SHOA

TECHNICAL REPORT

TONGA VOLCANO EVENT
JANUARY 15, 2022

ELABORATED BY TSUNAMI MODELING DIVISION
OCEANOGRAPHY DEPARTMENT
FEBRUARY 2022

HYDROGRAPHIC AND OCEANOGRAPHIC SERVICE OF THE CHILEAN NAVY

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Elaborated by Tsunami Modeling Division
Oceanography Department
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1. GENERAL BACKGROUND OF THE EVENT

Hunga Tonga-Hunga-Ha'pai volcano eruption on January 15, 2022 generated a tsunami which spread across all the Pacific Ocean, causing damages at a local and regional level, and on some farther coasts. One of the most affected areas was the Tonga archipelago, made up by 177 islands, of which approximately 36 are inhabited. The resulting tsunami hit Tongatapu, the archipelago's main island and where the capital of the government of Tonga, Nuku'alofa, is located, about 65 km south of the volcano. According to the first reports, the tsunami waves which hit the western coasts of Tongatapu Islands, 'Eua and Ha'apai, reached a run up between 15 to 20 m, while floods of 500 m in Nomuka and 600 m in Mango were observed, both locations belonging to the Ha'pai island (Fa'anunu, 2022)..

The tsunami waves also spread through the vast ocean to the northeast Pacific, where sea level variations where recorded in Alaska, Oregon, British Columbia, California, Mexico and parts of South America. The same situation was recorded in eastern countries, such as Japan and Australia..

Tonga's volcanic oceanic eruption and the resulting tsunami was an incredibly impulsive and high energy event. The big explosion was heard by many countries of the region, such as New Zealand and Lakeba Island in Fiji. Such events can generate strong pressure waves in the atmosphere that can propagate into the Earth's ionosphere and modulate the plasma there (Themens et al., 2022), situation observed by international satellites. In some places the coupling of the atmospheric pressure wave with the ocean surface caused the generation of small tsunami waves observed in the Caribbean, the Atlantic and the Indian Ocean.

This is the first time that the Pacific Tsunami Warning and Mitigation System (PTWS) has responded to such a destructive volcanic event, as its efforts have been mainly focused in earthquake-generated tsunamis, so there were no established protocols for the management of this type of threat nor regionally nor internationally. Owing to the above, the National Tsunami Warning Centers were forced to use local Standard Operating Procedures (SOPs) to face the emergency so as to safeguard the coastal communities' lives. Many countries issued warning, advisory and alert bulletins, which in some places meant evacuating the population. The Pacific Tsunami Warning Center (PTWC), notified technical problems for the issuance of warning bulletins and tsunami amplitude forecasts due to the particular characteristics of this event, so the information initially distributed only to the PTWS Focal Points, was based on SOPs for earthquake-generated tsunamis and sea level monitoring. In total, the PTWC issued 12 bulletins within 20 hours and reported 117 tsunami wave measurements from 26 countries (ITIC, 2022).

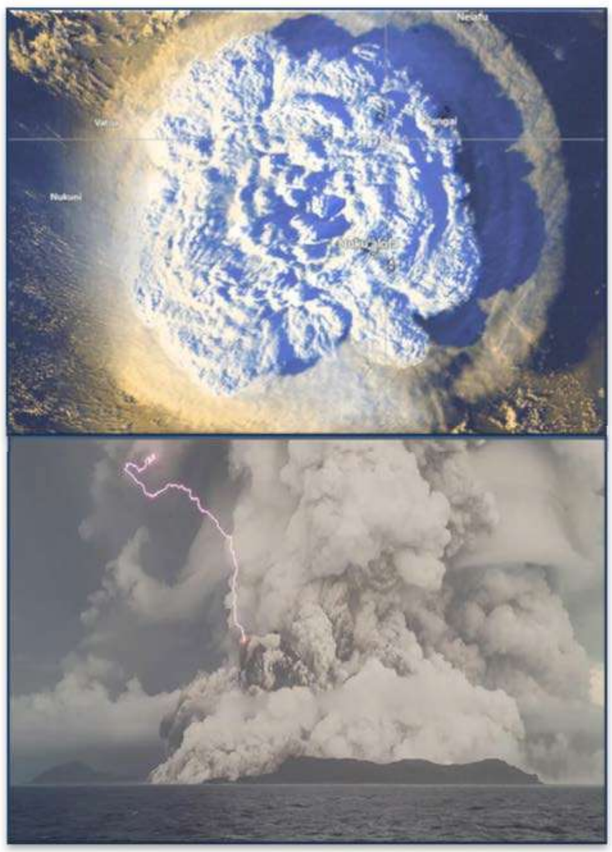

Figure 1. Hunga Tonga-Hunga Ha'apai volcano eruption on January 15, 2022 (Source: Twitter)

2. HUNGA TONGA-HUNGA HA'APAI VOLCANO

2.1 Geological Context

Hunga-Tonga-Hunga-Ha'apai volcano is one the many volcanoes in the Tonga-Kermadec volcanic arc which originated as a response to the Pacific Plate subduction beneath the Indo-Australian Plate.

The Tonga-Kermadec subduction zone is part of the extended Australia-Pacific plate boundary and reflects a multi-stage tectonic history related to the global rearrangement of plate convergence in the southwest Pacific (Bonnardot et al., 2007). Muchos procesos geodinámicos contribuyen al complejo patrón tectónico actual observado a lo largo de los 2700 km del sistema Tonga-Kermadec. Many geodynamic processes contribute to the complex current tectonic pattern observed along the 2700 km of the Tonga-Kermadec system. This subduction system is characterized by a N 15°E trending back-arc, that is mostly parallel to the volcanic arc. The back-arc domain exhibits strong variations of the stress state and orientations of the tectonic structures from north to south. In fact, back-arc spreading is well established in the Lau Basin, in contrast to back-arc rifting within the Havre Trough (Karig, 1971) (Figura 2).

The Tonga-Kermadec subduction system, is the deepest trench in the southern hemisphere and the second deepest in the world. The convergence rate between the Pacific plate on the east and the Tonga Kermadec arc to the west is about 15 cm/year, which demonstrates this zone records the fastest subduction speed on Earth (Kusky, 2022).

The northern termination of the Tonga-Kermadec subduction zone is controlled by additional mechanisms, that are expected to affect locally the state of stress within the overriding plate. First, the northern edge of the Tonga trench is characterized by the tearing of the Pacific subducting plate. On the basis of the earthquake distribution and their focal mechanisms, Millen & Hamburger (1998) showed that the Pacific plate is progressively downwarped as it enters into the northern part of the trench and torn from 18 down to 88 km in depth over the entire lithospheric thickness. Second, the trench extends westward as a large transform fault with a right lateral strike-slip motion, that accommodates the westward Pacific plate motion.

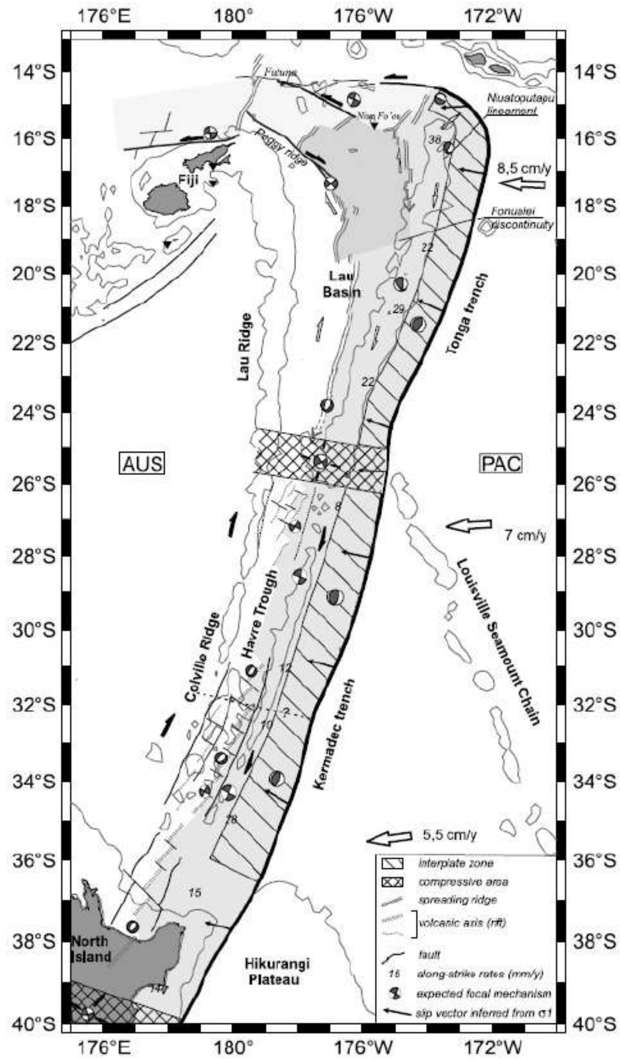

Figure 2. Summarized tectonic model for the Tonga-Kermadec subduction zone and its main units. (Source: Bonnardot et al., 2007)

Tonga is located in the northern part of the Tonga-Kermadec system, where the Hunga Tonga-Hunga Ha'apai volcano and a reef to their south sit on the rim of a submarine caldera. The islands and the reef are the only surface features betraying the presence of the largely submerged Hunga volcano (Figure 3). Before 2014, it was composed of two small andesitic uninhabited islands, Hunga-Ha'pai and Hunga-Tonga, which protrude about 100 m above sea level, but hidden under the sea there is a huge volcano, of about 1800 m height and 20 km width, whose caldera is a depression similar to a crater of about 5 km diameter (Cronin, 2022).

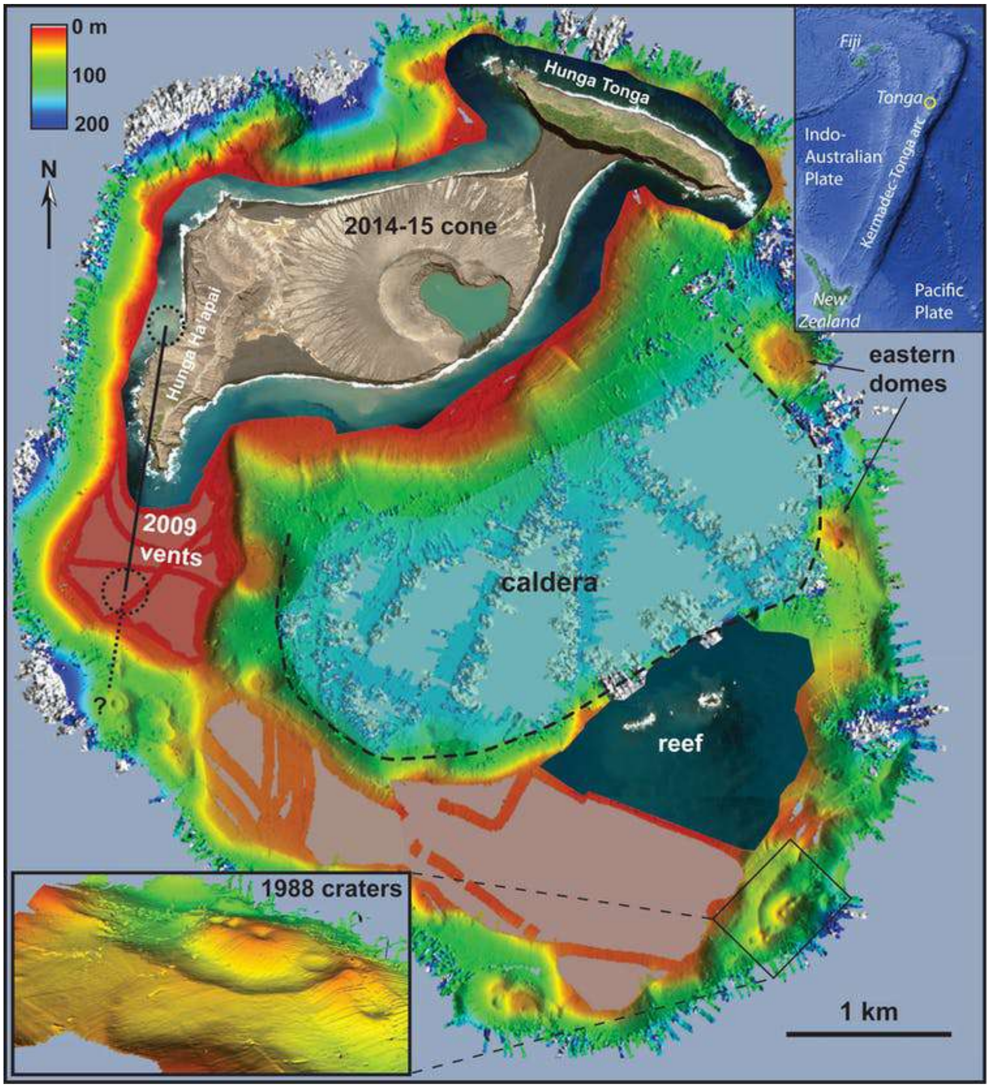

Figure 3. Map of the Hunga Tonga-Hunga Ha'apai islands and the submarine caldera complex. The summit platform of the submerged volcanic edifice is shown. The dashed black line outlines a previously undocumented caldera, which lies 150 to 180 meters below the surface. Traces of past eruptions along the caldera rim are clearly visible; the inset gives the locations of the 1988 eruptions in greater detail. Areas colored white represent depths greater than 200 meters, beyond the range of the sonar (Source: Cronin et al., 2017).

The published studies indicate that the Hunga volcano has had remarkable eruptions before the one that took place on January 15, 2022, which were recorded in 2015/2014, 2009, 1988, 1937 y 1912 (Bryan et al., 1972; Kusky, 2022).

On late December 2014, an undersea volcano erupted, sending steam and dense ash plumes into the air. By the time the eruption ended about 5 weeks later, a new island had formed, eventually bridging the gap between the original islands of Hunga- Ha'apai and Hunga-Tonga. Some information suggest that this volcano has had catastrophic eruptions, similar to the 2022 eruption, about 1000 and 2000 years ago, and it is possible that the volcanic edifice was a huge volcano that periodically collapses during these events. (Kusky, 2022; Cronin, 2022).

2.2 Last eruptive process

The scientific community agrees that it is still in the midst of this major eruptive sequence and many aspects remain unclear, therefore, a big volcanic upheaval of Hunga-Tonga-Hunga-Ha'pai could be expected within many weeks or even years. The two initial eruptions of this new cycle took place on December 20, 2021 and January 14, 2022, of moderate size, and produced clouds of up to 17 km elevation and added new land to the 2014/15 combined island.

The January 14 event began with a major eruption of ash and steam, accompanied by a magnitude 5.8 earthquake at 5 km depth (GDACS, 2022), and with a volcanic plume that quickly reached more than 20 km into the atmosphere. Subsequently, on January 15, 2022 at approximately 4:10 UTC (01:10 LT), the biggest eruption occurred, together with an important 4.5 magnitude earthquake associated with this volcanic activity and a big sonic blast reported by residents of New Zealand, Australia, and Alaska. The eruption was highly energetic and of great expansive force, caused by the interaction of seawater and magma outcropping with a temperature near 1000 °C, which produced a highly explosive steam. The height of the eruptive plume was about 30 km and is the highest captured since satellite imaging technology. (Kusky, 2022).

Additionally, the volcanic eruption caused a barometric pressure pulse, globally spreading out in concentric circles from the volcano, circling the Earth for at least two days (Figures 4a and 4b). The pressure pulse is called an atmospheric Lamb wave, which is generated by the expansion of the air around the volcano due to the heat of the eruption (Kataoka *et al.*, 2022).

Lamb waves travel at ~310 m/s, slightly slower than the sound speed, and are characterized by weak attenuation over long distances (Nishida et al., 2014).

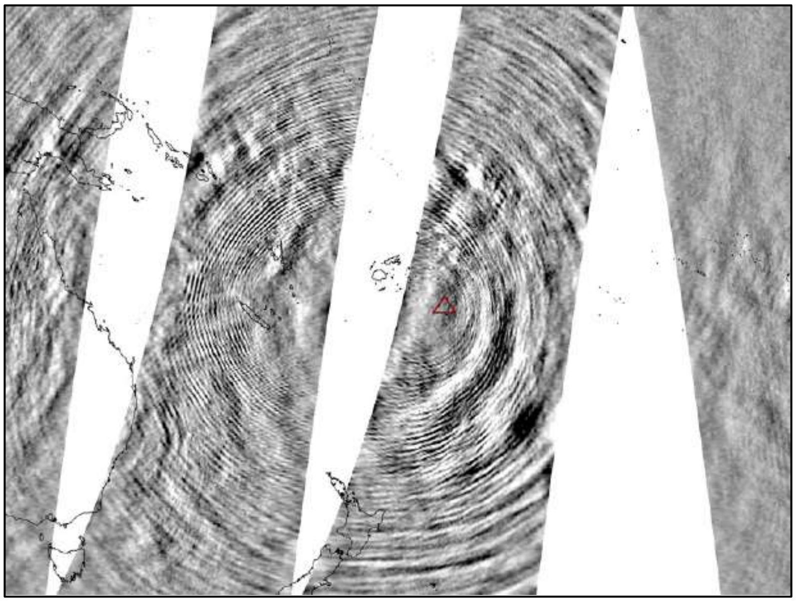

Figure 4a. Images from the Infrared Atmospheric Sounder on NASA's Aqua Satellite show dozens of concentric circles, which are atmospheric waves of fast movement. (Source: Lars Hoffmann, Jülich Supercomputing Centre. AIRS level 1 Data from NASA's DES DISC; Adam, 2022).

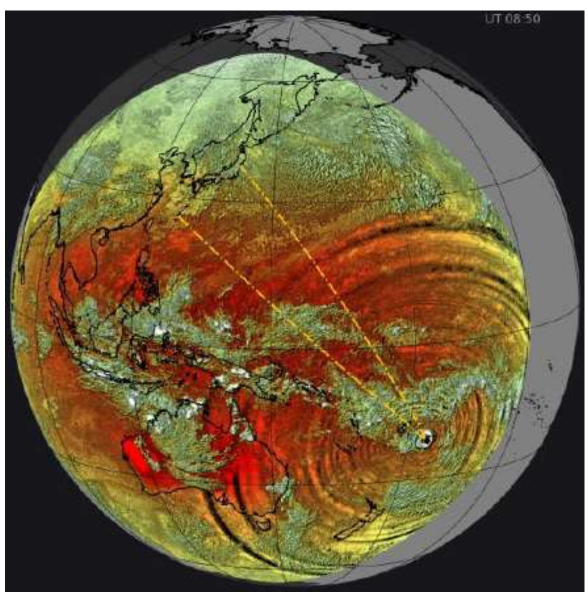

Figure 4b. Lamb waves analysis and propagation generated by the volcanic eruption via satellite images. (Source; Kataoka et al., 2022).

On the other hand, Kusky (2022), suggests that from the preliminary observations, the eruption of the Hunga Tonga-Hunga Ha'apai volcano seems to be remarkably similar to one of the most devastating volcanic eruptions in recorded history; Thera volcano, 3650 years ago, in what is now modern-day Santorini island in Greece. The eruption of Thera caused vast destruction across the Mediterranean and the downfall of the Minoan civilization that inhabited Crete at that time.

The reconstructions of the eruptive sequence of Thera reveal four main phases, which bear an uncanny resemblance to what we know about what happened in Tonga. The first was a massive eruption of ash and pumice that was ejected high into the atmosphere, collapsing back on Thera and covering nearby oceans with 3 to 4 m of pyroclastic deposits. This phase was probably a Plinian eruption column and its devastating effects on Thera made the island uninhabitable. This may be equivalent to the previous months of very active Plinian eruptions from Hunga Tonga- Hunga Ha’pai. For Thera, next, huge fissures in the volcano began to open in the second phase, and seawater entered these and initiated large steam eruptions and mudflows, leaving deposits up to 20 m thick. The third phase was the most cataclysmic, as seawater began to enter deep into the magma chamber initiating huge blasts that were heard across southern Europe, northern Africa and Middle East. Sonic blasts, much like those accompanying the January 15 Hunga Tonga-Hunga Ha’apai eruption. Huge amounts of ash and aerosols were ejected into the atmosphere, probably causing several days of partial darkness over the eastern Mediterranean. Finally, the fourth phase of the eruption was marked by continued production of pyroclastic flows which deposit many layers of ash, pumice and other pyroclastic deposits around the island and the near Aegean (Kusky, 2022).

In the same way, Brenna et al., 2022, postulates that the preliminary eruptions of the Hunga volcano were small releases of a big magma reservoir, so a possible hypothesis for the January 15 event, is that the volcano caldera has collapsed, releasing the big magma chamber and causing a big explosion. Besides, the occurrence of a submarine slide cannot be ruled out, until not carrying out a new analysis of the bathymetry of this complex area. The scientific community agrees in saying that it is unclear if this was the eruptive process climax and effectively represents a major release of magma pressure, that the system may sit. Nevertheless, from the geological deposits evidence of the previous volcano eruptions, it has been observed that this complex sequences show that each one of the main eruptions episodes of the caldera, with a 1000-year reoccurrence, involve many separated explosion events.

3. TSUNAMI ANALYSIS

The violent and explosive eruption of the Hunga Tonga-Hunga Ha'apai volcano (HTHH) on January 15, 2022, caused a strong tsunami in all the Pacific Ocean and in other oceanic basins, including the Caribbean and Mediterranean seas, surprising experts of the Tsunami Warning Centers that monitored the event and the scientific community, which now is studying the data recorded by the different sensors networks, such as the Global Navigation Satellite System (GNSS), DART systems networks and sea level stations, and also meteorological networks.

The first hypothesis point out that in this case the tsunami generation source is complex and it could be the result of a combination of volcanic mechanisms which include underwater explosion, pyroclastic flow, submarine slides, caldera collapse together with the lava bench, which interacts with the surrounding seawater, shock and atmospheric pressure waves, among others.

Within the Pacific Ocean basin, the maximum tsunami amplitudes recorded oscillated within the range of 0.1 to 2 m. According to what was informed by the Pacific Tsunami Warning Center (PTWC) and published by the National Centers for Environmental Information (NCEI) of NOAA, the largest amplitudes, with values greater than 0.8 m, were measured at the Tonga, Fiji, New Caledonia, New Zealand, Cook Islands, Vanuatu, Japan, Hawaii, California (USA), Mexico, Peru and Chile stations (Table 1 and Figure 5). Within this group, it is worth mentioning that the largest amplitudes were recorded at the Beach Naylamp station, Lambayeque, Peru, with 2 m, and in Chañaral station, Chile, with 1.96 m.

Table 1. Maximum Amplitudes Record measured by Sea Level Stations in the Pacific Ocean Basin (Source: NCEI/NOAA – SHOA).

Country	Sea Level Station Location	Maximum Amplitude (m)
PERU	Playa Naylamp,Llambayeque	2.0
CHILE	Chañaral	1.96
CHILE	Coquimbo	1.47
VANUATU	Port Vila, Isla Efate	1.41
CHILE	Arica	1.37
USA	Arena Cove, CA	1.34
USA	Port San Luis, CA	1.34
JAPAN	Kominato, Isla Amami	1.2
NEW CALEDONIA	Ouinne	1.13
CHILE	Coliumo	1.13
USA	Crescent city, CA	1.1
JAPAN	Kujiko	1.1
CHILE	Iquique	1.09
CHILE	Bahía mansa	1.03
MEXICO	Manzanillo	1.03
CHILE	Punta de Choros	1.03
USA	King cove, AK	1.0
CHILE	Talcahuano	0.97
JAPAN	Kushimoto	0.96
JAPAN	Tosa-shimizu	0.93
NEW ZEALAND	Jackson bay	0.91
JAPAN	Kiritappu	0.9
CHILE	Caldera	0.9
JAPAN	Gobo	0.9
COOK ISLANDS	Rarotonga	0.9
NEW CALEDONIA	Isla Lifou	0.89
CHILE	Puerto Aldea	0.88
CHILE	Valparaíso	0.87
CHILE	Quintero	0.84
USA	Kahului, Maui, HI	0.83
TONGA	Nukualofa (nuku'alofa)	0.82
USA	Hanalei, Kauai,HIi	0.82
CHILE	Mejillones	0.82
FIJI	Cakova, Isla moala	0.8
JAPAN	Yaene, Isla hachijo	0.8
USA	Point Reyes,CA	0.8
CHILE	Corral	0.8
JAPAN	Murotomisaki	0.8
FIJI	Vakano, Isla Lakeba	0.8

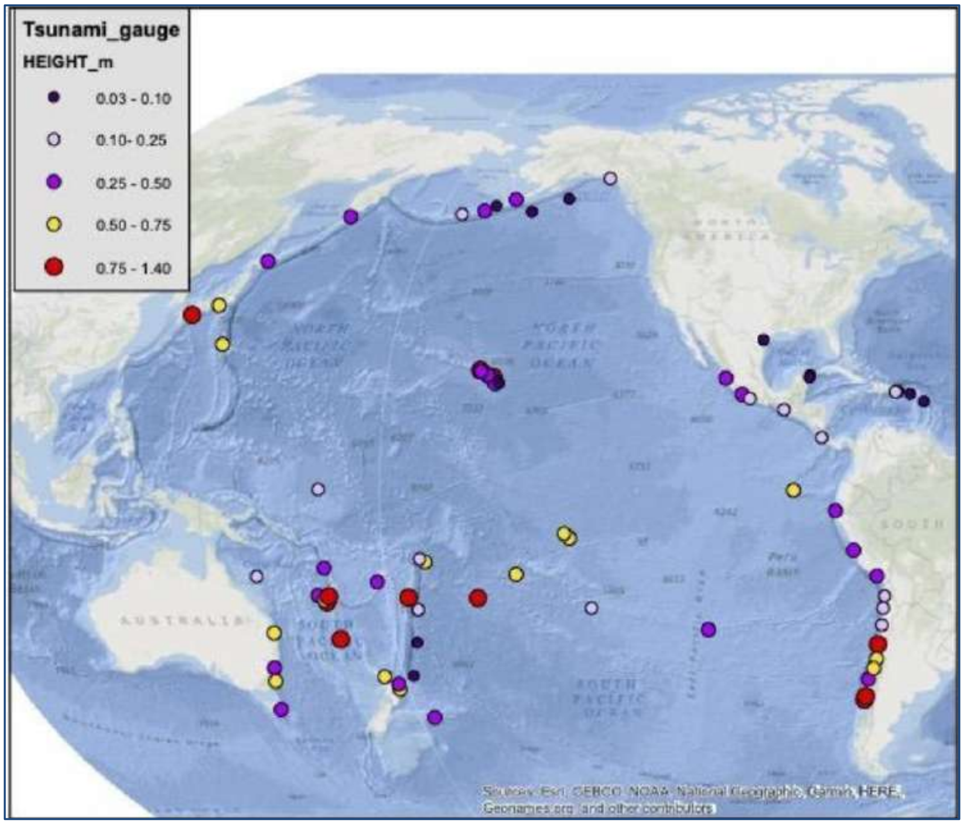

Figure 5. Maximum Amplitudes of January 15 tsunami reported by PTWC (Source: McCreery, 2022)

On the other hand, some Mediterranean and Caribbean stations showed maximum amplitudes in the order of 0.1 m, which turns remarkable owing to their distance and location related to the volcano. This may be appreciated in figure 6, showing the record of three stations located in the Mediterranean at ~ 18000 km distance from HTHH (Gusman & Roger, 2022) and in figure 7, showing two stations in the Caribbean at ~ 13000 km de distance, respectively. Additionally, the tsunami was also recorded at stations from the Indian Ocean, such as Indonesia, Malaysia, Sri Lanka, Maldives Islands and South Africa, among others, with amplitudes no greater than 0.1 m (Figure 8). Such records have been associated with the barometric pressure pulse, globally spreading out in concentric circles from the volcano, circling the Earth for at least two days (Kataoka et al., 2022). This phenomenon is known as meteorological tsunami or meteotsunami. As proposed by Harkrider and Press (1962), similar pulses and a meteotsunami were produced in the past during the Krakatoa volcano eruption in 1883.

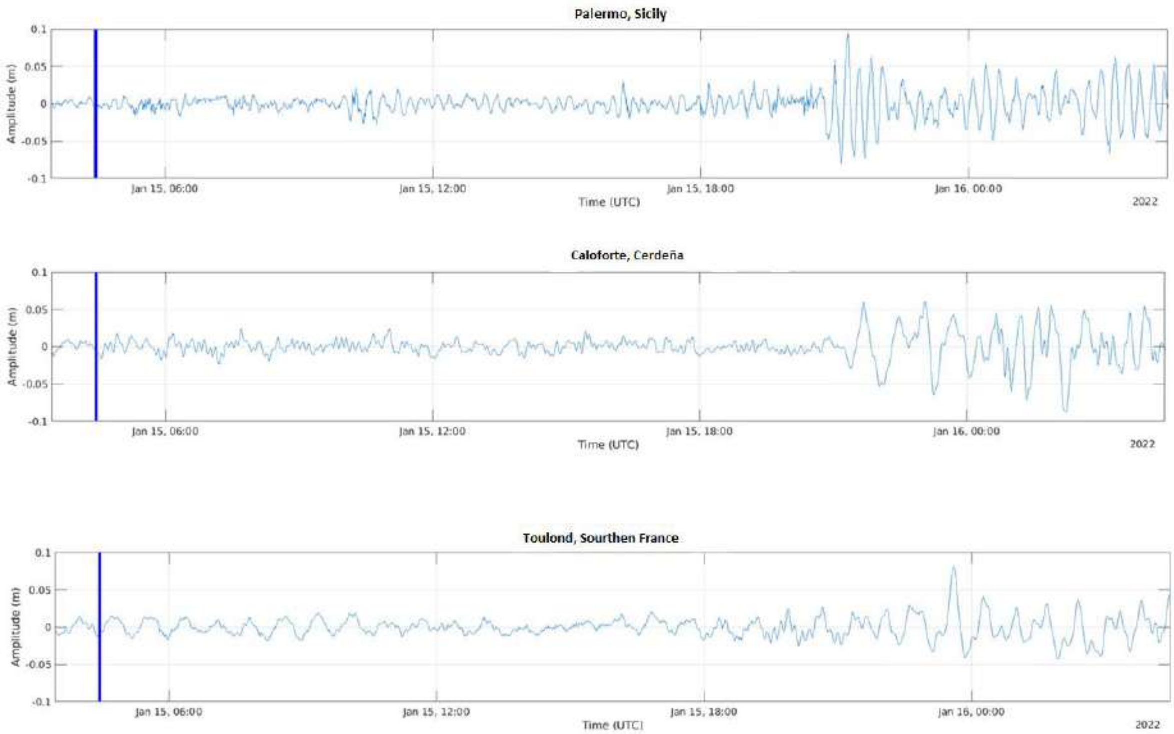

Figure 6. Sea level variations recorded at coast stations of Palermo, (Sicilia, IT), Carloforte (Sardinia, IT) and Toulon (FR), after Tonga volcano eruption. (Source: Gusman & Roger, 2022).

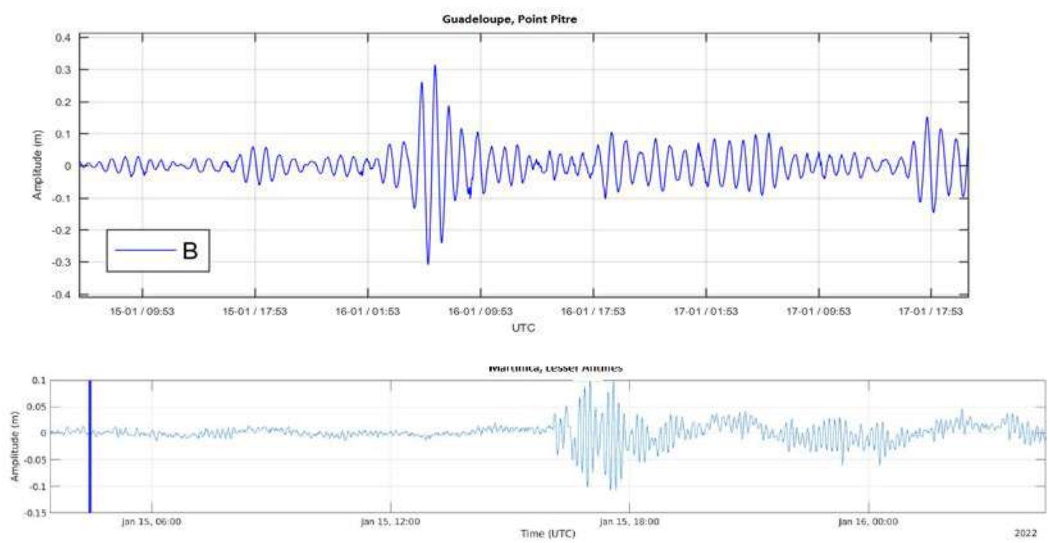

Figure 7. Sea level variations recorded in the Caribbean Sea at the stations of Guadalupe (FR) and Martinique (FR) after Tonga volcano eruption (Source: COI/SHOA, 2022; Gusman & Roger, 2022).

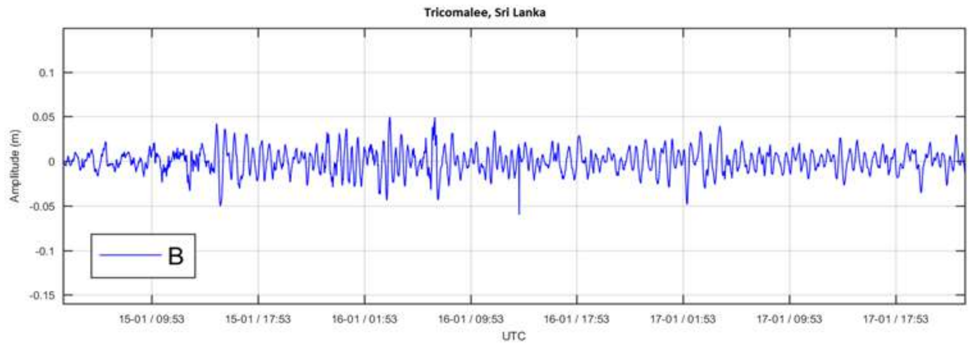

Figure 8. Sea level variations recorded in the Indian Sea at Tricomalee station, (Sri Lanka) after Tonga volcano eruption. (Source: COI/SHOA, 2022).

3.1 Tsunami analysis for the Chilean coasts

As previously mentioned, the tsunami generated by the HHTH eruption on January 15, 2022, was recorded along the coast of Chile and the insular zones, at 40 sea level stations of the National Network, from Arica to Base O'Higgins in Chilean Antarctica (Annex "A"). From the records analysis, it can be seen that sea level fluctuations were observed in 33 stations, much earlier than expected for the arrival of the oceanic long wave tsunami, which should have been generated by the eruption. These fluctuations can be attributed to the passage of the Lamb wave front or atmospheric pressure through the respective stations, whose average amplitude was 1.60 mBa and maximum of 2.17 mBa (Annex "D").

The atmospheric pressure fluctuation was first recorded at the insular station of Easter Island, at 7:28 LT, and it was sequentially spreading from south to north around the coast stations. The first atmospheric peaks on coast were measured at the southern stations of Puerto Aguirre and Melinka at 9:30 and 9:32 LT, followed by O’Higgins Base at 9:35 LT and Puerto Williams at 9:36 LT. The last record was measured almost two hours later at Arica station at 11:07 LT (Table 2). Notwithstanding the foregoing, the onset of sea level fluctuations associated with the Lamb wave passage was not recorded in the same order of sequential arrival from south to east at the stations network.

In table 2, it can be observed that the first sea level fluctuation was measured approximately at 9:46 LT at Melinka station, followed by Lebu, Nehuentue, Constitucion, Ancud, San Antonio, Boyeruca, and Pichidangui stations, in the time range between 10:11 LT and 10:35 LT. The last stations that measured such initial fluctuation were Mejillones, Arica and Patache at 11:39 LT, 11:49 LT y 12:33 LT, respectively.

Table 2. Atmospheric pressure waves arrival record, sea level fluctuations and predicted hours of arrival for the tsunami (Source: SHOA).

Sea Level Station	Predicted Arrival Time (TTT) (Local Time)	Atmospheric Peak Time (Local Time)	Arrival first sea level fluctuation (Local Time)	Δt1	Observed Tsunami Arrival (Local Time)	Δt2
EASTER ISLAND	15-01-2022 10:43	7:28	N/D		10:49	6
PUERTO AGUIRRE		9:30	N/D		15:37	*
MELINKA		9:32	9:46	14	14:34	*
BASE PRAT	15-01-2022 14:26	9:33	10:38	65	13:13	73
BASE OHIGGINS	15-01-2022 14:56	9:35	N/D		13:36	80
PUERTO WILLIAMS		9:36	N/D		13:46	*
CASTRO	15-01-2022 16:29	9:37	N/D		16:28	1
ANCUD	15-01-2022 14:53	9:39	10:25	46	14:33	20
BAHIA MANSA	15-01-2022 14:38	9:43	N/D		14:07	31
CORRAL	15-01-2022 14:49	9:46	11:34	108	14:30	19
JUAN FERNANDEZ	15-01-2022 14:12	9:46	11:36	110	13:52	20
NEHUENTUE	15-01-2022 14:48	9:47	10:22	35	14:49	1
QUEULE	15-01-2022 15:00	9:49	10:41	52	14:51	9
LEBU	15-01-2022 14:33	9:53	10:11	18	14:10	23
SAN FELIX ISLAND	15-01-2022 14:38	9:56	N/D		14:11	27
CORONEL	15-01-2022 14:57	9:57	11:04	67	14:07	50
COLIUMO	15-01-2022 15:02	9:59	10:48	49	14:21	41
TALCAHUANO	15-01-2022 14:49	9:59	11:09	10	14:41	8
CONSTITUCION	15-01-2022 14:59	10:06	10:22	16	14:42	17
BOYERUCA	15-01-2022 14:58	10:09	10:30	21	14:39	19
PICHIDANGUI	15-01-2022 15:13	10:16	10:35	19	14:48	32
SAN ANTONIO	15-01-2022 15:09	10:16	10:25	9	14:24	45
QUIRIQUINA ISLAND	15-01-2022 14:49	10:16	11:14	58	14:57	8
QUINTERO	15-01-2022 15:13	10:17	10:38	21	14:47	26
VALPARAISO	15-01-2022 15:05	10:18	10:42	24	14:46	19
PUERTO ALDEA	15-01-2022 15:14	10:26	10:38	12	15:06	8
COQUIMBO	15-01-2022 15:20	10:27	10:56	29	15:09	11
PUNTA CHOROS	15-01-2022 15:23	10:29	11:20	51	15:03	20
HUASCO	15-01-2022 15:28	10:35	10:42	7	15:04	24
CALDERA	15-01-2022 15:35	10:38	10:51	13	15:21	14
CHAÑARAL	15-01-2022 15:44	10:43	11:04	21	16:31	47
TALTAL	15-01-2022 15:52	10:45	10:58	13	16:11	19
CALETA PAPOSO	15-01-2022 15:53	10:47	11:01	14	15:50	3
MEJILLONES	15-01-2022 16:03	10:53	11:39	46	15:20	43
ANTOFAGASTA	15-01-2022 15:59	10:58	11:19	21	15:48	11
TOCOPILLA	15-01-2022 16:11	11:00	11:11	11	15:48	23
PATACHE	15-01-2022 16:23	11:01	12:33	92	16:02	21
IQUIQUE	15-01-2022 16:20	11:03	11:21	18	16:03	17
PISAGUA	15-01-2022 16:26	11:04	11:30	26	15:14	72
ARICA	15-01-2022 16:28	11:07	11:49	42	18:02	94

Δt1: Time difference in minutes between the atmospheric peak and the first sea level fluctuation.
Δ21: Time difference in minutes between the predicted arrival time of the tsunami and the observed time.
N/D: Not Detected.

Regarding the analysis of the time difference between the passage of the atmospheric pressure wave and the first fluctuation of the sea level measured at the stations, a great variability can be observed in the time values recorded at the stations, being for example the minimum difference of 7 minutes at the Huasco station (Figure 9) and the maximum of 110 minutes at the Juan Fernandez station (Figure 10). It is worth mentioning that a latitudinal pattern is not observed in the distribution of the time differences measured. In figure 11, the percentage distribution of the observed time differences is shown, by ranges, of which it is obtained that in 34% of the cases the time difference between the atmospheric peak and the onset of the first sea level fluctuation was between the range of 16 to 20 minutes, in 27% between the first 15 minutes and in 18% between the range of 46 to 60 minutes.

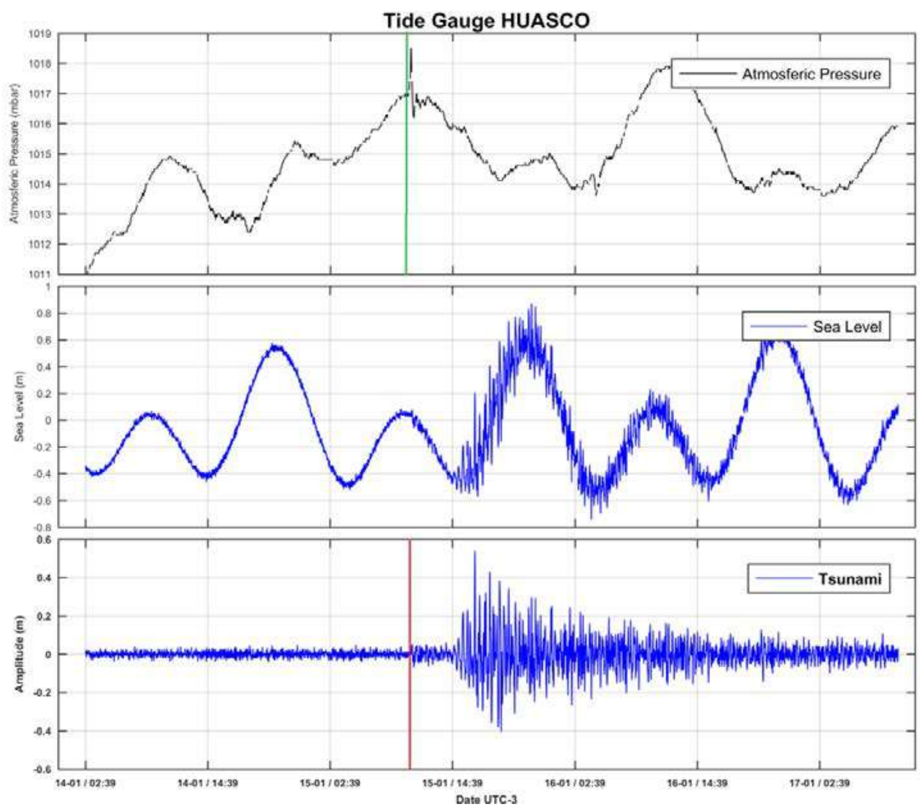

Figure 9. Pressure variation and sea level fluctuations record resulting from the HTHH volcanic eruption, at Huasco Tide gauge. The green line indicates the detection of the surface atmospheric pressure anomaly, and the red line the onset of the sea level fluctuation. (Source: SHOA, 2022).

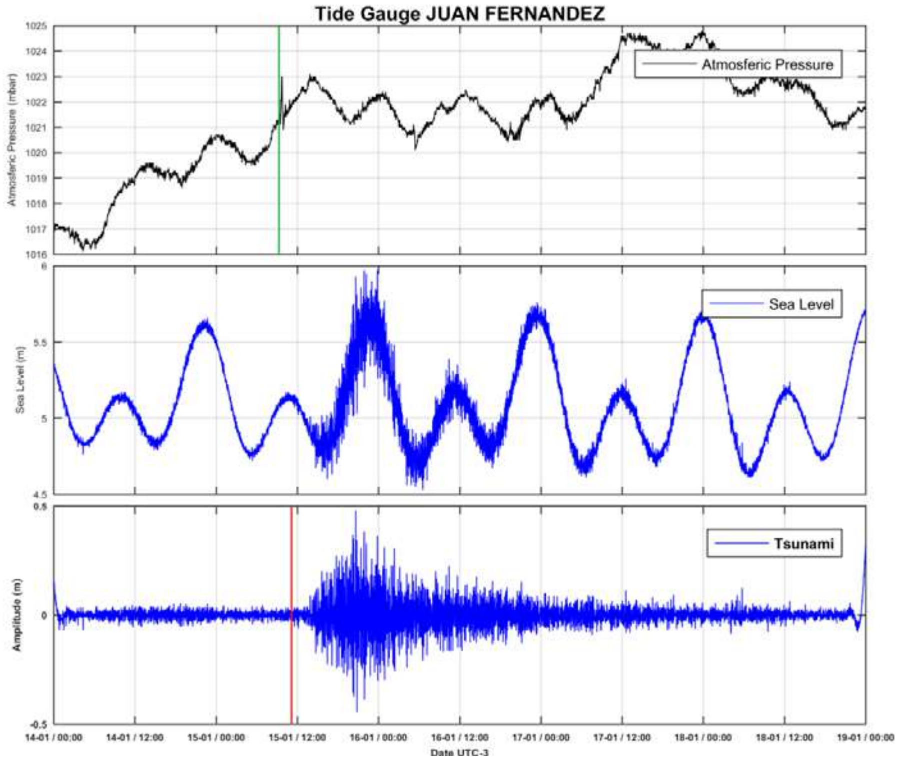

Figure 10. Pressure variation and sea level fluctuations record resulting from the HTHH volcanic eruption, at Juan Fernandez insular Tide gauge. The green line indicates the detection of the surface atmospheric pressure anomaly, and the red line the onset of the sea level fluctuation. (Source: SHOA, 2022).

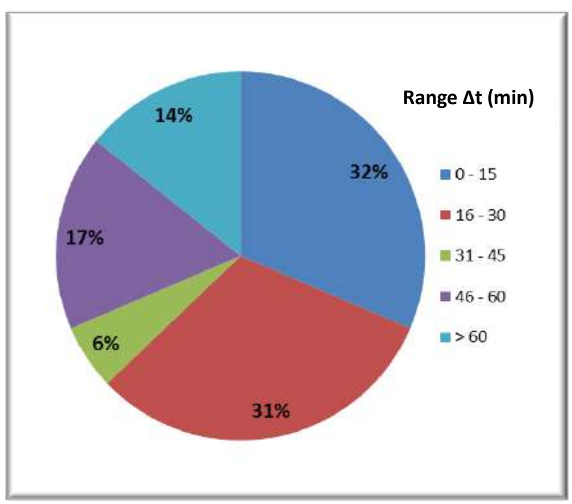

Figure 11. Percentage distribution of the time differences between the atmospheric peak and the onset of the first sea level fluctuation, measured at sea level stations. (Source: SHOA, 2022).

In the same way, from the analysis of the differences between the times of arrival predicted by TTT and the tsunami times of arrival (long waves) observed at the stations network, it is concluded at in 86.5% of the cases, the observed arrival time is less than predicted, that is to say, the tsunami waves were recorded before than what was estimated according to the ocean long wave theory which spread with a phase velocity equal to v= $\sqrt{gH}$ (being g the gravitational acceleration and H is the water depth). The only stations that recorded arrivals after than predicted were Easter Island, Quiriquina Island, Taltal, Chañaral and Arica, with differences of 6, 8, 19, 47 y 94 minutes, respectively (Table 2).

Taking into account the obtained results, it is feasible to indicate that, in general terms, the tsunami waves were recorded at the national network stations well in advance regarding the predicted time, which could be attributable on the one hand to the fluctuations triggered by the passage of the atmospheric wave forced by the pressure wave travelling at a velocity of ~ 310 m/s, which according to Sekizawa & Kohyama (2022) became synchronised with the atmospheric forcing above the ocean basin, so as to propagate and spread later at the free waves velocity in the continental slope. This could explain the arrival of the first fluctuation on the coast with a delay of a few tens of minutes with respect to the measured pressure peak. Additionally, the observed time differences between the atmospheric peak and the first sea level fluctuation, as well as between the predicted tsunami arrival time v/s the observed arrival time, could also be due to the complex characteristics of the tsunami generation source together with the particularities of the regional and local bathymetry, the presence of trench, seamounts, local coastal geomorphology and reflection processes between the coast and trench which produce edge waves.

On the other hand, table 3 shows the records of maximum tsunami amplitudes measured by the insular and coast tide gauges of the national network, where it can be appreciated that the highest values observed fluctuated between a minimum of 0.6 and a maximum of 1.96 m. The station that recorded the largest amplitude was Chañaral, with 1.96 m, followed by Coquimbo with 1.47 m and Arica with 1.37 m. In general terms, 63% of the stations recorded maximum amplitudes within the range of 0.3 and 1.0 m, 20% with values smaller than 0.3 m and only 17% (7 stations) showed amplitudes higher than 1.0 m (Figure 12).

Tabla 3.Registro de amplitudes máximas y períodos más energéticos medidos en las estaciones de nivel del mar para el tsunami del 15 de enero de 2022 (Fuente: SHOA).

Sea Level Station	Maximum Amplitude (+) (m)	Maximun Amplitude (-) (m)	Maximun Amplitude Time (+) (LT)	Maximun Amplitude Time (-) (LT)	Most energetic periods (min)
CHAÑARAL	1,74	1,96	15-01-2022 18:24	15-01-2022 19:14	30 -12 -5
COQUIMBO	1,47	1,09	15-01-2022 18:38	15-01-2022 18:24	33 - 19 - 13
ARICA	1,37	1,06	15-01-2022 19:29	15-01-2022 19:34	28 -10 - 2
IQUIQUE	1,09	0,77	15-01-2022 19:07	15-01-2022 19:00	14 - 26 - 5
COLIUMO	1,07	1,13	15-01-2022 21:38	15-01-2022 21:22	37 -7 - 3
TALCAHUANO	0,97	0,95	15-01-2022 23:52	15-01-2022 23:06	90 - 32 - 18 - 3
PUNTA CHOROS	0,96	1,03	15-01-2022 20:03	15-01-2022 20:14	24 - 10
PUERTO ALDEA	0,88	0,86	15-01-2022 18:29	15-01-2022 21:23	32 - 18 - 14 - 9 - 4
CALDERA	0,87	0,90	15-01-2022 19:10	15-01-2022 19:32	28 - 15 - 6 - 3
VALPARAISO	0,87	0,69	15-01-2022 17:51	15-01-2022 16:32	36 - 9
QUINTERO	0,84	0,70	15-01-2022 19:19	15-01-2022 17:15	23 - 10 - 4
MEJILLONES	0,78	0,82	15-01-2022 22:36	15-01-2022 21:36	40 - 25 - 18 - 9
PICHIDANGUI	0,73	0,69	15-01-2022 17:06	15-01-2022 17:12	12 - 17 - 5
BAHIA MANSA	0,72	0,69	15-01-2022 17:58	15-01-2022 19:14	7 - 29 - 12
CORRAL	0,66	0,93	15-01-2022 15:56	15-01-2022 16:09	35 - 87 - 9
BOYERUCA	0,65	0,62	15-01-2022 19:30	15-01-2022 19:35	10 - 37 - 24
SAN ANTONIO	0,61	0,68	15-01-2022 16:33	15-01-2022 17:37	49 - 29 - 19 - 11 - 5
QUIRIQUINA ISLAND	0,61	0,71	15-01-2022 23:56	15-01-2022 21:47	90 - 33 - 13 - 8
CALETA PAPOSO	0,57	0,73	15-01-2022 16:55	15-01-2022 18:43	19 - 32 - 10 - 4
ANTOFAGASTA	0,55	0,61	15-01-2022 18:33	15-01-2022 17:36	43 - 23 - 15 - 7
HUASCO	0,54	0,40	15-01-2022 16:51	15-01-2022 19:26	21 - 14 - 7 - 3
PATACHE	0,53	0,75	15-01-2022 20:55	15-01-2022 18:29	51 - 32 - 24 - 18
EASTER ISLAND	0,50	0,54	15-01-2022 14:12	15-01-2022 14:14	5
PISAGUA	0,50	0,45	15-01-2022 21:03	15-01-2022 21:36	38 - 13 - 4
CORONEL	0,48	0,38	16-01-2022 0:01	15-01-2022 18:48	33 - 45 - 11 - 4
JUAN FERNANDEZ	0,48	0,45	15-01-2022 20:39	15-01-2022 20:50	
TALTAL	0,48	0,51	15-01-2022 21:53	15-01-2022 18:43	31 - 9 - 4
SAN FELIX ISLAND	0,47	0,43	15-01-2022 22:26	15-01-2022 19:30	
TOCOPILLA	0,46	0,56	15-01-2022 17:22	15-01-2022 17:15	31 - 14 - 3
LEBU	0,42	0,63	15-01-2022 14:40	15-01-2022 16:40	26 - 42 - 12 - 4
CONSTITUCION	0,41	0,49	15-01-2022 19:48	15-01-2022 19:39	58 - 23
QUEULE	0,39	0,29	15-01-2022 20:11	15-01-2022 21:05	119 - 80 - 38 - 16
BASE PRAT	0,27	0,26	15-01-2022 15:36	15-01-2022 15:52	32 - 19 -5
ANCUD	0,24	0,28	15-01-2022 17:04	15-01-2022 18:47	118 - 95 - 27 - 4
CASTRO	0,22	0,25	15-01-2022 20:08	15-01-2022 19:19	101
PUERTO WILLIAMS	0,19	0,12	15-01-2022 17:31	15-01-2022 20:20	
NEHUENTUE	0,14	0,15	15-01-2022 19:00	14-01-2022 21:00	
MELINKA	0,13	0,13	15-01-2022 16:56	15-01-2022 15:46	62 - 28 - 39 - 14
BASE OHIGGINS	0,12	0,11	17-01-2022 10:50	17-01-2022 11:30	56 -12 - 3
PUERTO AGUIRRE	0,07	0,06	14-01-2022 1:29	14-01-2022 2:09	

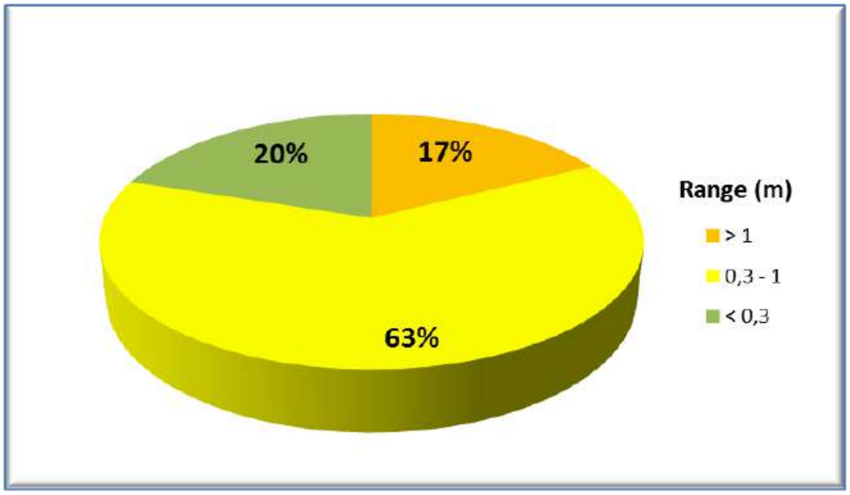

Figure 12. Percentage distribution of maximum amplitudes range measured at sea level stations (Source: SHOA, 2022).

It is worth mentioning that all the values of maximum amplitudes of the records are associated with the arrival of the long wave tsunami, caused by the volcanic eruption, and not with the initial fluctuation caused by the Lamb waves passage (meteotsunami), which subsequently couples with the long waves spreading along the Pacific Ocean.

Of equal importance, it must be mentioned that the values of maximum amplitudes were observed at bays showing resonance, which may be defined when in a waterbody, whether open sea, bays or ports, a series of free or natural oscillations is seen, named normal modes of oscillation which depend to a large extent on the seawater shape and deepness (De Grau, 2010). These oscillations or “seiches” may keep on during many cycles before they begin to decline owing to the friction effect. There are different physical phenomena that may lead to the free oscillation of a waterbody, among them, tsunamis and meteotsunamis. When the wave entering a basin has a wide spectrum, the oscillations which share their frequency bands with the frequencies of the different normal modes of oscillations of the waterbody are in resonance, so the arriving tsunami waves will always amplify, and then the instrumentally recorded amplitudes.

From the spectral analysis of the tsunami signals (Annex “C”), the most energetic periods were identified, which in general fluctuated around 5, 10, 30, 45 and 90 minutes. There is no evidence of a clear pattern in relation to the periods which allows to establish a direct relationship regarding the waves associated to the meteotsunami and the tsunami long waves. This variability is explained by the local geomorphological characteristics of the coast line, bays, resonance and the station location. An example of this may be appreciated for the stations of Chañaral, Valparaíso and Talcahuano. An energetic peak around 30 minutes may be observed in Chañaral, and also a pronounced signal is identified, separated from the main, which could be attributed to the meteotsunami with periods of 12 and 30 minutes (Figure 13). For Valparaíso, instead, only two energetic periods are observed constantly in the spectrum, being the highest of 36 minutes (Figure 14). Finally, for Talcahuano, the energy peak is concentrated around 90 minutes and also a signal is observed, separated from the main, around 11:00 LT, with periods between 18 and 32 minutes, which could be explained by the sea level fluctuation resulting from the pressure wave (Figure 15). Nevertheless, this is not seen in all the stations analysed for this event.

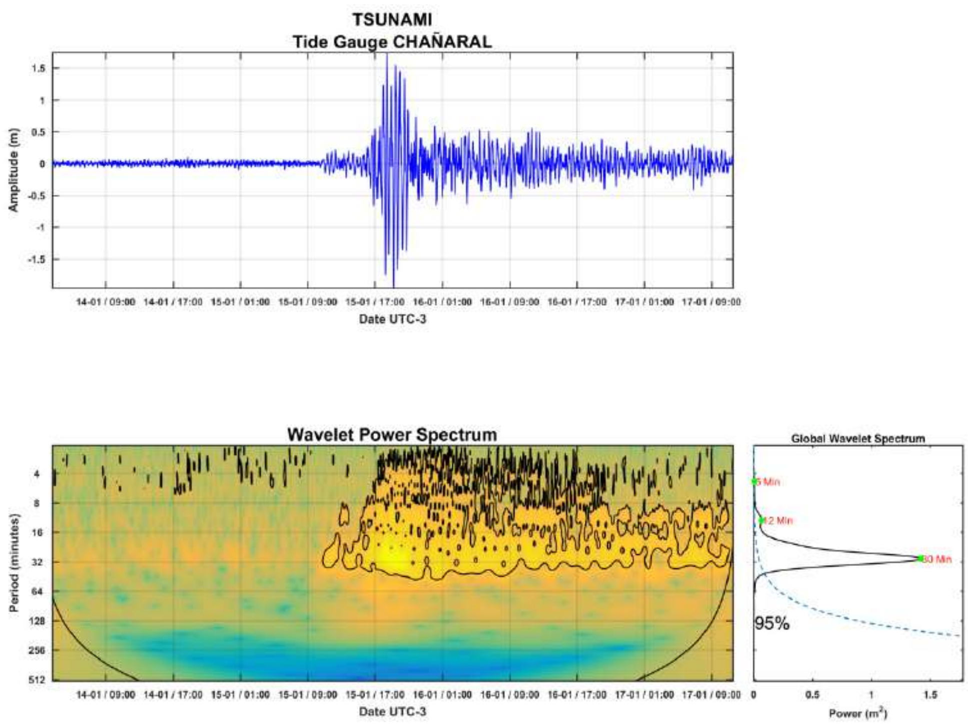

Figure 13. Energy spectrum for the tsunami signal recorded at Chañaral Tide gauge. (Source: SHOA, 2022).

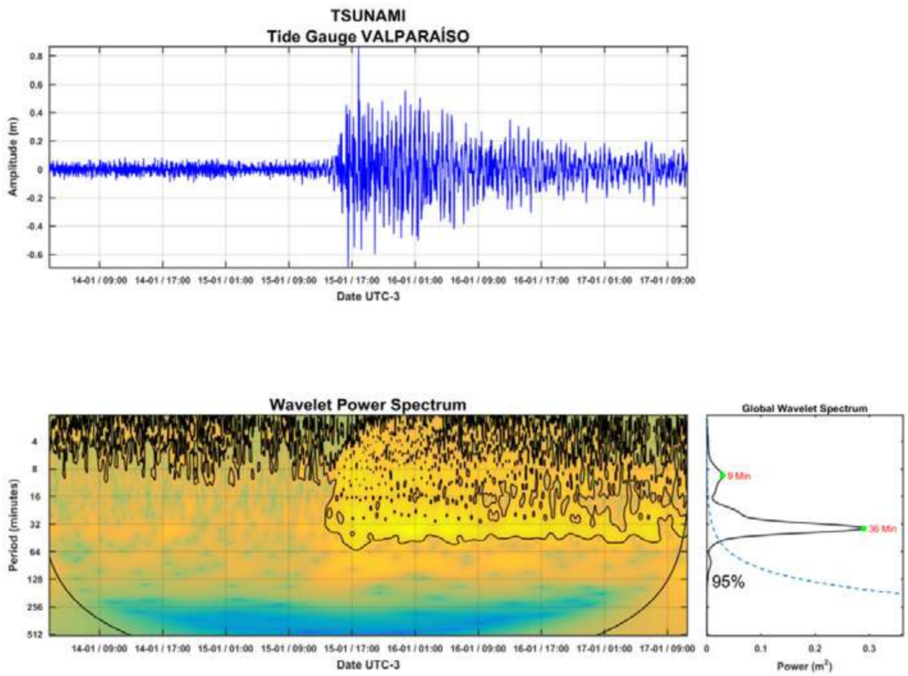

Figure 14. Energy spectrum for the tsunami signal record at Valparaíso Tide gauge (Source: SHOA, 2022).

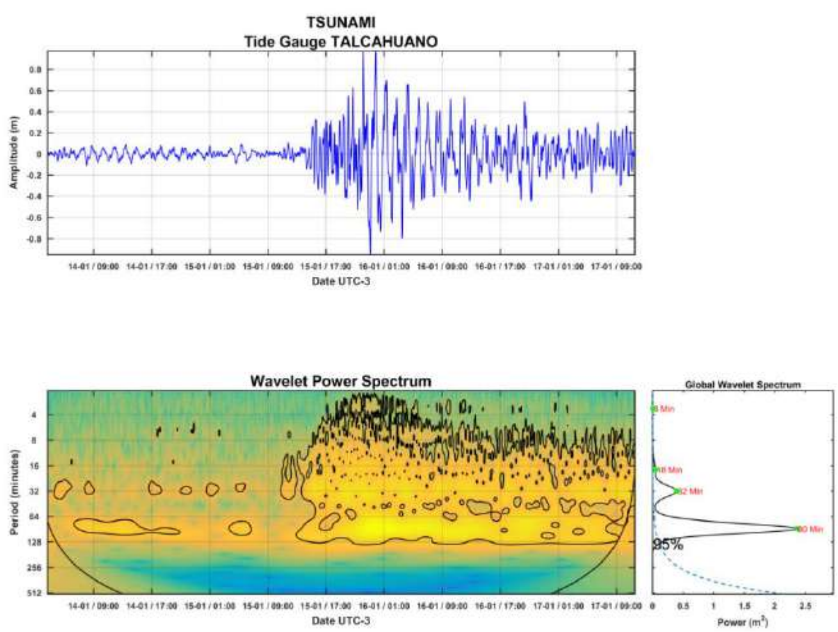

Figure 14. Energy spectrum for the tsunami signal record at Talcahuano Tide gauge (Source: SHOA, 2022).

As for the sea level stations, the tsunami was recorded by four DART systems that are part of the national monitoring network, and whose arrival times and approximate maximum amplitudes are shown in table 4 and Annex "B". For the first peak recorded in the DARTs, the maximum amplitudes fluctuate between 1 and 3 cm, while the associated arrival times range from 10:15 LT in Pichidangui to 10:46 LT in Mejillones. Similarly, the approximate maximum amplitudes of the record range between 7 and 10 cm, being the stations of Iquique and Caldera the ones with the highest values. On the other hand, the arrival times of the maximum amplitudes follow the same sequential pattern as those observed for the first peak and fluctuate between 14:16 LT in Pichidangui and 15:13 LT in Mejillones. In general terms, it is observed that the highest amplitude does not occur in the first wave, but several hours later with the passing of the long waves of the tsunami generated by the eruption of the volcano (Table 4). In this regard, some components of this initial waveforms may be a consequence of pressure changes caused directly by the volcanic shockwave rather than changes in the water surface level, although this is still being evaluated by the scientific community (Gusman & Roger, 2022).

Table 4. Record of maximum amplitudes and arrival times measured in the DART systems for the tsunami of 15 January 2022 (Source: SHOA).

DART Station	First peak amplitude (cm)	Arrival time First amplitude peak (H.L)	Maximum amplitude(cm)	Maximum amplitude time (LT)
Iquique	2	10:44	10	15:09
Mejillones	3	10:46	8	15:13
Caldera	1	10:25	10	14:33
Pichidangui	2	10:15	7	14:16

Another theory that could explain the amplitudes measured in the DART systems may be due to the fact that the pressure-forced wave is amplified by the Proudman resonance over the deep ocean basin (~ 6000 m) (Sekizawa & Kohyama, 2022), which occurs when the propagation speed of the atmospheric disturbance is equal to the wave propagation speed in the ocean, presenting a coupling between both and amplifying the wave in the ocean.

Finally, as can be seen in tables 2 and 4, the tsunami record was first measured by the DART systems and then at coastal stations. An example of the record observed by the DART systems is shown in figure 16, in which the first peak measured is clearly observed at 10:44 LT at the Iquique DART and the maximum amplitude of about 10 cm, almost four hours later. In contrast, at the Iquique coastal sea level station, the arrival of the first fluctuation was measured at 11:21 LT, about 37 minutes after the first peak recorded at the DART.

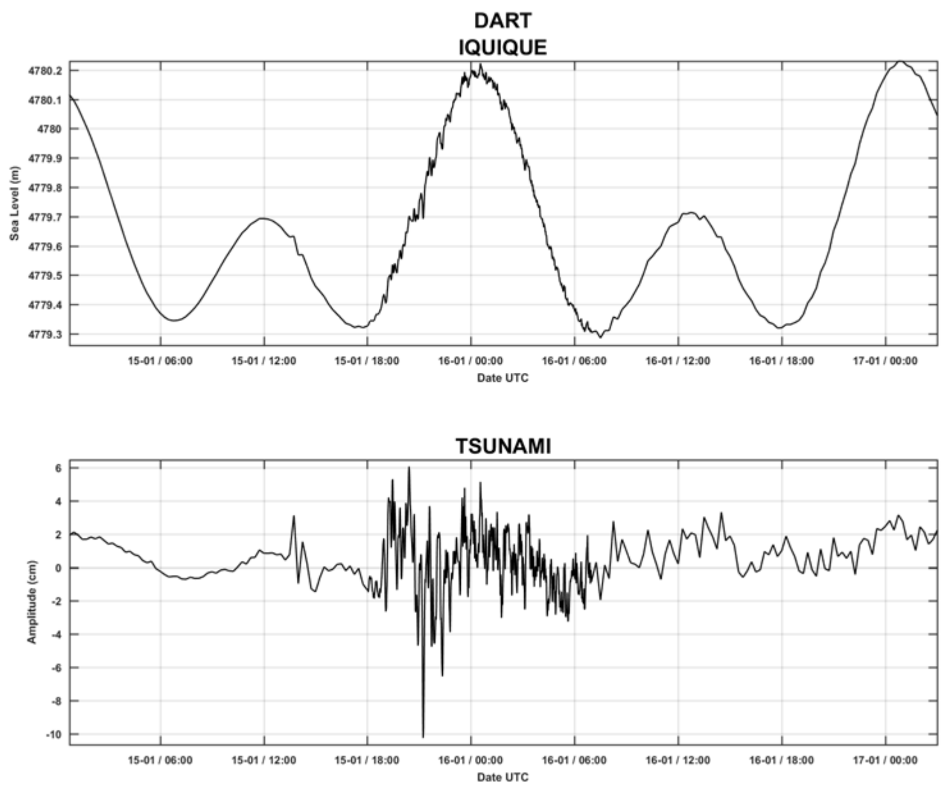

Figure 16.Record of the tsunami at the Iquique DART system (Source: SHOA, 2022)

3.2 Comparative analysis of the tsunami

As a reference, a brief comparative analysis was made of the tsunami signals recorded along the Chilean coast for the Kermadec Islands - New Zealand event, which occurred on 4 March 2021, with the signals recorded for the Tonga event of 2022. Although they are totally different events given the tsunami generation process, the location of both sources is associated with the Tonga-Kermadec subduction zone and they are separated at an estimated distance of 1029 km, so the directivity of the tsunami is not very different from that of the Tonga event, so the wave directivity of the tsunami waves generated by the 8.1 Mw earthquake is comparable to the waves produced by the eruption of the HTHH volcano. Accordingly, and considering the distance of generation of the tsunami with respect to the coasts of Chile, it is feasible to make a general comparison of the arrival times of the long tsunami waves that propagate through the Pacific Ocean, for both cases, since they can be approximated to a point source.

In this regard, for the Kermadec Islands event, it was observed that the tsunami waves arrived at the stations between 10 and 126 minutes after the event predicted by the TTT. Thus, at 11% of the stations, the time lag was in the range from 0 to 15 minutes, in 43% the time lag was in the range from 30 to 60 minutes after the time estimated by the TTT (Figure 17). In addition, it was observed that the time difference regarding the TTT forecast did not present a latitudinal pattern with respect to the location of the stations that could directly explain it. In the case of the Tonga event, there was also a significant time lag between the observed and predicted arrival times, which was in the range from 3 to 126 minutes. However, unlike the Kermadec event, in 83.8% of the cases, the observed arrival time is shorter than predicted, i.e., the tsunami waves were recorded earlier than estimated according to the oceanic long wave theory and there is no latitudinal pattern that can be directly explained by the tsunami directivity. Taking into account what has been observed for both cases, it can be pointed out that the predicted arrival times can present important differences with respect to what has been observed, which can be attributed to various factors, such as the type of tsunami generation source and its respective processes, the location of the source, regional and local bathymetry and coastal configuration, among others, which causes the propagation speed of the waves to be affected and, therefore, the calculation of arrival times is not accurate and causes the time lag examined.

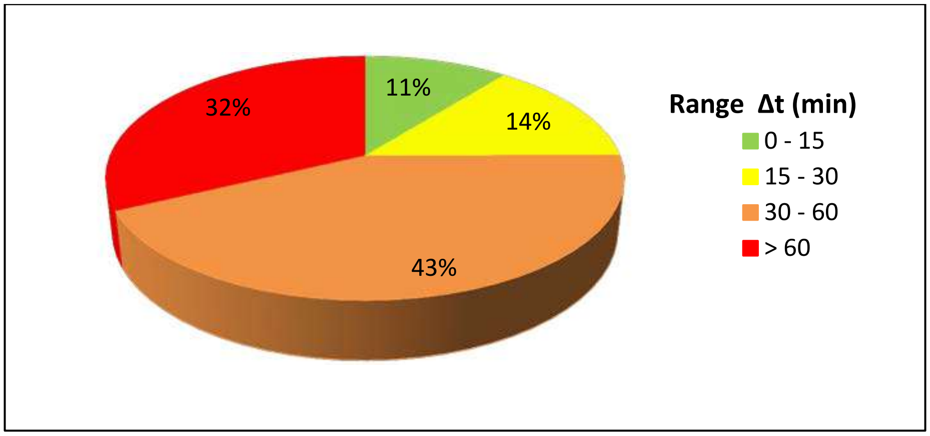

Figure 17. Representation of the percentages of stations with arrival time lags categorized by time lag range for the Kermadec Islands event, 2021.(Source: SHOA, 2021).

On the other hand, for the parameter of maximum amplitudes recorded for the Kermadec tsunami, it was observed that in general terms the amplitude values in most of the stations were within the range of 0.10 m and 0.30 m, being the stations of Bahia Mansa, Chañaral, Caldera and Arica the ones with the highest values, while for the Tonga event the amplitudes were higher, reaching up to almost 2 m at the Chañaral station. Comparatively, for the Tonga event, the stations with the highest amplitude records include those determined for the Kermadec Islands event (Arica, Chañaral, Caldera and Bahia Mansa), but they are not coincident when categorizing and ordering them by amplitude records from highest to lowest (Table 5).

Table 5. Comparative record of maximum amplitudes for the tsunamis of 4 March 4 2021 (Kermadec I.) and 15 January 15 2022 (HTHH, Tonga), taking as reference the stations with the highest tsunami recording level of the Kermadec Islands (Source: SHOA).

Station	Maximum amplitude Kermadec event (m)	Station	Maximum amplitude Tonga event (m)
Bahia Mansa	0,33 (-)	Chañaral	1.96 (+)
Chañaral	0.31 (-)	Arica	1.37 (+)
Caldera	0,24 (+)	Caldera	0.90 (-)
Arica	0.22 (+)	Bahía Mansa	0.72 (+)

The similarity of all the stations analyzed in this comparison, is that in the bays in which the stations are located, resonance phenomena is recorded, which in turn allows the amplification of the waves and by default the maximum amplitudes recorded.

In terms of energy, the tsunami events in the Kermadec Islands and Tonga are not comparable, since they have very different sources of generation, and for the volcanic eruption it is not feasible to establish an effective energy transfer ratio into the water column to cause the deformation that propagated through the ocean. For seismic events, this relationship is established by determining the fault rupture parameters, through the use of the Okada method, which in turn makes it possible to perform the modeling and forecasting for the event. However, if we take as a reference the measurements of tsunamis in deep water by the DART systems, the tsunami event generated by a subduction zone earthquake, which has produced tsunami amplitudes at the Iquique DART station, similar to those observed for the tsunami of 15 January 2022 (~ 10 cm), is the massive tsunami of Japan in 2011, for which a maximum amplitude of 11 cm was recorded (Figure 18). Consequently, it could be said that, in terms of energy, the tsunami resulting from the eruption of the HTHH volcano is comparable to the tsunami generated by the 9.1 Mw earthquake in Japan, so it would be possible to make an estimate of the expected effects of the tsunami waves on the coast, but not of the maximum amplitudes or the most affected areas, since the tsunami directivity for the 2011 event is very different from that observed for the Tonga event, so it is not possible to establish a direct relationship of the maximum amplitudes on the coast from the measurements at the DART station.

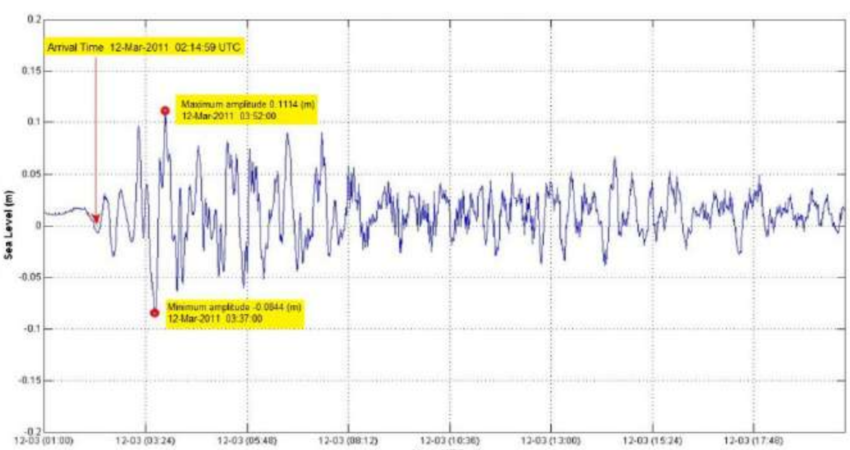

Figure 18. Record of the tsunami in the Iquique DART system for the Japan event on March 11, 2011 (Source: SHOA, 2022).

4. ACTIONS AND BULLETINS ISSUED BY THE SNAM

Due to the eruption of the Hunga Tonga-Hunga Ha'apai volcano on January 15, 2022, at 01:10 LT and subsequent tsunami that spread across the Pacific Ocean and was recorded at sea level stations and DART buoys located in that basin, the corresponding local Tsunami Warning Centers (NTWC), the Pacific Tsunami Warning Center (PTWC) and the National Tsunami Warning System (SNAM), faced the challenge of assessing the tsunami threat to the coastal communities of the different countries of the oceanic basin, based on instrumental monitoring of sea level variations that were recorded as time went by since the eruption.

As of the date of the event, the Pacific Tsunami Warning and Mitigation System (PTWS) did not have Standard Operating Procedures (SOP) for tsunami hazard assessment and issuance of bulletins to the corresponding Warning Centers, for tsunamis other than those produced by earthquakes, particularly those of subduction. Given the above, it was also not possible to have models and forecasts that would allow an adequate estimation of the maximum amplitudes to be expected, as well as a correct calculation of the arrival times of the tsunami waves.
Considering the technical limitations during the emergency, the PTWC decided to issue adapted bulletins based on volcanic eruption information only to the focal points (FP) of each PTWS member country. Because this form of bulletin issuance is not the one officially used, some countries did not receive the information from the PTWC sent to the FPs (bulletins N°1 to N°6) and therefore they did not have background of the event until the PTWC could resume the usual way to send bulletins as of N°7 (Table 6).

In the particular case of Chile, although the bulletins were received by the FP, they needed to be retransmitted to the SNAM Operations Room and, as a consequence, SNAM received the information with a slight delay.

SNAM began monitoring the event around 02:30 HL, observing the tsunami propagation process through the stations and DART systems located in the Pacific basin. SNAM started monitoring the event around 02:30 LT, the tsunami propagation process was observed at the DART stations and systems located in the Pacific basin. With this information, plus the evaluation of the amplitudes recorded at the stations of Hawaii (0.43 m) and

Rikitea (0.40 m) in French Polynesia, and with a distance of about 2.600 km from Easter Island, the preparation of the first SNAM bulletin was established since, considering expert criterion, it was very probable that tsunami waves could initially arrive on Easter Island with amplitudes similar to or greater than those observed, which implied the establishment of Advisory status for that territory in view of the tsunami threat. At the same time, around 10:16 LT, PTWC bulletin No. 4 was received, indicating that a larger area could be affected by tsunami waves and confirming the coasts of Chile and Antarctica, so we proceeded to supplement and issue the first Threat to Chile bulletin, indicating a Caution status for Easter Island, Juan Fernandez Archipelago, San Felix Island and Chilean Antarctica.

The SNAM bulletin N°1 was issued at 10:27 LT, considering a referential magnitude of 1.0, and taking into consideration the PTWC bulletins and that the tsunami generated was not due to a seismic event. Immediately after the issuance of this Threat bulletin, bulletin No. 2 was issued with Arrival Times for the locations with the Advisory status. The estimated arrival times for these locations were for Easter Island at 10:43 LT, Juan Fernandez at 14:12 LT and San Félix Island at 14:38 LT, and for the Prat Base at 14:26 LT and the O'Higgins Base at 14:56 LT, both in Chilean Antarctica.
The tsunami started to arrive in the coast of Chile at 10:49 LT on Easter Island, with an amplitude of 0.3 m corresponding to a minor tsunami. Subsequently, it continued to propagate and was recorded by four DART systems and 40 sea level stations.

Once the arrival of the tsunami was confirmed, SNAM continued monitoring until the threat to the coasts of the country was over, which was about 14 hours after the first bulletin was issued. SNAM issued a total of 45 bulletins, which included information on tsunami Threat status, Arrival times, Maximum amplitude record, Partial cancellation and Total cancellation (Table 7). Bulletin N° 45 was issued at 14:29 LT, on January 16, 2022.

Based on the information sent by SNAM and in accordance with the ONEMI-SHOA protocol in force, ONEMI proceeded to inform the Civil Protection System of the Warning status for the regions of Arica and Parinacota, Tarapaca, Atacama, Coquimbo, Los Rios and Los Lagos; as well as the Advisory status for the regions of Antofagasta, Valparaiso, O'Higgins, Maule, Ñuble, Biobio and La Araucania, in addition to the Antarctic and insular territory.

Considering this background, ONEMI declared a Red Alert for the coastal sectors of the regions of Arica and Parinacota, Tarapaca, Atacama, Coquimbo, Los Rios and Los Lagos; 24 messages were also issued from the Emergency Alert System (SAE) platform, directed to the affected areas, and in accordance with the threat states determined by the SNAM, in order to support the abandonment and evacuation processes.

Thanks to the actions taken by the Disaster Prevention and Response System and how responsible was the population in complying with the instructions of the authorities, there were no casualties to report as a result of this emergency. The effects of the tsunami waves reported for the coasts of Chile were very specific and related, for example, to people isolated in Biobío, in the Coliumo area, an artisanal dock affected in Isla Rey, near Valdivia, as well as minor flooding in wetlands of Tongoy, in Coquimbo, and some summer visitors affected while staying in the north of the country.

Figure 19. Tsunami assessment and monitoring in the SNAM Operations Room (Source: SHOA, 2022).

Figure 20.Monitoring at the SNAM Operations Room of the tsunami recorded at sea level stations (Source: SHOA, 2022).

Figure 21. Media monitoring at SNAM Information Room (Source: SHOA, 2022).

Figure 22. Part of the staff on watch at the SNAM Operations Room during the 15 January 2022 event (Source: SHOA, 2022).

Figure 23. Evacuation in the coast of Viña del Mar, Chile, after the preventive tsunami warning due to the eruption of the Tonga volcano (Source: Infobae.com: REUTERS/Rodrigo Garrido, 2022).

Figure 24. Empty beach after the mass evacuation of the coast in La Serena, Chile, after the tsunami threat warning (Source: Infobae.com: REUTERS/Rodrigo Garrido, 2022)

Table 6. Summary of actions and bulletins issued by the PTWC for the tsunami event of 15 January 2022 (Source: SHOA).

DATE	UTC TIME	ACTIONS AND BULLETINS
15-01-2022	06:23	PTWC issued Tsunami Threat bulletin N° 1 for the coasts of Tonga, Niue, Fiji, Wallis and Futuna, American Samoa, Samoa and Kermadec Island. Arrival times were included.
15-01-2022	07:20	PTWC issued Tsunami Threat bulletin N° 2 for the coasts of Tokelau, Cook Island, Vanuatu, Tuvalu, New Zealand, Kiribati, Howland and Baker, New Caledonia, French Polynesia, Nauru, Marshall Island, Solomon Island, Palmyra Island, Kosrae, Johnston Island and Papua New Guinea. Arrival times were included.
15-01-2022	08:52	PTWC issued bulletin N° 3 amplifying the Tsunami Threat for the coasts of Australia, Pitcairn, Pohnpei and Wake Island. Arrival times were included
15-01-2022	12:46	PTWC issued bulletin N° 4 expanding the Tsunami Threat for the coasts of Antarctica, Chuuk, Minamitorishima, Indonesia, Yap, Chile, Japan, Palau, Russia, the Philippines and Mexico. Tsunami arrival times and observations were included.
15-01-2022	14:32	PTWC issued bulletin N° 5 expanding the Tsunami Threat to the coast of Taiwan. Tsunami arrival times and observations were included.
15-01-2022	16:45	PTWC issued bulletin N° 6 expanding the Tsunami Threat for the coasts of the Republic of Korea, Ecuador, Costa Rica, China, Guatemala, El Salvador, Peru, Vietnam, Malaysia, Nicaragua, Panama and Honduras. Tsunami arrival times and observations were included.
15-01-2022	20:06	PTWC issued bulletin N° 7 expanding the Tsunami Threat for the coasts of Colombia and Brunei. Arrival times and observed tsunami were included.
15-01-2022	21:46	PTWC issued bulletin N° 8 amplifying the Tsunami Threat to the Northwest coast of Hawaii, Midway Island. Tsunami arrival times and observations were included.
15-01-2022	23:11	PTWC issued bulletin N°9 indicating Tsunami Threat for the coasts of Antarctica, Chile, Japan, Russia, Mexico, Ecuador, Costa Rica, Guatemala, El Salvador, Peru, Nicaragua, Panama, Honduras and Colombia. Tsunami observations were included.
16-01-2022	00:43	PTWC issued bulletin N° 10 indicating Tsunami Threat for the coasts of Chile, Japan and Peru. Tsunami observations were included.
16-01-2022	01:45	PTWC issued bulletin N° 11 maintaining the status of Tsunami Threat for the coasts of Chile, Japan and Peru. Tsunami observations were included.
16-01-2022	02:46	PTWC issued final bulletin N° 12 indicating that the Tsunami Threat from the volcanic eruption has passed. Authorities must maintain monitoring and minor fluctuations in sea level may continue in the following hours. Tsunami observations were included.

Table 7. Summary of actions and bulletins issued by the SNAM for the tsunami event of 15 January 2022 (Source: SHOA).

DATE	LOCAL TIME	ACTIONS AND BULLETINS
15-01-2022	01:27	Eruption of the Tonga volcano.
15-01-2022	10:27	SNAM issued Tsunami Threat bulletin N° 1 indicating an Advisory status for Juan Fernandez, San Felix Island, Easter Island and Chilean Antarctica.
15-01-2022	10:34	SNAM issued Tsunami Threat bulletin N° 2 with arrival times for sea level stations of the places informed.
15-01-2022	11:31	SNAM issued bulletin N° 3 indicating a tsunami amplitude recorded on Easter Island of 0.3 m
15-01-2022	12:54	SNAM issued bulletin N° 4 indicating a tsunami amplitude recorded on Easter Island of 0.3 m.
15-01-2022	14:00	SNAM issued bulletin N° 5, indicating a tsunami amplitude recorded on Easter Island of 0.6 m.
15-01-2022	14:28	SNAM issued bulletin N° 6 expanding the Tsunami Threat for Arica y Parinacota and Coquimbo, indicating Advisory status.
15-01-2022	14:35	SNAM issued bulletin N° 7, indicating a tsunami amplitudes recorded on : 0.4 m Arica, 0.6 m Isla de Pascua and 0.3 m Coquimbo.
15-01-2022	15:08	SNAM issued bulletin N° 8 expanding the Tsunami Threat for Ñuble-Bíobío, Araucanía, Los Rios, Los Lagos Norte and Los Lagos Sur, indicating Advisory status.
15-01-2022	15:38	SNAM issued bulletin N° 9, indicating a new tsunami amplitudes recorded: 0.5 m Punta de Choros, 0.5 m Coquimbo, 0.4 m Pichidangui, 0.7 m Coliumo, 0.4 m Lebu, 0.3 m Corral and 0.5 m Bahía Mansa.
15-01-2022	15:47	SNAM issued Tsunami Threat bulletin N° 10 indicating an new Advisory status for O'Higgins.
15-01-2022	16:05	SNAM issued Tsunami Threat bulletin N° 11 indicating an new Advisory status for a Atacama Norte and Valparaíso.
15-01-2022	16:20	SNAM issued bulletin N° 12, indicating a new tsunami amplitudes recorded : 0.4 m Caldera, 0.4 m Puerto Aldea, 0.7 m Pichidangui, 0.6 m Quintero, 0.5 m San Antonio, 0.5 m Boyeruca and 0.3 m Base Prat.
15-01-2022	17:04	SNAM issued Tsunami Threat bulletin N° 14 indicating a new Advisory status for Tarapaca and Atacama Sur; and a Tsunami Warning for Coquimbo.
15-01-2022	17:13	SNAM issued bulletin N° 15 updating and indicating a new reported tsunami amplitudes.
15-01-2022	17:36	SNAM issued Tsunami Threat bulletin N° 16 indicating a new

		Tsunami Warning status for Los Lagos Norte.
15-01-2022	18:22	SNAM issued Tsunami Threat bulletin N° 17 indicating a new Tsunami Warning status for Atacama Norte
15-01-2022	18:40	SNAM issued bulletin N° 18 updating and indicating new reported tsunami amplitudes.
15-01-2022	19:36	SNAM issued Tsunami Threat bulletin N° 19 indicating a new Tsunami Warning status for Arica and Parinacota and for Tarapaca.
15-01-2022	19:55	SNAM issued bulletin N° 20 updating and indicating new reported tsunami amplitudes.
15-01-2022	20:46	Bulletin N° 21 of the SNAM was issued, indicating a reduction in the status of Warning to Advisory for Los Lagos Norte.
15-01-2022	21:14	SNAM issued bulletin N° 22 indicating Partial Cancellation for Chilean Antarctica.
15-01-2022	21:29	Bulletin N° 23 of the SNAM was issued, indicating a reduction in the status of Warning to Advisory for Tarapaca and Los Rios.
15-01-2022	22:35	SNAM bulletin N° 24 was issued, indicating that the threat levels of bulletin N° 23 are maintained.
15-01-2022	22:44	Bulletin N° 25 of the SNAM was issued, indicating a reduction in the status of Warning to Advisory for Coquimbo.
15-01-2022	23:07	Bulletin N° 26 of the SNAM was issued, indicating a reduction in the status of Warning to Advisory for Atacama Norte.
15-01-2022	23:40	Bulletin N° 27 of the SNAM was issued, indicating a reduction in the status of Warning to Advisory for Arica and Parinacota.
16-01-2022	00:28	SNAM issued bulletin N° 28 indicating Partial Cancellation for Juan Fernandez, San Felix Island and Easter Island.
16-01-2022	00:58	SNAM issued bulletin N° 29 indicating Partial Cancellation for Atacama Sur and Los Lagos Sur.
16-01-2022	01:33	SNAM issued bulletin N° 30 indicating Partial Cancellation for a Maule and Araucanía.
16-01-2022	02:12	SNAM issued bulletin N° 31 indicating Partial Cancellation for O'Higgins and Los Ríos.
16-01-2022	02:53	SNAM issued bulletin N° 32 indicating Partial Cancellation for Antofagasta Sur.
16-01-2022	03:27	Se emitió boletín N° 33 del SNAM, indicando Cancelación Parcial para Tarapacá.
16-01-2022	04:04	SNAM issued bulletin N° 34 indicating Partial Cancellation for Antofagasta Norte and Los Lagos Norte.
16-01-2022	05:16	SNAM issued bulletin N° 35 indicating Partial Cancellation for Valparaíso.
16-01-2022	06:19	SNAM bulletin N° 36 was issued, indicating that the threat levels of bulletin N° 35 are maintained.
16-01-2022	07:19	SNAM bulletin N° 37 was issued, indicating that the threat levels of bulletin N° 36 are maintained.

16-01-2022	08:20	SNAM bulletin N° 38 was issued, indicating that the threat levels of bulletin N° 37 are maintained.
16-01-2022	09:39	SNAM bulletin N° 39 was issued, indicating that the threat levels of bulletin N° 38 are maintained.
16-01-2022	10:24	SNAM issued bulletin N° 40 indicating Partial Cancellation for Arica and Parinacota.
16-01-2022	11:21	SNAM bulletin N° 41 was issued, indicating that the threat levels of bulletin N° 40 are maintained.
16-01-2022	12:11	SNAM issued bulletin N° 42 indicating Partial Cancellation for Coquimbo.
16-01-2022	13:16	SNAM bulletin N° 43 was issued, indicating that the threat levels of bulletin N° 42 are maintained.
16-01-2022	13:33	SNAM issued bulletin N° 44 indicating Partial Cancellation for Atacama Norte.
16-01-2022	14:29	SNAM issued bulletin N° 45 indicating Total Cancellation of the Tsunami Warning status for the coasts of Chile resulting from the Tonga volcanic eruption.

5. CONCLUSIONS

- For the eruption of the Hunga Tonga-Hunga Ha'apai volcano on January 15, 2022, the scientific community agrees in saying that it is not clear whether this was the climax of the eruptive process and represents a major release of magma pressure, which may settle the system, as many aspects remain unclear and, hence, great volcanic upheaval could be expected within several weeks or years. Therefore, it is not feasible to predict the characteristics of a possible new eruption and whether it could generate a new tsunami.

- From the evidence of the geological deposits of previous volcano eruptions, it has been documented that these complex sequences have a recurrence period of 1000 years.

- The source of the tsunami generation caused by the Hunga-Tonga-Hunga-Ha'apai volcano eruption is complex and could be the result of a combination of mechanisms of volcanic origin that includes submarine explosion, pyroclastic flow, submarine landslides, caldera collapse, lava bank collapse, shock waves and atmospheric pressure, among others.

- Tsunami signals recorded at stations of the national network show sea level fluctuations produced by the perturbation of atmospheric pressure waves and tsunami long waves coupled with waves produced by the effects of regional and local bathymetry and reflection processes between the coast and the trench that generate edge waves that propagate along the shelf.

- The atmospheric pressure wave front measured at the stations presented a maximum amplitude value of 2.2 mbar and was recorded sequentially from south to north in the network of stations, showing a clear latitudinal pattern over time. While the fluctuation of the sea level, attributable to this wave front, did not show the same recorded sequential and latitudinal pattern in the arrival time.

- The arrival of the tsunami at the sea level stations occurred in 83% of the cases before the estimated time by the TTT, which can be attributed to factors such as the type and complexity of the tsunami generation source, its location, the regional and local bathymetry and coastal configuration, among others, which causes the propagation speed of the waves to be affected and, therefore, a linear approximation for the calculation of arrival times is not accurate.

- The maximum amplitudes recorded at the stations of the national network were measured in the bays that present the resonance phenomenon, which has been documented for previous tsunamis measured at the same stations and consequently, in case of a new event, it is expected that these bays will again record the maximum amplitudes due to the amplification of the tsunami waves.

- The tsunami record in the 4 DART systems in Chile showed the same pattern, with the presence of an initial fluctuation that could be a consequence of pressure changes caused directly by the volcanic shock wave or that the pressure-forced wave is amplified by the Proudman resonance over the deep ocean basin, to later give way to the tsunami long waves that produced maximum amplitudes.

- The Tonga event is comparable, in terms of energy released into the water column, to the 2011 Japan event and in terms of tsunami directivity to the Kermadec Islands event.

- Tsunami wave behavior is highly modulated at the beginning of the record by the generation source, the submarine topography of the ocean basin through which they propagate, and the regional and local bathymetry, and then influenced by the coupling of waves propagated by local phenomena such as reflection with the trench, local geomorphological configuration and resonance effects.

- The operational procedures used by the National Tsunami Warning System to establish the threat levels for the Chilean coast and insular zones and subsequent monitoring of the event were efficient and the emergency was satisfactorily managed by the National Disaster Prevention and Response System, despite the fact that it was a tsunami event whose generation source is not considered in the protocol.

- The network of sea level stations and DART systems located in the Pacific basin and in the national territory are essential for the efficient management of the far-field tsunami threat and complex non-seismic sources, such as volcanic, due to the impossibility of having real-time forecasts and models that allow to estimate the maximum amplitudes to be expected.

6. RECOMMENDATIONS

- Considering that the event resulting from the eruption of the Hunga Tonga-Hunga Ha'apai volcano is still under study by the international scientific community, the analyses and hypotheses presented in this report should be taken as a reference, given that as more scientific background becomes available, the conclusions can be complemented and the theories presented can be validated.

- In the same way, it is recommended to use the data and tables for reference purposes only, maintaining the interpretations in this report, and not to make forecasts based on this information.

- It is recommended to participate in workshops, seminars or other scientific meetings where results and studies on the Tonga event are presented, in order to gather knowledge and gain a better understanding of the phenomenon and thus work on the implementation of tools and improve procedures that might be useful for decision making in the SNAM in case of a new event with similar characteristics.

- In order to improve communication on the risks to population, it is recommended that during the emergency the dissemination of information be complemented with the meaning of the Threat status issued by the SNAM and the actions to be taken for each of them, especially in social networks through the official institutional accounts.

- Optimize the monitoring process by selecting the sea level stations and DART systems located in the Pacific basin that showed a good record of the event and thus prioritize the process of observing the propagation of the tsunami through the ocean, in case of an event similar to the one in Tonga.

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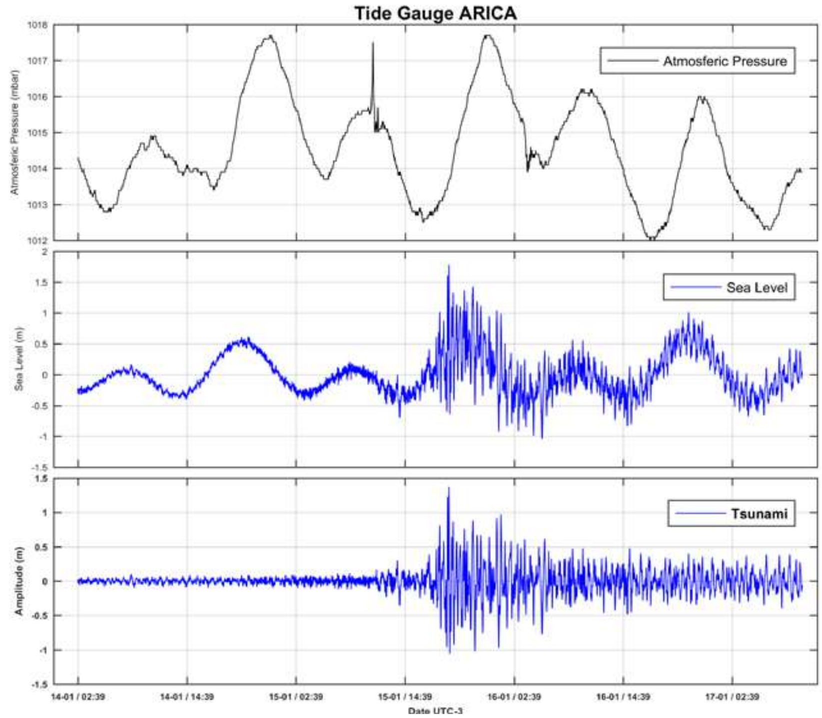
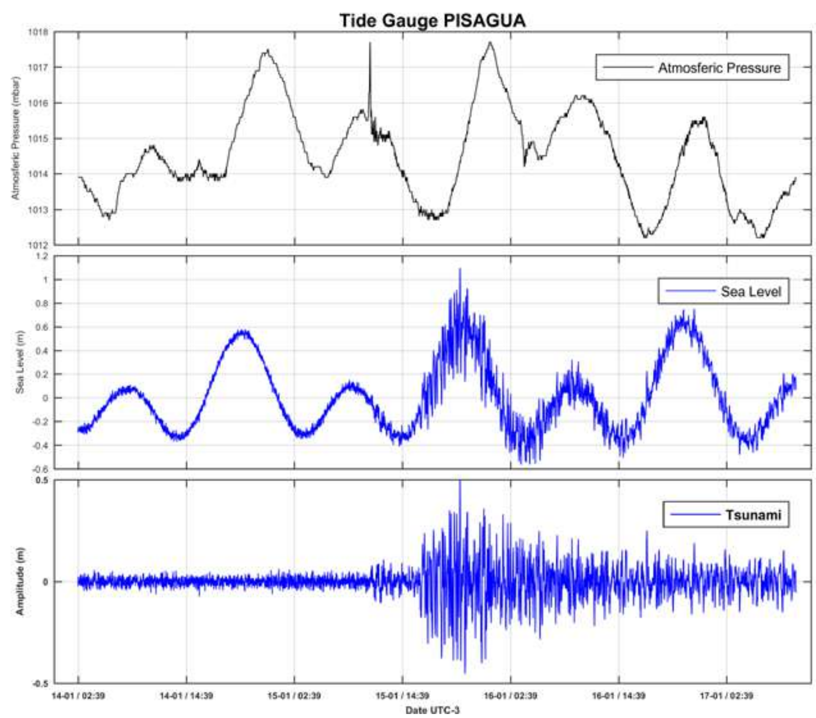
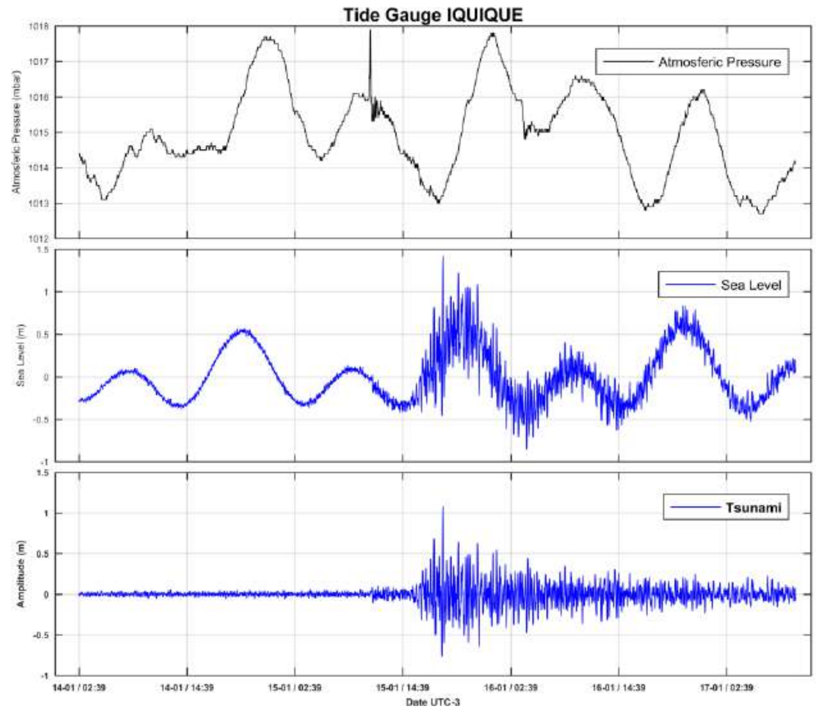
ANNEX "A"

" Tsunami record at Sea Level Stations and Atmospheric Pressure variations"



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Tsunami
Amplitude (m)
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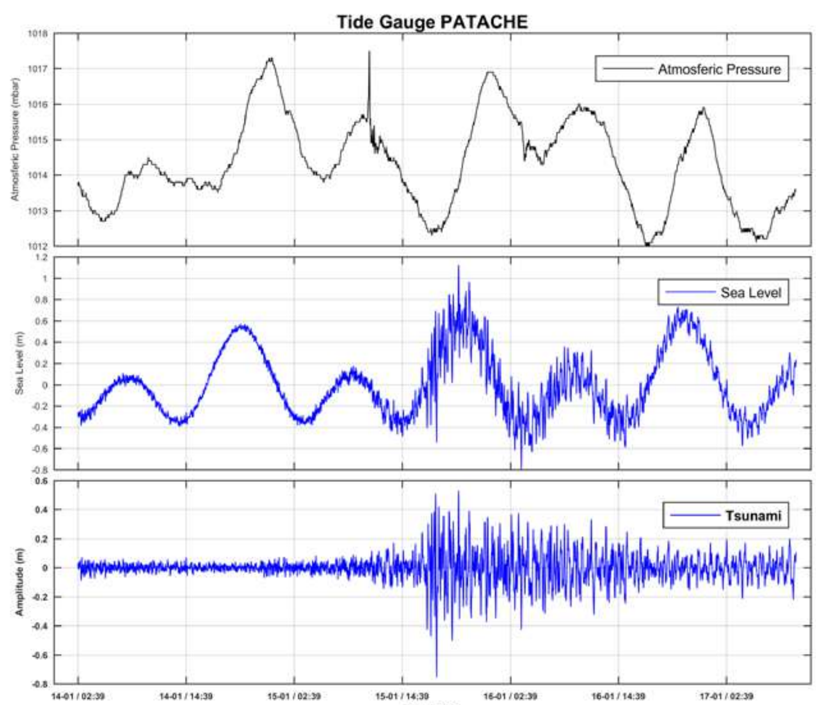
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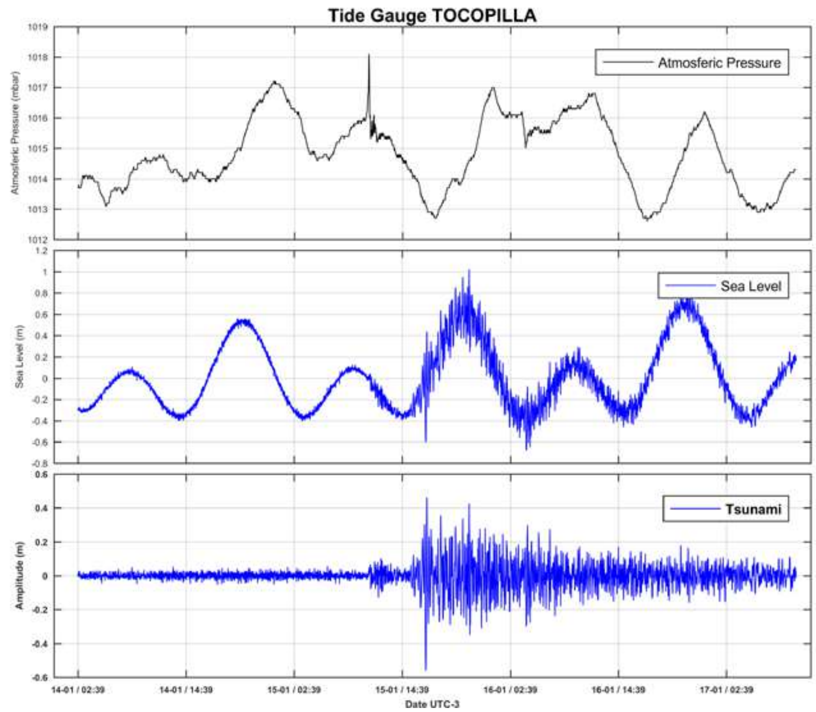
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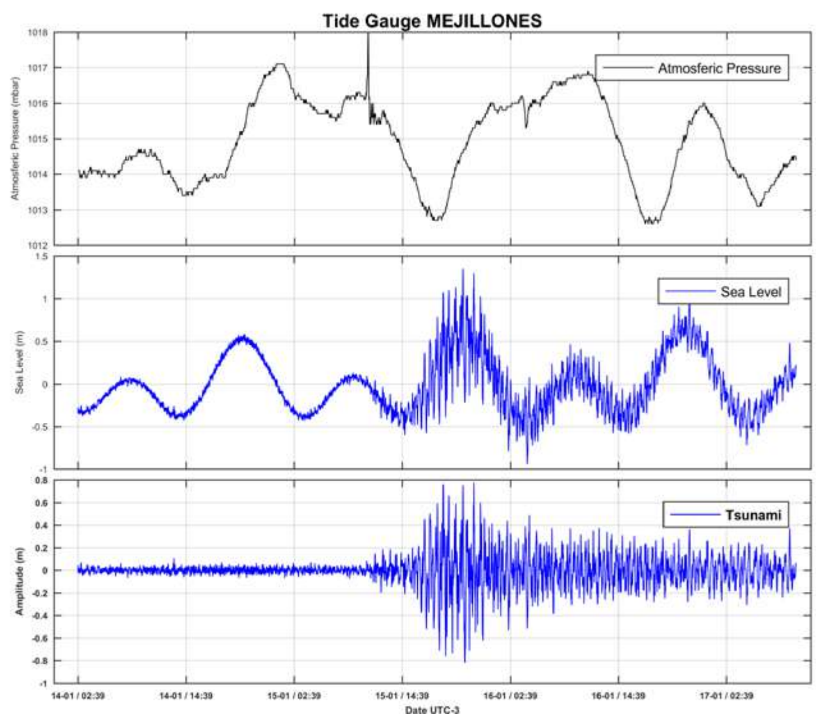
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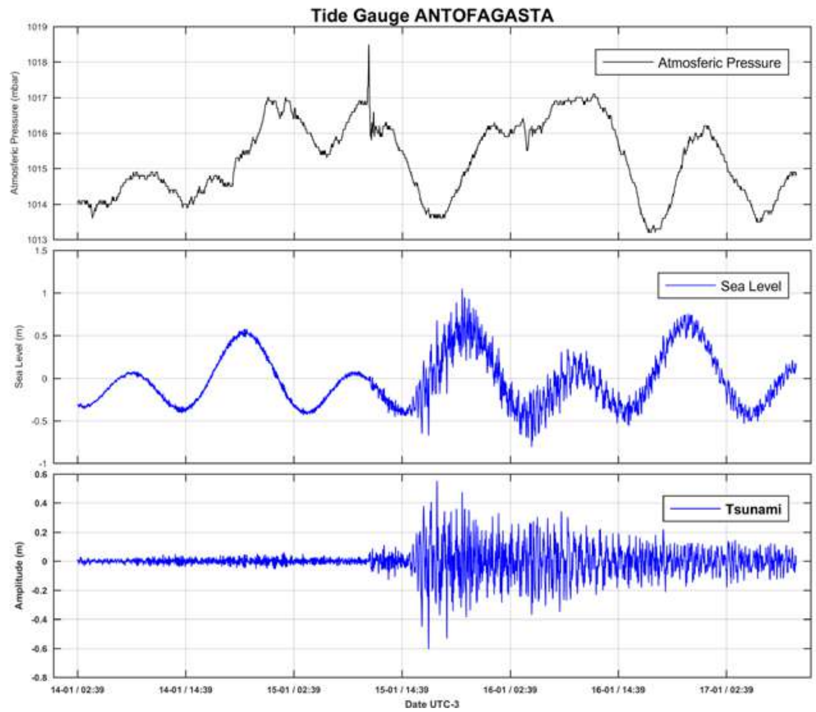
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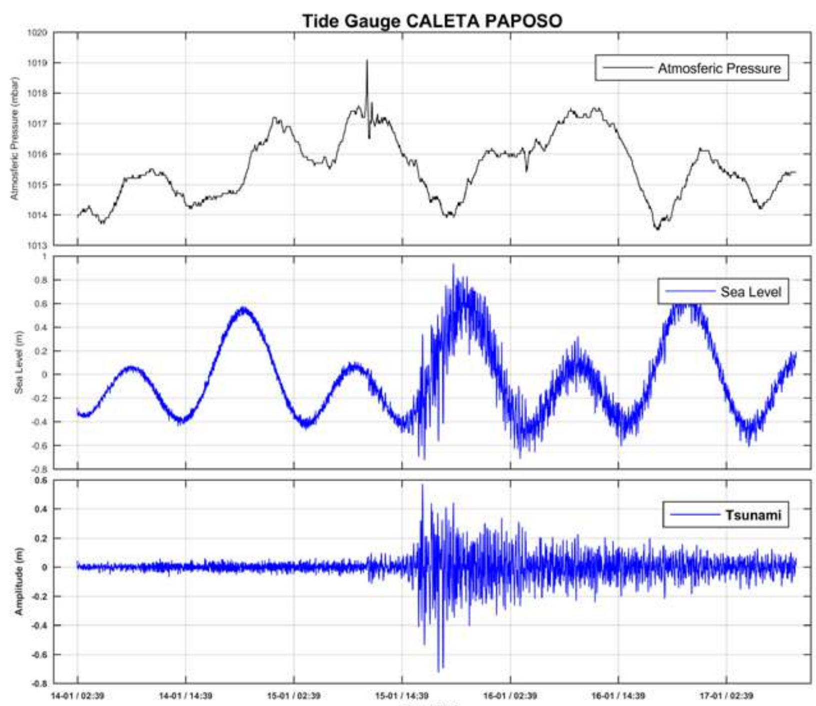
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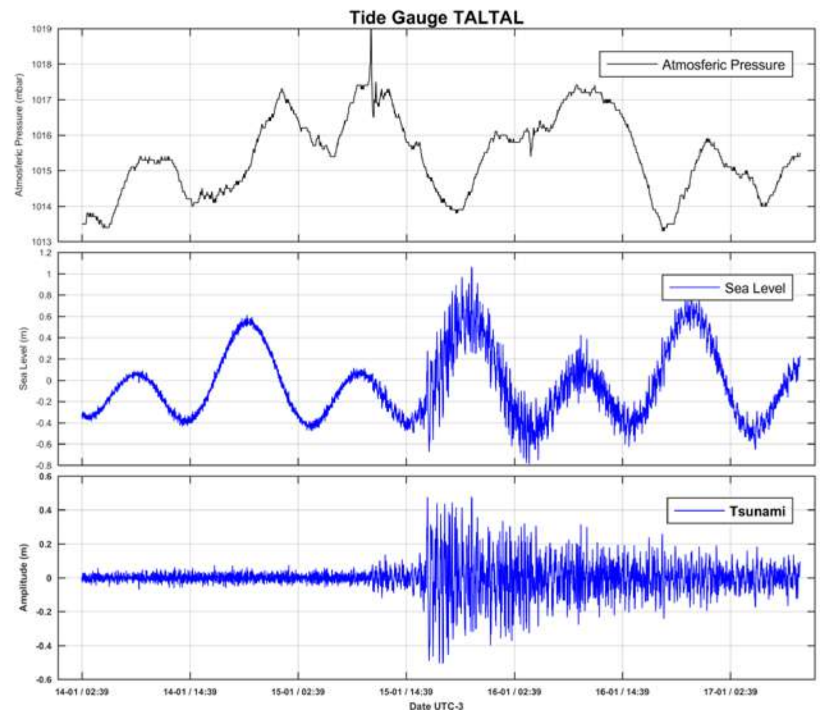
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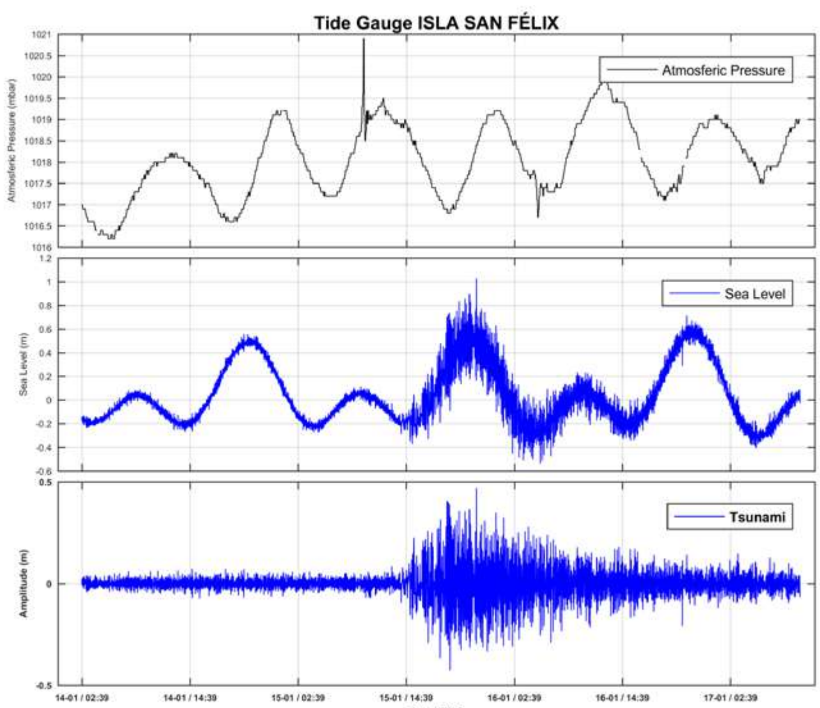
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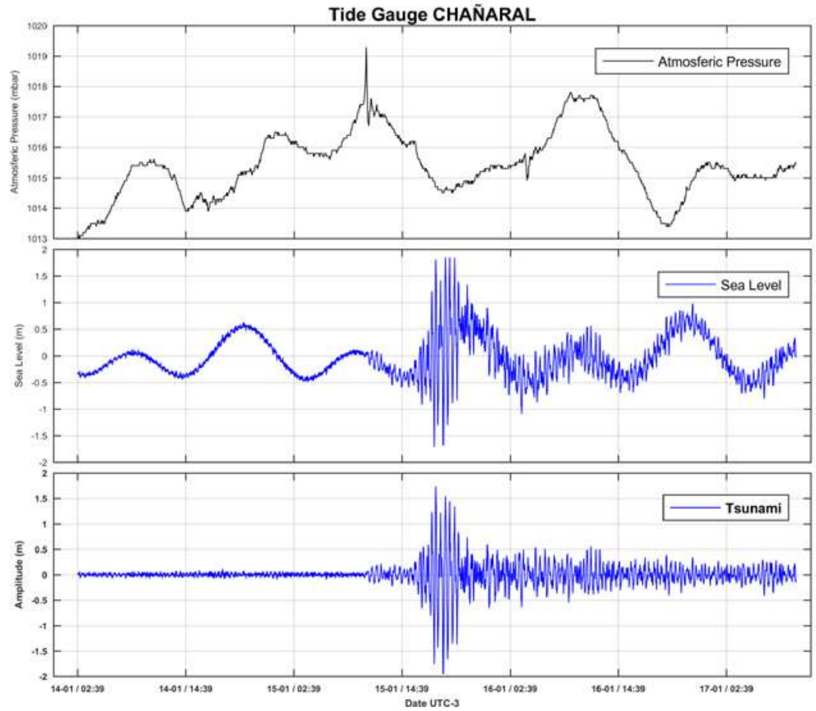
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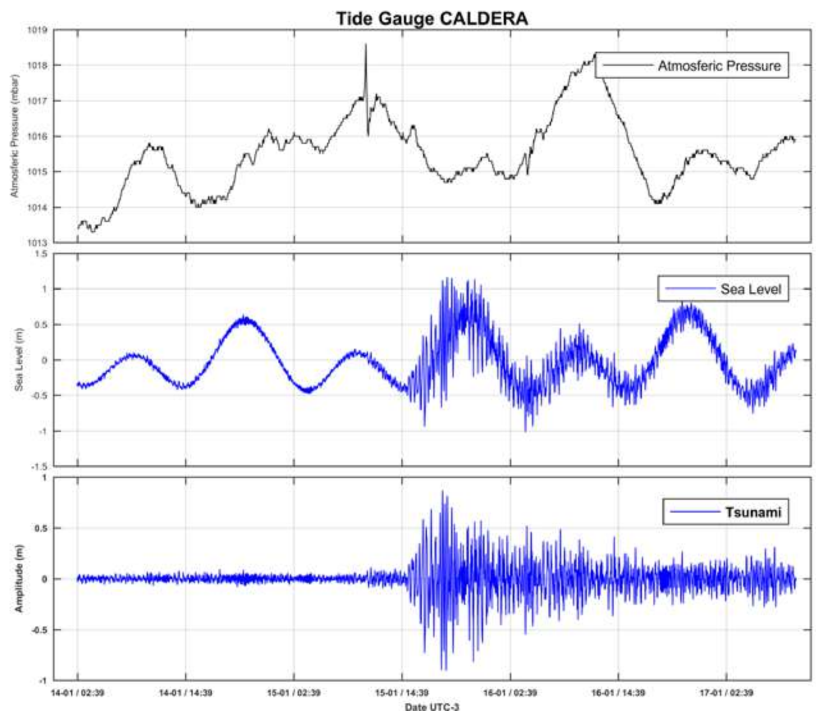
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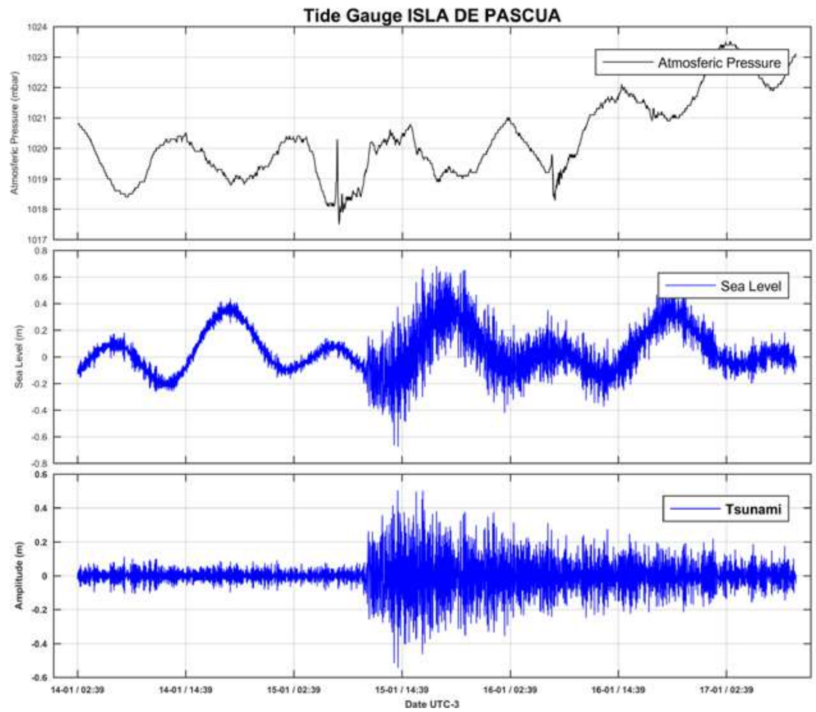
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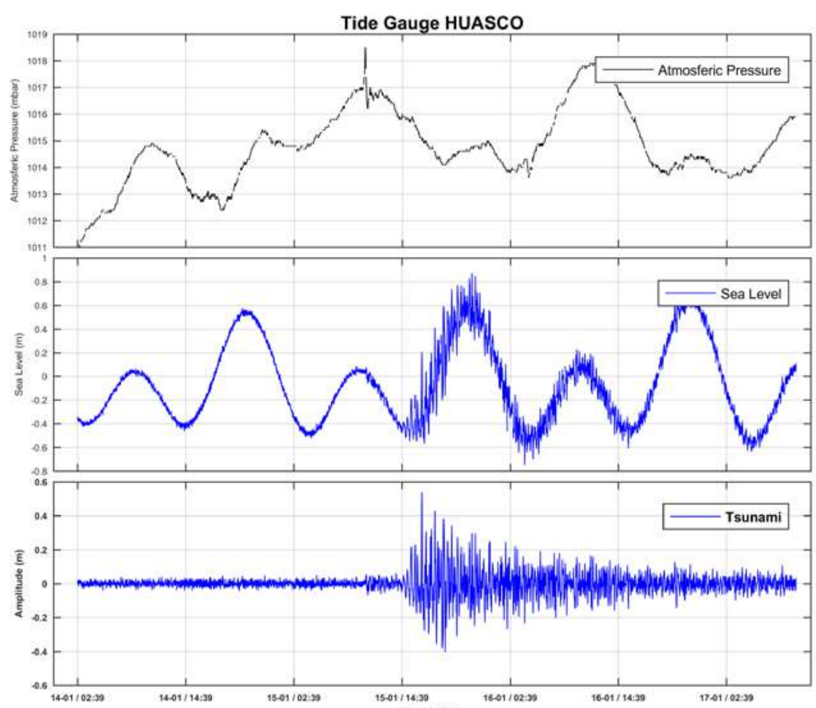
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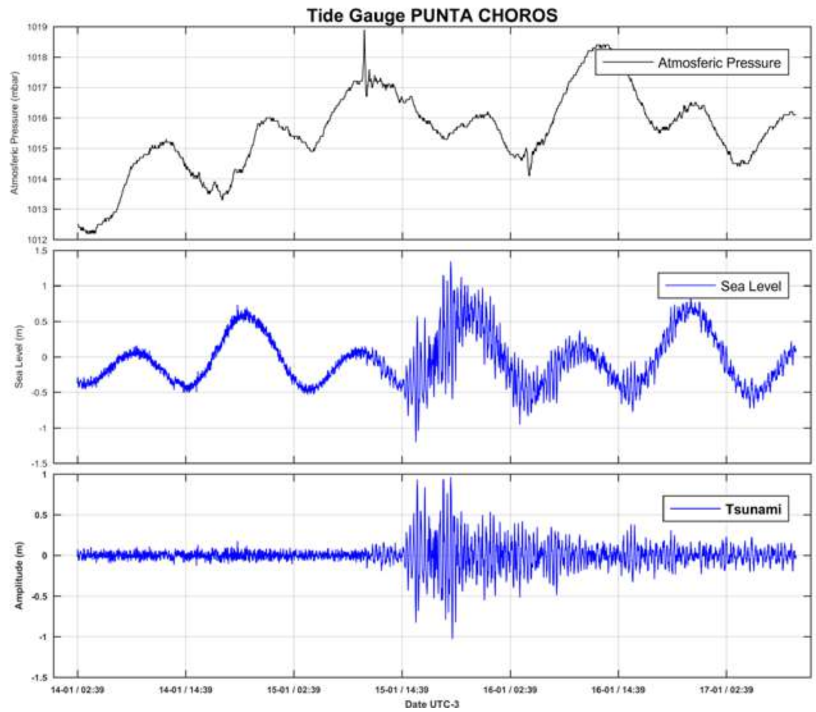
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Tsunami
Amplitude (m)
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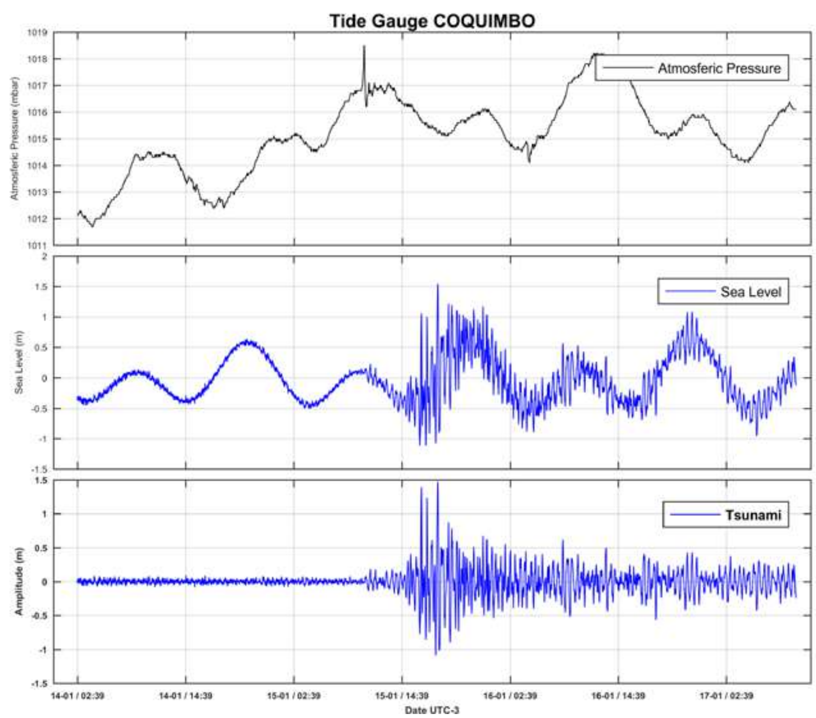
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Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
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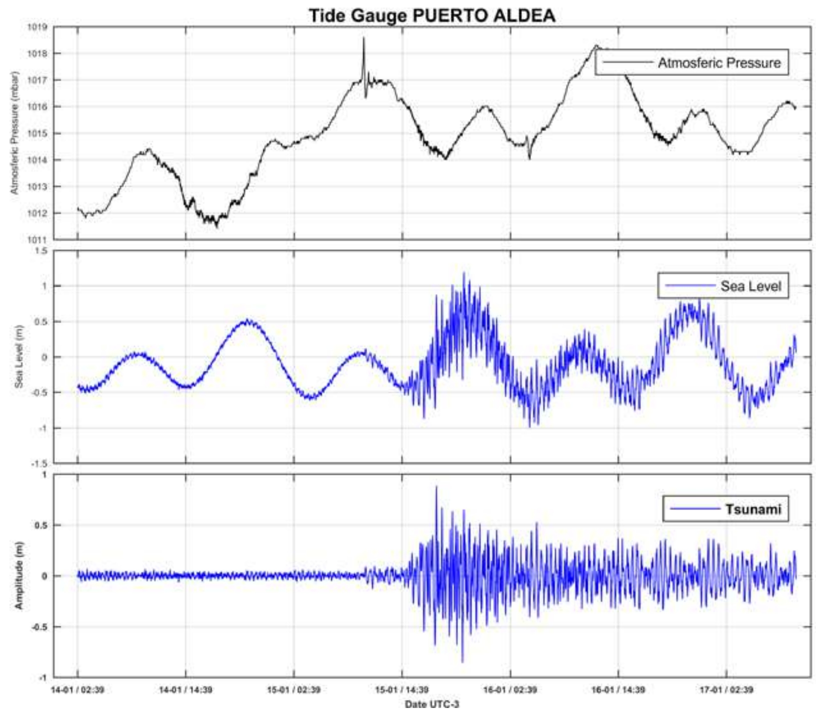
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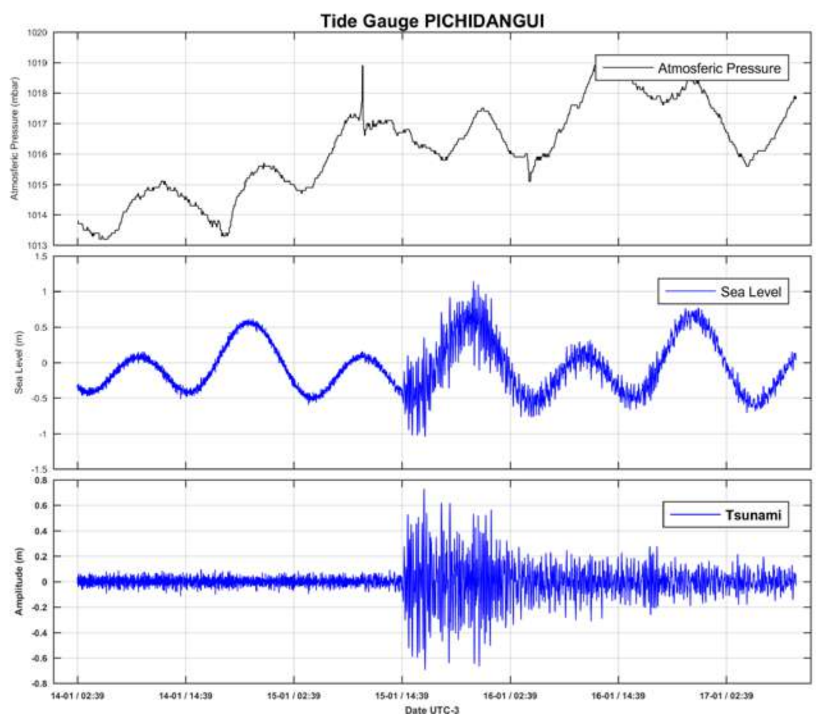
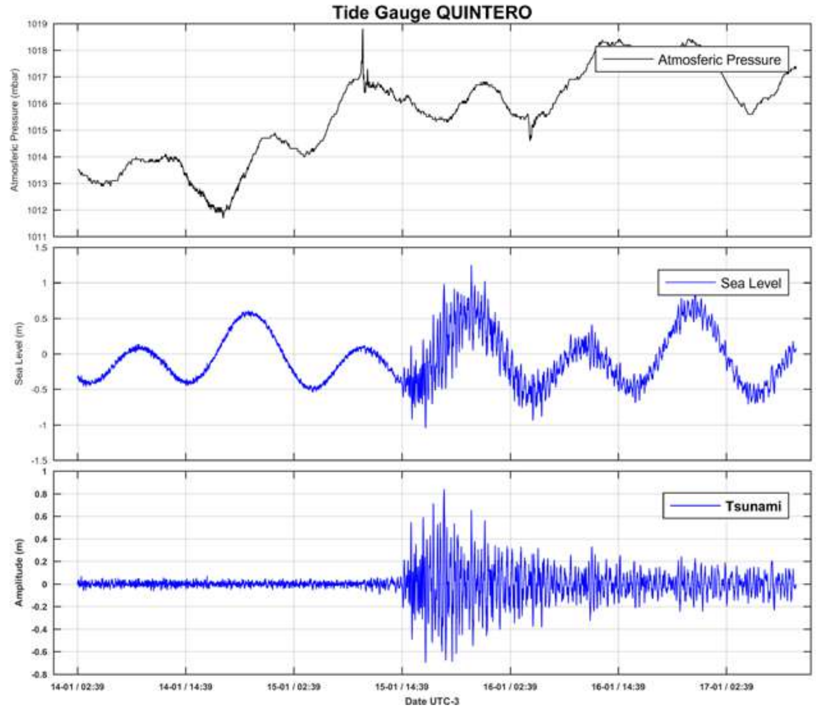
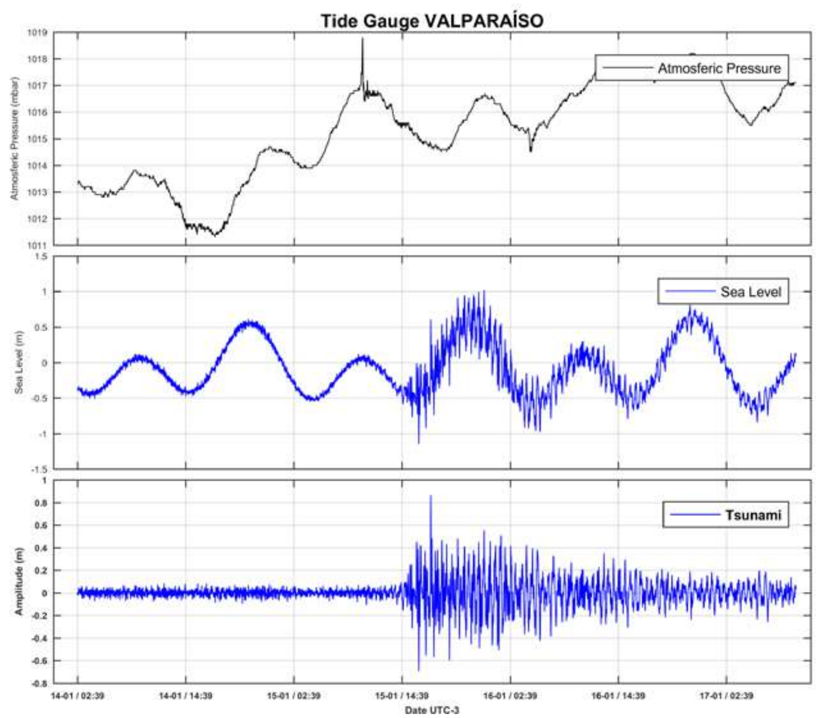
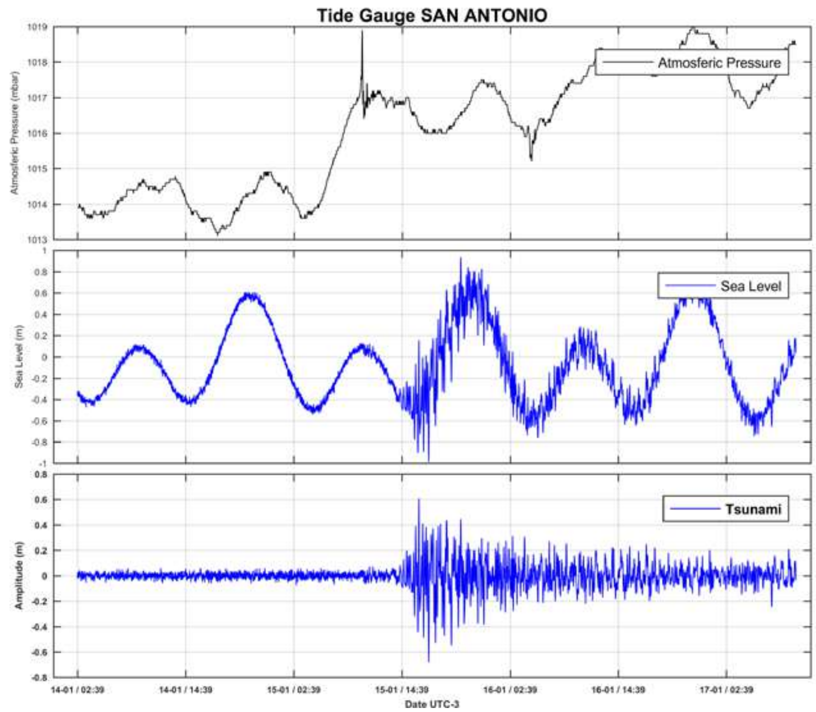
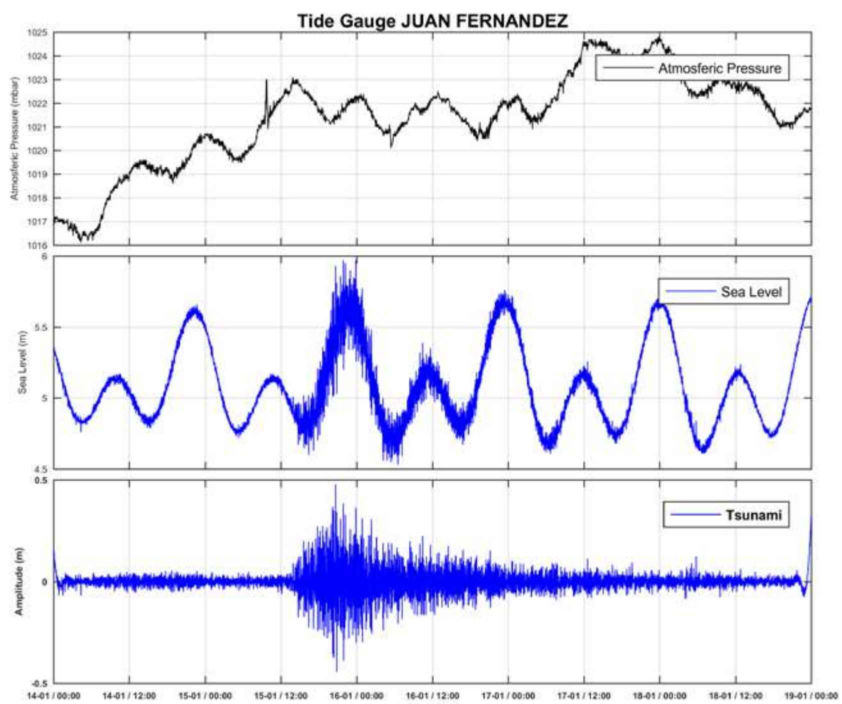
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

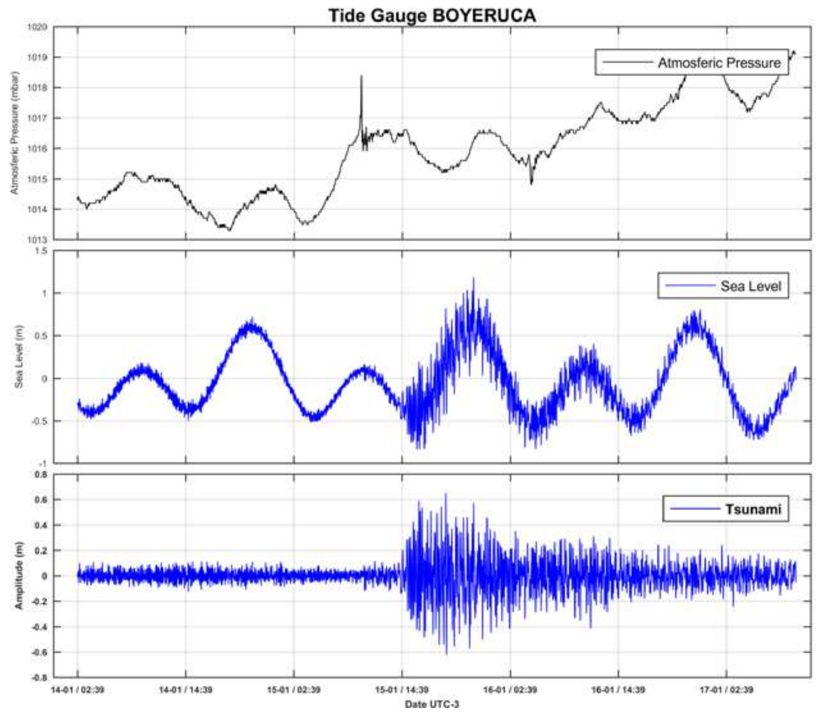

Tide Gauge PICHIDANGUI
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

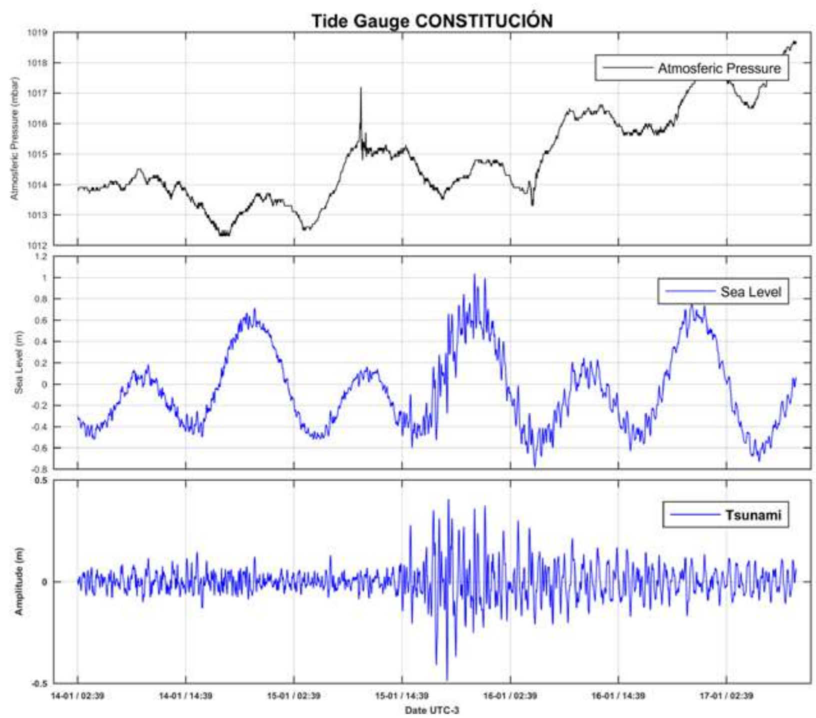

Tide Gauge QUINTERO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

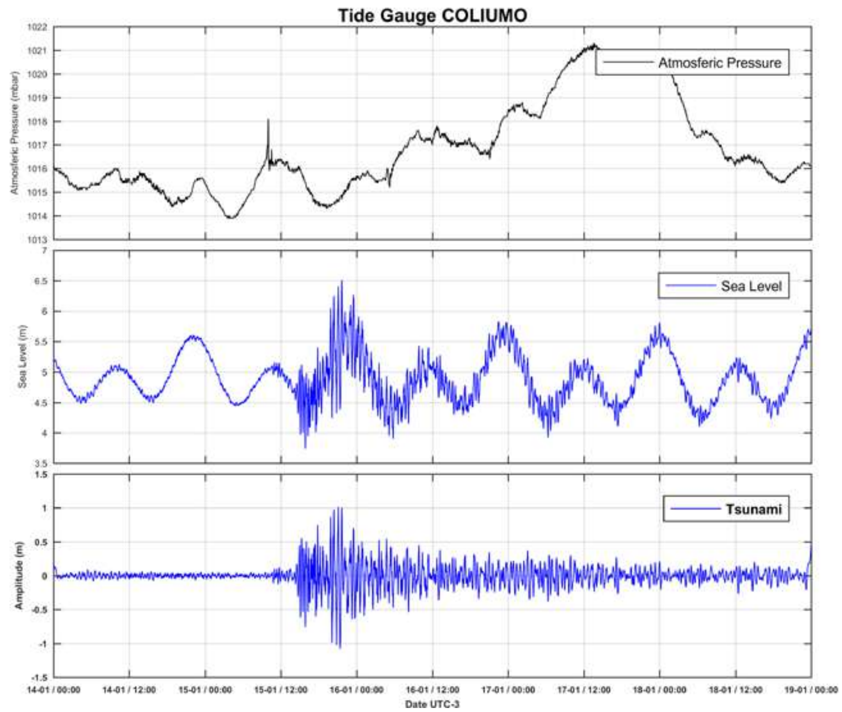

Tide Gauge VALPARAÍSO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

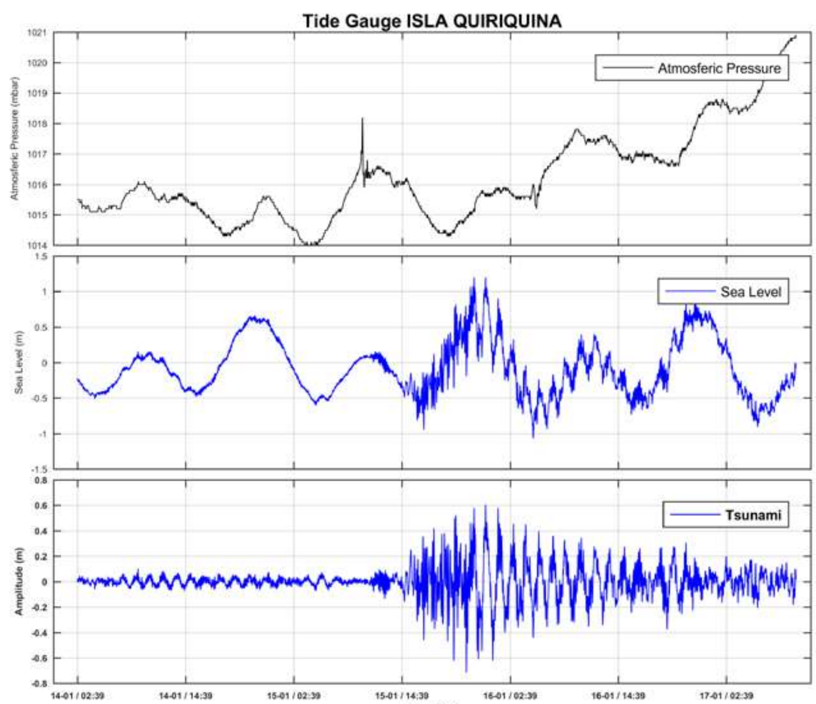

Tide Gauge SAN ANTONIO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

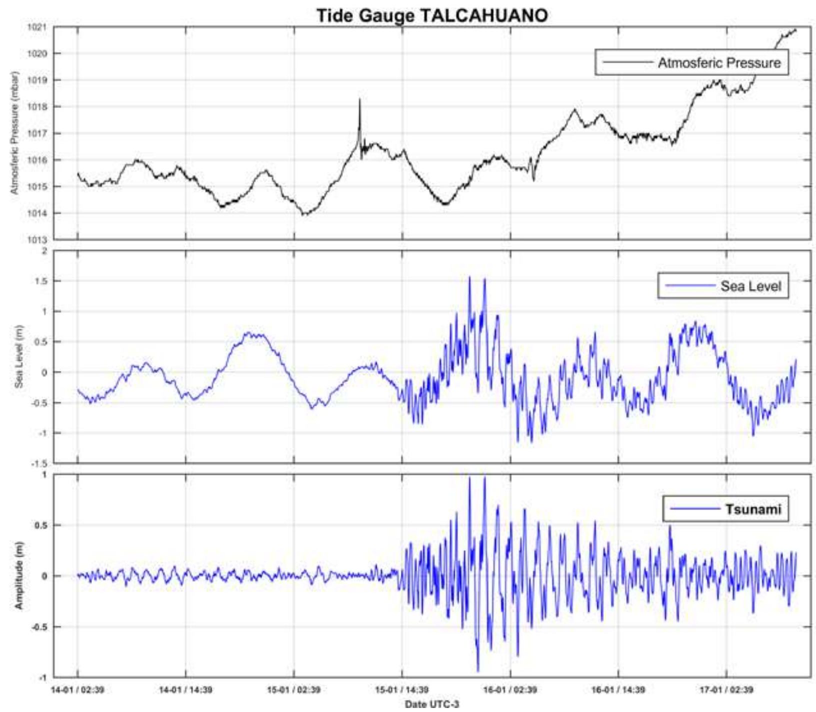

Tide Gauge JUAN FERNANDEZ
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 00:00
14-01 / 12:00
15-01 / 00:00
15-01 / 12:00
16-01 / 00:00
16-01 / 12:00
17-01 / 00:00
17-01 / 12:00
18-01 / 00:00
18-01 / 12:00
19-01 / 00:00
Date UTC-3


Tide Gauge BOYERUCA
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

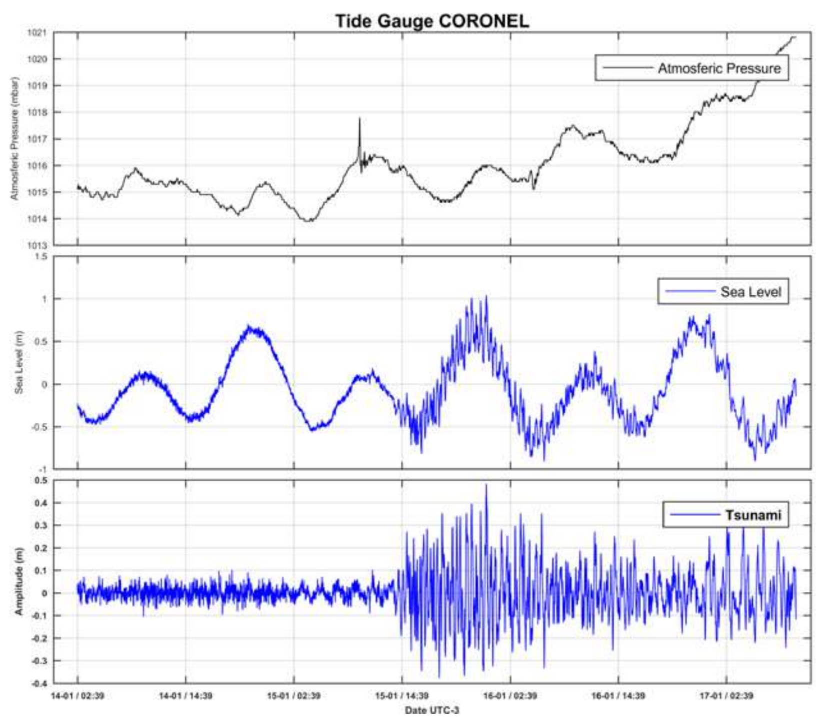

Tide Gauge CONSTITUCIÓN
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3


Tide Gauge COLIUMO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
Date UTC-3

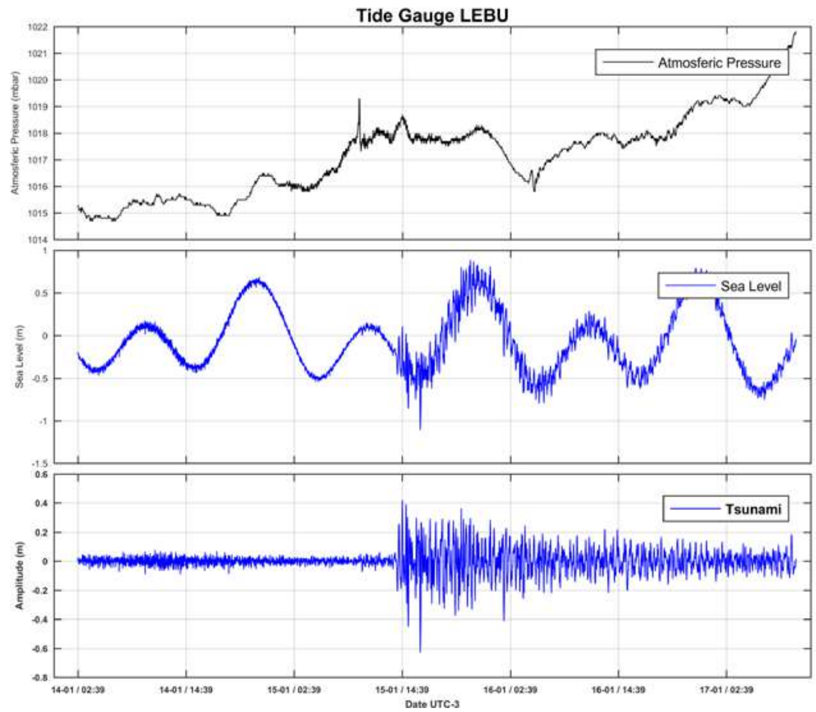

Tide Gauge ISLA QUIRIQUINA
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
Date UTC-3

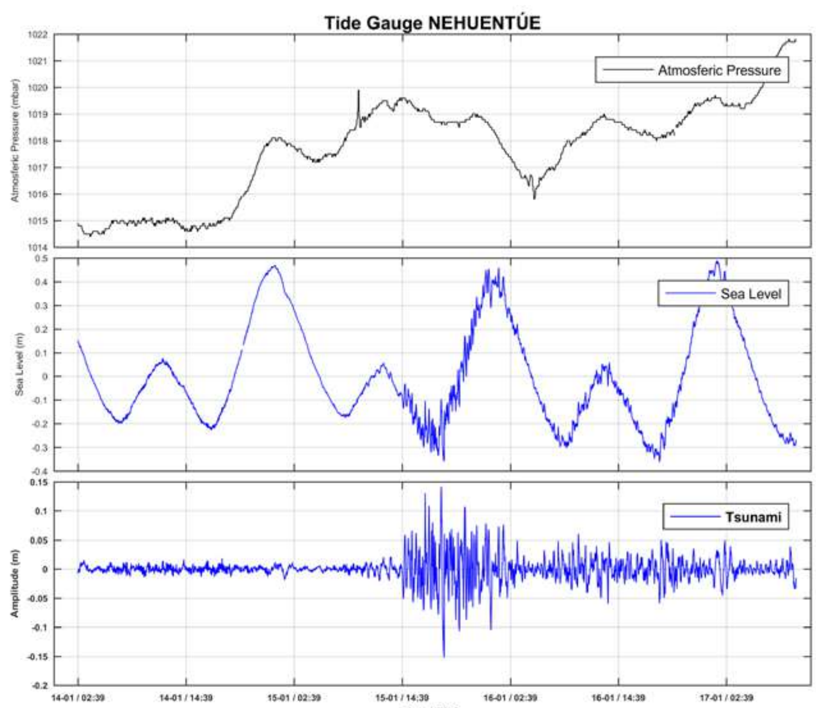


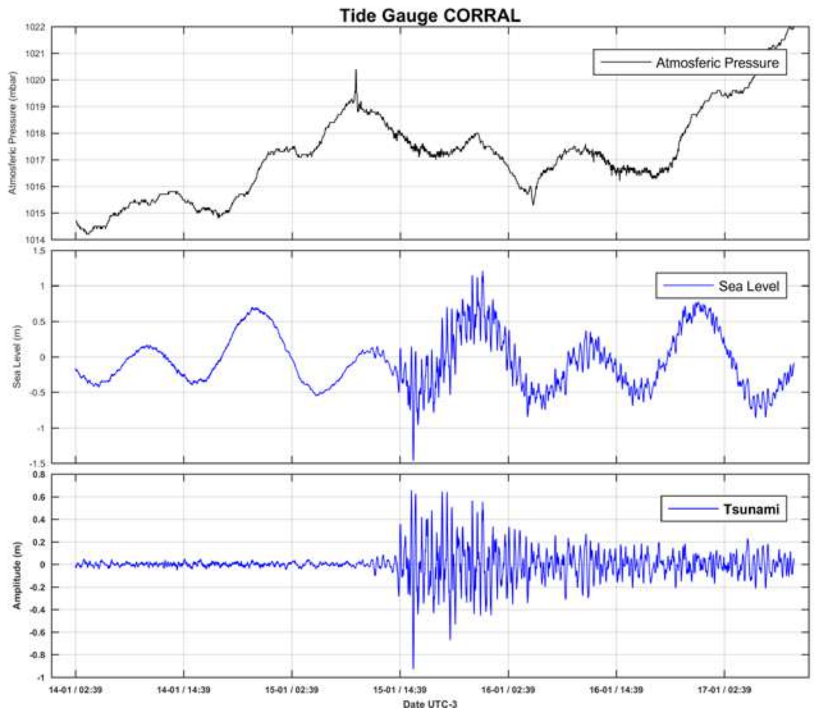
Tide Gauge TALCAHUANO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

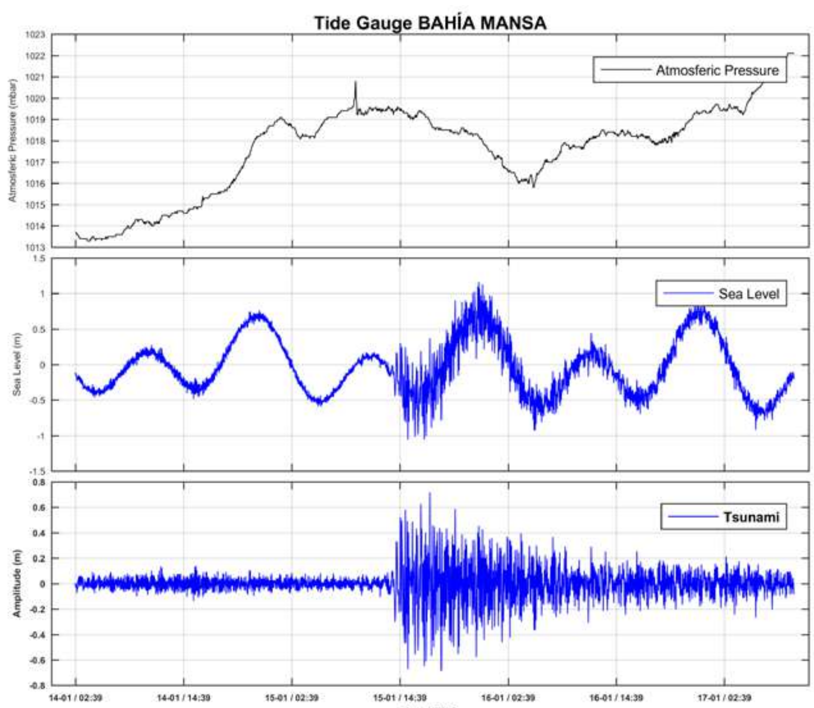


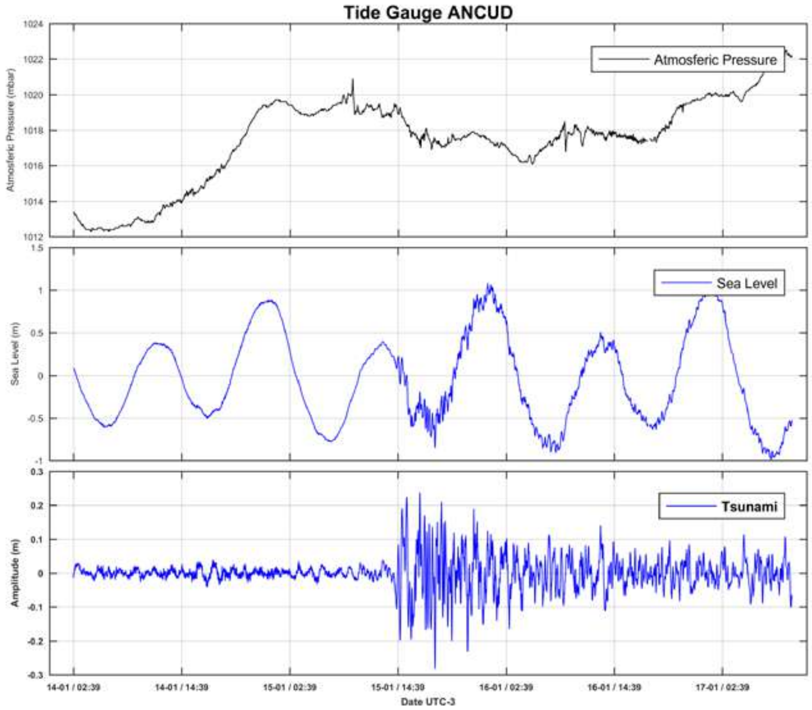
Tide Gauge CORONEL
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

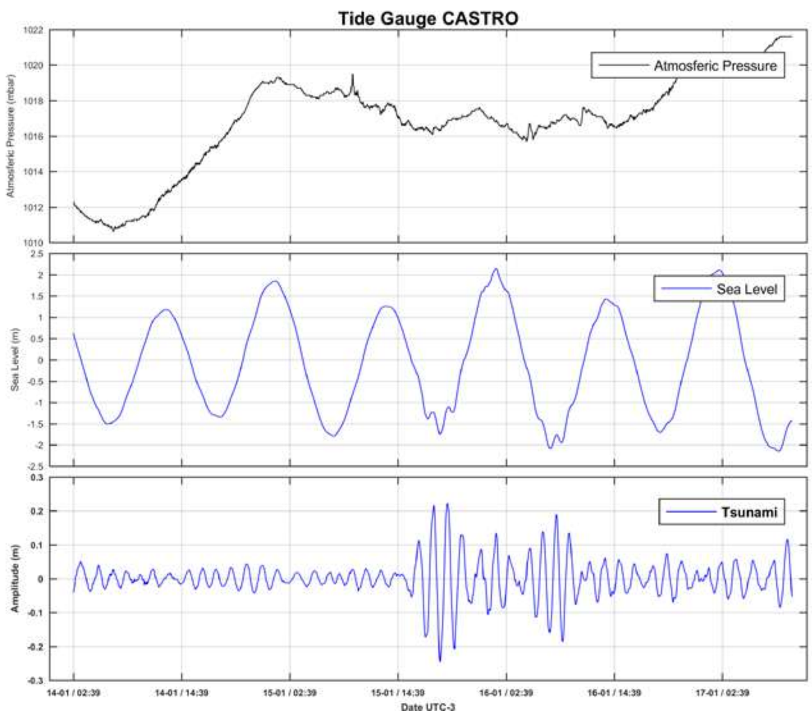

Tide Gauge LEBU
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

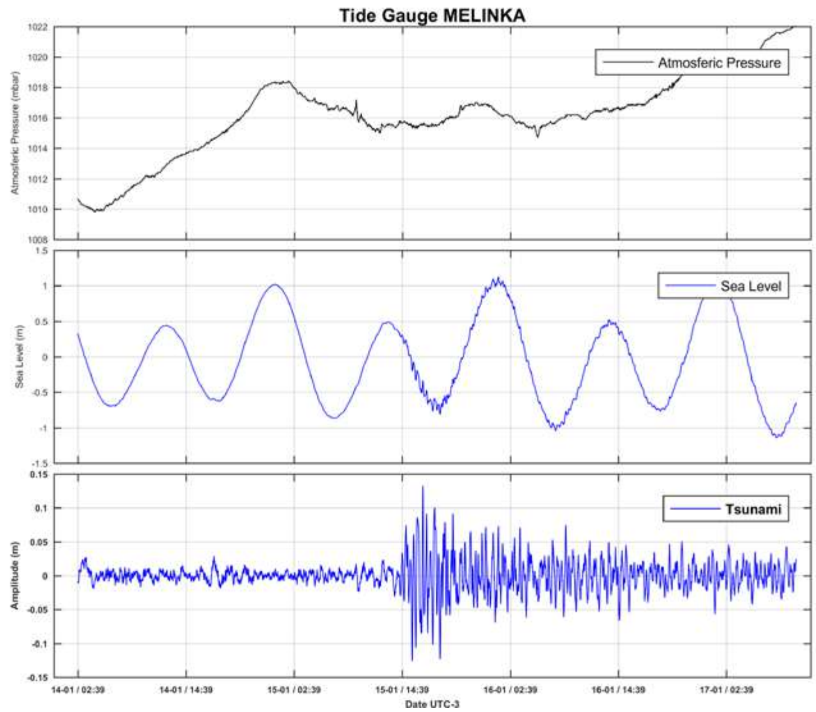

Tide Gauge NEHUENTÚE
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

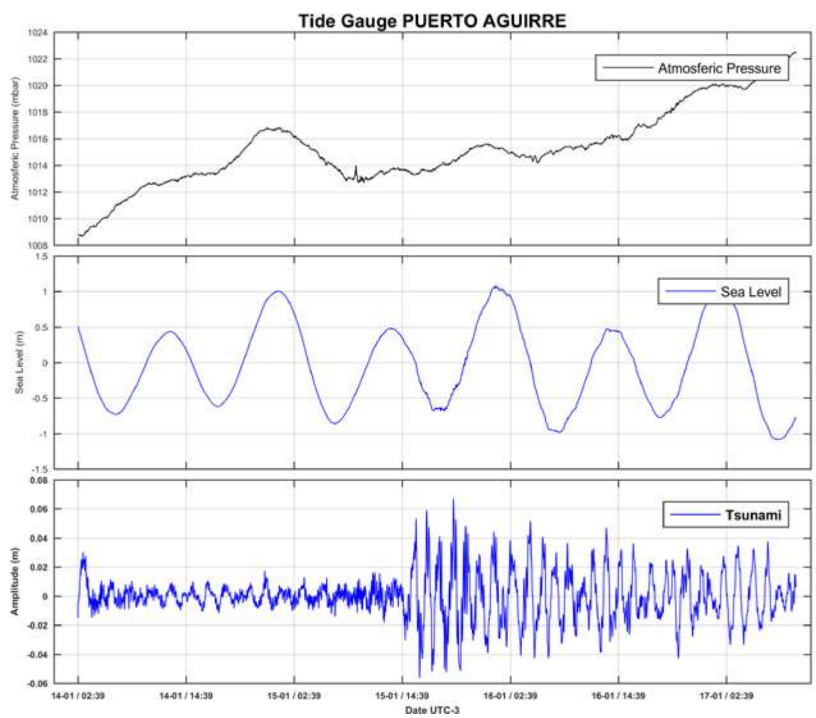

Tide Gauge CORRAL
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

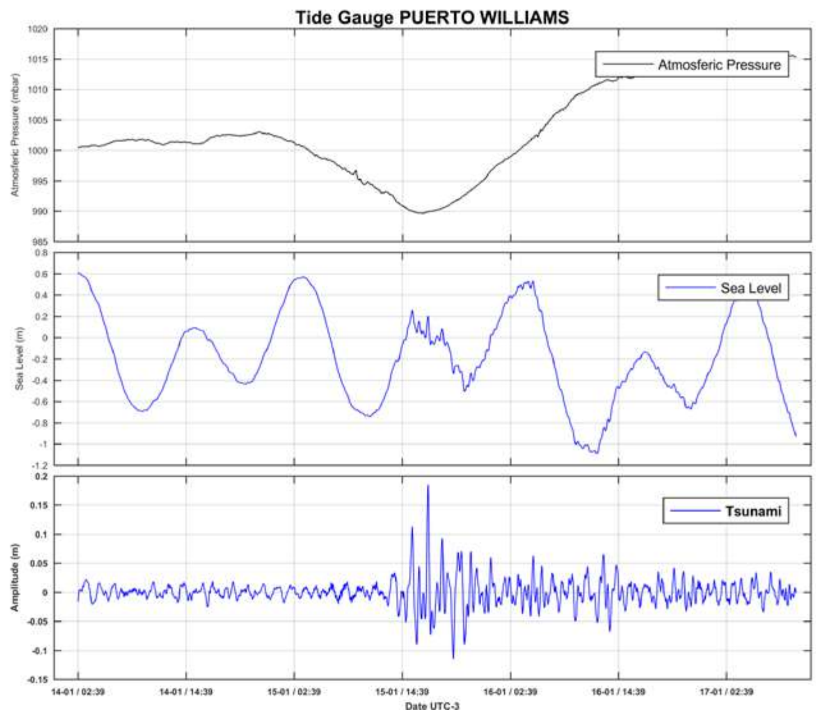

Tide Gauge BAHÍA MANSA
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

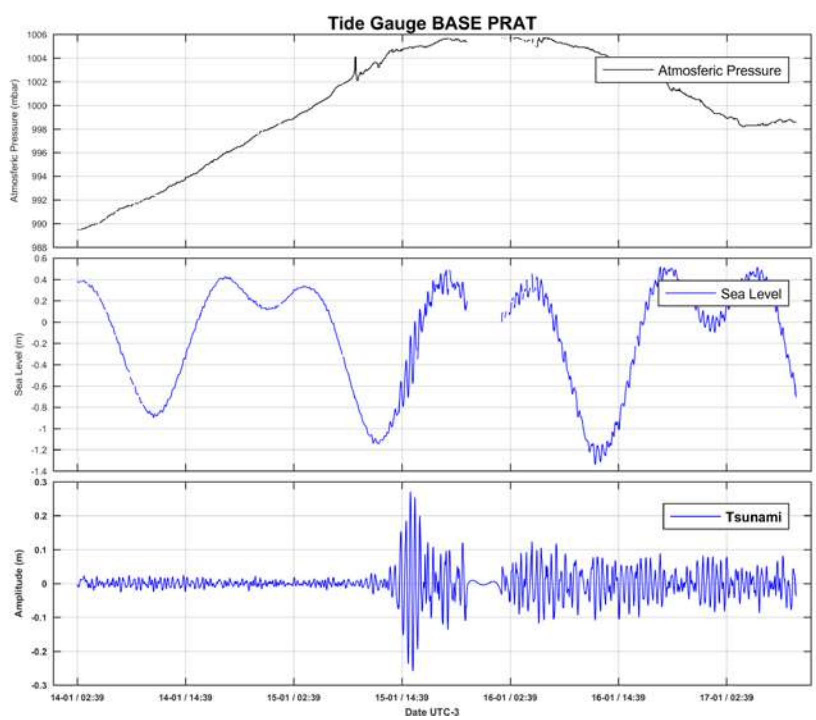

Tide Gauge ANCUD
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

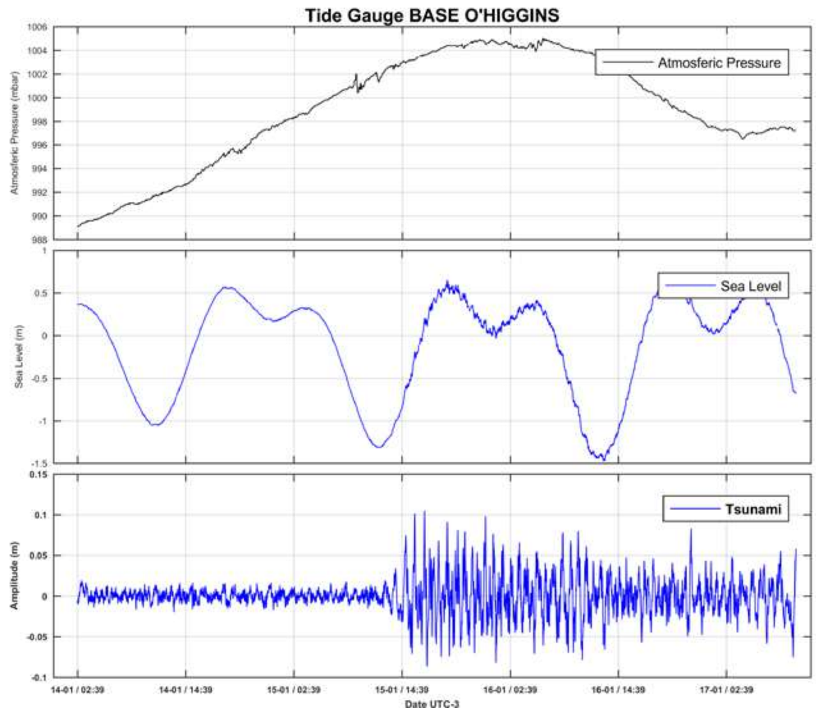

Tide Gauge CASTRO
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3


Tide Gauge MELINKA
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3


Tide Gauge PUERTO AGUIRRE
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

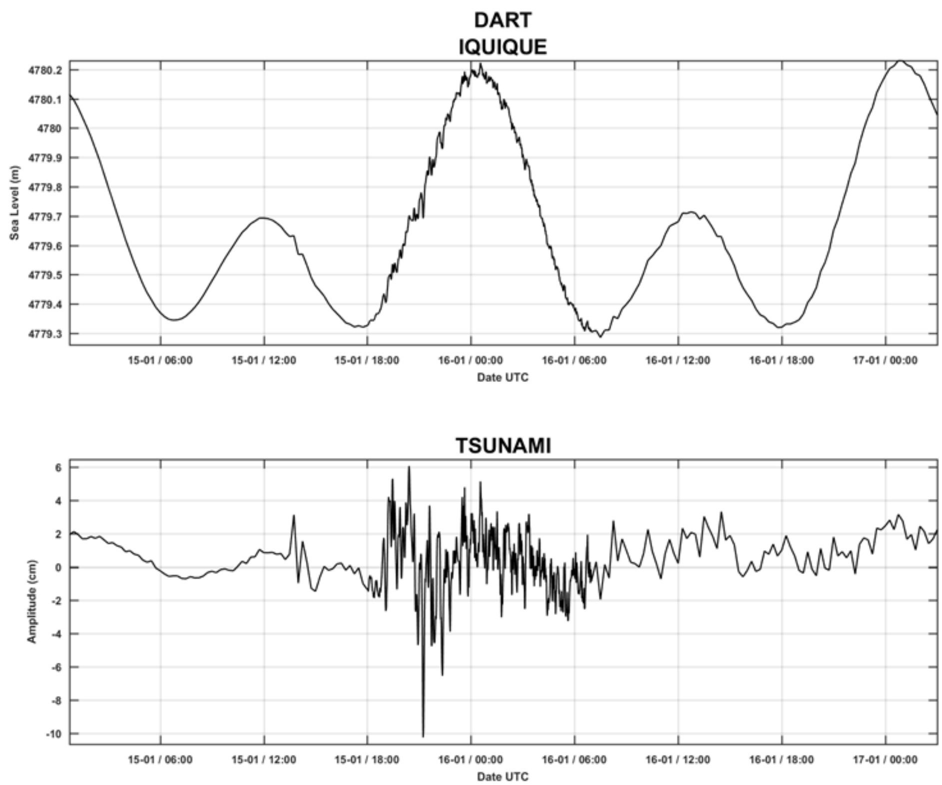

Tide Gauge PUERTO WILLIAMS
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

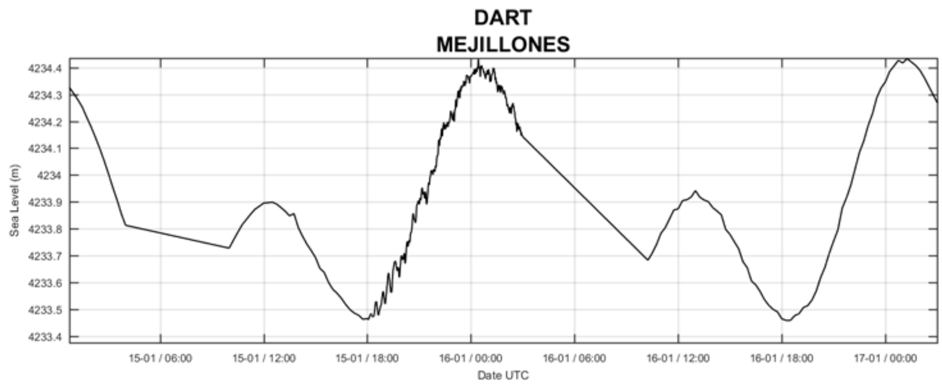

Tide Gauge BASE PRAT
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

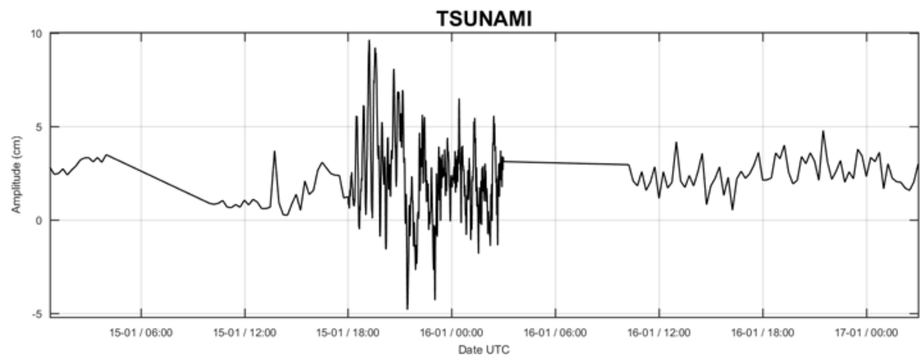

Tide Gauge BASE O'HIGGINS
Atmosferic Pressure
Atmosferic Pressure (mbar)
Sea Level
Sea Level (m)
Tsunami
Amplitude (m)
14-01 / 02:39
14-01 / 14:39
15-01 / 02:39
15-01 / 14:39
16-01 / 02:39
16-01 / 14:39
17-01 / 02:39
Date UTC-3

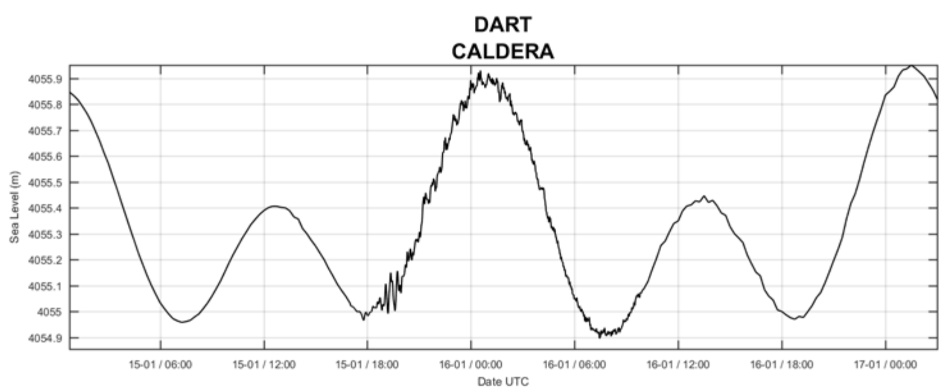
ANNEX "B"

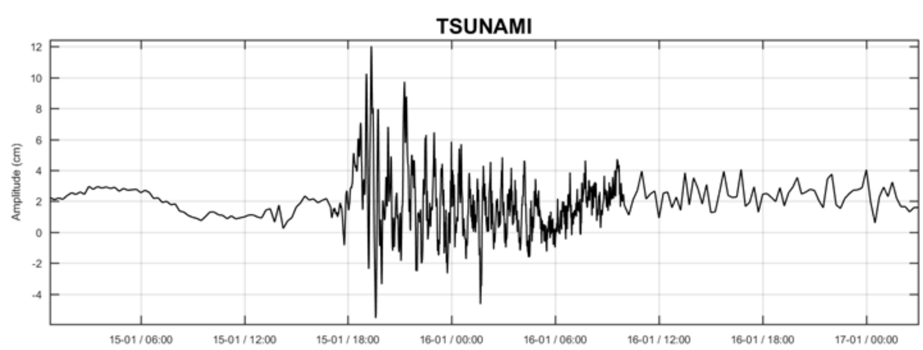
"Tsunami record in DART systems"

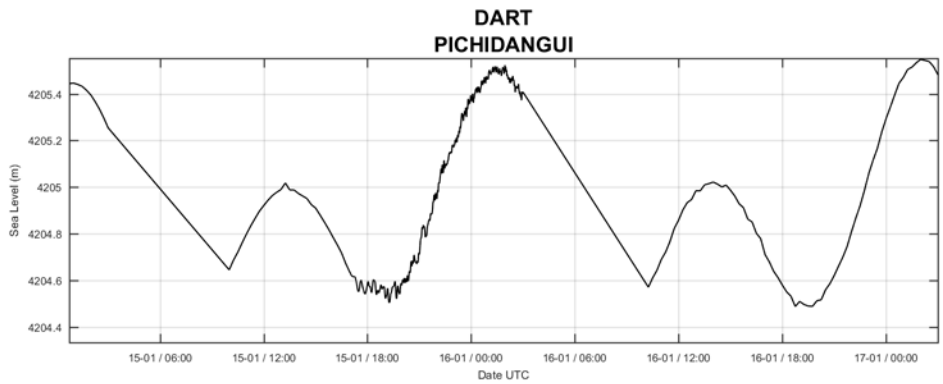


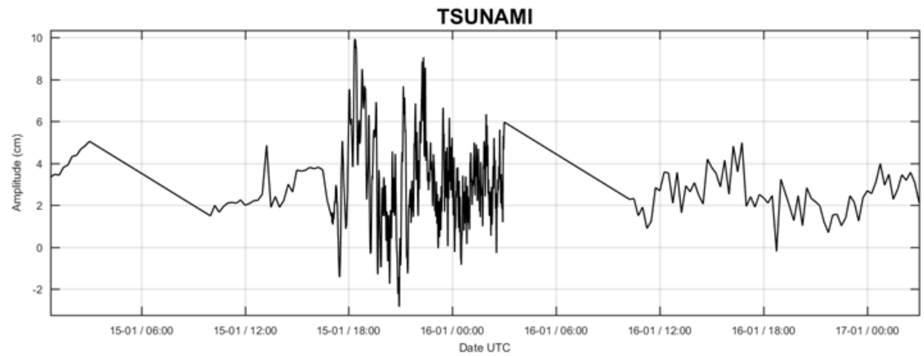

DART
MEJILLONES
Sea Level (m)
4234.4
4234.3
4234.2
4234.1
4234
4233.9
4233.8
4233.7
4233.6
4233.5
4233.4
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC


TSUNAMI
Amplitude (cm)
10
5
0
-5
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC


DART
CALDERA
Sea Level (m)
4055.9
4055.8
4055.7
4055.6
4055.5
4055.4
4055.3
4055.2
4055.1
4055
4054.9
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC

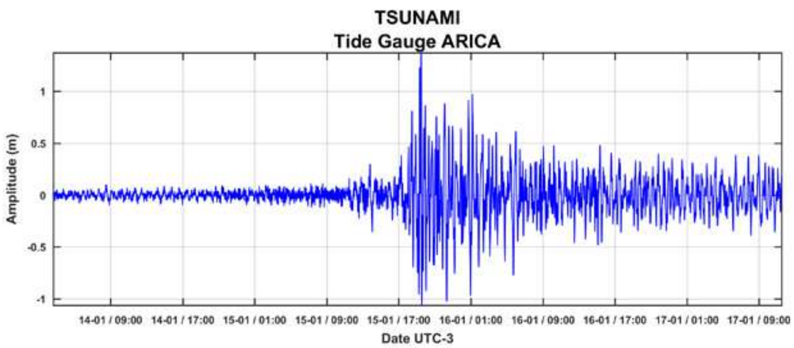

TSUNAMI
Amplitude (cm)
12
10
8
6
4
2
0
-2
-4
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC

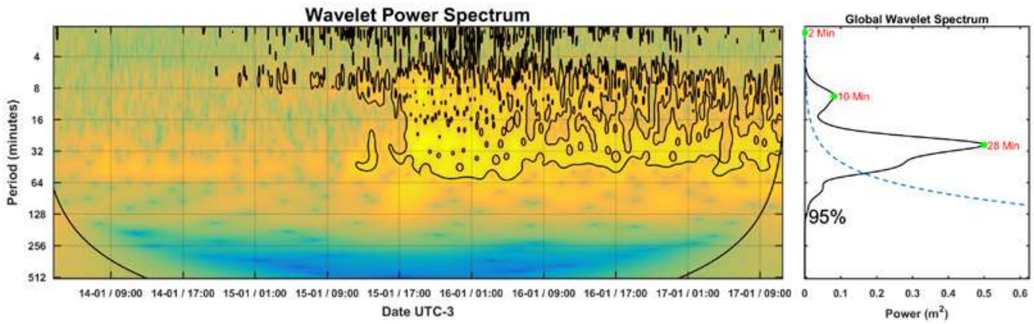

DART
PICHIDANGUI
Sea Level (m)
4205.4
4205.2
4205
4204.8
4204.6
4204.4
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC

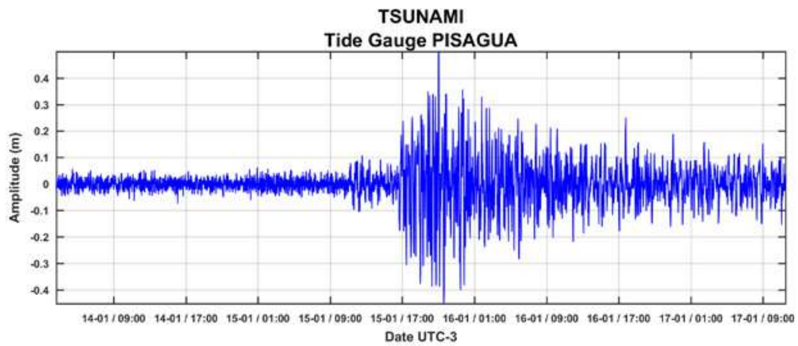

TSUNAMI
Amplitude (cm)
10
8
6
4
2
0
-2
15-01 / 06:00
15-01 / 12:00
15-01 / 18:00
16-01 / 00:00
16-01 / 06:00
16-01 / 12:00
16-01 / 18:00
17-01 / 00:00
Date UTC

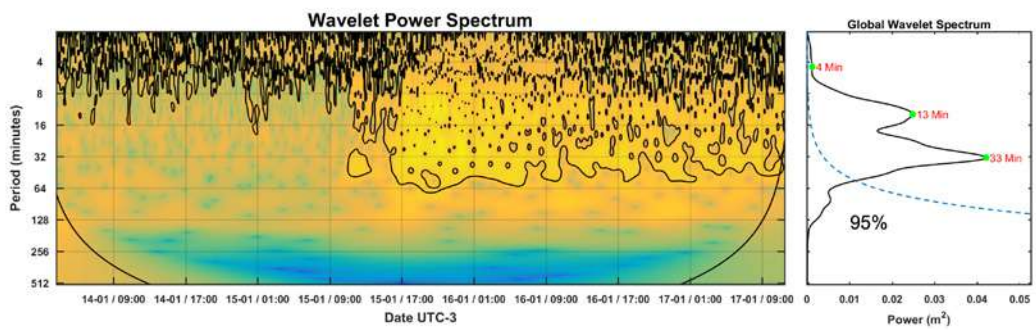
ANNEX "C"

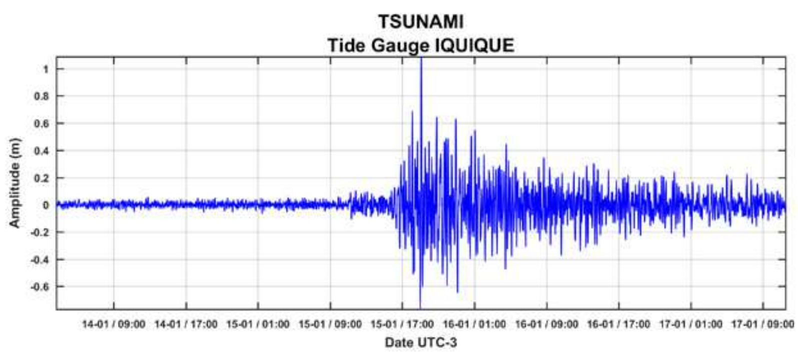
" Energy spectra for tsunami records at Sea Level Stations"

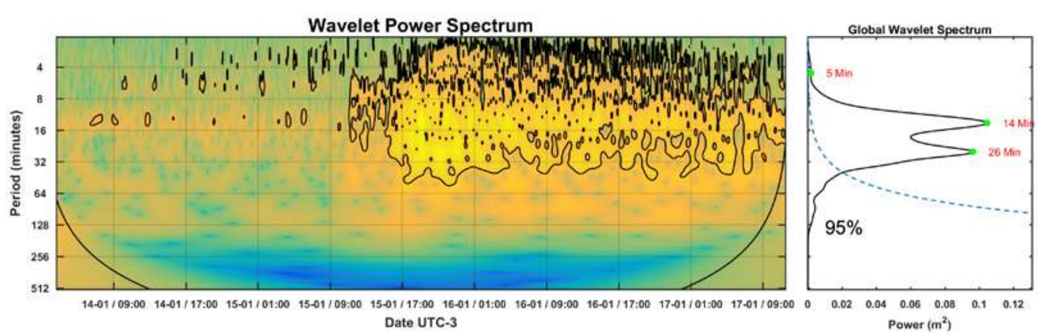


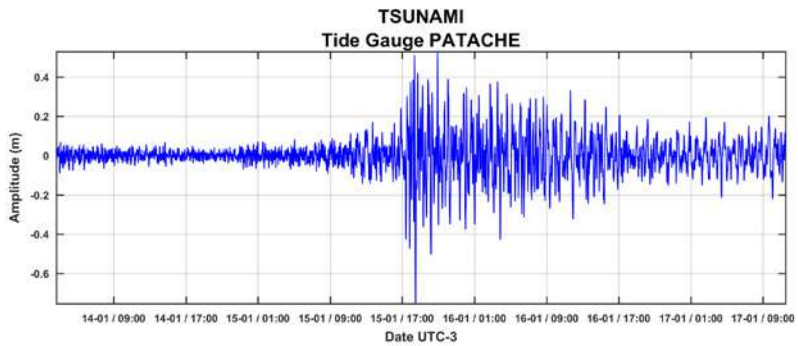


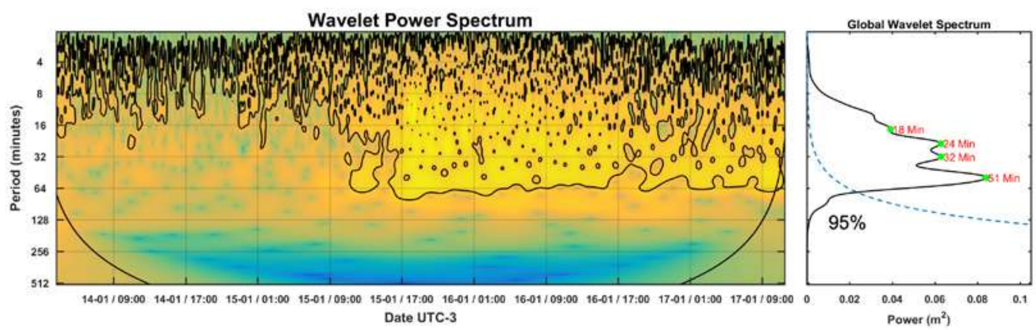

TSUNAMI
Tide Gauge PISAGUA
Amplitude (m)
Date UTC-3

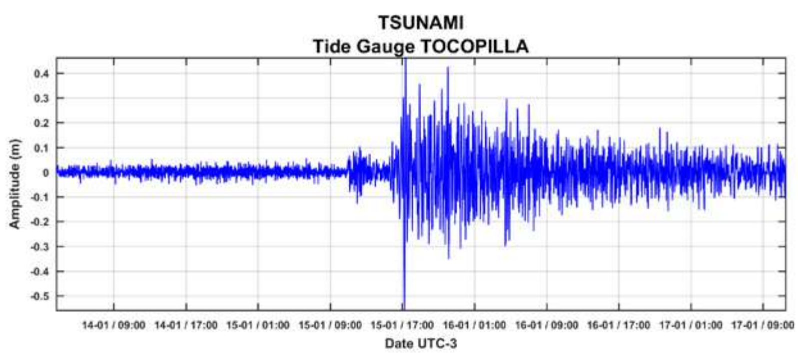

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
13 Min
33 Min
95%
Power (m^2)

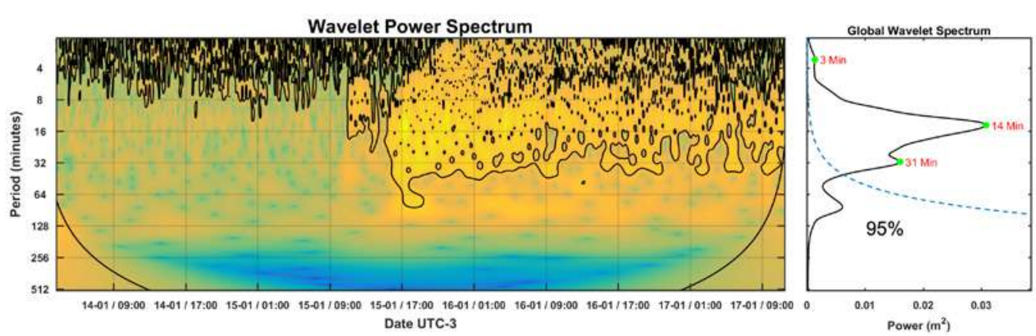

TSUNAMI
Tide Gauge IQUIQUE
Amplitude (m)
Date UTC-3

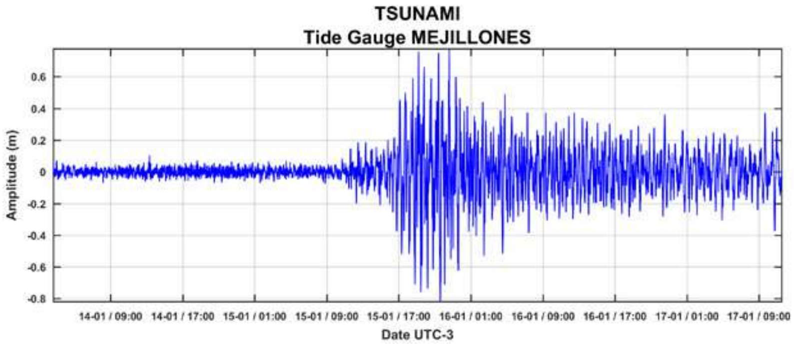

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
14 Min
26 Min
95%
Power (m^2)

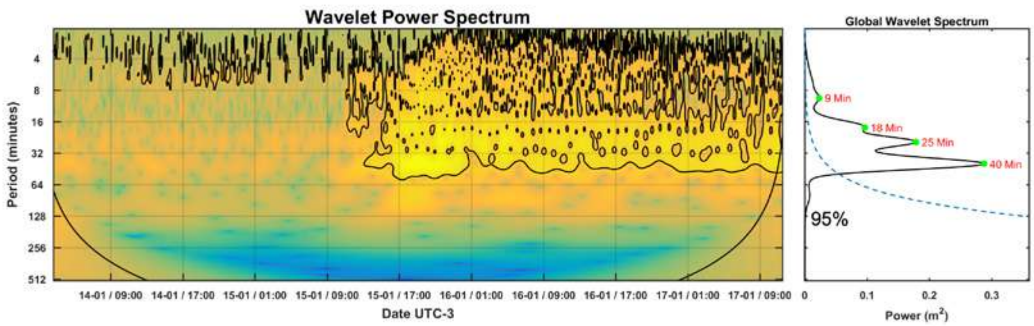

TSUNAMI
Tide Gauge PATACHE
Amplitude (m)
Date UTC-3

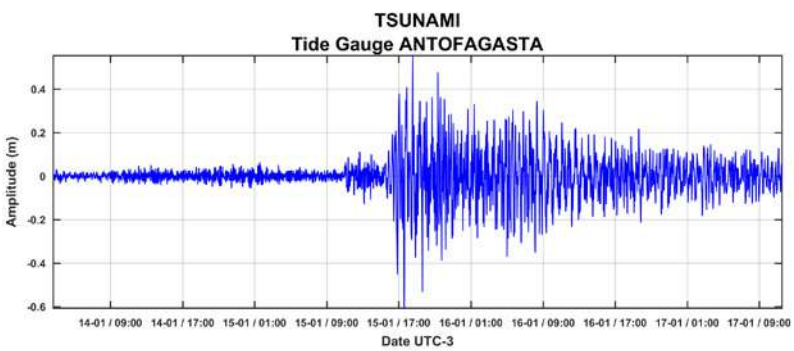

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
18 Min
24 Min
32 Min
51 Min
95%
Power (m²)

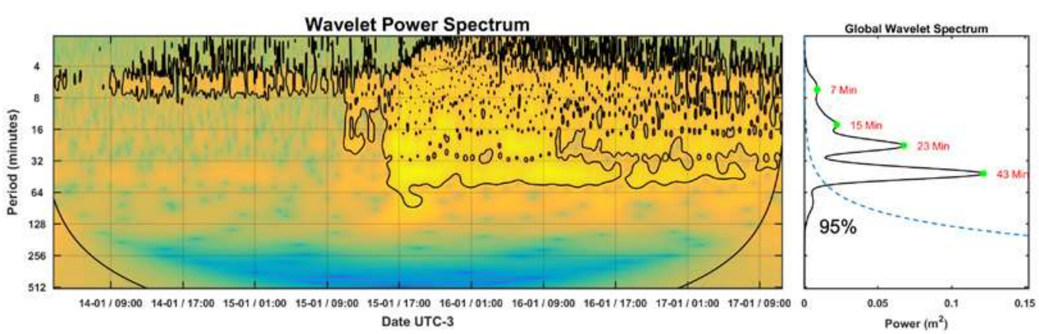

TSUNAMI
Tide Gauge TOCOPILLA
Amplitude (m)
Date UTC-3

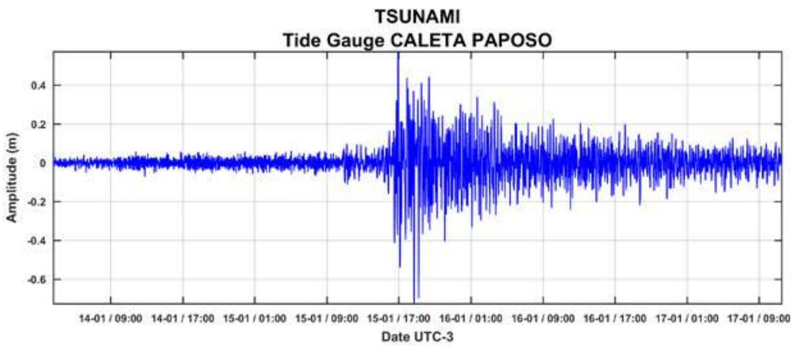

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
3 Min
14 Min
31 Min
95%
Power (m²)

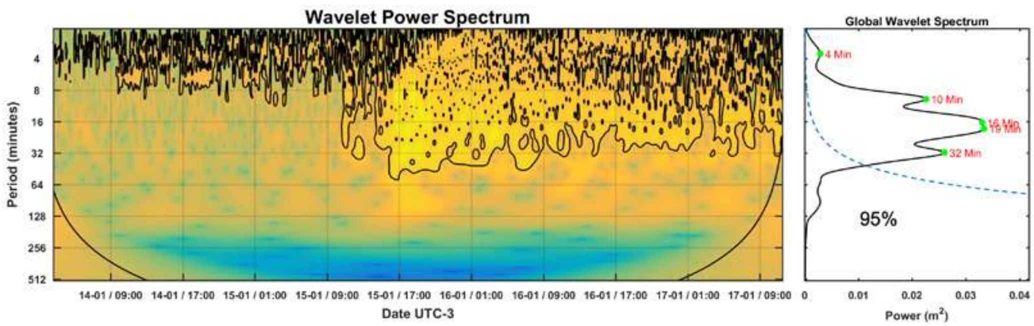

TSUNAMI
Tide Gauge MEJILLONES
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

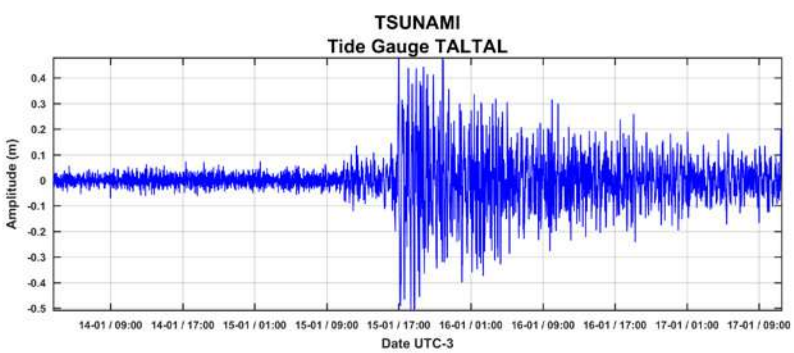

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
9 Min
18 Min
25 Min
40 Min
95%
Power (m²)

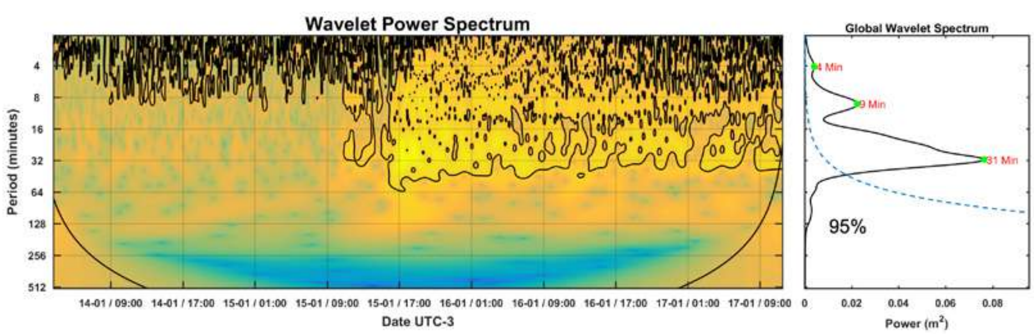

TSUNAMI
Tide Gauge ANTOFAGASTA
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

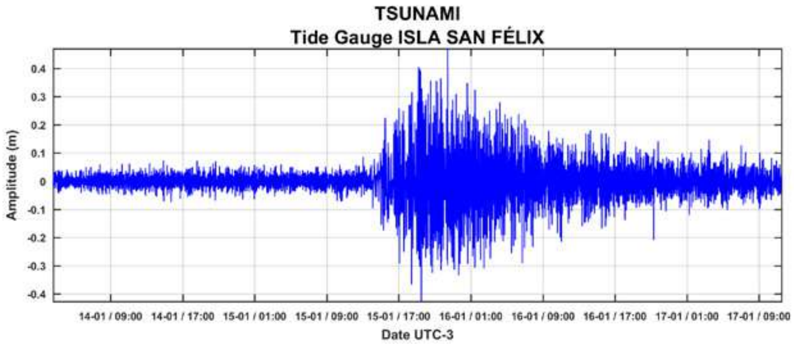

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
7 Min
15 Min
23 Min
43 Min
95%
Power (m²)

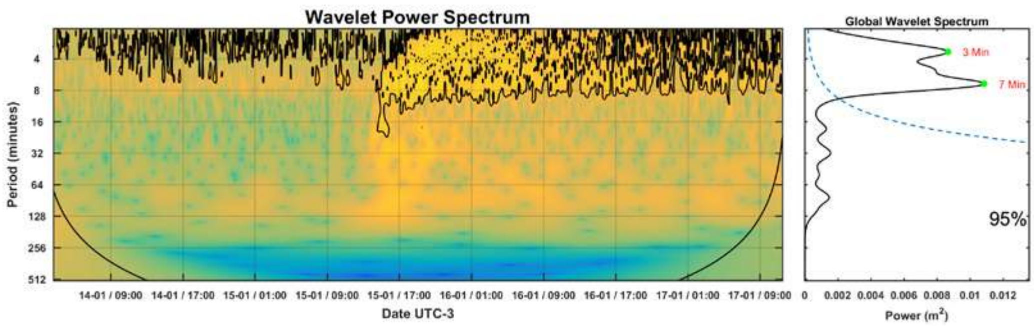

TSUNAMI
Tide Gauge CALETA PAPOSO
Amplitude (m)
Date UTC-3

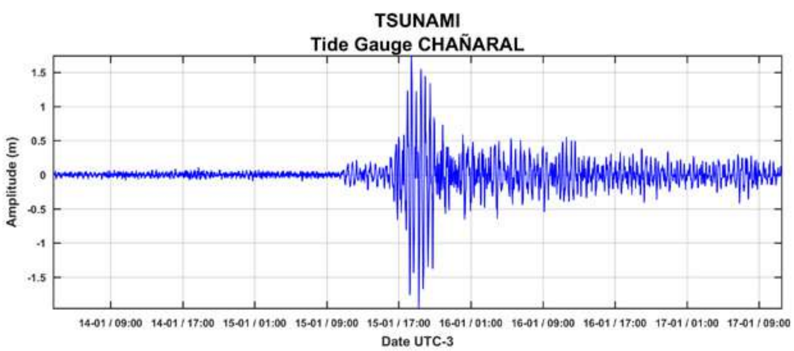

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
10 Min
32 Min
95%
Power (m^2)

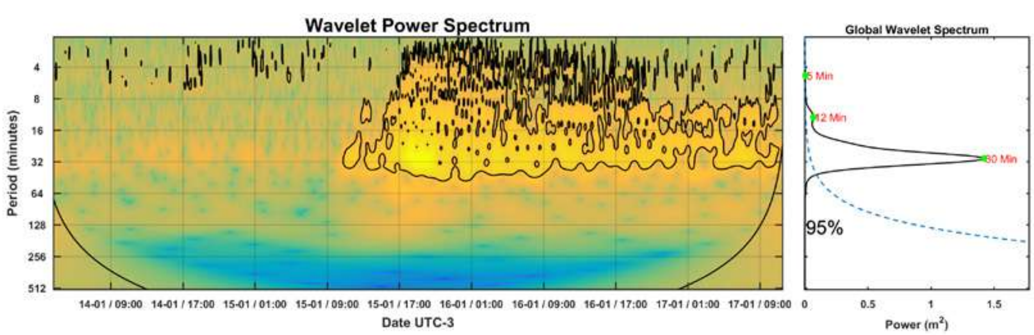

TSUNAMI
Tide Gauge TALTAL
Amplitude (m)
Date UTC-3

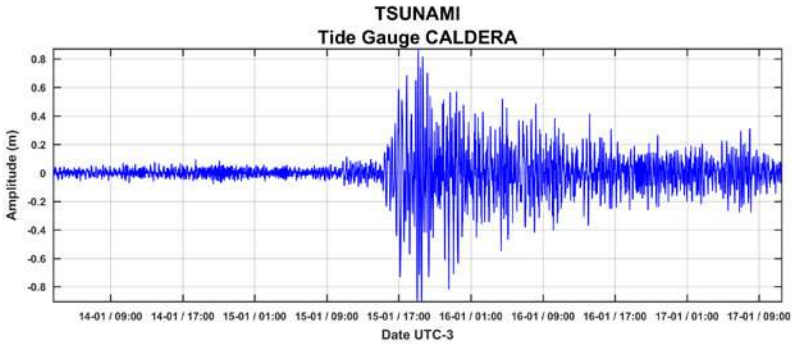

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
9 Min
31 Min
95%
Power (m^2)

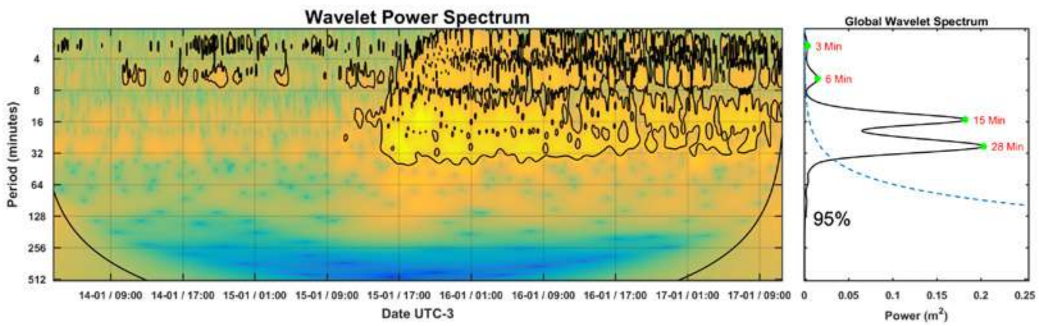

TSUNAMI
Tide Gauge ISLA SAN FÉLIX
Amplitude (m)
Date UTC-3

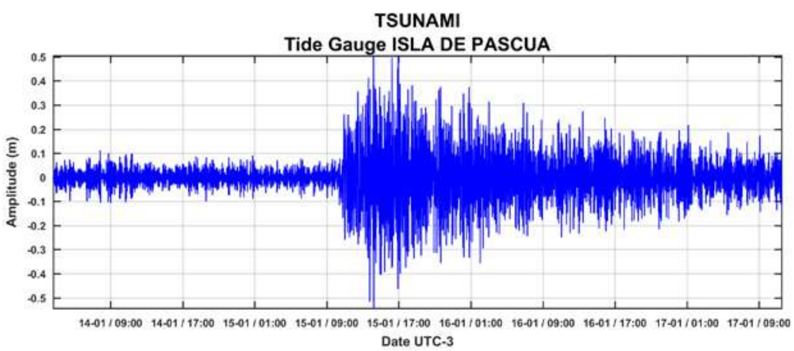

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
3 Min
7 Min
95%
Power (m²)

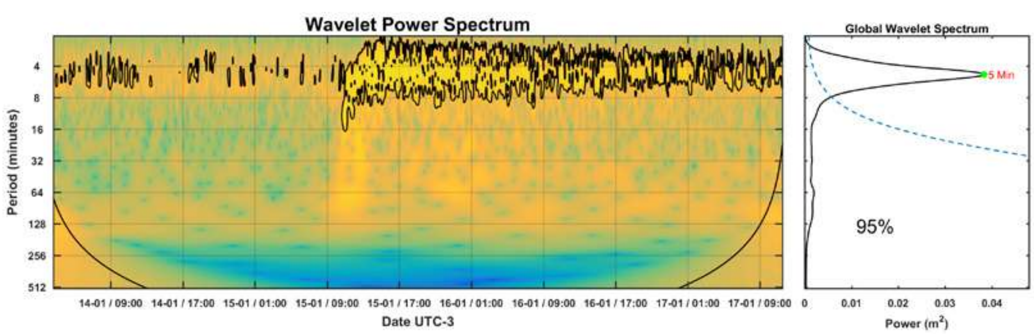

TSUNAMI
Tide Gauge CHAÑARAL
Amplitude (m)
Date UTC-3

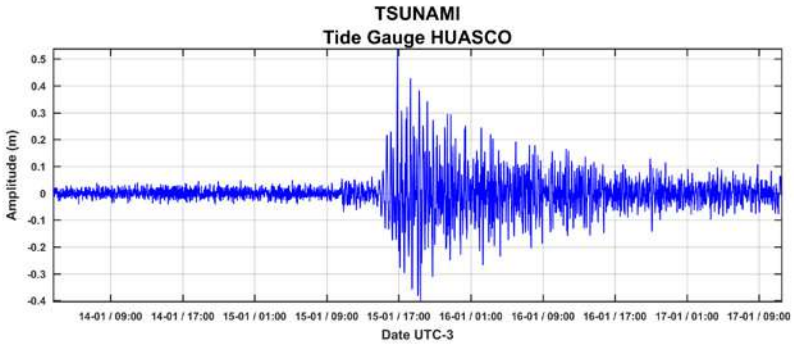

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
12 Min
30 Min
95%
Power (m²)

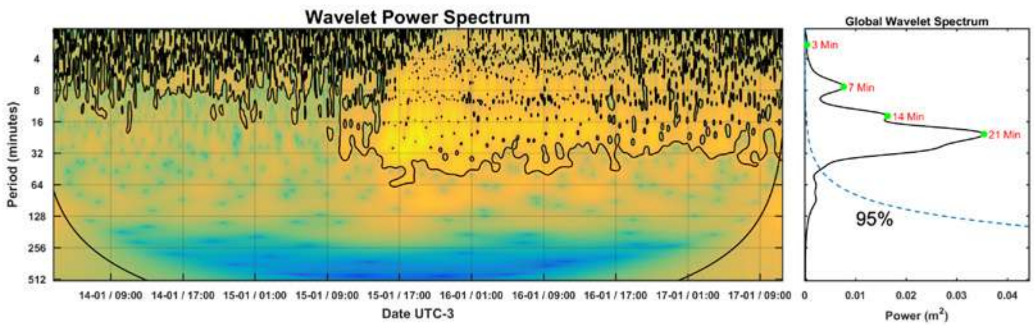

TSUNAMI
Tide Gauge CALDERA
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

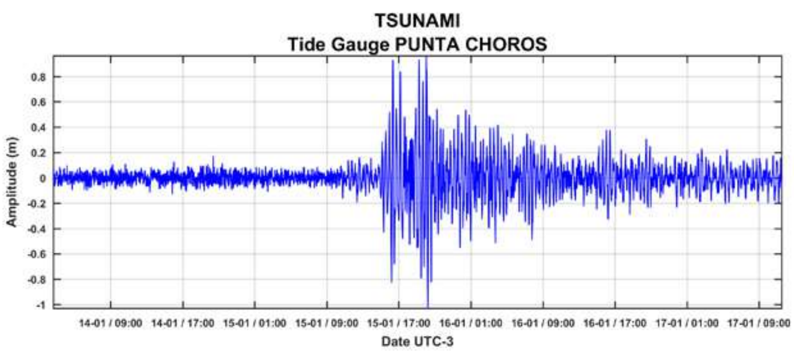

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
3 Min
6 Min
15 Min
28 Min
95%
Power (m^2)

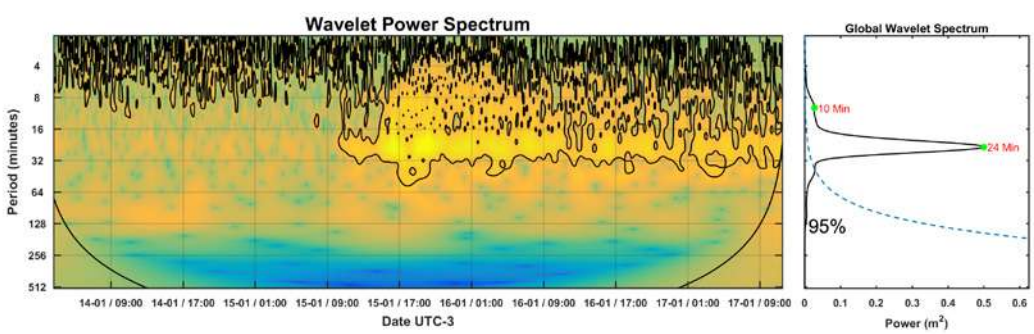

TSUNAMI
Tide Gauge ISLA DE PASCUA
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

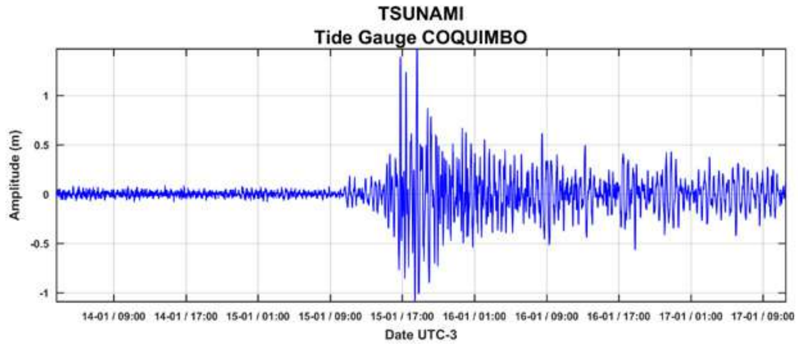

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
95%
Power (m^2)

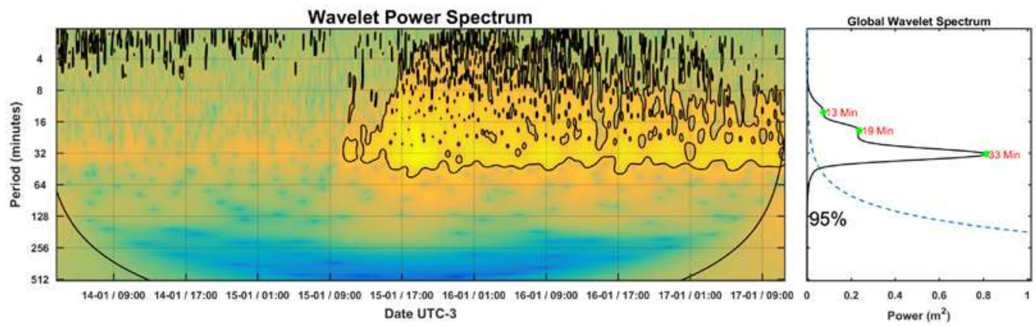

TSUNAMI
Tide Gauge HUASCO
Amplitude (m)
Date UTC-3
14-01 / 09:00
14-01 / 17:00
15-01 / 01:00
15-01 / 09:00
15-01 / 17:00
16-01 / 01:00
16-01 / 09:00
16-01 / 17:00
17-01 / 01:00
17-01 / 09:00

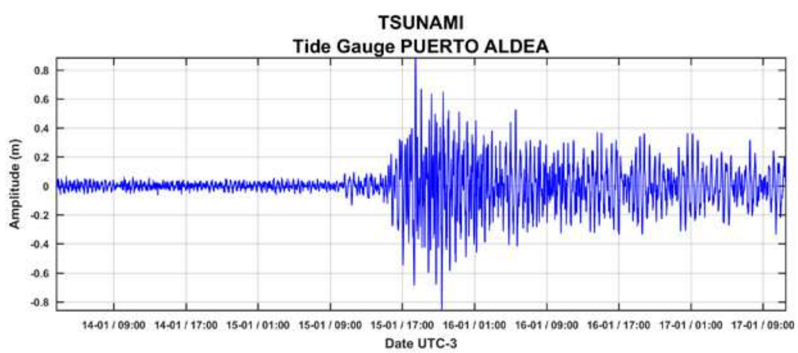

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
3 Min
7 Min
14 Min
21 Min
95%
Power (m^2)

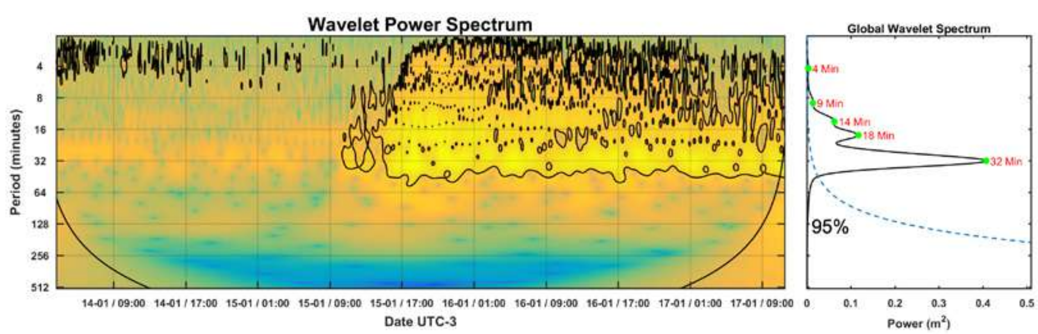

TSUNAMI
Tide Gauge PUNTA CHOROS
Amplitude (m)
Date UTC-3

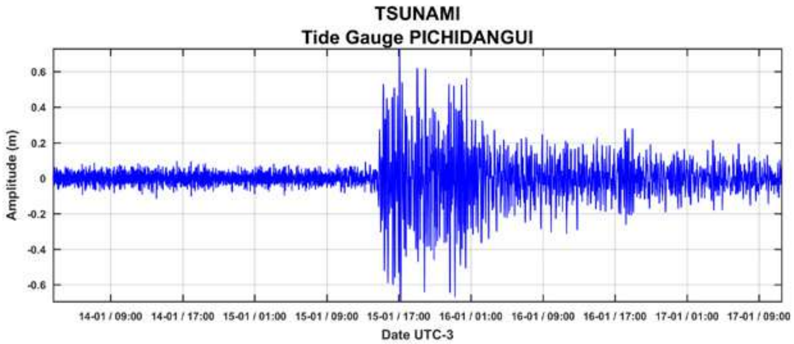

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
10 Min
24 Min
95%
Power (m^2)

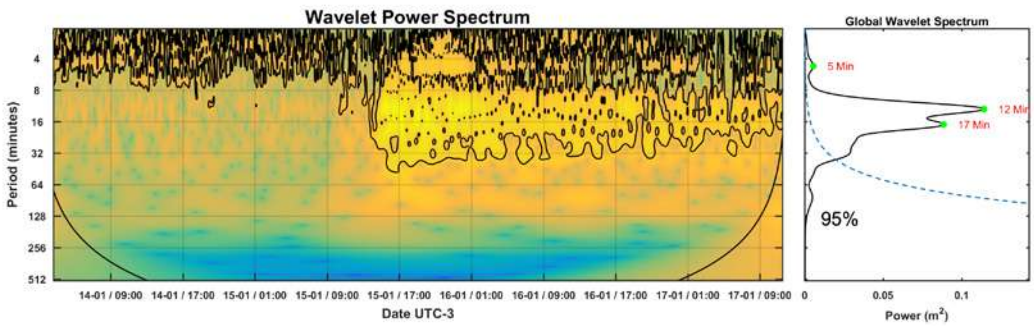

TSUNAMI
Tide Gauge COQUIMBO
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

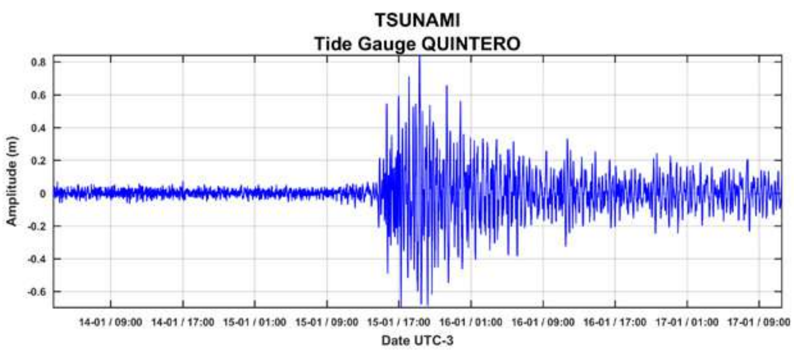

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
13 Min
19 Min
33 Min
95%
Power (m^2)

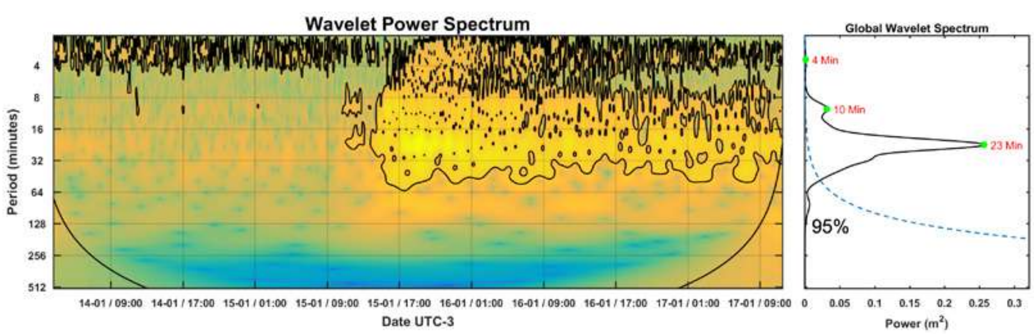

TSUNAMI
Tide Gauge PUERTO ALDEA
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

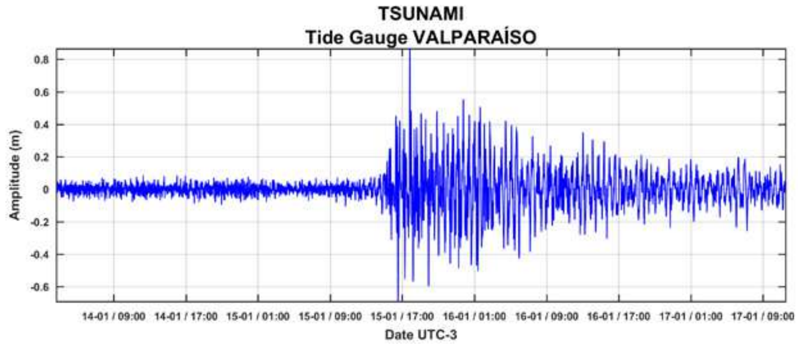

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
9 Min
14 Min
18 Min
32 Min
95%
Power (m^2)

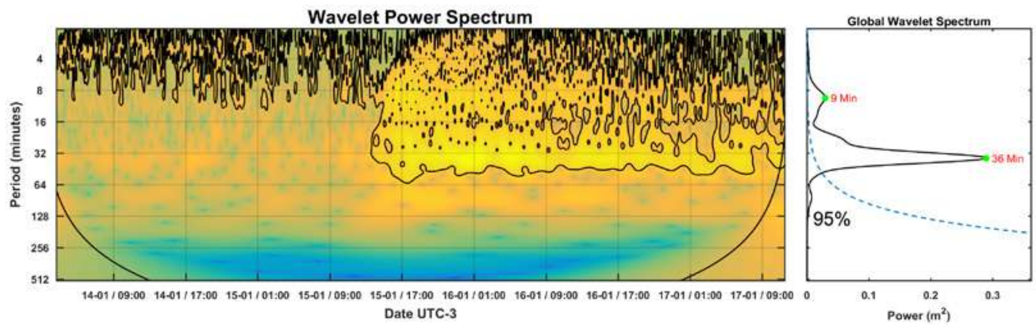

TSUNAMI
Tide Gauge PICHIDANGUI
Amplitude (m)
Date UTC-3

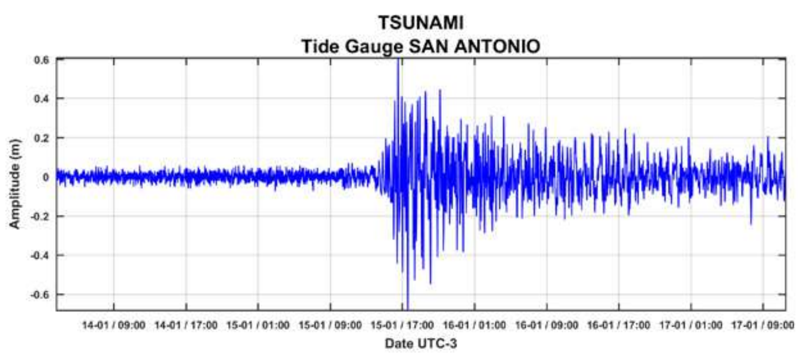

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
12 Min
17 Min
95%
Power (m²)

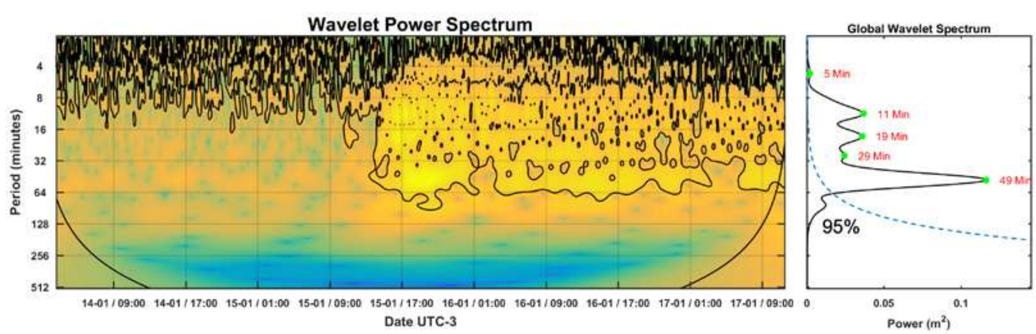

TSUNAMI
Tide Gauge QUINTERO
Amplitude (m)
Date UTC-3

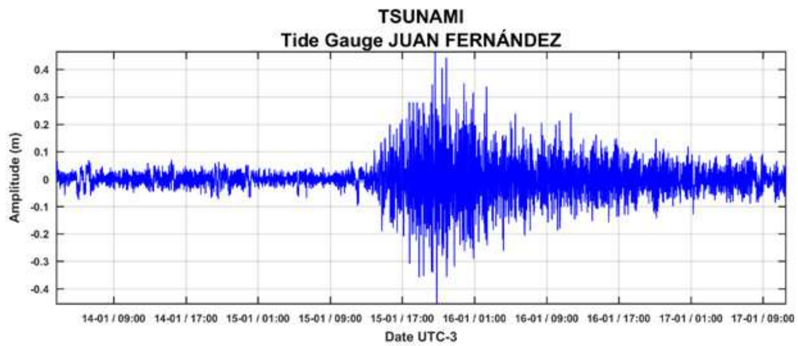

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
10 Min
23 Min
95%
Power (m²)

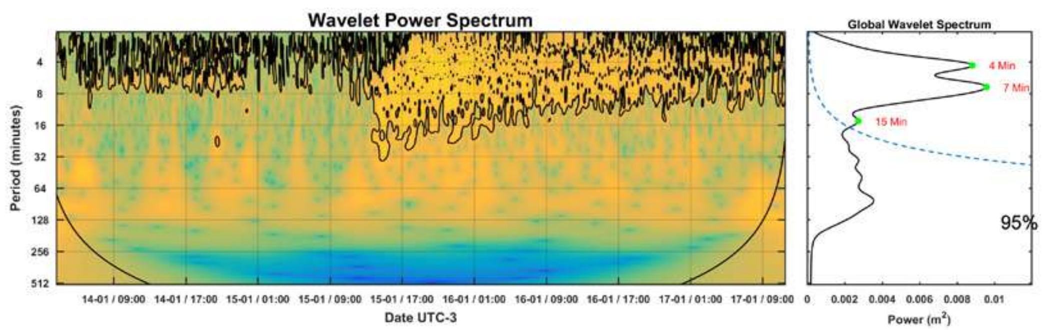

TSUNAMI
Tide Gauge VALPARAÍSO
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

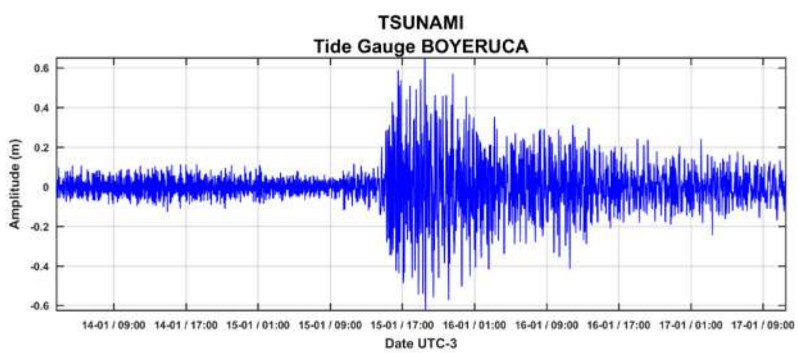

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
9 Min
36 Min
95%
Power (m^2)

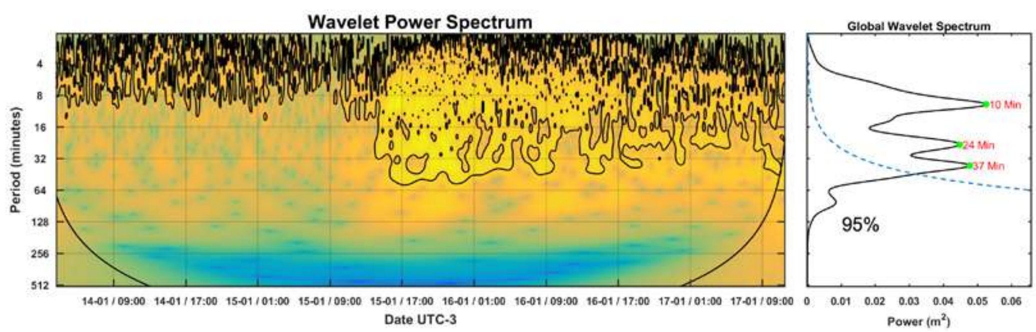

TSUNAMI
Tide Gauge SAN ANTONIO
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00

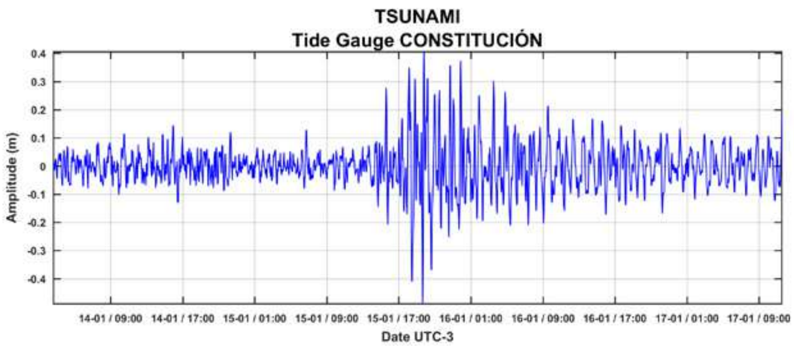

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
11 Min
19 Min
29 Min
49 Min
95%
Power (m^2)

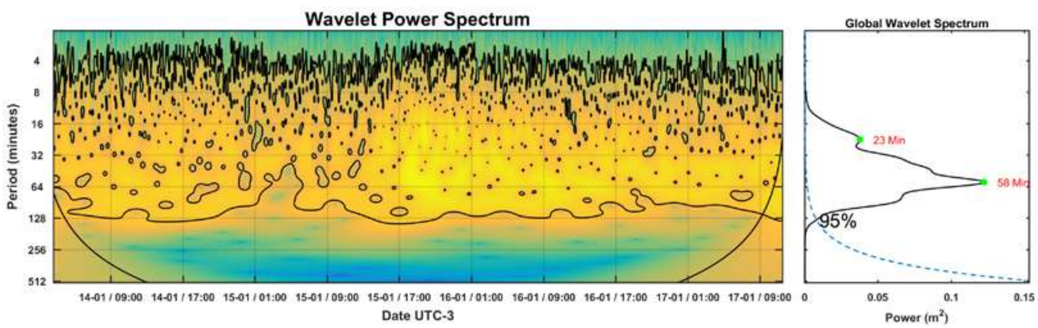

TSUNAMI
Tide Gauge JUAN FERNÁNDEZ
Amplitude (m)
Date UTC-3

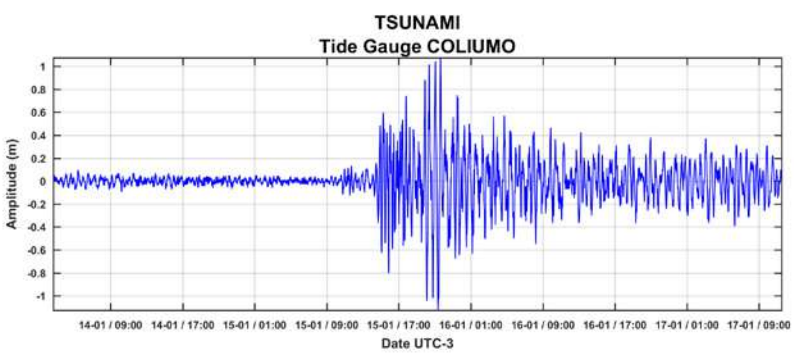

Wavelet Power Spectrum
Global Wavelet Spectrum
Period (minutes)
4 Min
7 Min
15 Min
95%
Date UTC-3
Power (m²)

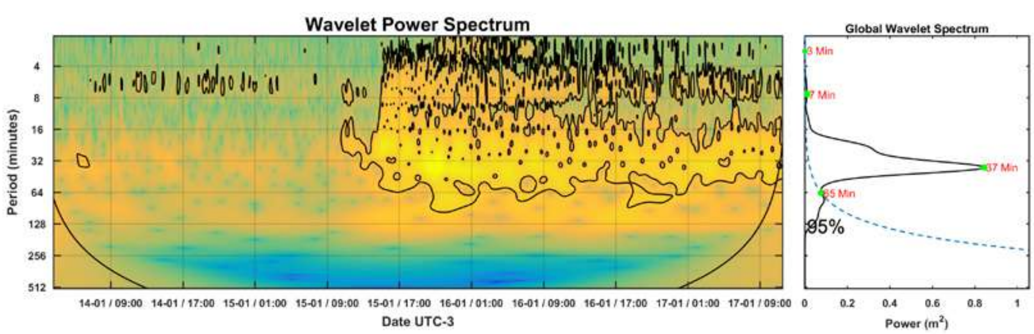

TSUNAMI
Tide Gauge BOYERUCA
Amplitude (m)
Date UTC-3

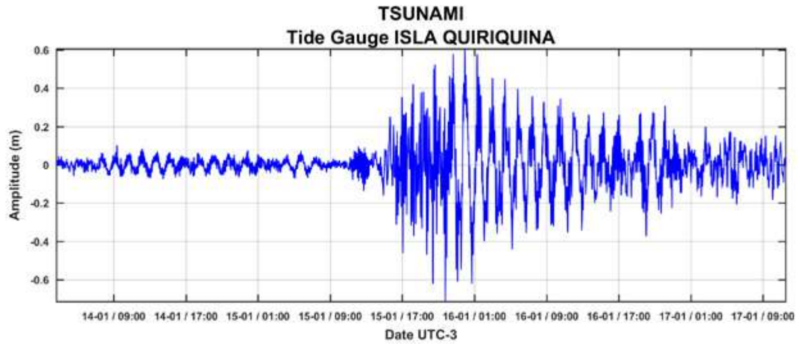

Wavelet Power Spectrum
Global Wavelet Spectrum
Period (minutes)
10 Min
24 Min
37 Min
95%
Date UTC-3
Power (m²)

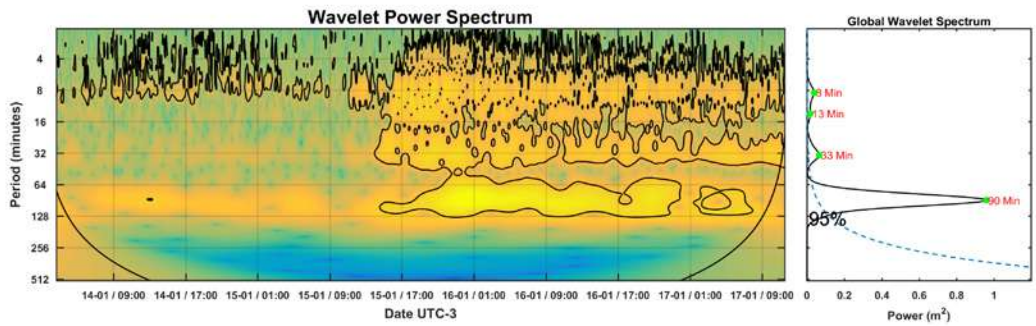

TSUNAMI
Tide Gauge CONSTITUCIÓN
Amplitude (m)
Date UTC-3

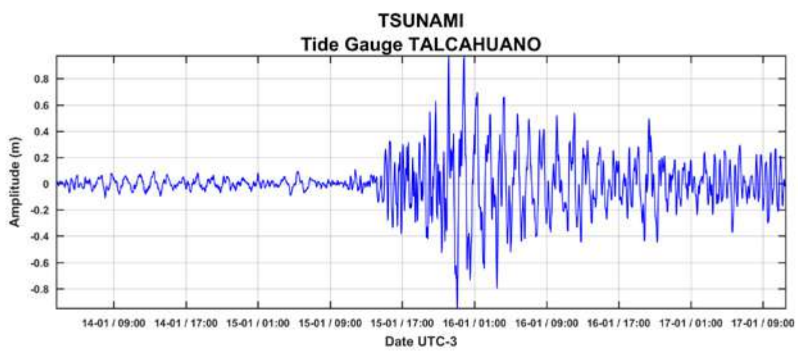

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
23 Min
58 Min
95%
Power (m²)

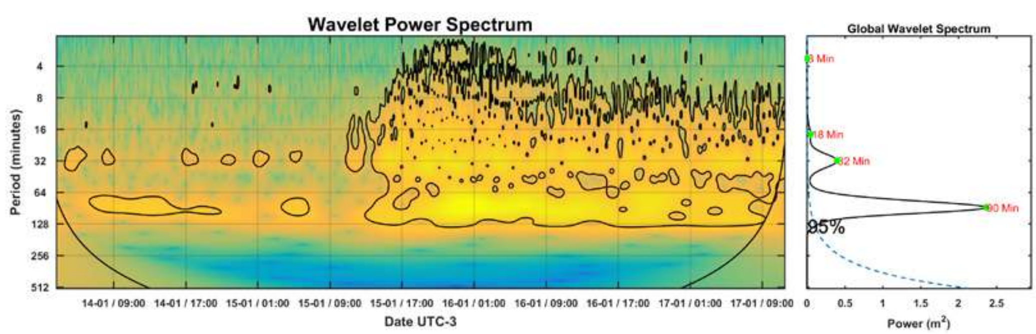

TSUNAMI
Tide Gauge COLIUMO
Amplitude (m)
Date UTC-3

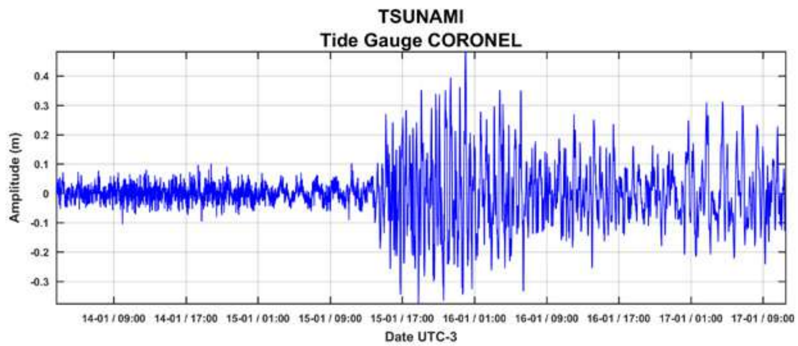

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
37 Min
95%
Power (m²)

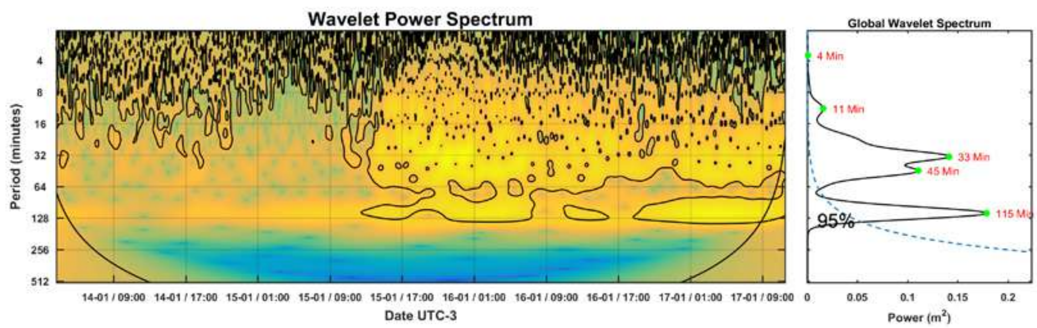

TSUNAMI
Tide Gauge ISLA QUIRIQUINA
Amplitude (m)
Date UTC-3
14-01 / 09:00
14-01 / 17:00
15-01 / 01:00
15-01 / 09:00
15-01 / 17:00
16-01 / 01:00
16-01 / 09:00
16-01 / 17:00
17-01 / 01:00
17-01 / 09:00

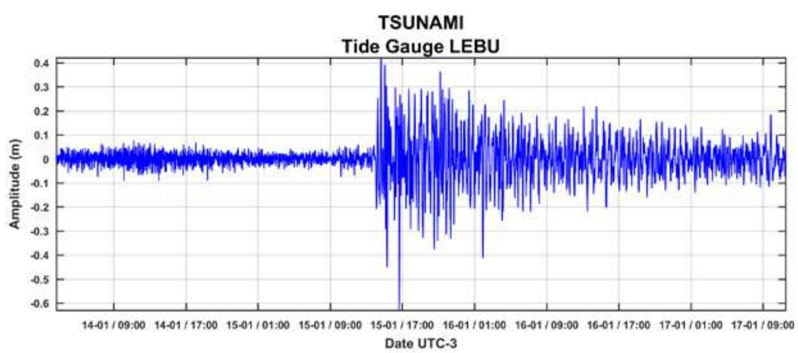

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
8 Min
13 Min
33 Min
90 Min
95%
Power (m^2)

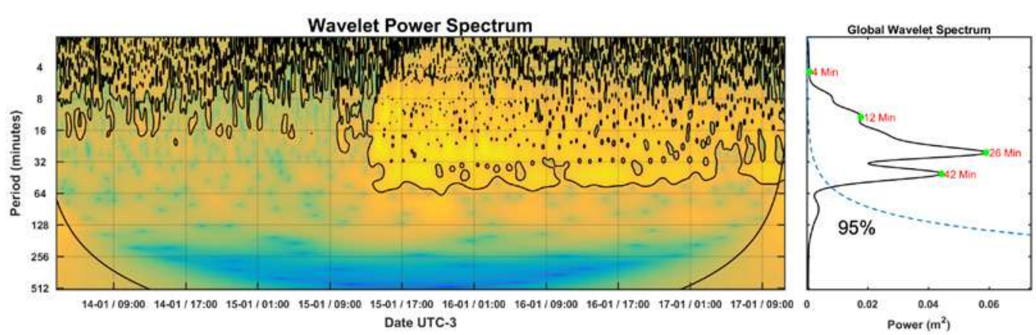

TSUNAMI
Tide Gauge TALCAHUANO
Amplitude (m)
Date UTC-3

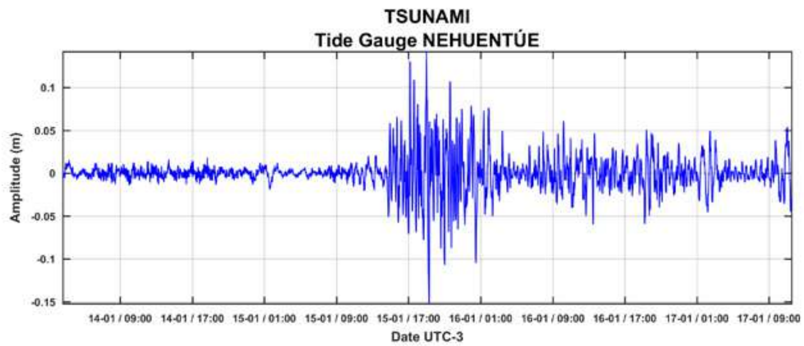

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
3 Min
18 Min
32 Min
90 Min
95%
Power (m^2)

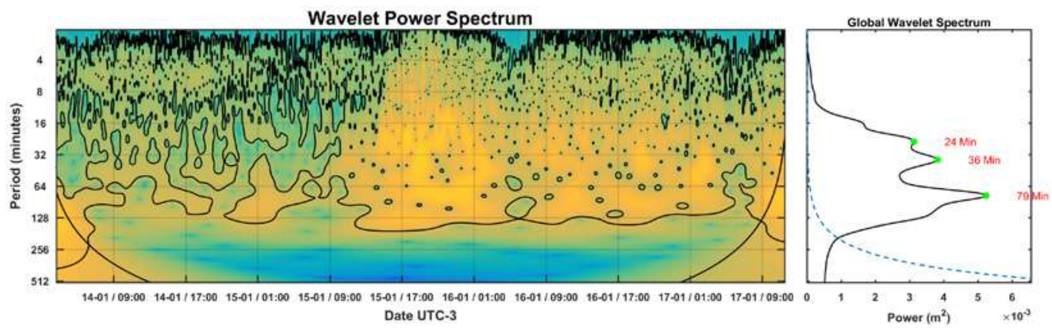

TSUNAMI
Tide Gauge CORONEL
Amplitude (m)
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3

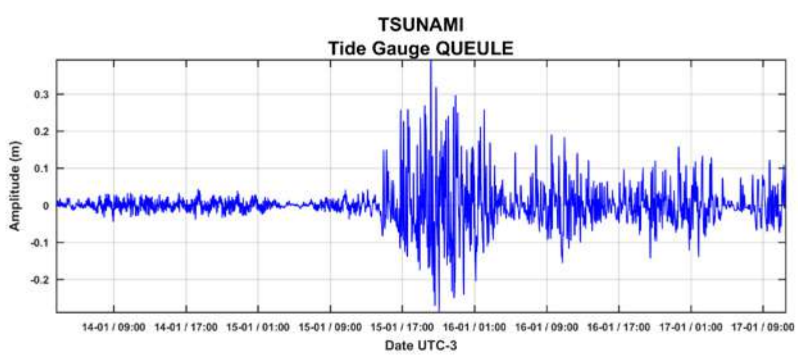

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
11 Min
33 Min
45 Min
115 Min
95%
Power (m²)

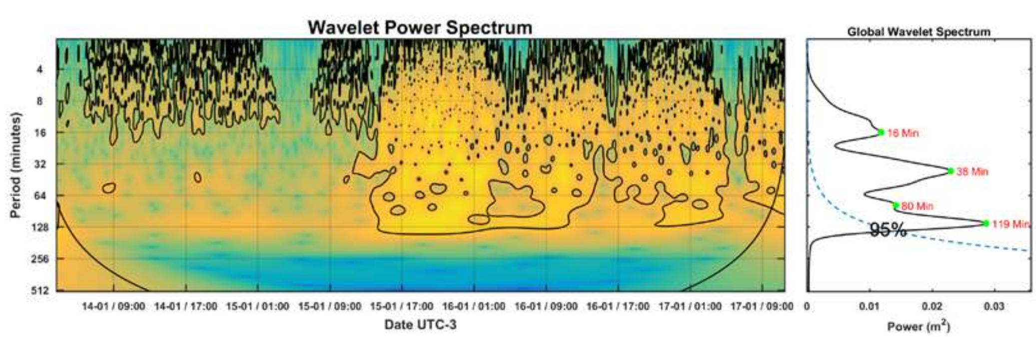

TSUNAMI
Tide Gauge LEBU
Amplitude (m)
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3

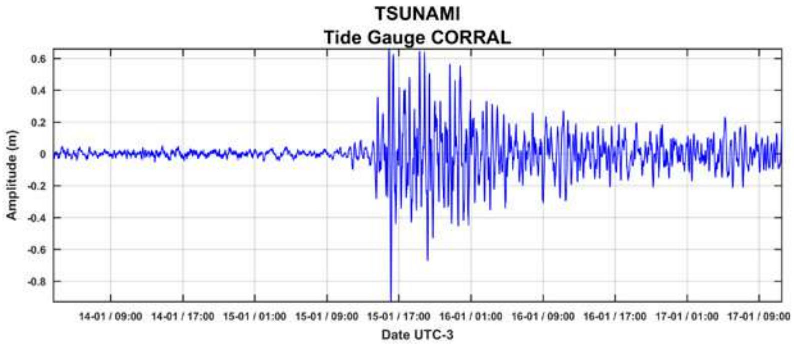

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
12 Min
26 Min
42 Min
95%
Power (m²)

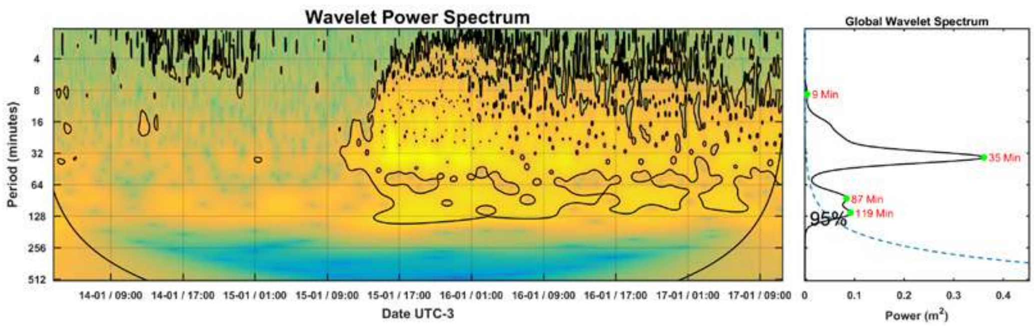

TSUNAMI
Tide Gauge NEHUENTÚE
Amplitude (m)
Date UTC-3

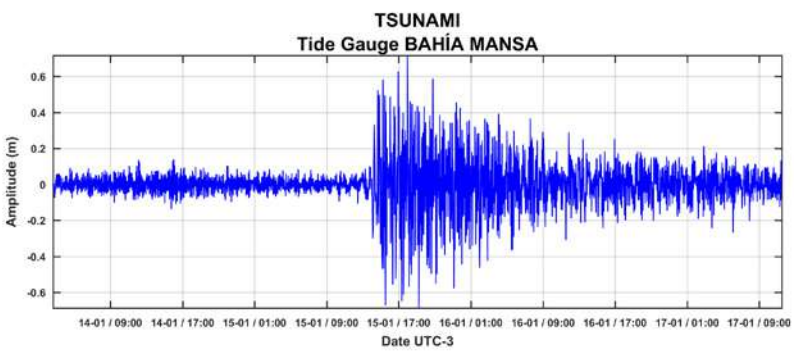

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
24 Min
36 Min
79 Min
Power (m²)

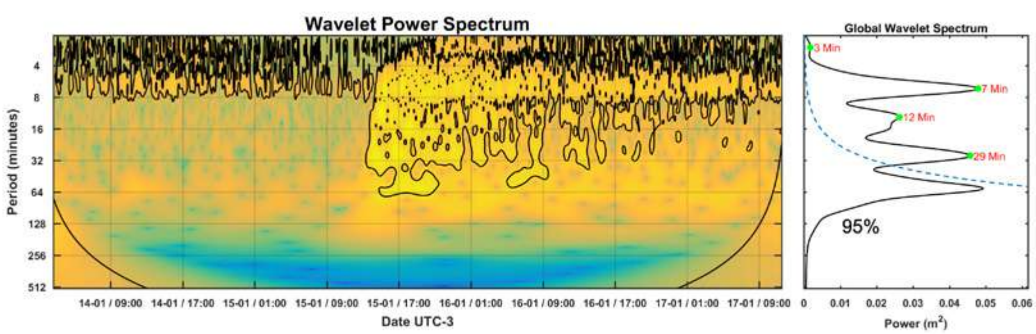

TSUNAMI
Tide Gauge QUEULE
Amplitude (m)
Date UTC-3

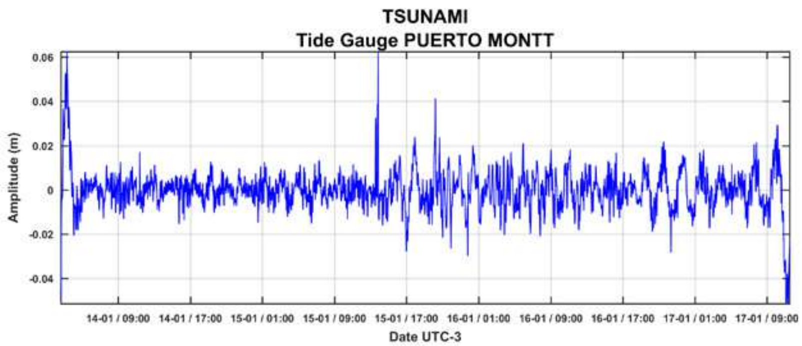

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
16 Min
38 Min
80 Min
119 Min
95%
Power (m²)

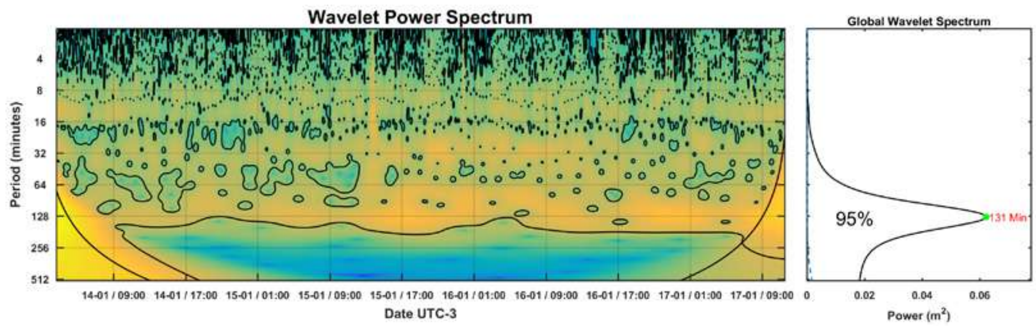

TSUNAMI
Tide Gauge CORRAL
Amplitude (m)
Date UTC-3

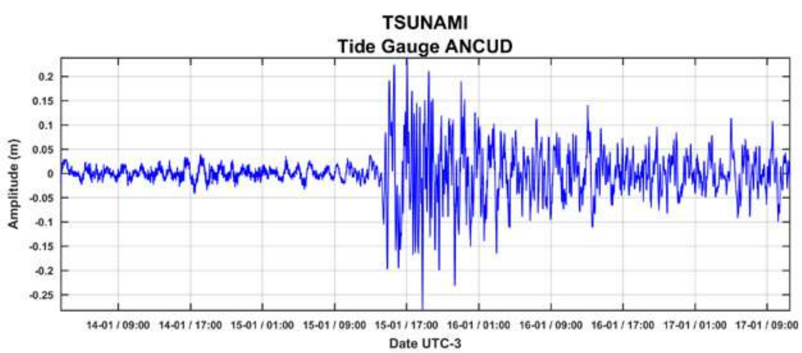

Wavelet Power Spectrum
Global Wavelet Spectrum
Period (minutes)
Date UTC-3
Power (m²)
9 Min
35 Min
87 Min
119 Min
95%

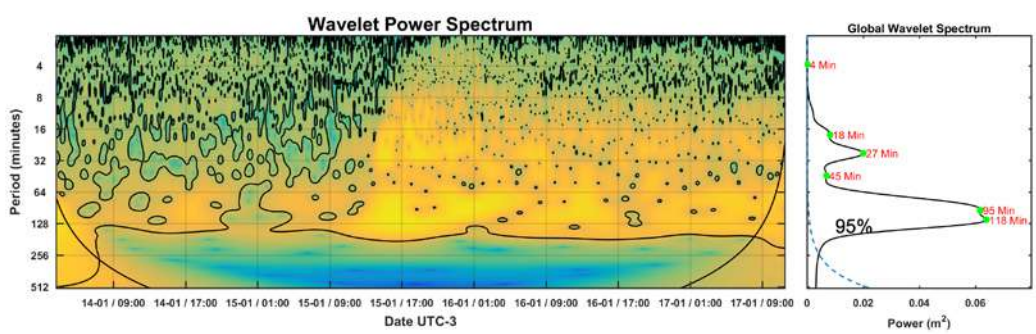

TSUNAMI
Tide Gauge BAHÍA MANSA
Amplitude (m)
Date UTC-3

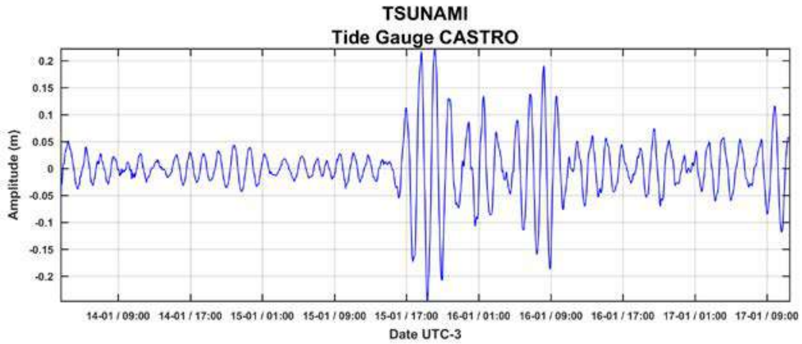

Wavelet Power Spectrum
Global Wavelet Spectrum
Period (minutes)
Date UTC-3
Power (m²)
3 Min
7 Min
12 Min
29 Min
95%

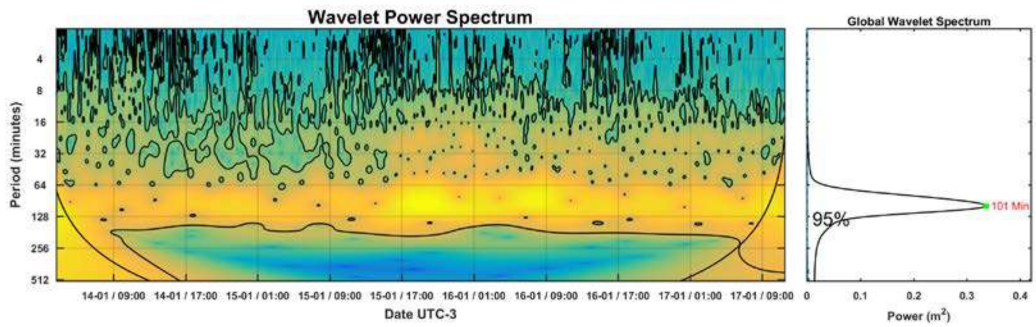

TSUNAMI
Tide Gauge PUERTO MONTT
Amplitude (m)
Date UTC-3
14-01 / 09:00
14-01 / 17:00
15-01 / 01:00
15-01 / 09:00
15-01 / 17:00
16-01 / 01:00
16-01 / 09:00
16-01 / 17:00
17-01 / 01:00
17-01 / 09:00

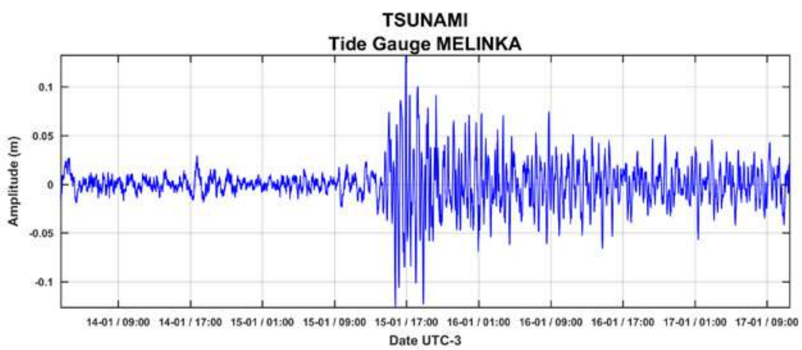

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
95%
131 Min
Power (m^2)

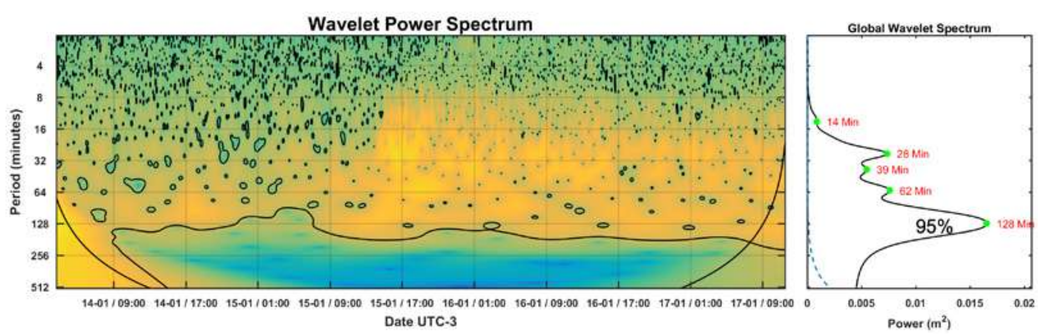

TSUNAMI
Tide Gauge ANCUD
Amplitude (m)
Date UTC-3

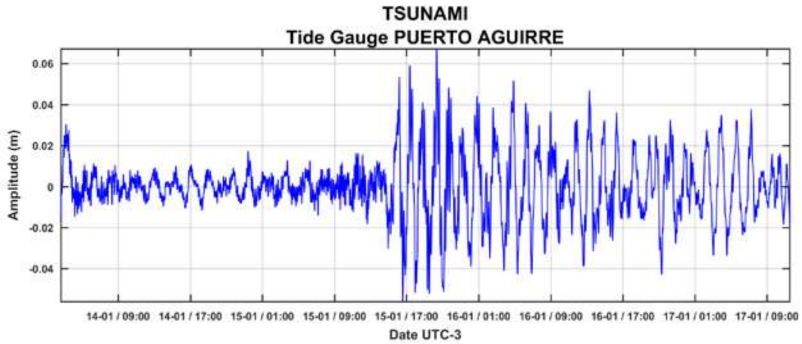

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
4 Min
18 Min
27 Min
45 Min
95 Min
118 Min
95%
Power (m^2)

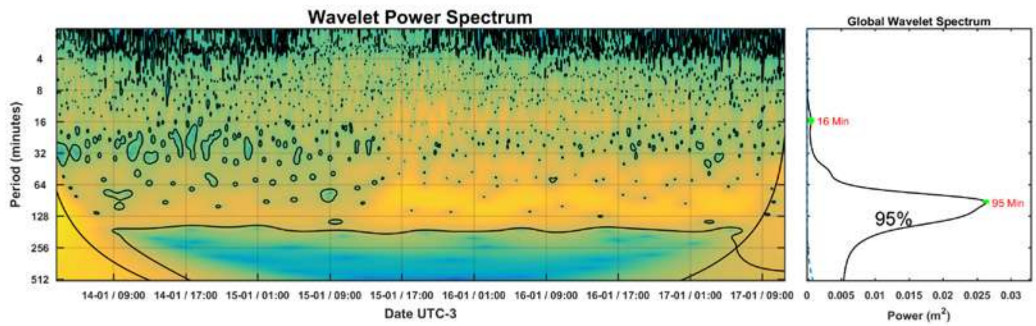

TSUNAMI
Tide Gauge CASTRO
Amplitude (m)
Date UTC-3

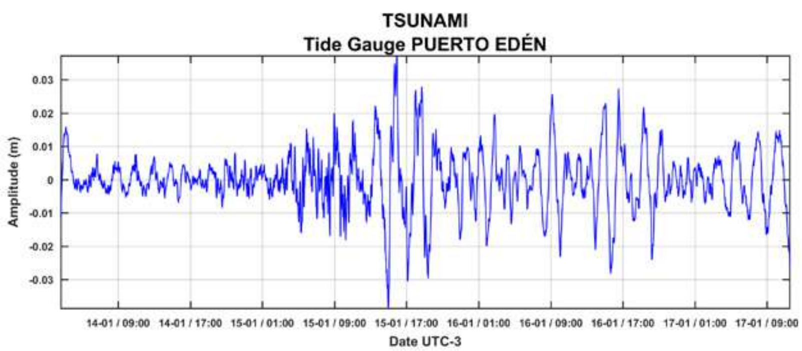

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
101 Min
95%
Power (m²)

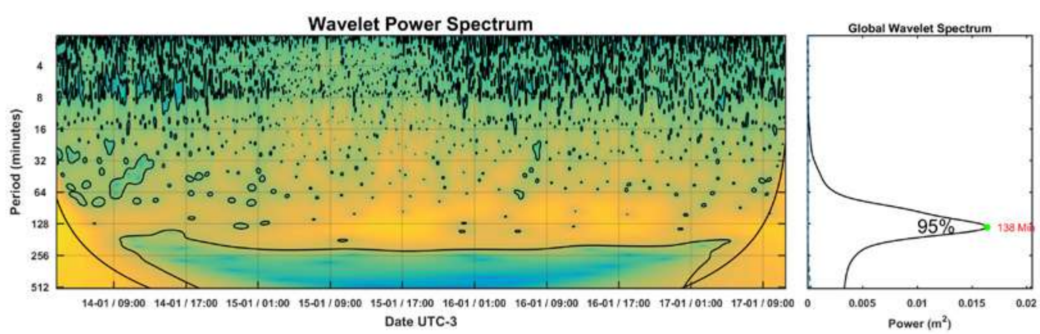

TSUNAMI
Tide Gauge MELINKA
Amplitude (m)
Date UTC-3

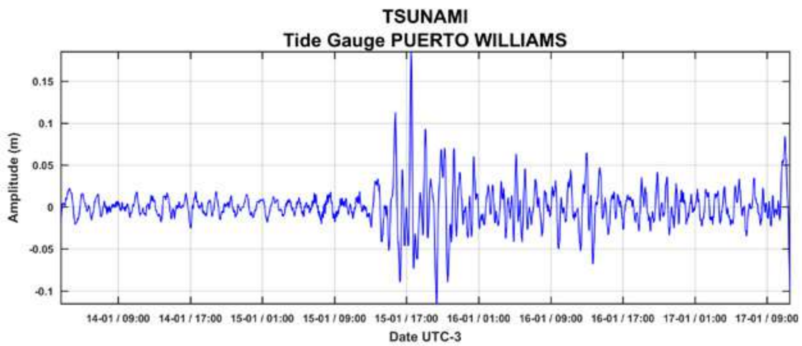

Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
14 Min
28 Min
39 Min
62 Min
128 Min
95%
Power (m²)

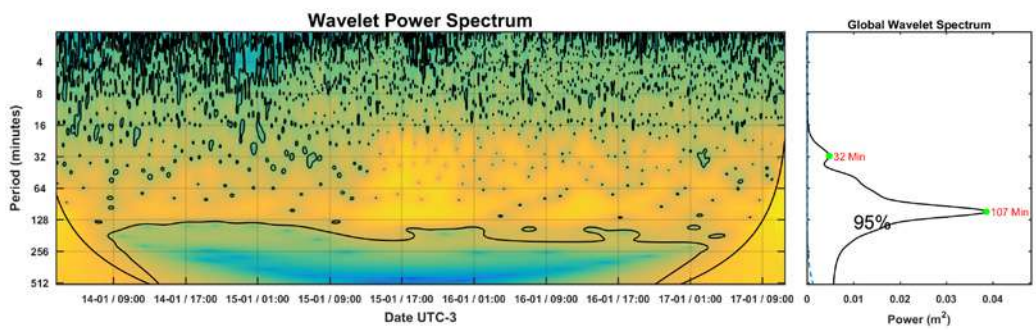

TSUNAMI
Tide Gauge PUERTO AGUIRRE
Amplitude (m)
0.06
0.04
0.02
0
-0.02
-0.04
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3

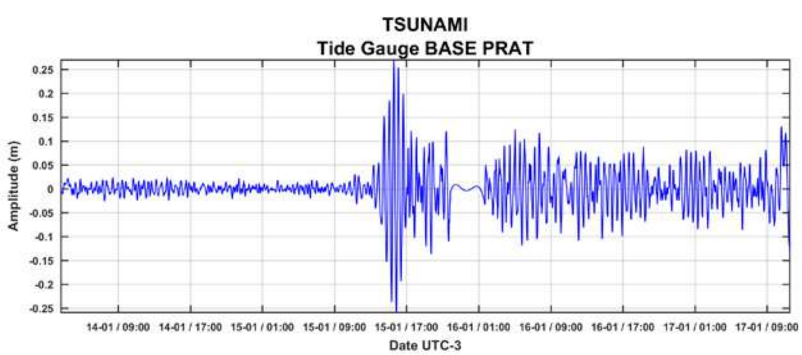

Wavelet Power Spectrum
Period (minutes)
4
8
16
32
64
128
256
512
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3
Global Wavelet Spectrum
16 Min
95 Min
95%
0 0.005 0.01 0.015 0.02 0.025 0.03
Power (m²)

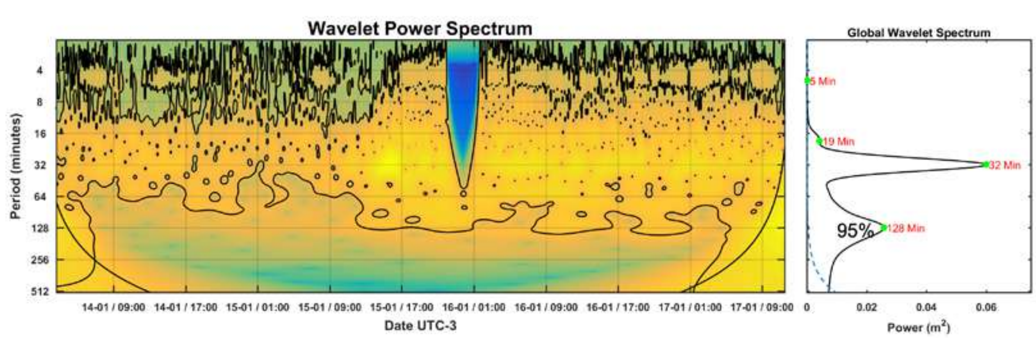

TSUNAMI
Tide Gauge PUERTO EDÉN
Amplitude (m)
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3

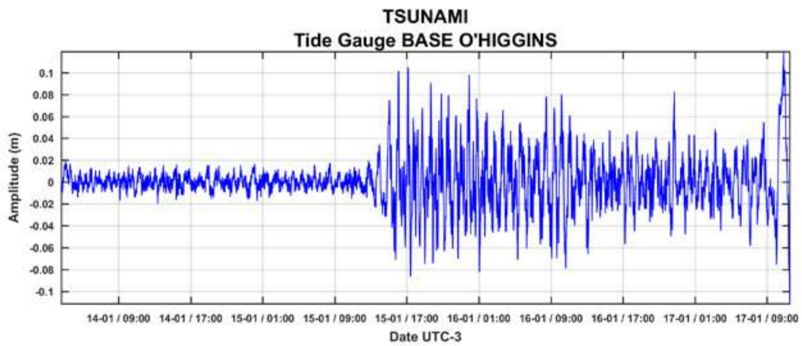

Wavelet Power Spectrum
Period (minutes)
4
8
16
32
64
128
256
512
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00
Date UTC-3
Global Wavelet Spectrum
95%
0 0.005 0.01 0.015 0.02
Power (m²)

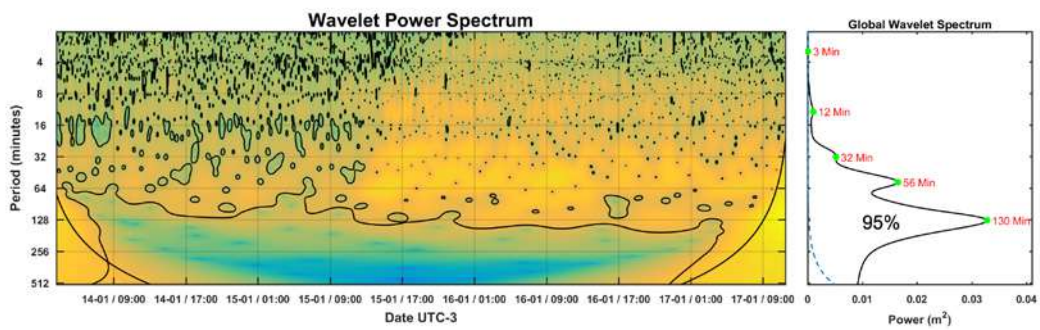

TSUNAMI
Tide Gauge PUERTO WILLIAMS
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00


Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
32 Min
107 Min
95%
Power (m²)


TSUNAMI
Tide Gauge BASE PRAT
Amplitude (m)
Date UTC-3
14-01 / 09:00 14-01 / 17:00 15-01 / 01:00 15-01 / 09:00 15-01 / 17:00 16-01 / 01:00 16-01 / 09:00 16-01 / 17:00 17-01 / 01:00 17-01 / 09:00


Wavelet Power Spectrum
Period (minutes)
Date UTC-3
Global Wavelet Spectrum
5 Min
19 Min
32 Min
128 Min
95%
Power (m²)


TSUNAMI
Tide Gauge BASE O'HIGGINS
Amplitude (m)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
14-01 / 09:00
14-01 / 17:00
15-01 / 01:00
15-01 / 09:00
15-01 / 17:00
16-01 / 01:00
16-01 / 09:00
16-01 / 17:00
17-01 / 01:00
17-01 / 09:00
Date UTC-3


Wavelet Power Spectrum
Period (minutes)
4
8
16
32
64
128
256
512
14-01 / 09:00
14-01 / 17:00
15-01 / 01:00
15-01 / 09:00
15-01 / 17:00
16-01 / 01:00
16-01 / 09:00
16-01 / 17:00
17-01 / 01:00
17-01 / 09:00
Date UTC-3
Global Wavelet Spectrum
3 Min
12 Min
32 Min
56 Min
130 Min
95%
0
0.01
0.02
0.03
0.04
Power (m²)

ANNEX "D"

"Atmospheric Pressure Anomaly Record at Sea Level Stations"

Atmospheric Pressure Anomaly Record at Sea Level Stations						
Sea Level Stations	Atmospheric pressure peak onset time (LT)	Atmospheric peak time (LT)	Maximum atmospheric pressure amplitude (mbar)	Atmospheric pressure peak height (mbar)	ΔT1	ΔT2
Boyeruca	15-01-2022 09:51	15-01-2022 10:09	2,168	2,504	8:41:00	9:59:00
Pisagua	15-01-2022 10:49	15-01-2022 11:04	2,122	2,617	9:39:00	10:54:00
Easter Island	15-01-2022 07:11	15-01-2022 07:28	2,112	2,801	6:01:00	6:28:00
Tocopilla	15-01-2022 10:39	15-01-2022 11:00	2,087	2,808	9:29:00	9:50:00
San Felix Island	15-01-2022 09:36	15-01-2022 09:56	2,004	2,405	8:26:00	8:46:00
Constitución	15-01-2022 09:52	15-01-2022 10:06	1,975	2,404	8:42:00	9:56:00
Coliumo	15-01-2022 09:43	15-01-2022 09:59	1,925	2,207	8:33:00	8:49:00
San Antonio	15-01-2022 09:54	15-01-2022 10:16	1,921	2,496	8:44:00	9:06:00
Valparaíso	15-01-2022 10:04	15-01-2022 10:18	1,908	2,406	8:54:00	9:08:00
Patache	15-01-2022 10:46	15-01-2022 11:01	1,895	2,603	9:36:00	10:51:00
Iquique	15-01-2022 10:48	15-01-2022 11:03	1,888	2,600	9:38:00	10:53:00
Chañaral	15-01-2022 10:23	15-01-2022 10:43	1,814	2,614	9:13:00	9:33:00
Quintero	15-01-2022 09:58	15-01-2022 10:17	1,808	2,395	8:48:00	9:07:00
Arica	15-01-2022 10:51	15-01-2022 11:07	1,807	2,503	9:41:00	10:57:00
Mejillones	15-01-2022 10:38	15-01-2022 10:53	1,801	2,605	9:28:00	9:43:00
Talcahuano	15-01-2022 09:45	15-01-2022 09:59	1,797	2,299	8:35:00	8:49:00
Quiriquina Island	15-01-2022 09:57	15-01-2022 10:16	1,781	2,313	8:47:00	9:06:00
Pichidangui	15-01-2022 09:57	15-01-2022 10:16	1,707	2,306	8:47:00	9:06:00
Coquimbo	15-01-2022 10:09	15-01-2022 10:27	1,696	2,306	8:59:00	9:17:00
Paposo	15-01-2022 10:35	15-01-2022 10:47	1,682	2,591	9:25:00	9:37:00
Juan Fernandez	15-01-2022 09:32	15-01-2022 09:46	1,656	2,095	8:22:00	8:36:00
Puerto Aldea	15-01-2022 10:10	15-01-2022 10:26	1,604	2,306	9:00:00	9:16:00
Coronel	15-01-2022 09:41	15-01-2022 09:57	1,603	2,102	8:31:00	8:47:00
Punta Choros	15-01-2022 10:12	15-01-2022 10:29	1,603	2,197	9:02:00	9:19:00
Antofagasta	15-01-2022 10:48	15-01-2022 10:58	1,598	2,684	9:38:00	9:48:00
Caldera	15-01-2022 10:26	15-01-2022 10:38	1,508	2,612	9:16:00	9:28:00
Base Prat	15-01-2022 09:21	15-01-2022 09:33	1,506	1,996	8:11:00	8:23:00
Huasco	15-01-2022 10:23	15-01-2022 10:35	1,494	2,314	9:13:00	9:25:00
Taltal	15-01-2022 10:25	15-01-2022 10:45	1,488	2,514	9:15:00	9:35:00
Nehuentúe	15-01-2022 09:35	15-01-2022 09:47	1,403	1,399	8:25:00	8:37:00
Lebu	15-01-2022 09:36	15-01-2022 09:53	1,395	2,000	8:26:00	8:43:00
Queule	15-01-2022 09:25	15-01-2022 09:49	1,299	1,601	8:15:00	8:39:00
Bahía Mansa	15-01-2022 09:29	15-01-2022 09:43	1,298	1,597	8:19:00	8:33:00
Corral	15-01-2022 09:34	15-01-2022 09:46	1,204	1,608	8:24:00	8:36:00
Castro	15-01-2022 09:25	15-01-2022 09:37	1,102	1,212	8:15:00	8:27:00
Ancud	15-01-2022 09:28	15-01-2022 09:39	0,996	2,000	8:18:00	8:29:00
Puerto Aguirre	15-01-2022 09:19	15-01-2022 09:30	0,994	1,286	8:09:00	8:20:00
Base O'Higgins	15-01-2022 09:21	15-01-2022 09:35	0,990	1,612	8:11:00	8:25:00
Melinka	15-01-2022 09:19	15-01-2022 09:32	0,888	1,502	8:09:00	8:22:00
Puerto Williams	15-01-2022 09:17	15-01-2022 09:36	0,706	1,503	8:07:00	8:26:00

Maximum atmospheric pressure amplitude*: represents the difference between the maximum and the mean value of the record.*
Atmospheric pressure peak height*: represents the difference between the maximum value and the consecutive minimum reached by the pressure fluctuation in the record.*
ΔT 1*: is the time difference between the onset of the atmospheric peak and the time of the volcanic eruption.*
ΔT 2*: is the time difference between the atmospheric peak and the time of the volcanic eruption.*

SHOA

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