

Tracking Volcanic Atmospheric Waves: Insights from the 2022 Hunga Tonga Eruption observed with an Open Sensor Network in Bulgaria

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Abstract. The January 2022 eruption of Hunga Tonga was one of the most powerful volcanic events of the modern era, generating a vertical plume that reached over 50 kilometres above Earth’s surface. The initial explosion, followed by a high-speed atmospheric jet, triggered waves that circled the globe multiple times. The effects of the eruption on Bulgarian territory were detected and analysed using data from the METER.AC network, which includes a wide array of custom-designed and assembled ground monitoring stations, enhanced by a set of certified professional weather stations. These stations utilise the Internet of Things (IoT) paradigm to collect data from a variety of sensors and provide open access to the recorded measurements. We have developed a suite of algorithms to process the collected data through several methods, including semi-automated detection of wave minima and maxima, Fourier spectral analysis, and the integration of data from nearby instruments. This approach enabled us to identify and analyse the first two atmospheric waves that reached Bulgaria and to calculate their average propagation speeds—301 m/s and 315 m/s, respectively. This research highlights the significance and capability of the citizen science network, METER.AC, in providing valuable data for understanding global phenomena, particularly large-scale volcanic events. It also highlights the potential of IoT-based systems and data processing algorithms in advancing atmospheric research and environmental monitoring.

Key words: Hunga Tonga–Hunga Ha’apai Eruption, Atmospheric Waves, Monitoring network, METER.AC, IoT.

Introduction

Hunga Tonga–Hunga Ha’apai is a submarine volcano in the South Pacific, located approximately 30 km south-southeast of Falcon Island (“Report on Hunga Tonga–Hunga Ha’apai (Tonga),” 2022). Several eruptions have been recorded in this region, beginning with the first documented event in 1912. Until recently, all eruptions in the area had Volcanic Explosivity Index (VEI) ratings between 0 and 3. The mid-January 2022 eruption of Hunga Tonga–Hunga Ha’apai was the most powerful ever recorded in the region, reaching a VEI of 5. Volcanic activity began on December 20, 2021, and peaked on January 15,

2022, at 4:15 AM UTC (Tarumi & Yoshizawa, 2023). The explosion was so intense that it was heard over 6,000 miles away (Tonga’s Strange Volcanic Eruption Was Even More Massive than We Knew, National Geographic, n.d.). In addition to the atmospheric impact, the eruption generated tsunamis that caused damage across a wide area, including Fiji, Hawaii, Chile, California, Japan, Russia, and New Zealand (In Depth: Surprising Tsunamis Caused by Explosive Eruption in Tonga, U.S. Geological Survey, n.d.).

Scientists reported observing unusual concentric circles of atmospheric gravity waves, which may have passed the globe multiple times—an

event with no recorded precedent in the past 20 years (Adam, 2022). Pressure anomalies associated with these waves were detected worldwide using standard meteorological instruments (Harrison, 2022).

In the context of Bulgaria, the effects of the Hunga Tonga-Hunga Ha'apai volcano eruption were detected and analysed using data from the METER.AC network (Terziyski et al., 2020). Similar effects from the eruption were observed in various countries around the world. In this study, we examine how sensors from the METER.AC network recorded signals associated with the eruption, and we present our observations and data analysis for the period surrounding the event.

Materials and methods

The data used in this study were obtained from the METER.AC network (Terziyski et al., 2020), an open-access, real-time environmental monitoring system featuring a well-distributed array of sensors across the territory of Bulgaria (Fig. 1). The network is developed, maintained, and continuously expanded by the C.lab research

group at the University of Plovdiv. Since its establishment in September 2018, METER.AC has been steadily growing. It includes both custom-designed and self-assembled ground-based monitoring stations (GBMS), as well as certified weather stations (CWS) manufactured by GILL, La Crosse, Lufft, etc.

The system operates within the framework of the Internet of Things (IoT), collecting data from a diverse array of environmental sensors. All collected data is publicly accessible. Currently, the network comprises over 200 ground-based monitoring stations (GBMS) and more than 20 certified weather stations (CWS). The GBMS are equipped with sensors that measure temperature, relative humidity, atmospheric pressure, particulate matter (PM_{2.5} and PM₁₀), and background gamma radiation. The CWS provide additional measurements, including wind speed and direction, precipitation, and solar radiation. The primary objective of the METER.AC network is to facilitate long term, high-resolution monitoring of a broad spectrum of natural processes through a dense and evenly distributed array of ground-based stations.

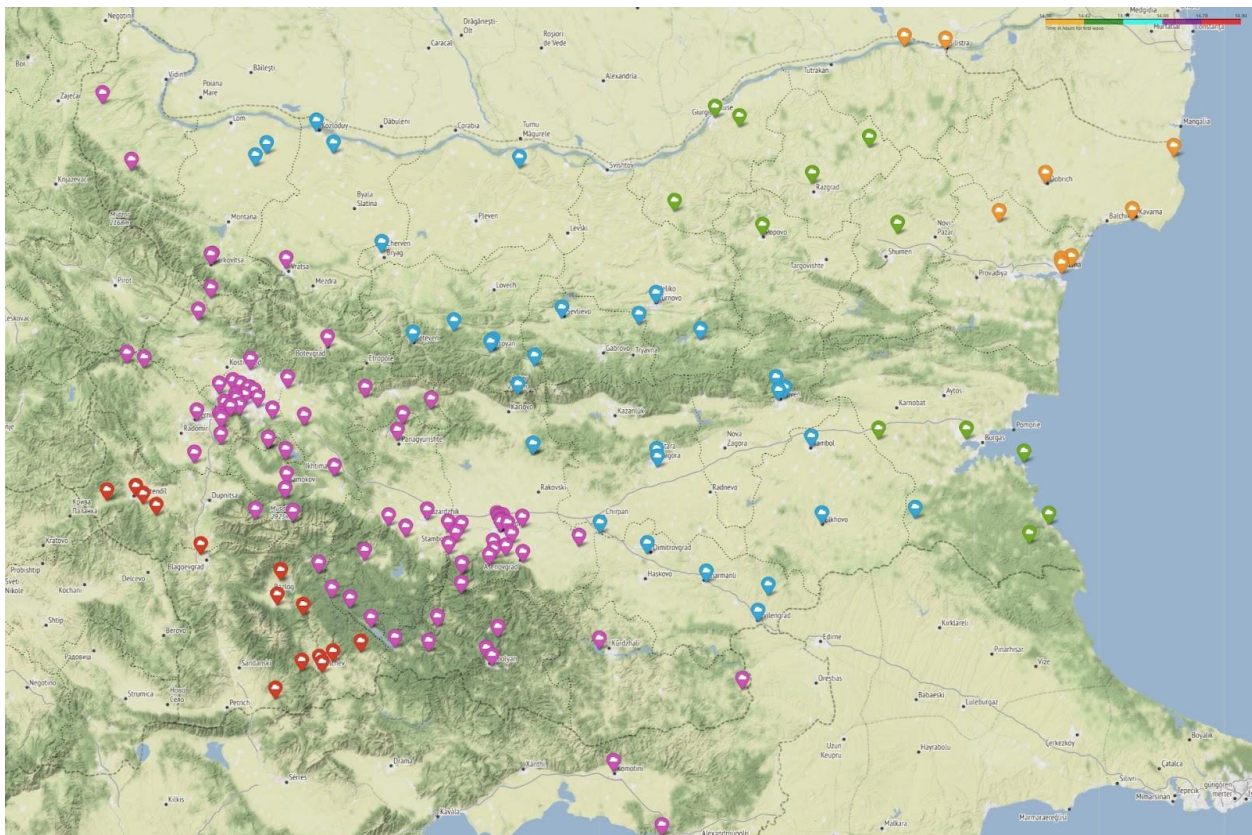


Fig. 1. METER.AC network coverage with colour-coded time zones, each representing an 8-minute interval, beginning from the moment of the first pressure anomaly record.

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The methodology used to obtain the results is illustrated in Fig. 2. Sensor nodes distributed throughout Bulgaria continuously monitor and record various environmental parameters. The collected data is transmitted to the central METER.AC

database. Custom-built Jupyter Note-books (Python scripts) are then used to extract both the data and associated metadata, which are stored locally to facilitate efficient and flexible analysis.

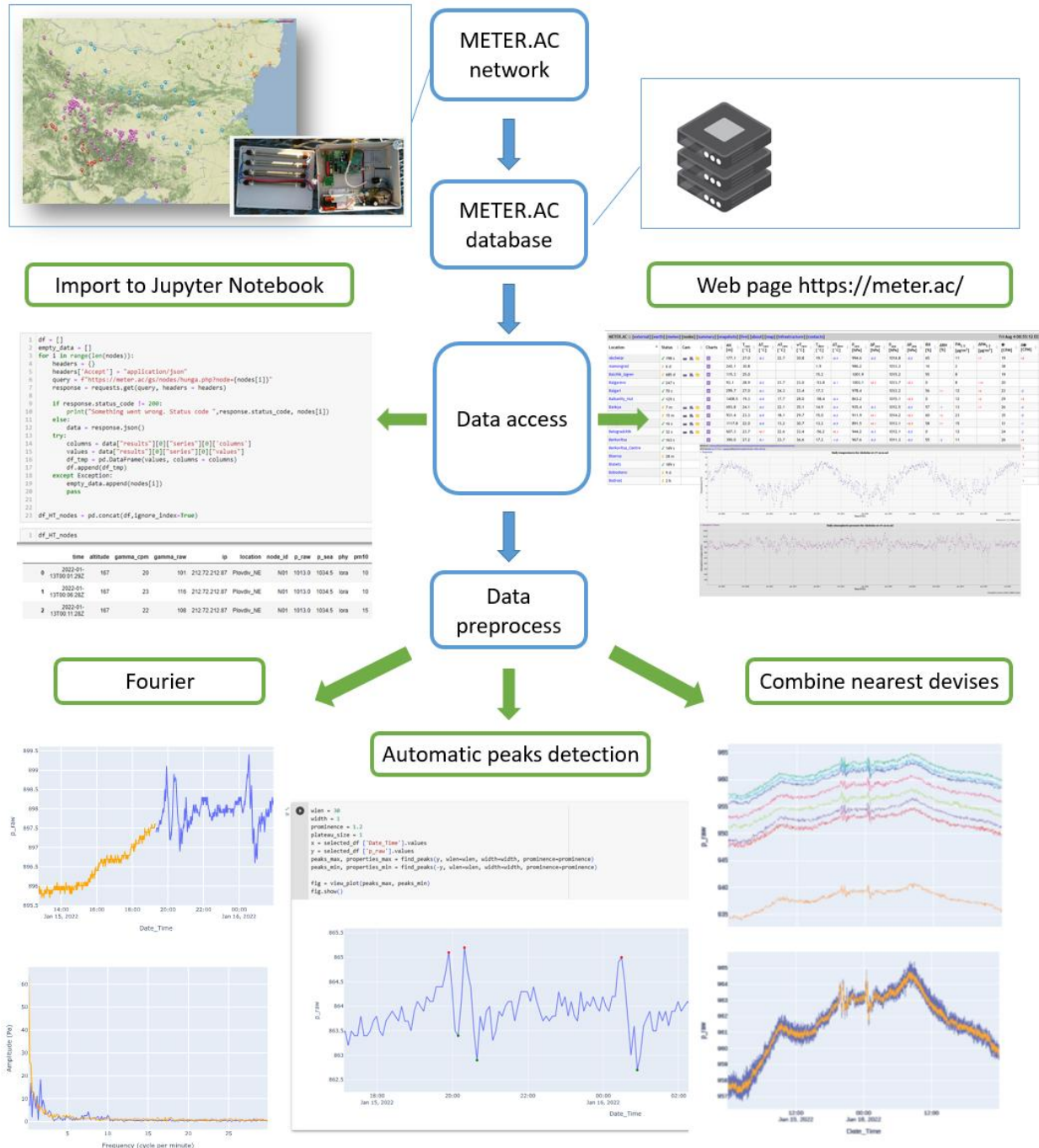


Fig. 2. Data analysis workflow: data gathering (METER.AC), data storage, pre-processing, anomaly detection and automatic data processing features.

METER.AC nodes measure pressure using the MS8607 sensor from TE Connectivity (PHT Combination Sensor MS8607). This sensor offers a resolution of 0.1 mbar and can accurately measure

pressure within the range of 10 to 2000 mbar, with an accuracy of ± 2 mbar. Data is reported every 5 minutes. Collected data is transmitted to the server infrastructure via one of three internet connec-

tivity options: Wi-Fi, LoRa, or Ethernet. From there, the data is made available to end users through the public network site.

Electronic notebooks for data extraction, visualisation and processing

Separate Jupyter notebooks are used for specific data extraction from METER.AC database, pre-processing, and processing to manage and analyse the data efficiently. These include scripts for converting UTC dates to timestamp format, filtering data by specified periods, and selecting data based on specific columns. Additionally, a separate electronic notebook was developed to collect and aggregate data from approximately 5,000 devices worldwide. These devices, deployed by Luftdaten and AirBG (<https://Sensor.Community/>, n.d.), utilise BME280-type sensors for environmental monitoring.

Fig. 1 illustrates the geographical coverage of METER.AC across the country, using colour

coding to indicate the time zone distribution of measurement devices that detected atmospheric pressure anomalies following the Hunga Tonga–Hunga Ha’apai volcanic eruption. A dedicated electronic notebook for Fourier analysis features a function that divides the recorded signal into two segments—before and after the wave anomaly. Additional functions perform the Fourier transformation and generate visualisations of overlaid spectra, as shown in Fig. 3.

To improve the local temporal resolution of the network, data from selected nearby nodes are aggregated using Python scripts that merge individual signals based on alignment of the anomaly peaks. The resulting combined signal is then smoothed using a Savitzky-Golay filter, which fits a polynomial of chosen degree to a moving window of data points and uses the resulting coefficients to estimate smoothed values. In this case, we applied an 11-point window with a second-degree polynomial.

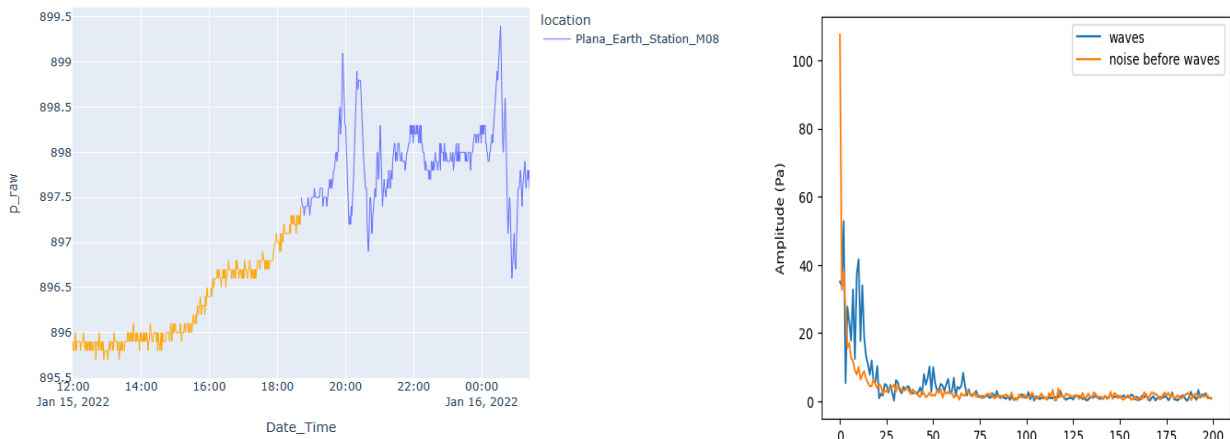


Fig. 3. Results from the Fourier analysis notebook used to detect and examine recorded anomalies. The data is based on measurements from a device located at Teleport Plana.

Electronic notebook for automatic anomaly detection

After selecting a location for anomaly detection, an algorithm using the Python library `scipy.signal` identifies local maxima and minima by comparing neighbouring values. For finer adjustment, parameters such as peak width, peak height, and the size of the neighbouring window can be manually tuned to suit specific requirements. The results are displayed on an interactive graph (Fig. 4), with detected local maxima marked in red and local minima in green.

Definitions:

First wave - in this paper, the authors define the first wave as the atmospheric wave traveling from the eruption site towards Bulgaria along the shortest path—southeast to northwest;

Second wave - the second wave refers to the corresponding atmospheric wave traveling from the eruption site towards Bulgaria in the opposite direction along the longest path around the globe.

Using the results from automatic anomaly detection, detailed wave statistics were calculated, including the times of maxima and minima for the

first and second waves, pressure amplitudes, and estimated average wave speeds. The average wave speeds were determined by considering the path length from the Hunga Tonga–Hunga Ha’apai volcano to each monitoring node in Bulgaria, along with the exact timing of the wave anomaly. Distance calculations were initially per-

formed using GPS coordinates, assuming the Earth as a perfect sphere. A second, more precise method - the Vincenty formula - was also applied. Since the differences between the two methods were negligible, the simpler spherical Earth approach was used for all results reported in this paper.

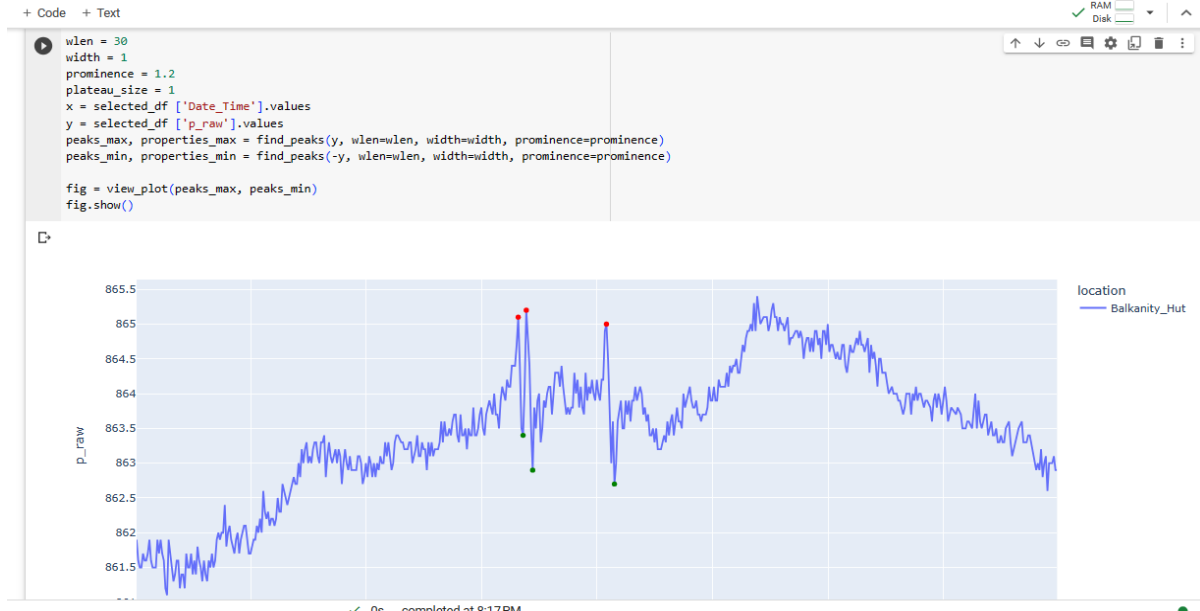


Fig. 4. Screenshot of a Jupyter notebook for automatic anomaly detection.

The average wave speeds across Bulgaria were estimated by forming two clusters of nodes: (1) the group of earliest nodes, $\{NR_1, NR_2, \dots, NR_k\}$, and (2) the group of latest nodes $\{NL_1, NL_2, \dots, NL_k\}$ based on the waves' arrival times. The distances between each node in the first group and every node in the second group were then calculated as: $d_{ij} = \text{distance}(NR_i, NL_j)$.

The speed for node pair (i, j) is calculated as $v_{ij} = d_{ij} / (t_{ij}^R - t_{ij}^L)$. The average value of all $\{v_{ij}\}$ is used to estimate the wave speed across Bulgaria.

All raw measurements from the METER.AC network nodes are publicly available on the official website: <https://meter.ac>. Additionally, Jupyter notebooks, Python scripts, and computed results can be found in the supplementary materials hosted in a Zenodo repository: <https://doi.org/10.5281/zenodo.16534447>.

Results

As shown in Fig. 1, the METER.AC nodes are divided into five subsets based on the arrival time of the first wave travelling from northeast to

southwest over Bulgaria. These subsets are colour-coded as follows: orange (14.5 h), green (14.6 h), blue (14.7 h), purple (14.8 h), and red (14.9 h). The values represent the number of hours after the eruption at which each group of sensors detected the anomaly. The orange group corresponds to the earliest time zone, including all nodes that first registered pressure changes. The group of latest nodes is marked in red. Each time zone represents approximately a 6-8-minute interval. Based on the recorded data, the wave crossed the country from northeast to southwest over a span of approximately 40 minutes.

The wave's direction is visible in the Fig. 5, propagating from northeast to southwest. The earliest detection, based on the timing of the wave's minimum pressure value, occurred near Silistra at approximately 7:39 PM UTC on January 15, 2022. The first detection of the second wave, travelling in the southwest-to-northeast direction over Bulgaria, was recorded by the "Popovi Liva-di" node at 12:28 AM UTC on January 16, 2022, based on the timing of the pressure minimum.

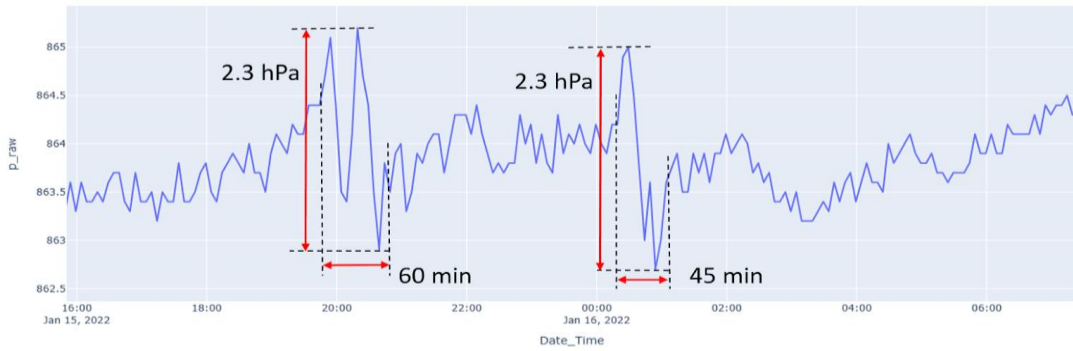


Fig. 5. A typical atmospheric pressure signal recorded by the METER.AC network at the Balkanity Hut location on January 15–16, 2022.

As illustrated in Fig. 5, the wave signal in Bulgaria is characterised by a sharp pressure increase, followed by a rapid decrease, forming two distinct sinusoidal patterns. The first wave spans approximately 50–60 minutes, while the second wave lasts about 40–45 minutes. The second oscillation of the latter exhibits a reduced amplitude, nearly negligible at some locations outside Bulgaria. The overall pressure wave profile is consistent across all nodes, as shown in Fig. 6. To enable direct comparison of all signals from the

METER.AC network, atmospheric pressure measurements were adjusted to the mean sea level using the standard correction formula:

$$P_{corr} = P \left(1 - \frac{0.0065h}{T + 0.0065h + 273.15} \right)^{-5.257}$$

where P is the measured station pressure in hectopascals (hPa), T is the ambient temperature in degrees Celsius ($^{\circ}\text{C}$), and h is the elevation above sea level in meters (m).



Fig. 6. Atmospheric pressure signals (hPa) from all METER.AC nodes across the territory of Bulgaria, with all values corrected to mean sea level pressure.

Discussion

Based on data from 131 METER.AC nodes (see Table S1 in the supplementary materials), the following key statistics were obtained for the atmospheric waves generated by the Hunga Tonga–Hunga Ha’apai volcano eruption:

- The first wave exhibited an average speed of 301 m/s (SD = 1.09 m/s) and an average pressure amplitude of 1.6 hPa (SD = 0.3 hPa).
- The second wave had a slightly higher average speed of 315 m/s (SD = 0.58 m/s) and a

larger average pressure amplitude of 2.6 hPa (SD = 0.3 hPa).

The calculated average speed of the first wave (301 m/s) from the eruption epicenter to Bulgaria corresponds to a path with a relatively longer section through the Northern Hemisphere, where lower atmospheric temperatures in January result in a reduced speed of sound. In contrast, the second wave, which travelled along a path with a longer section through the Southern Hemisphere, exhibited a higher average speed of 315

m/s, consistent with the generally warmer atmospheric conditions along that route.

A sensitivity analysis was conducted on the cluster size parameter, k , used to estimate the average wave speed across Bulgaria (see Materials and Methods). The results are summarised in Table 1. Interestingly, increasing the size of the selected node groups (i.e., the earliest and latest wave detections) leads to a deterioration in the statistical quality of the estimates—for example, the standard deviations increase, despite the substantial rise in the number of node pairs. This effect can be attributed to the relatively small geographical area of Bulgaria. As the group size grows, the spatial proximity between nodes increases, reducing the precision of individual

pair-based speed estimates and introducing more variability into the overall calculation.

We consider the result obtained from the smallest cluster size ($k = 5$) to be the most accurate estimate of the average wave speed achievable with our experimental setup, based on the METER.AC nodes. Distances within Bulgaria are relatively short (on the order of hundreds of kilometers) compared to the vast distance between Bulgaria and the Tongan archipelago—over 16,000 km for the first wave and more than 23,000 km for the second. Consequently, the local wave speed estimates exhibit standard deviations approximately 40 times greater than those of the average speeds calculated for the waves travelling from the volcano epicenter to Bulgaria.

Table 1. Statistical summary of average wave speed estimates across Bulgaria, calculated using varying cluster sizes.

Cluster size (in nodes)	Number of pairs	First wave average speed	First wave SD	Second wave average speed	Second wave SD
5	25	306 m/s	39 m/s	263 m/s	22 m/s
10	100	313 m/s	79 m/s	275 m/s	33 m/s
30	900	343 m/s	113 m/s	300 m/s	70 m/s

Compared to the global speeds, the speed relationship shown in Table 1 is reversed - the average local speed of the first wave is higher. The wave speeds measured within Bulgaria differ from the global average speeds, likely due to temperature variations along the wave paths, considering the nearly linear dependence of sound speed on air temperature. Additionally, the reversed relationship between the local speeds of the first wave (306 m/s) and the second wave (263 m/s) can be attributed to the second wave arriving around mid-night, when temperatures in Bulgaria are lower, as well as to this point being the northernmost location along the wave's trajectory. It is important to note that the data in Table 1 carry considerable uncertainty due to the relatively short distances involved and the limited time resolution of the METER.AC network for measurements at this scale.

We compared results from the METER.AC network with multiple recordings of the same phenomenon across various locations worldwide. Fig. 7 shows the air pressure profiles from twelve different sites, which can be compared to the typical profiles obtained from nodes in Bulgaria (see Fig. 2).

The spectral profiles - the Fourier-transformed signals shown on the right for each location - vary significantly between geographical regions, as do the air pressure anomaly peak profiles. In some locations, the second wave was either not detected with statistical significance or was absent altogether. Furthermore, the comparison is complicated by differences in technical setups, sensor types, and detection time resolutions. Despite these challenges, the general spectral shapes provide valuable insight. In most cases, there is a clear distinction between the spectrum of normal pressure signals (often resembling a Gaussian shape, shown in orange) and that of signals containing anomalies (depicted by the blue Fourier spectrum curves). A possible explanation for the profile differences is the unique geographical configuration of the Bulgarian mountains, which may affect the air pressure signal anomalies differently than other locations. Additionally, the combined geographical and meteorological factors along the entire wave trajectory likely contribute to these variations.

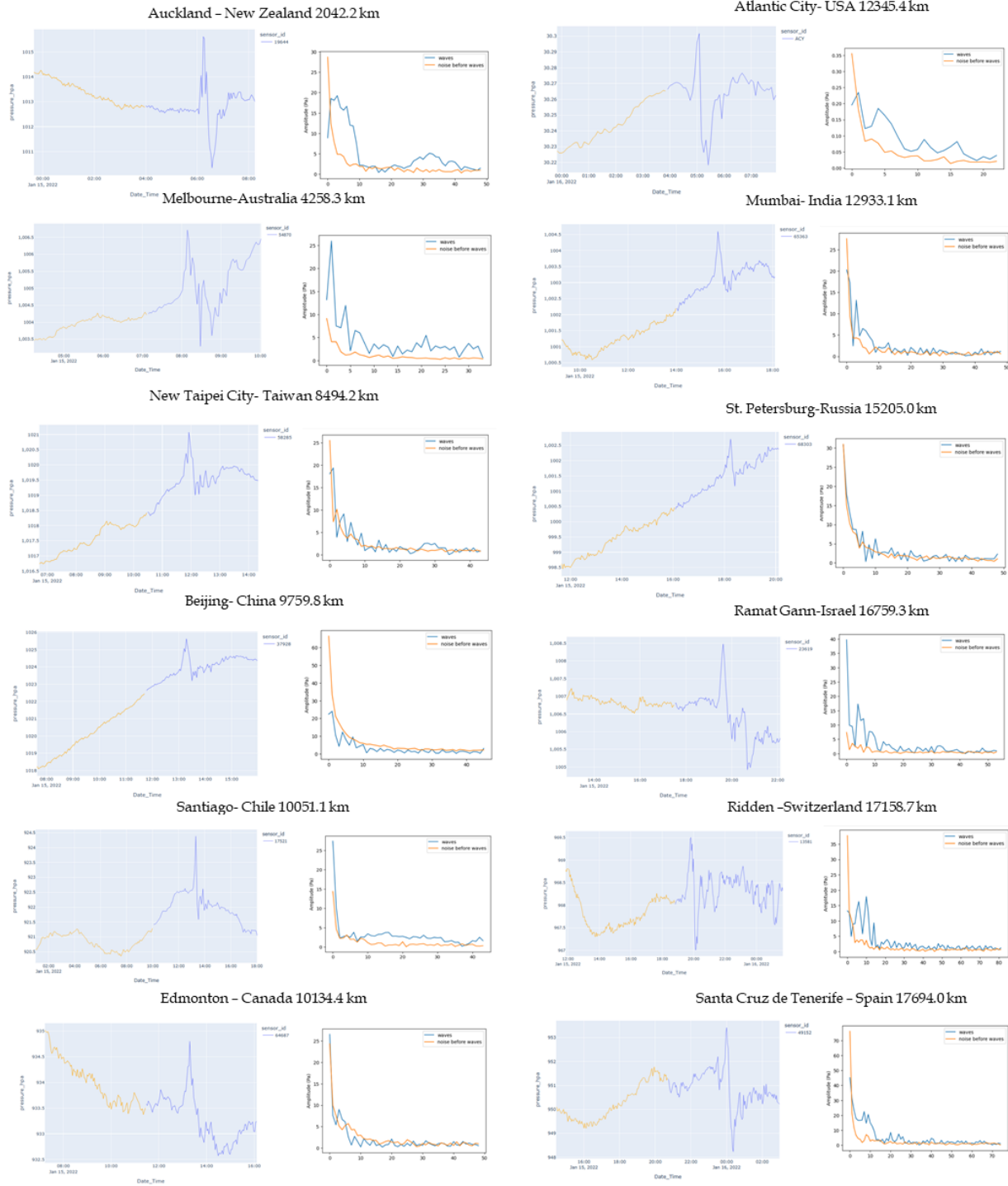


Fig. 7. Wave profiles from various global locations. Each pair shows the pressure signal on the left and its Fourier transform (signal spectrum) on the right.

The METER.AC network provides near-uniform coverage across Bulgaria, enabling a novel data usage approach referred to as “network collective work.” This method improves the network’s effective local temporal resolution by combining data from selected nodes situated close to each other within a single populated area. First,

signals from neighbouring nodes are aligned based on the peak of the detected Hunga Tonga volcano eruption anomaly (see the data for three nodes near Varna in Fig. 8). Due to their proximity, temporal shifts between these nodes can be neglected during signal alignment.



Fig. 8. Air pressure signals recorded simultaneously by three devices located within the city of Varna.

The combined signal, calculated as the average of all three signals, is smoothed using a Savitzky-Golay filter to reduce noise. In Fig. 9, the combined raw signal is shown in blue, while the smoothed signal is displayed in orange. This new combined signal contains roughly three times

more data points, since the METER.AC node measurements are not temporally synchronised. Noise amplification resulting from signal combination is mitigated through filtering, yielding a higher-resolution representation of the anomaly.

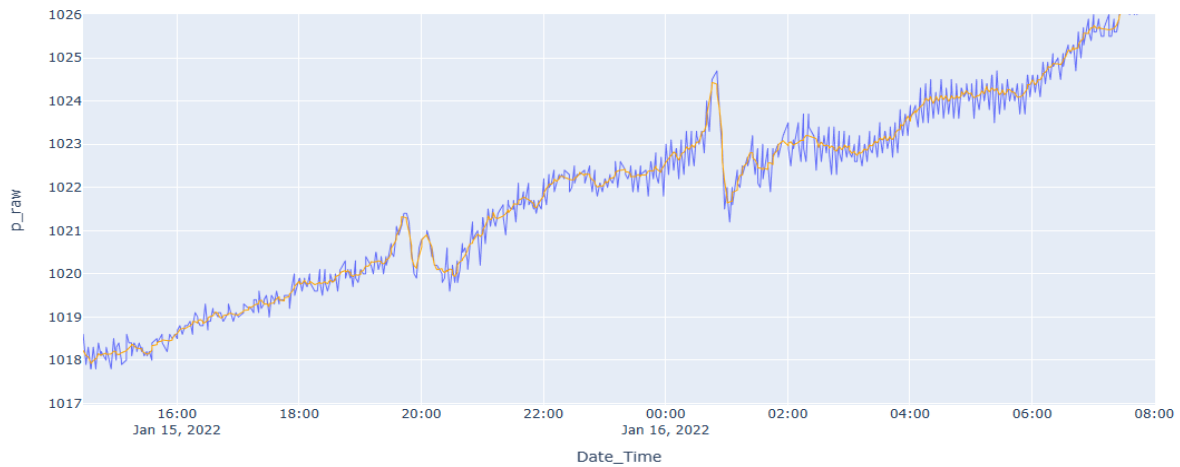


Fig. 9. Smoothed signal with enhanced resolution, derived from the combined data of three nodes in the Varna area.

Conclusions

This research confirms the capability of the METER.AC network as a high-resolution, open-access monitoring system for detecting atmospheric disturbances resulting from large-scale geophysical events. The analysis of pressure anomalies across 131 sensor nodes enabled the quantification of propagation speeds and wave amplitudes associated with the first and second atmospheric waves from the 2022 Hunga Tonga–Hunga Ha‘apai eruption. The observed variation

in wave speeds - both globally and locally - corresponds with known atmospheric temperature distributions and supports existing models of sound propagation. These results emphasise the scientific value of decentralised, IoT-based sensor networks in atmospheric research, particularly when paired with reproducible, open-source data analysis workflows. The use of Fourier spectral analysis and signal aggregation allows further study by comparing METRE.AC data with data registered from multiple sites all over the world.

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