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Anomalies of air pressure in Serbia as a result of the eruption of the volcano Hunga Tonga–Hunga Ha'apai in mid-January 2022

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Abstract

The aim of the study is to show the anomalies of air pressure registered at meteorological stations in Serbia during the passage of shock waves on January 15 and 16, 2022, as a result of the Hunga Tonga–Hunga Ha'apai volcano eruption. Based on the assumption that the atmosphere of our planet behaves like a fluid, such and many other disturbances can be detected in any part of the Earth. Calculations have shown that the great circle distance from Belgrade (the capital of Serbia) to Hunga Tonga is 16,952 km. It was further determined that during the passage of the shock waves of such a distant phenomenon in the Pacific, air pressure anomalies, which were not related to the existing synoptic situation (the synoptic situation was stable, the weather was completely clear), had occurred in Serbia. The first stronger eruption occurred at 04:00 UTC on January 15. After the first stronger eruption, the research showed that two main shock waves had been distinguished in Serbia: the first one was registered around 19:00 UTC on January 15, and the second one was registered around 00:00 UTC on January 16. In both cases, in the next 2–3 h (19–22 UTC and 00–02 UTC), barographs at meteorological stations in Serbia recorded a pronounced oscillation of air pressure in a synoptically stable atmosphere. Also, the first shock wave return was noticed on January 17, around 08:00 UTC. Based on the distance and time registration of the shock wave in the form of air pressure anomaly at selected meteorological stations in Serbia, the speed of the shock wave was mathematically determined to be approximately 1,130 km h^{-1}, which is close to the speed of sound.

Keywords: Volcanic eruption, Air pressure, Shock wave, Hunga Tonga–Hunga Ha'apai, Serbia

Introduction

Both volcanic phenomena and the effects of volcanism on nature and human society fascinate and frighten men. Volcanic eruptions are classified as dangerous phenomena. But volcanic activity can cause other very dangerous phenomena. Many studies have shown a link between volcanic activity and earthquakes, especially in the most active belt, the Pacific Ring of Fire (Kennett et al. 1995; Bronto 2006; Wassermann 2012; Nugraha et al. 2017, 2018; Santoso et al. 2018; Supendi et al. 2018; Albino et al. 2019; Gunawan et al. 2020). Volcanic eruptions can cause catastrophic tsunamis, landslides, submarine explosions and a number of other dangerous phenomena (Mutaqin et al. 2019). Tsunami waves can also occur when the sides of submarine and island volcanoes collapse (Ye et al. 2020). It is estimated that tsunami waves caused about 20% of deaths from volcanism in the last 400 years (Grilli et al. 2019). There are still no reliable methods for predicting volcanic activity, but many phenomena can be monitored through certain parameters. For example, McGuire (1992) points out that changes in volcanic activity can be monitored through physico-chemical parameters: physical changes in volcanic smog from the crater, changes in the chemical composition of volcanic smoke and dust, changes in crater temperature,

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changes in microseismic activity, volcanic deformation, etc.

The eruption of the Krakatoa volcano in 1883 is well known, both for great human casualties and material damage, and for great tsunamis (Simkin and Fiske 1983). However, the shock wave, which occurred during the cataclysmic eruption of Krakatoa, caused anomalies of air pressure on a global scale. It is believed that the shock wave, visible through pressure anomalies on barographs, traveled the planet Earth at least four times (Verbeek 1884; Strachey 1888). These records of pressure anomalies on barographic strips were the introduction to the discovery of infrasound (Evers and Haak 2010). Infrasound with frequencies of less than 20 Hz, which is produced by volcanic activity, and which can travel thousands of kilometers without weakening at all, can be used to detect volcanic events at regional and global distances (Fee and Matoza 2013; Matoza et al. 2018; Perttu et al. 2020). Williams et al. (2020) believe that infrasound is becoming a popular method for monitoring volcanoes in remote areas, and their study presented a new method for processing volcanic infrasound signals, which is based on reducing acoustic noise from various sources.

A similar global shock wave, which caused pressure anomalies over long distances, occurred during the eruption of the Hunga Tonga–Hunga Ha'apai volcano (HT–HH) mid-January 2022, which is the subject of this study. HT–HH ($\phi = -\ 20^0\ 34'\ 12''$, $\lambda = -\ 175^0\ 22'\ 48''$, h[1] = 114 m AMSL) is a caldera-shaped submarine volcano located in the South Pacific, 65 km north of the capital (Nukualofa) of the Kingdom of Tonga and 30 km south-southeast of Falcon Island. Volcano HT–HH is about 2000 m wide and has a positive shape in the relief with altitude of 114 m, and the height of the volcano below sea level is about 1800 m (Smithsonian Institution 2022). So, the total height of the volcano is 1914 m. It is a part of the Pacific Ring of Fire and belongs to the volcanic region of New Zealand–Fiji, and is located in the very active seismic Kermadec–Tonga subduction zone. The volcano was formed in the process of subduction of the Pacific and Indo-Australian tectonic plates. The structure of this volcano is dominated by rocks of the andesitic and basaltic type. The estimated human population in the 5 km zone is 230 people, while about 86,000 people who live in the 100 km zone of the volcano (NASA Earth Data 2022) have been directly exposed to the dangers of this otherwise active volcano since 1912.

According to data from Smithsonian Institution (2022), the eruptive history of the HT–HH volcano can be described through the six most significant eruptions during the Holocene. The first known historical eruption occurred on April 29, 1912, with an unknown cessation date and *V*olcanic *E*xplosivity *I*ndex (VEI[2]) was rated 2. The second eruption of this volcano occurred in 1937, also with an unknown cessation date and a VEI of 2. According to the data from the Smithsonian Institution, activity area or Unit is not clearly stated for this and previous eruptions. The third eruption occurred on June 1, 1988 and lasted until June 3 of the same year. The activity area of this eruption was 1 km south-southeast of the island of Hunga–Ha'apai. The VEI of the eruption was 0. The fourth confirmed eruption, which occurred on March 17 and 22, 2009 (±1 day), covered the island of Hunga–Ha'apai and had a VEI of 2. Between December 19, 2014, and January 23, 2015 (±3 days), the fifth confirmed eruption occurred which lasted the longest, more than a month. The activity area of this eruption was not specified, and the VEI was 2. During this eruption on December 24, 2014, 14 kt (kilotons) of SO_2 emissions were registered up to 3 km altitude in the atmosphere by the Aura Ozone Monitoring Instrument satellite (Smithsonian Institution 2022).

The latest sixth eruption took place on January 14 and 15, 2022. According to the report of Tonga Geological Service (TGS), on January 13, at 15:20 UTC, a plume of smoke formed that was about 5 km wide at the base, and reached the height of 20 km, that is, it broke through the tropopause and spread in the stratosphere with a diameter of 240 km. Pyroclastic material fell into the surrounding ocean, and according to satellite data, about 50,000 tons of SO_2 were released into the atmosphere. The Tonga Meteorological Service (TMS) issued a tsunami warning (20 cm) on the same day saying that it could affect the coastal parts of the capital Nukualofa. In addition to the regional effects of the tsunami in this part of the Pacific, the Global Lightning Detection Network (GLD360) recorded over 190,000 lightning strikes between January 14 and 15, i.e., about 30,000 lightning strikes per hour (GLD360 2022). Already on January 15 at 04:00 UTC, there was the first stronger eruption, which, according to the VAAC Wellington (2022), reached a smoke height of 30 km, while according to Simon Proud (Proud 2022), the smoke height was about 39 km, and some parts of the eruption reached a height of up to 55 km.

Previous data indicate a strong and powerful eruption, and NASA's Earth Observatory (2022) claims that the eruptions were of the order of 4–18 megatons of

[1] h denotes the height above mean sea level (AMSL) in meters.

[2] *Volcanic Explosivity Index (VEI)* is the relative numerical scale of the explosiveness of a particular historical volcanic eruption. The scale is logarithmic and open, and the numerical value of 0 is given to non–explosive volcanic eruptions, while the numerical value of 8 denotes mega–colossal volcanic eruptions (Newhall and Self 1982).

TNT (100 atomic bombs). The diameter of the smoke was about 600 km in the atmosphere, and, based on the estimates of satellite measurements, about 400,000 tons of CO_2 were released into the atmosphere. Also, the GLD360 network (2022) recorded about 400,000 lightning bolts in smoke. To this we can add the fact that the eruption of the volcano HT—HH, according to the data from National Weather Service Alaska Region and thanks to Dr. David Fee from the Univeristy of Alaska Fairbanks/ Alaska Volcano Observatory (NWS Alaska Region 2022), was heard in audible range in Anchorage and Fairbanks between 11:30–12:00 UTC on January 15 (03:30–04:00 AKST January 15), although the distance between the volcano and these cities is 9,366 km.

The HT–HH eruption created a strong shock wave that caused pressure anomalies, a jump of 2–3 hPa, which was registered at all meteorological stations on Earth (Díaz and Rigby 2022). According to estimates, the shock wave arrived in Europe sometime after 19:00 UTC, when it was registered at meteorological stations (MS) in Serbia. Therefore, the aim of the research of this paper is to present the anomalies of air pressure registered after the passage of the shock wave, which is a consequence of the strong and powerful eruption of the HT–HH volcano in the South Pacific. The shock waves traveled around the Earth at least three times (The Weather Channel), their speed was close to the speed of sound and the eruption blast produced signals with high-frequency that were audible to human ear and they were heard all across the state of Alaska (Alaska Public Media 2022), which is more than 9,000 km away from the volcano HT–HH.

Subject, database and research methods

The subject of this study is the variation of atmospheric pressure over Serbia as a consequence of the impact of HT–HH volcano eruptions. If there is a connection between this distant eruption, i.e., shock wave that was created, then this connection must be manifested in the form of anomalies (peaks) of air pressure on the MS in Serbia. Data on air pressure were obtained from the Republic Hydrometeorological Service of Serbia, from 4 MS, which are located in different parts of the country and at different altitudes (Fig. 1). Also, for the purpose of verification, data from MS of the neighboring country, Montenegro, were used, and the data from MS in other neighboring countries and Europe were also taken into account (SYNOP analysis[3]) in order to confirm the initial hypothesis with a comparative method.

Relevant data sources of the volcano itself and the volcanic eruption were used for the study, i.e., data obtained from the Geological and Meteorological Service of Tonga, Smithsonian Institution, then data and satellite images of the volcanic eruption from the official NASA website. For the purpose of analyzing the synoptic situation over Serbia and the Balkan Peninsula during the passage of the shock wave, which is a consequence of the eruption of HT–HH volcano, surface pressure (MSL) and the 500 mb maps (geopotential height of 500 hPa) were considered. Table 1 gives the name and location of the sources from which the data were taken.

The sampling rate of air pressure data from automatic weather stations of the Republic Hydrometeorological Service of Serbia is in real time and it depends of a sensor sensitivity in a particular weather station—it can trace changes in air pressure data several times in a second. Also, the air pressure data from the main meteorological station Podgorica (Montenegro) are obtained using barograph and the sampling rate is every hour. It should be pointed out that the sampling rate of air pressure data was in real time, allowing the precise monitoring of changes in air pressure during the passages of pressure waves that were generated by HT–HH volcano eruption. These changes were depicted by providing the necessary air pressure graphs (in hPa) generated by automatic weather stations of the Republic Hydrometeorological Service of Serbia (RHSS). We have also done the extensive synoptic analysis of the structure of the surface and upper-level atmosphere (at 500 mb level) over Serbia during the observed time period in order to demonstrate that the atmosphere was stable and the weather was clear that day, so the sudden change in air pressure originated only from one source—HT–HH volcano eruption. Table 2 shows the physical quantities of the used data and their relations with the purpose of our paper.

The shortest distance (orthodromic distance, z) between Belgrade (T_1: $\phi_1 = 44° 48' 33{,}5''$, $\phi_1 = 20° 28' 17{,}25''$) and the Hunga Tonga volcano (T_2: $\phi_2 = -20° 34' 12''$, $\phi_2 = -175° 22' 48''$) is obtained by solving the first nautical spherical triangle $T_1T_2P_N$ on the globe (Fig. 2).

According to the cosine formula for the sides of an oblique spherical triangle (Tadić, 2004, p. 66), we get,

$$\cos z = \sin \varphi_1 \cdot \sin \varphi_2 + \cos \varphi_1 \cdot \cos \varphi_2 \cdot \cos (\lambda_2 - \lambda_1). \quad (1)$$

When the specified values of geographic coordinates are included in the formula, $z = 152.447°$ (16,952.65 km) is obtained.

[3] Surface Synoptic Observations (SYNOP) is a numerical code defined by the World Meteorological Organization (WMO), and used for reporting weather observations made by manned and automated weather stations.

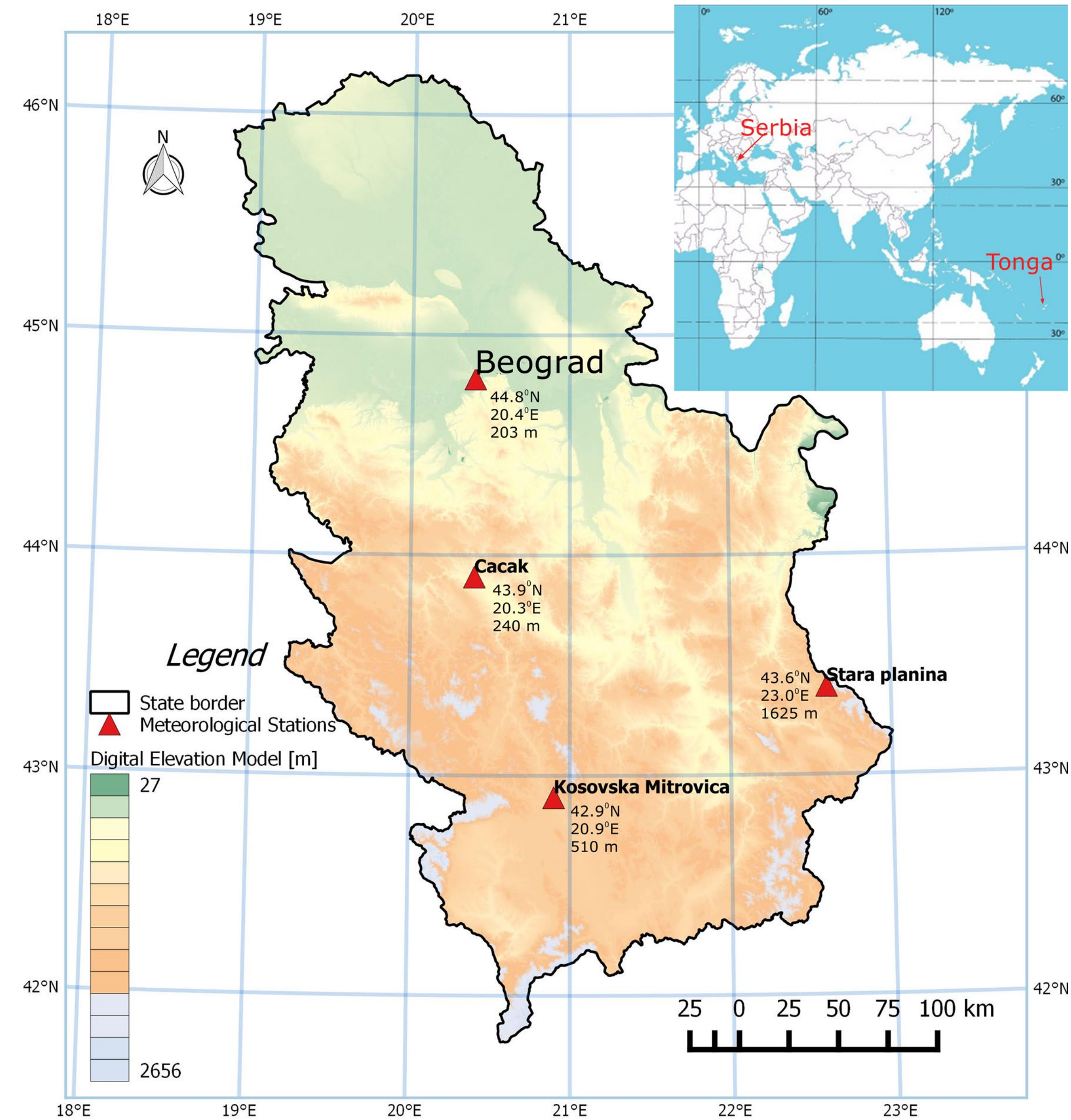

Fig. 1 Geographical position of meteorological stations in Serbia included in the analysis

Points T_2, T_1 and T_2' lie on the same great circle so that the shortest distance between points T_1 and T_2' (z_1) is equal to the complement of orthodromic distances to half the circumference of the great circle on the globe, that is (z_1 is the missing distance to the maximum orthodromic distance which is 20,015 km),

$$z_1 = R\pi - z = 3062.437\ km. \quad (2)$$

In order to show the direction of the shock wave propagation, first it was necessary to calculate mathematically the position of the antipodal point of the point T_2, and we marked that point with T_2'. Therefore, the antipodal point has the coordinates:$T_2' : -(\phi_2);\ -(\lambda_2)$. Then we found that point on the globe and it is located in the Sahara (Algeria).[4] Therefore, the shock wave moved radially from the point T_2 to the antipodal point T_2′ along the orthodrome (the orthodromic distance z is shown mathematically exactly in Fig. 2, as well as the mathematical

[4] The antipodal point T_2' has mathematical-geographical coordinates: T_2': $\phi_3 = 20°\ 34'\ 12''$, $\lambda_3 = 4°\ 37'\ 12''$.

Table 1 List of institutions from which data were taken

Institution	Website
Volcano eruption data HT–HH	
Tonga Meteorological Services	http://met.gov.to
Tonga Geological Services	http://www.naturalresources.gov.to https://www.facebook.com/tongageologicalservice
Ministry of Lands and Natural Resources	https://www.lands.gov.to https://www.facebook.com/tongalands
Smithsonian Institution—National Museum of Natural History Global Volcanism Program	https://volcano.si.edu
Bureau of meteorology, Australia	https://twitter.com/BOM_au/status/1482592498992427009
National weather service Alaska	https://www.weather.gov/arh/; https://twitter.com/NWSAlaska
NASA	https://earthdata.nasa.gov/worldview/worldview-image-archive/explosive-eruption-of-hunga-tonga-hunga-ha-apai-volcano https://earthobservatory.nasa.gov/images/149367/dramatic-changes-at-hunga-tonga-hunga-haapai
Data on the synoptic situation over Serbia and the Balkan Peninsula	
Wetter online	https://www.wetter3.de/Archiv/
Data on air pressure at stations in Serbia and Montenegro	
Republic Hydrometeorological service of Serbia	https://www.hidmet.gov.rs/index.php
Institute of Hydrometeorology and Seismology of Montenegro	http://www.meteo.co.me/

Table 2 Description of the physical and mathematical quantities of the data used in the study and their relation with the study purpose

Physical/mathematical quantity	Equation	Relation with the study purpose
Atmospheric pressure $[mb\ or\ hPa]$	$p = h\rho g_0$[a]	Pressure anomalies were shock waves, which were generated by HT-HH volcano eruption at certain times
Speed $[km\,h^{-1}]$	$\upsilon_0 = z_0/t_0$	Speed was calculated in order to describe the physics of the shock wave propagation
Average speed $[km\,h^{-1}]$	$\upsilon_{sr} = z_u/t_u$	This physical quantity was used in order to describe the physics of the second shock wave and the "first shock wave return"
Orthodromic distance $[km\ or\ nm]$	$\cos z = \sin\varphi_1 \cdot \sin\varphi_2 + \cos\varphi_1 \cdot \cos\varphi_{M2} \cdot \cos(\lambda_2 - \lambda_1)$	This mathematical quantity was used in order to calculate distance between MS in Serbia and HT-HH volcano, as well as to calculate the speed of the of the shock wave propagation; further on, this quantity was used in order to describe the direction of the shock wave propagation

[a] In the equation *p* denotes the atmospheric pressure; *h*- the height of the mercury column; *ρ*- density of air; g_0- Earth-surface gravitational acceleration

procedure for solving the first nautical spherical triangle). During that propagation, it narrowed radially towards the point T_2', that is, the direction of the first shock wave propagation, in relation to the position of the MS in Serbia, was from the north because of the propagation towards Algeria, i.e., to the antipodal point T_2'. And the propagation direction of the second wave was the opposite (from south to north in relation to the position of the MS in Serbia) since it was propagating from the antipodal point T_2' to point T_2 (Fig. 3 in the polar Postel projection). Therefore, we have provided the proof of the propagation direction of the first, as well as, of the second shock wave, by resorting to mathematical cartography and mathematical geography. Our proof is mathematically exact and visually displayed in Fig. 3 in the polar Postel projection (the following links[5, 6] provide the physical proof of our previous statements). Based on the animations shown in the links, it is clear that the propagation direction of the first shock wave was from north to south, while the second shock wave propagation

[5] https://twitter.com/StefFun/status/1482793707673956353

[6] https://twitter.com/StefFun/status/1483123215367303168.

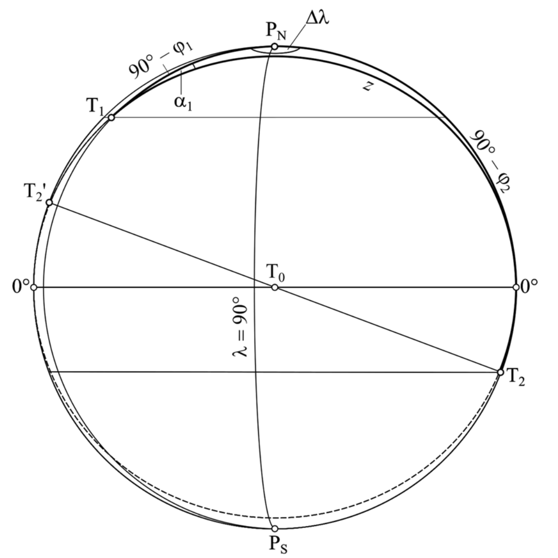

Fig. 2 Earth's hemisphere shown in equatorial orthographic projection with construction pole T_0 ($\varphi_0 = 0^0$, $\lambda_0 = 90^0$-(λ_2—180^0)*:* T_1 is Belgrade, T_2 is Hunga Tonga volcano, and T_2' is the antipode of point T_2 ($\varphi = 20.5^0$S, $\lambda = 175.4.^0$ W, $h = 114$)

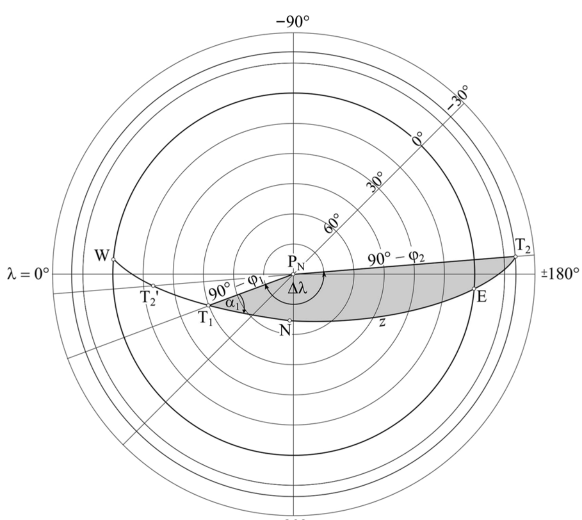

Fig. 3 View of part of the Earth's globe (up to the parallel $\varphi = -30°$) shown in the polar. Postel projection T_1 is Belgrade, T_2 is Hunga Tonga volcano, and T_2' is the antipode of point T_2.

direction was from south to north, in relation to the position of the MS stations included in the analysis.

In order to have a better graphic representation of the first and the second shock wave propagation, we have used a free online form to create the map in azimuthal projection (NS6T's Azimuthal Map 2022). In order to create maps, we have used two construction poles: Belgrade and Hunga Tonga–Hunga Ha'apai. For the purposes of this research, the speed of the shock wave propagation was also calculated (υ_0):

$$\upsilon_0 = z_0/t_0 \cdot \left[km\,h^{-1}\right], \tag{3}$$

where z_0 is the orthodromic distance between Belgrade and the HT–HH volcano for the first shock wave, and t_0[7] is the time elapsed from the eruption to the registration of the first peak at meteorological stations in Serbia. Similarly, we can calculate the speed of the shock wave propagation of the second shock wave, as well as of the first pressure wave return, applying the following equations:

$$\upsilon_1 = z_1/t_1, \tag{4}$$

and

$$\upsilon_2 = z_2/t_2, \tag{5}$$

where z_1 and z_2 are the orthodromic distance between Belgrade and the HT–HH volcano for the second shock wave and the first pressure wave return, and t_1 and t_2 are times elapsed from the eruption to the registration of the second and the third peak at meteorological stations in Serbia. Also we have calculated the average speed of all three pressure waves registered on the MS stations in Serbia and included in this research by applying the following equation:

$$\upsilon_{sr} = z_u/t_u, \tag{6}$$

where z_u is the sum of orthodromic distances between Belgrade and the HT–HH volcano for all three pressure waves, and t_u is the time sum elapsed from the eruption to the registration of all 3 pressure waves at meteorological stations in Serbia.

Results and discussion

Synoptic material analysis

Changes in air pressure are primarily related to cyclonic and anticyclonic weather types. In order to be sure that the appearance of peaks on the chart of air pressure on the MS in Serbia is a consequence of the shock wave of the HT–HH volcano, the first necessary step was to analyze the surface and upper-level structure of the atmosphere. For these purposes, synoptic material was

[7] For t_0 we use the time of the first stronger eruption that occurred at 04:00 UTC on January 15.

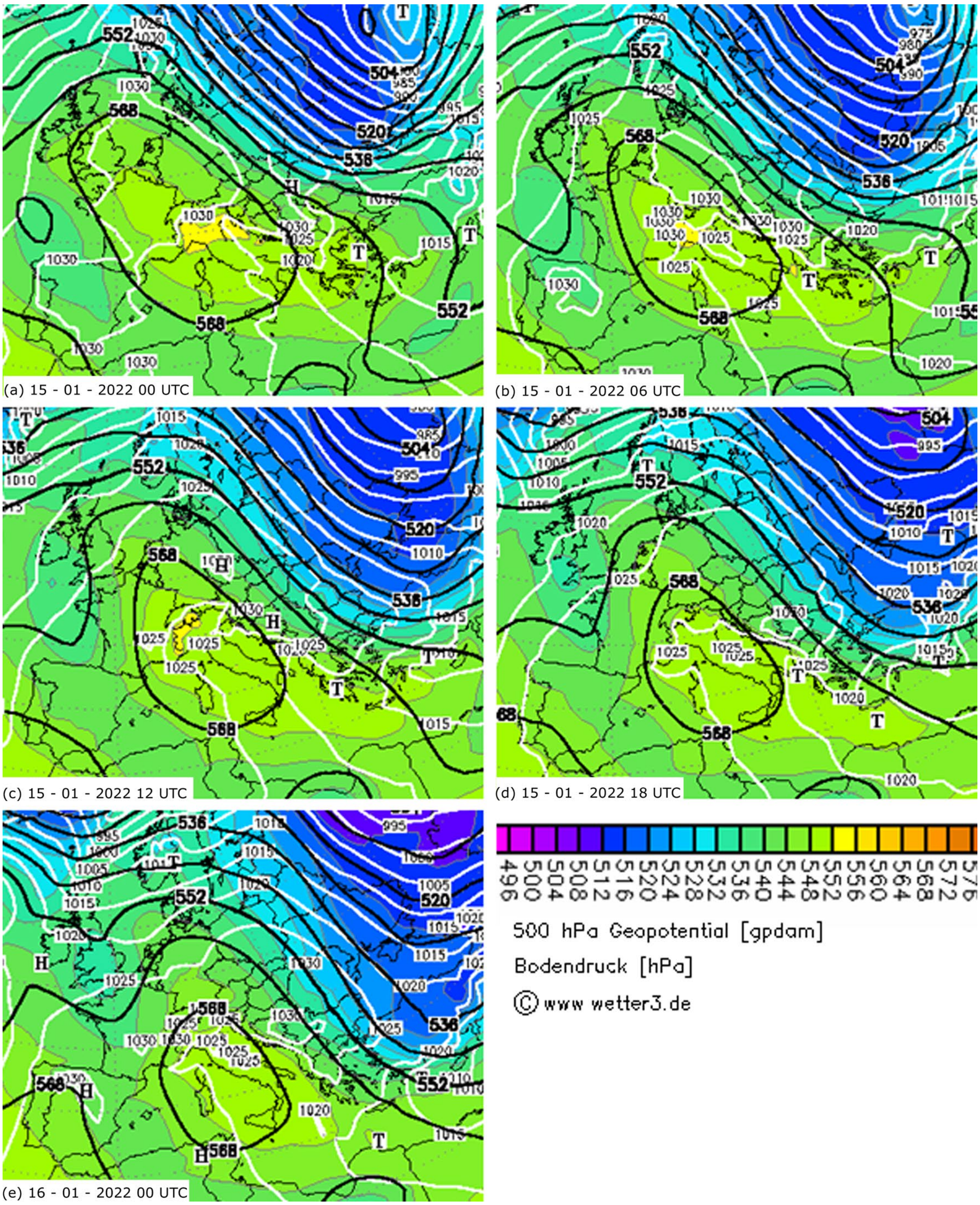

Fig. 4 Upper-level structure of the atmosphere (500 hPa geopotential/temperature maps) on January 15, 2022: 00 UTC (**a**), 06 UTC (**b**), 12 UTC (**c**), 18 UTC (**d**) and on January 16, at 00 UTC (**e**)

used, i.e., upper-level maps (at 500 hPa isobaric surface height), as well as analytical maps (at sea level pressure) made on the basis of SYNOP reports from MS across Europe. In other words, it was necessary to remove the suspicion that the occurrence of pressure peaks was caused by the existing synoptic situation.

The structure of the atmosphere on January 15, 2022, in the period from 00 UTC (Fig. 4a) was characterized by a vast high-pressure field on the surface with the center

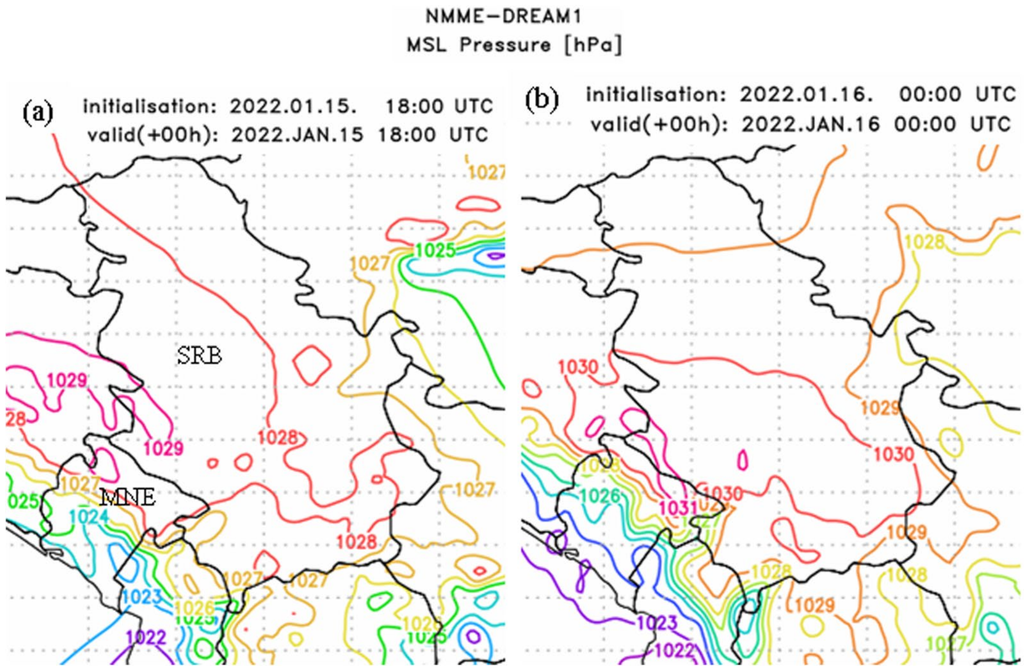

Fig. 5 Distribution of air pressure over Serbia (SRB) and Montenegro (MNE) at 18 UTC 15 January (**a**) and on 16 January at 00 UTC (**b**)

a little north of the Alps. The ridge of the anticyclone also covered the area of Serbia, that is, the entire Balkan Peninsula. The upper-level structure (at 500 hPa isobaric surface) shows the influx of polar air within the trough whose axis extends from the northern parts of Scandinavia to the Black Sea. Serbia and the Balkans are beyond the reach of this upper-level trough. So, both on the surface and in the upper-level, a stable atmosphere can be seen above Serbia and the Balkan Peninsula, in general. At 06 UTC (Fig. 4b) the structure of the atmosphere above Serbia did not change significantly, except that the center of the high pressure field moved a little further to the south and is now above the Alps region. At this synoptic hour, as well as at the previous one, the isobars of 1025 and 1030 hPa cover the entire territory of Serbia and the Western Balkans. According to data from 12 UTC (Fig. 4c), the center of the surface-level anticyclone continued to move south and is now located west of Serbia (above Bosnia and Herzegovina). The atmospheric pressure over Serbia is still between 1025 and 1030 hPa.

Considering that the first peak of the shock wave of the HT–HH volcano is around 19 UTC, the structure of the atmosphere at 18 UTC is very important. Therefore, at the mentioned synoptic hour, the center of the surface pressure field is slightly shifted to the east, i.e., it is located above the border of Serbia and Bosnia and Herzegovina. In other words, the zone of air divergence just above Serbia is clear, which indicates stable weather conditions (Fig. 4d). The atmospheric stability was also influenced by the slight shift of the mentioned upper-level trough of instability to the east and northeast, that is, further from Serbia compared to the synoptic situation from the beginning of the day. Above the area of Italy and the Adriatic Sea during the whole day (January 15), the 500 hPa isobaric surface was at a height of about 568 geopotential meters (gpm) and its peripheral part covered the area of the Western Balkans, i.e., Serbia. This value (568 gpm) indicates that the air pressure above Serbia was from normal to slightly elevated. Data from 00 UTC on January 16 indicate that the stability of the atmosphere over Serbia has been maintained (Fig. 4e).

In order to verify the above, analytical maps, which were made on the basis of SYNOP reports from MS across Europe, were also analyzed. A detailed analysis confirmed that during January 15, 2022 the atmosphere over Serbia and the Balkans was stable, i.e., it was mostly clear, with temperatures around or slightly above the average for that period of the year and with high air pressure (mainly between isobar 1,025 and 1,030 hPa). The wind was mostly moderate to strong, with gusts from the north and northeast. For clarity, using the NMME-DREAM model (Nonhydrostatic Meso Model on E-ARAKAWA grid—Dust Regional Atmospheric), which is in operational use at IHMSM,[8] with horizontal

[8] http://nwp2.meteo.co.me/nwp/modeli/nmmdream/oper11/scripts/prmsl.php.

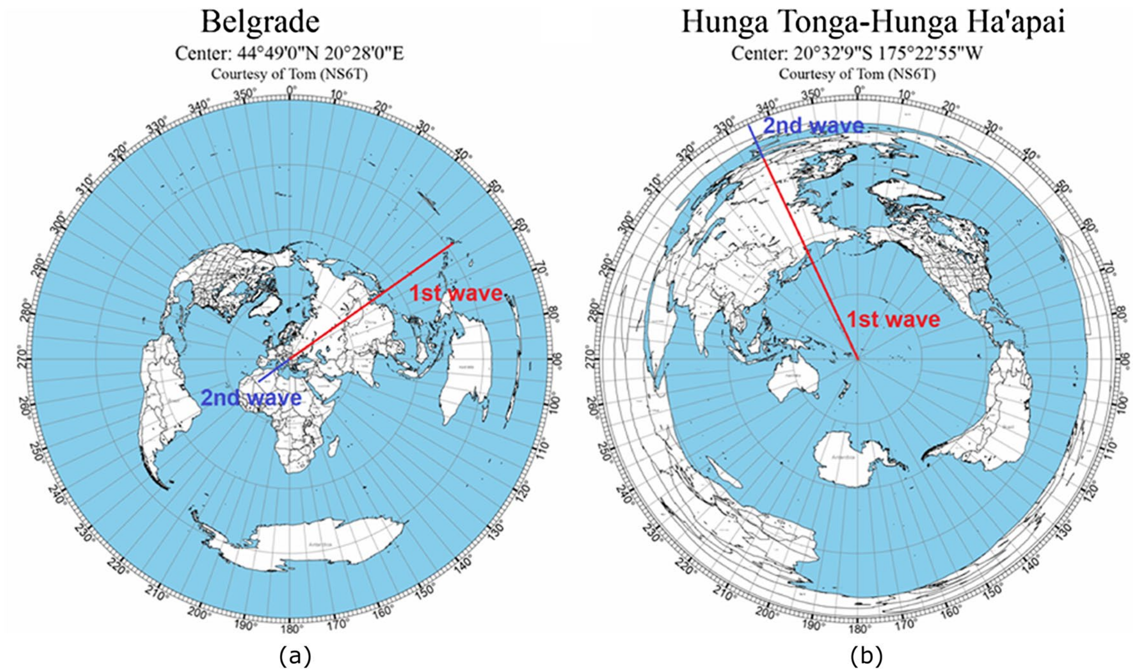

Fig. 6 Azimuthal map with two construction poles: Belgrade (**a**) and HT–HH (**b**). The red line indicates the direction of the first shock wave propagation, and the blue line the direction of the second shock wave propagation

resolution dx = dy = 0.05 degree, the air pressure distribution (isobars) is shown only over Serbia and Montenegro. Data from the global ECMWF model (European Center for Medium-Range Weather Forecasts), which is a high deterministic model, were used as input. For these purposes, all SYNOP data that are in international exchange are used, namely for initialization in two terms: from 18 UTC on January 15 (Fig. 5a) and from 00 UTC on January 16, 2022 (Fig. 5b).

Concluding this segment of the analysis, we can state that on January 15, 2022, the atmosphere above Serbia was stable, that is, there was a high pressure field both on the surface and at the upper-level (at 500 hPa isobaric surface). This means that the synoptic situation could not cause fluctuations in air pressure on the MS included in the analysis in the form of a sudden jump (peaks).

Relationship between HT–HH eruption and air pressure in Serbia

Based on the analysis of satellite images (NASA Earth Observatory 2022) and according to available data from relevant sources (Smithsonian Institution 2022), it is known that the HT–HH volcanic eruption broke through the first three layers of the Earth's atmosphere (approximate eruption height is over 30 km), and the volcanic ash itself reached the mesosphere (approximately up to a height of 55 km). These data indicate a very strong nature of this volcanic eruption. Since we observe the Earth's atmosphere as a fluid, when such a strong disturbance occurs in such an environment, pressure waves will appear on the entire Earth as a consequence. Thus, the shock waves spread radially from the site of the volcanic eruption in all directions—through Asia, Africa, North and South America, until they reached Europe and Serbia.

As already mentioned, knowing that the shock waves spread radially from the point T_2 to the point T_2', and also in the opposite direction, it can be concluded that the propagation direction of the first shock wave was from north to south (southward-propagating part of the shock wave), while the propagation direction of the second wave was the opposite: south–north (northward-propagating part of the shock wave). For the purpose of a more detailed and understandable graphic presentation of the propagation directions of shock waves, we presented an azimuthal map with two construction poles: Belgrade (Fig. 6a) and the HT–HH volcano (Fig. 6b). The propagation direction of the first and the second shock wave is clearly visible on the maps.

After determining the propagation directions of the shock waves, which were registered on the MS barometers in Serbia, the analysis of the air pressure graphs

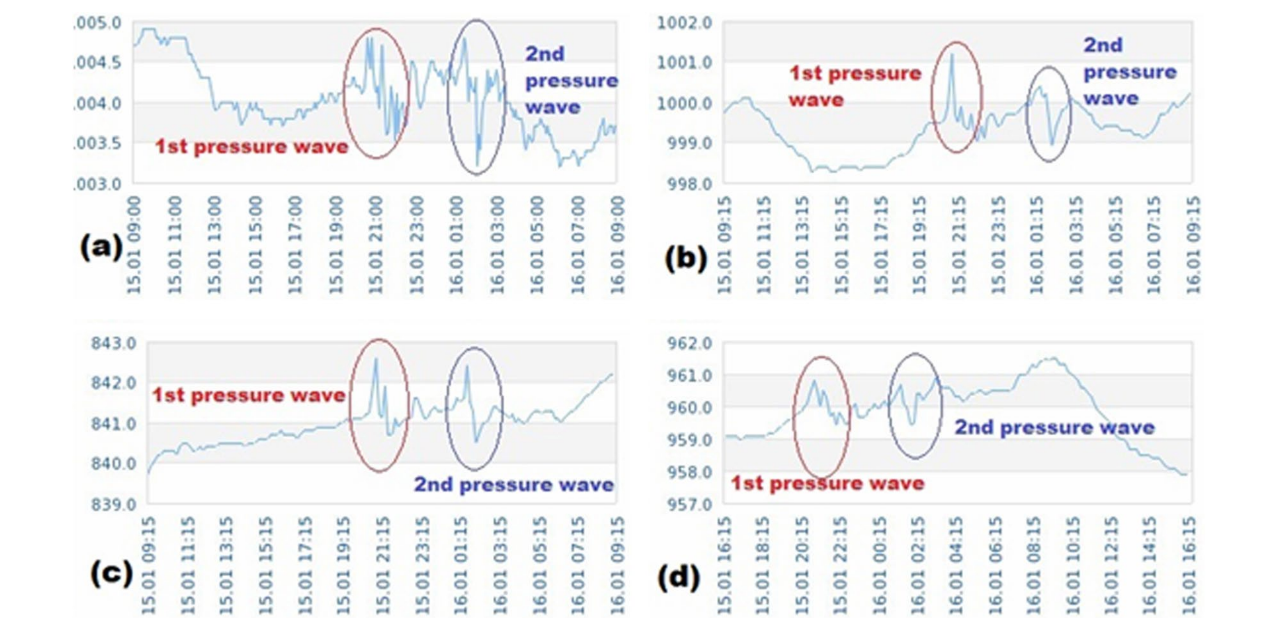

Fig. 7 Graphic representation of air pressure changes in hPa on MS in Serbia on 15 and 16 January 2022: **a** Belgrade, **b** Čačak, **c** Stara planina and **d** Kosovska Mitrovica (x-label denotes date and time: 15.01. 09:15 = January 15 at 09:15 CET or 08:15 UTC)

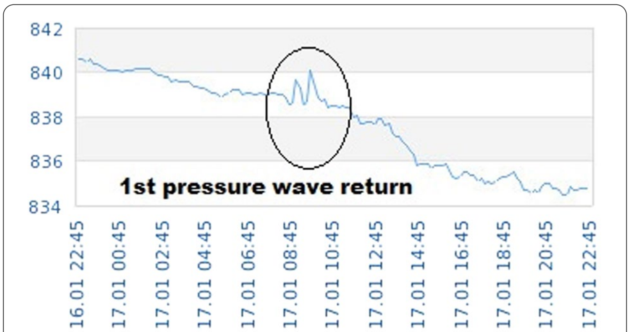

Fig. 8 Air pressure flow in hPa on MS Stara planina on January 17, 2022 (x-label denotes date and time: 16.01. 22:45 (January 16 at 22:45 CET); time is given in CET (UTC + 1))

(Fig. 7a–d) in hPa on 4 MS in Serbia was conducted. The analysis showed the following:

- The first peak of air pressure (increase in air pressure by 1.5 hPa/h) was registered on January 15 at around 19:00 UTC. This first peak of air pressure is the consequence of the southward-propagating part of the shock wave. The first shock wave was registered on the MS in Serbia 15 h after the first stronger eruption (January 15 at 04:00 UTC). After the shock wave, the barographs on all observed MS registered a distinct air pressure oscillation in the next 2–3 h (19–22 UTC).
- After going south, across the Mediterranean to the Sahara (to the point T_2'), the propagation direction of the second part of the shock wave was to the north (in the opposite direction), and it was registered at the MS in Serbia about 5 h later than the first, i.e., January 16, around 00:00 UTC. Thus, the second pressure shock wave was registered on the MS in Serbia more than 20 h after the eruption (t_0) of the HT–HH volcano in the South Pacific. In this case too, pronounced air pressure oscillations were noticeable for the next 2–3 h.
- On January 17, most likely around 08:00 UTC, the first pressure wave return was registered on the Stara Planina MS (Fig. 8). The third peak in air pressure was about 1.5 hPa/hour. Based on the third anomaly of air pressure registered on the Stara Planina MS, i.e., 52 h after the eruption, it unequivocally indicates that the first shock wave circled (made a full circle) around the Earth.

It is very likely that confirmations of the previously presented conclusions regarding pressure peaks can be found in other MS at the same longitude. The basis in this claim is the timing of the peaks, which will most likely be very similar to those observed on the MS in Serbia along the same meridian. Serbia borders Montenegro in the southwest. In order to verify the previous statement, an analysis of the SYNOP report of the main MS

```
a) ZCZC
   SMMK10 LYPG 151800
   AAXX 15181
   13463 32970 00204 10093 21066 30178 40240 52012 333 10141 91122=

b) ZCZC
   SMMK10 LYPG 160000
   AAXX 16001
   13463 32970 00205 10085 21081 30185 40247 52008 333 91116=
```

Fig. 9 SYNOP report MS Podgorica (Montenegro) for 15.01.2022 at 18 UTC (**a**) and 16.01.2022 at 00 UTC (**b**)

Podgorica (Montenegro) was performed. In the period from 18:00 UTC on January 15, 2022, a sharp increase in air pressure was observed. The second pressure peak is registered at the beginning of the next day—around 00:00 UTC. It should be pointed out a SYNOP report has 8–15 groups (sometimes 16 or 17 groups, depending on the type of weather). Each group has 5 digits, and each digit has its own meaning. The group starting with the number 5 refers to the pressure tendency. The second digit (digit 2) in group 5 shows the sign of the pressure tendency in the previous hour (digit 2 means a positive tendency). The remaining three digits show the value of the pressure change. Specifically, group 52012 (marked in Fig. 9a) shows that the pressure is increasing by 1.2 hPa. Group 52008 (also marked, Fig. 9b), means that the pressure tendency is (pressure increased) 0.8 hPa.

It is still necessary to determine the speed of the shock waves: the first shock wave, the second shock wave, and the first pressure wave return. In order to indirectly calculate the speed of the shock waves, the orthodromic distance (z) was first determined using Eqs. (1). The obtained orthodromic distance (z) between the MS included in the analysis and the HT–HH volcano is approximately 16.95 thousand km ($z = 152.447° = 16{,}952.65$ km). For comparison, this distance is approximately equal to half the circumference of the Earth's great circle ($O_E = 40{,}075$ km), and is greater than the diameter of the Earth at the equator (12,756 km). Using Eqs. (3), (4), (5), and (6), the approximate speed of the first shock wave of 1,130 km h^{-1} was obtained. The second shock wave, and the first pressure wave return share the similar speed of 1,000.75 km h^{-1}, and 1,095 km h^{-1}, respectively. Also, they share the same average speed of 1,079.8 km h^{-1}. The obtained value is close to the speed of sound, and the confirmation of this claim is the statement of the Bureau of Meteorology of Australia (BOM AUS 2022), where speeds of over 1,000 km h^{-1} are mentioned. Based on the claims of the Alaska Public Media (2022), infrasonic measurements indicate that the eruption of the HT–HH volcano was also heard in audible range all across Alaska, so it can be concluded that the speed of the initial waves were close to the speed of sound.

Conclusion

On January 14 and 15, 2022, strong eruptions of the HT–HH volcano occurred in the South Pacific, causing a local disturbance in the atmosphere, which spread throughout the Earth. Satellite images indicate that volcanic ash had reached the mesosphere and the eruption the stratosphere. This disturbance affected the first three layers of the Earth's atmosphere. This study started from the assumption that the atmosphere of the planet Earth behaves like a fluid, and therefore a disturbance of any kind can be detected in any part of it. Research has shown that 15 h after the first stronger eruption, the first shock wave was registered at meteorological stations (MS) in Serbia, and the second shock wave 20 h after the eruption, while the first pressure wave return was recorded 52 h after the eruption. This indicates that the first wave traveled around the entire planet Earth. Sudden jumps (peaks) of air pressure were recorded along the same meridians, indicating that this was not an isolated case. Also, based on a detailed analysis of prognostic and analytical material (prognostic surface pressure maps, the 500 hPa maps, and SYNOP analysis), it can be concluded that the registered pressure peaks are not due to some dominant characteristics of baric topography over Serbia, such as air fronts. Therefore, the main goal of the research was to determine the distance (between Serbia and HT–HH), the time and the propagation speed of the shock waves, and the return wave, after proving that the changes in air pressure in Serbia (and Montenegro) are a consequence of the HT–HH eruption. In the absence of modern instruments, the set tasks were done mathematically and using spherical trigonometry.

The calculated orthodromic distance (z) between the MS included in the analysis and the HT–HH volcano is approximately equal to half the circumference of the Earth or greater than the diameter of the Earth at the equator, and the speed of the first shock wave was an incredible 1,130 km h^{-1}. A sonic boom was recorded in the state of Alaska in audible range, i.e., the eruption could be heard by residents of Alaska. Thus, it is obvious that any disturbance in the Earth's atmosphere, regardless of geographical location, has an impact on the global atmosphere. The HT–HH volcanic eruption unequivocally confirms this. The consequences of this strong eruption on other meteorological parameters, including the Earth's climate, remain to be determined. The question arises, what kind of anomalies and disturbances would a volcanic eruption, potentially stronger and geographically closer to us, cause?

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Declarations

Competing interests
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