of H08S data from November 29, 2018, to December 11, 2018, encompassing 24–12 days before the onset of the climactic eruption and flank collapse. The waveform and spectrogram have been beamformed in the direction of Anak Krakatau. Panel **b** shows a reduced pressure range from -5 to 5 Pa to show detail of smaller events. Solid teal circles on the waveforms indicate coherent PMCC detections from the direction of Anak Krakatau, which we interpret as submarine eruption activity. Panels **d** and **e** show that the hydroacoustic events with corresponding PMCC detections tend to be impulsive and band-limited from ~ 3 to < 40 Hz. PMCC: Progressive Multi-Channel Correlation

Fig. 7 Scatter plot and 2D histograms of PMCC pixels (that belong to a PMCC family) at hydroacoustic station H08S and infrasound station IS06. Scatter plot (top panel) in each case shows PMCC pixels plotted as backazimuth vs. time and color-coded by frequency. The 2D histogram (lower panel) in each case shows the same backazimuth-time points but grouped into bins of 5-h time increments by 0.1° backazimuth increments, to show the density of points. H08S shows a hydroacoustic swarm extending from November 29, 2018, to December 13, 2018, but no clear activity during the climactic phase. IS06

shows infrasound detections from November 30, 2018, to December 5, 2018, partially overlapping the H08S hydroacoustic swarm, followed by a period of quietude until December 18, 2018. This is followed by 5 days of higher-frequency infrasound, and then onset of the main eruption phase and flank collapse on December 22, 2018. This suggests that the eruption involved submarine activity at the same time as infrasound-generating activity was occurring, and which continued for 8 days after the infrasound detections ceased. PMCC: Progressive Multi-Channel Correlation

Hydroacoustic event similarity

We first create a starting catalog of hydroacoustic PMCC detections that are likely associated with eruptive activity at Anak Krakatau, without regard for waveform shape similarity. We apply a 2.5–10 Hz Butterworth bandpass filter to the H08S hydroacoustic data from November 29 to December 11, 2018, and then beamform the signal. The PMCC detections have a minimum 3-s time spacing, and we manually select these detections as “events” except when detections occur continuously, in which case we select every other detection (to avoid correlating the same waveform segments, as we use a 6 s time window for cross correlation). These detection events are windowed from 1 s prior to 5 s after the detection, for a total of 2169 detection events (shown on Fig. 8). We use these picks as input to waveform cross-correlation analysis (Matoza and Chouet 2010). Following Green and Neuberg (2006), Matoza and Chouet (2010), and Green et al. (2013), we calculate event similarity using cross-correlation for each of the hydroacoustic event waveforms with every other event, logging the maximum correlation coefficient into an m -by- m matrix, where m is

the number of detection events ($m = 2169$ here). We subsequently attempt to cluster the H08S hydroacoustic events into groups of similar signals (or “multiplets”) based on a correlation-coefficient threshold of 0.6 (Green and Neuberg 2006). However, this method resulted in poor correlation of the 2169 detection event waveforms, with only 7.9% of waveforms correlated above the 0.6 threshold.

Since many of the high-amplitude hydroacoustic events exhibit a longer duration than the 6-s cross-correlation time window, we conduct hydroacoustic signal envelope analysis to determine similarity of the longer signals. This analysis is based on the method of Talandier and Okal (2001), which used hydroacoustic T-phase signal envelopes to distinguish between subduction zone earthquakes, volcanic earthquakes, and explosive submarine events. We made a second set of hydroacoustic picks using only more significant signals with at least 5 successive PMCC detections, for a total of 247 events. Following the waveform cross-correlation method as described above, these events also display poor correlation at the 0.6 threshold (15.4% of events correlated above the 0.6 threshold). Therefore, for each event, we bandpass filter from 2 to 15 Hz, beamform, then produce envelopes using a

6-s rolling mean. We perform cross-correlation analysis on these envelopes, and of the 247 events, 219 (88.7%) were correlated above a correlation coefficient threshold of 0.75. The two largest envelope multiplets are shown on Fig. 9, with 96 waveforms and 101 waveforms, respectively. The

two envelope multiplets are qualitatively similar and presumably could be merged, though we do not attempt that here. Minor variations between multiplet 1 and multiplet 2 may be due to variations in source depth, seismo-acoustic coupling location, source location, or source process.

Fig. 8 a Timeline of eruption. Magenta circles indicate days with Sentinel-2 satellite thermal anomaly detections (modified Copernicus Sentinel Data 2019), teal circles indicate reported Surtseyan eruption (Global Volcanism Program 2019), red circles indicate days where lava flows were reported (Global Volcanism Program 2019), gray circles indicate days with eruption plumes reported (Global Volcanism Program 2019), and blue circles indicate days on which volcano-seismic events or eruption tremor at Anak Krakatau were reported by PVMBG (Pusat Vulkanologi dan Mitigasi Bencana Geologi 2018). Blue rectangles show the duration of hydroacoustic PMCC detections from H08S and H01W, and orange rectangles show the duration of infrasound detections from IS06 and IS52. **b, c** PMCC hydroacoustic pixel detections. **d, e** PMCC infrasound bulletin (summary) detections. Horizontal dashed black line on panels **b–e** indicates back-azimuth direction of Anak Krakatau, and vertical red-dashed lines indicate the approximate time of the flank collapse which triggered the tsunami. **f** Infrasound (IS06) and hydroacoustic (H08S) events. Infrasound events were picked using network STA/LTA with PMCC cross-checking method, while hydroacoustic events were picked manually corresponding to PMCC detections. **g** SAR satellite imagery from Sentinel-1 and thermal and visual satellite imagery from Sentinel-2 showing the effects of the eruption on the morphology of the volcanic edifice (modified Copernicus Sentinel Data 2019). The diameter of the island measured from its most northern to most southern point is approximately 2.2 km. STA/LTA: short-term average/long-term average; PMCC: Progressive Multi-Channel Correlation; PVMBG: Indonesian Centre of Vulcanology and Geological Hazard Mitigation

We compare examples of the volcanic waveforms from December 1, 2018, to other high-amplitude clutter signals, representing PMCC detections from a different direction (not Anak Krakatau) on this day (Fig. 9). The Krakatau waveforms are of shorter duration (~20 s), with a sharper onset and conclusion than the clutter waveforms. The volcanic envelopes are qualitatively more similar in shape to volcanic earthquake and explosive volcanism envelopes observed by Talandier and Okal (2001) at submarine Lō‘ihi volcano, Hawaii, whereas the clutter envelopes are more similar to tectonic earthquake envelopes described in that study.

Discussion

Intermittent infrasound, July–December 2018

IS06 is the closest IMS infrasound station to Anak Krakatau and recorded the most robust set of remote acoustic detections linked to this eruption. Intermittent pulses of infrasound were observed at IS06 from July to December 2018 from the back-azimuth of Anak Krakatau (Fig. 3), before the flank collapse and tsunami event. Due to their consistent back-azimuth range over the 6-month period and temporal coincidence with reports of seismic events, eruption plumes, lava flows, or thermal anomalies at the volcano (the occurrences of which are detailed on Fig. 8), we attribute these pulses to periods of subaerial explosive eruption activity at Anak Krakatau. These eruptive pulses were less powerful

than the main eruptive phase, but could have contributed to destabilization of the volcanic flank. However, not all instances of the seismic, plume, lava, or thermal events corresponded with co-eruptive infrasound at IS06, indicating a threshold of eruption signal power and atmospheric conditions needed to exceed the noise floor at the station (Green et al. 2013). For example, lava flows were reported from September 5 to October 12, 2018 (Global Volcanism Program 2019), but infrasound attributable to Anak Krakatau was not recorded at IS06 on 24 of these 38 days (Fig. 8). Thus, although lava flows and fountaining can produce locally detectable infrasound (Ulivieri et al. 2013; Gottschämmer et al. 2021), only more energetic explosive activity may produce infrasound powerful enough to be detected remotely.

Hydroacoustic swarm, November 29–December 11, 2018

The 12-day hydroacoustic swarm observed at H08S is coincident with the last significant pulse in infrasound activity before the onset of the main eruption phase (Fig. 7). Though this swarm overlaps with infrasound detections from November 29 to December 4, 2018, the hydroacoustic events could not be matched with infrasound events by comparing event time delays, indicating a separate source. The presence of this co-eruptive swarm suggests that the eruption produced a period of submarine activity (or earthquakes in the solid Earth coupled to the water column) coincident with subaerial eruptive activity. Due to the limitation of remote data and the challenges of visual observation in a submarine environment, the hydroacoustic source mechanisms are difficult to constrain. Therefore, the discussion presented here is speculative and represents one set of possible interpretations.

The hydroacoustic swarm events from Anak Krakatau are typically confined to the ~3–40 Hz frequency range, and less than 30 s duration with minutes to hours between events, suggesting an impulsive rather than sustained source. Impulsive submarine events at other volcanoes have been attributed to underwater phreatomagmatic explosions produced by the opening of a vent (Bohnenstiehl et al. 2013; Tepp et al. 2019), phreatomagmatic explosions as a result of dome building and collapse (Green et al. 2013), bursting magmatic gas bubbles (Chadwick et al. 2008; Dziak et al. 2015), or discrete, shallow volcanic earthquakes coupled into the water column (Dziak and Fox 1999; Dziak et al. 2005; Tepp et al. 2020).

Phreatomagmatic explosions typically have a broadband spectrum (Metz et al. 2016; Tepp et al. 2019), but the ~3–40 Hz band-limited character of the swarm signals could be a propagation effect. Longer hydroacoustic wavelengths diffract more easily around bathymetric obstructions and would be less attenuated (especially for

Fig. 9 **a** The two largest hydroacoustic envelope multiplets at H08S based on a correlation coefficient of 0.75. Waveforms were filtered from 2–15 Hz, beamformed, normalized, and the 6 s rolling mean calculated. Individual envelopes of the multiplets are shown in gray, and the master envelope stack of each multiplet in a black solid (multiplet 1) or dashed (multiplet 2) line. **b** Event matrices for the multiplets in chronological order with the first event at 0. The events are aligned via cross-correlation to the best-correlated envelope in the multiplet. **c** The 247 events with greater than 5 PMCC detections as the maximum amplitude of the event with time (black crosses) identifies the events assigned to the multiplet (red crosses). **d** Comparison of the average envelope of multiplet 1 and

multiplet 2, aligned by maximum amplitude. **e** Example envelopes from December 1, 2018, with PMCC detections from the direction of Anak Krakatau (interpreted as volcanic) and **d** clutter envelopes (possible earthquakes). The interpreted volcanic waveforms on **e** are solid if they belong to multiplet 1, and dashed if they belong to multiplet 2. Multiplet 1 envelopes show a slightly sharper onset and slightly sharper decline than multiplet 2 envelopes, and both multiplets differ significantly from the clutter waveforms, which we interpret as earthquakes based on observations of volcanic vs. tectonic earthquake multiplets in Talandier and Okal (2001)

station H01, where there is not a direct line of sight to Anak Krakatau). The loss of high frequencies is consistent with observations of Tepp et al. (2019) who noted explosion signals with reduced frequency content at a hydroacoustic station ~2250 km from its source at Ahui volcano, and Metz et al. (2016) who observed hydroacoustic signals from submarine phreatomagmatic explosions at Monowai volcano arriving at a hydrophone ~15,800 km away with

frequencies of 2–20 Hz. Observations of the 2018 eruption at Ioto volcano off the coast of Japan, another partially submerged volcano, showed similar impulsive hydroacoustic events in the 6–60 Hz range (Matsumoto et al. 2019).

The swarm coincides with reports of seismic events and eruption plumes at Krakatau (Fig. 8), suggesting that the eruption may have been taking place both subaerially and sub-aqueously. Seawater discoloration is a typical

feature of shallow submarine explosive volcanism (Ossaka 1975; Nogami et al. 1993; Urai and Machida 2005), but Sentinel-2 visual and thermal band satellite imagery was obscured by clouds during this time period, preventing identification of discoloration using this dataset. An alternative explanation is that the hydroacoustic swarm signals represent volcanic earthquakes (in the solid Earth in the region below Krakatau), coupled into the water column from the shallow Sunda Shelf.

The static back-azimuth of these events over 12 days (established by PMCC results) is typical of a volcanic source, and rules out many possible sources of transitory hydroacoustic signal (animal sources, ships, storms, etc.). The minute-to-hour long intervals between successive events and lack of near-perfectly repeating broadband waveforms rule out seismic surveying as the source of the swarm (Rose 2020), and cross-bearing paths of H08S and H01W place the swarm in the vicinity of the Sunda Strait ruling out iceberg or glacier noise (Evers et al. 2013). Though tectonic earthquakes are a major source of hydroacoustic signal in the oceans, the impulsive events of the hydroacoustic swarm occurred over a 12-day period and thus are inconsistent with tectonic earthquake signals which are typically singular events seconds to minutes long (Talandier and Okal 2001). Magmatic gas bubble bursts observed during other submarine eruptions were of much shorter duration (< 1 s) (Dziak et al. 2015) or displayed a characteristic gradual acoustic amplitude buildup and sudden amplitude increase corresponding to the destruction of a solidified lava plug (Chadwick et al. 2008), inconsistent with the results presented here. The intermittent nature of the signal is consistent with a series of explosions over several days as observed during other submarine eruptions, or a swarm of volcanic earthquakes beneath Anak Krakatau coupling efficiently into the water column from the shallow Sunda Shelf. Future work modeling seismo-acoustic coupling and long-range hydroacoustic propagation could further test these hypotheses.

Intense strombolian activity, ~ 06:43–13:55 UTC, December 22, 2018

The period of intense Strombolian activity reported by eyewitnesses at Anak Krakatau is visible in the IS06 infrasound waveform as a high-amplitude signal and on the spectrogram as a sharp increase in frequency content on December 22, 2018 (Fig. 5). PMCC detections change from low-amplitude intermittent to continuous, high-frequency, high-amplitude detections (Fig. 8). The Sentinel-1 SAR satellite overpass on December 19 before the onset of the main eruption shows the volcanic cone still intact (Fig. 8).

Flank collapse and tsunami, ~ 13:55 UTC, December 22, 2018

The flank collapse signal recorded infrasonically at IS06 exhibits the highest amplitude on the unfiltered, beam-formed signal on December 22, 2018, but was not detected at any other IMS stations from which data was analyzed (IS07, IS52, H01W, H08S), consistent with the analysis of Perttu et al. (2020). The tsunami was detected locally by tide gauges in the Sunda Strait (Grilli et al. 2019), and Perttu et al. (2020) report a ~40 min, 0.01–0.1 Hz seismic detection at station IA-CGJI (~64 km from Anak Krakatau) interpreted as the tsunami hitting the coasts of Sumatra and Java.

Submarine volcanic flank collapses and landslides are generally difficult to detect hydroacoustically, especially at long distances. For example, hydroacoustic signal from a 2008 submarine collapse at Monowai volcano was recorded at distances up to ~4270 km, but this signal was interpreted as having been generated mostly by explosive magma-seawater interactions rather than from the collapse itself (Wright et al. 2008). The submarine collapse of NW Rota-1 volcano was recorded hydroacoustically, but only by an in-situ hydrophone located ~150 m from the vent (Chadwick et al. 2012). Arguably, the best record of a submarine landslide recorded hydroacoustically at a remote distance was a landslide from the 1998 Papua New Guinea earthquake, which was recorded at a distance of 3600 km and had a relatively small spectral amplitude but high-frequency content (Okal 2003).

The interpretation of a lack of signal during the time of the main flank collapse is complicated by background noise for this dataset. The lack of hydroacoustic detection of the main eruption sequence on H08S and H01W coincides with a general decrease in clutter from other sources of hydroacoustic sound such as iceberg cracking and shipping (Fig. 2a). We attribute the decrease in these detections to a powerful interferer (clutter source) consisting of repetitive, broadband pulses, which we interpret as a marine seismic air-gun survey (Rose 2020). These surveys use air-guns to release a quantity of highly pressurized air approximately every 10 to 60 s, resulting in a series of high-amplitude pulses at frequencies of approximately 2–188 Hz at the source location (Nieukirk et al. 2012). Additional scans through H08S data reveal that these consistent pulses are recorded intermittently at H08S from October 28–November 26, 2018, and December 16–27, 2018, including (unfortunately) during the day of the flank collapse and tsunamis, which significantly raises the noise floor during that time. Thus, anthropogenic noise presents a challenge to hydroacoustic detection, as this noise can also propagate efficiently in the ocean waveguide.

Surtseyan activity, December 22, 2018–January 9, 2019

Surtseyan activity was reported at Anak Krakatau immediately after the flank collapse and continued until the vent closed off from the ocean on January 9, 2019 (Global Volcanism Program 2019; Fig. 8). The Surtseyan activity was accompanied by a continuous volcanic plume and seismic activity which correspond to the duration of the infrasound detections (Fig. 8a). The PMCC detections of this Surtseyan activity are of lower overall frequency content than the pre-collapse Strombolian eruption or the intermittent infrasound activity before the onset of the main eruptive phase. We attribute the overall decrease in frequency content to changes in vent morphology and the transition from subaerial Strombolian to Surtseyan activity as the vent was submerged. Co-eruptive infrasound (volcanic jet noise) has been observed to decrease as the diameter of the vent increases (Matoza et al. 2009), and a similar frequency decrease was observed at Bogoslof volcano during its 2016–2017 eruption, upon the transition from subaerial to shallow submarine explosive activity (Fee et al. 2020; Lyons et al. 2020). Strong detections continue until January 9, 2019, when they taper off with the conclusion of Surtseyan activity at the submerged vent. Pulses of higher-frequency PMCC detections are visible during the high-amplitude periods of Surtseyan eruption (Fig. 8). We speculate that these frequency changes may be caused by stronger explosions that temporarily cleared the vent, allowing radiation of infrasound directly into the atmosphere resulting in higher frequency content, similar to the vent “drying” observed during the 2016–2017 eruption of Bogoslof volcano (Fee et al. 2020). However, with the available data, we cannot rule out atmospheric propagation effects.

Conclusions

The eruptive activity leading up to, during, and following the 2018 major flank collapse and tsunami at Anak Krakatau was captured remotely on infrasound and hydroacoustic stations of the IMS global monitoring network (IS06, 1156 km range; IS52, 3638 km range; H08S, 3307 km range; and H01W, 3720 km range). We have investigated these infrasound and hydroacoustic signals using array processing, waveform and spectrogram analysis, and interpreted possible source processes for observed signals by comparing these with eyewitness reports and satellite imagery. Our analysis complements previous studies of this eruption by placing the catastrophic flank collapse and tsunami in the context of 7 months of prior eruption activity and post-collapse Surtseyan activity. Here we also observe a 12-day hydroacoustic swarm from the direction of Anak Krakatau which

coincided with eruption infrasound and which we interpret as submarine eruptive activity which ceased before the onset of the main eruption sequence. The 12-day hydroacoustic swarm may represent volcanic earthquakes coupling to the water column through seismo-acoustic conversion or underwater explosive magma-seawater interactions. Repetitive waveform envelopes with pulse durations of ~20-s for the hydroacoustic swarm with minor variations suggest repetitive volcanic activity possibly with variations in mechanism and/or location (e.g., changes in earthquake hypocenter and seismo-acoustic coupling location, changes of underwater explosion mechanism source-time-function).

Our results are of utility in the design of future systems to automatically detect submarine volcanism in order to warn ships and aircraft of possible maritime volcanic hazards. Acoustic-based automated detection of intense eruption or flank collapse signals could be added to existing tsunami early warning systems to improve volcanogenic tsunami detection capability, targeting volcanic eruptions as possible tsunami sources in addition to earthquake sources (Strunz et al. 2011). This case study further highlights the role that remote infrasound and hydroacoustic technology can play in the detection and characterization of eruptive activity at submarine and partially submerged volcanoes.

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Data availability We use data from seismic network code IM (International Monitoring System) downloaded from the IRIS DMC (<http://www.iris.edu>). Data from the CTBT IMS infrasound network are also available through the CTBTO vDEC platform (<https://www.ctbto.org/specials/vdec/>). Modified Copernicus Sentinel data from the European Space Agency (ESA) is available from Sentinel Hub (<https://apps.sentinel-hub.com/eo-browser/>).

Code availability The PMCC software (Le Pichon et al. 2010) is developed and maintained by the Commissariat à l’Energie Atomique (CEA). The ObsPy Python toolbox (Beyreuther et al. 2010) is available from www.obspy.org. The GMT toolbox (Wessel and Smith 1991) was used for plotting and is available at <https://www.generic-mapping-tools.org/>.

Declarations

Competing interests The authors declare no competing interests.

Disclaimer The views presented in this work are those of the authors and do not necessarily represent the views of the CTBTO or any other institution mentioned herein.

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