The world's first meteotsunami observation with muography

1. Release Highlights:

- A meteotsunami (Note 1) associated with Japan's 16th typhoon of 2021 was successfully detected with the undersea muographic array (Note 2) called HKMSDD for the first time.
- This was also the first time that muography (Note 3) was applied to observations of oceanographic phenomena.
- By deploying HKMSDD to other underwater tunnels globally, the cycles and processes of meteotsunamis and other dynamic oceanographic phenomena worldwide can be studied from different perspectives and with more detail than was available before.

2. Release Summary:

The University of Tokyo International Muography Research Organization (Muographix) has installed the world's first undersea muographic array called HKMSDD (Hyper KiloMetric Submarine Deep Detector), and has been continuously operating since then; recently this array in Tokyo Bay (also called TS-HKMSDD) has successfully observed a phenomenon called meteotsunami with muography for the first time in collaboration with the University of Tokyo Institute for Industrial Science, the University of Tokyo Graduate School of Frontier Sciences, the University of Tokyo Atmosphere and Ocean Research Institute, Kyushu University, NEC Corporation, the University of Sheffield, Durham University, STFC Boulby Underground Laboratory, Istituto Nazionale di Fisica Nucleare, the University of Salerno, Wigner Research Centre for Physics, Atacama University, and Oulu University Kerttu Saalasti Institute.

HKMSDD utilizes the muography technique, which is similar in principle to x-ray imagery in that it can be utilized for non-invasive, internal imaging, and it utilizes the characteristics of the cosmic-ray muon (Note 4) to act as a probe. Muography has successfully been proven to be a practical method to image the internal structures of large, solid land bodies such as volcanoes, nuclear reactors, and pyramids. With this new development, oceanographic phenomenon has been added to this list of applicable targets.

This particular meteotsunami that was detected is thought to be associated with Japan's 16th typhoon of 2021 during its passage near Tokyo Bay. There are still many mysteries about meteotsunami, particularly about its mechanism and cycles. HKMSDD arrays could contribute new data in places that are vulnerable to these meteotsunami events (almost all ports worldwide are potentially in this category) which are unsuitable for other detection devices (like tide gauge stations) at a comparatively low cost in pre-existing underwater structures.

3. Release Content:

Observation of a meteotsunami.

After being accelerated by galactic high-energy events such as supernova explosions, galactic cosmic rays travel vast distances before interacting with the Earth's atmosphere and generating the elementary particles called muons. These are the particles which are utilized as probes in muography. Muons are mainly generated in the uppermost troposphere (a part of the atmosphere of Earth which is approximately 13 km above sea level), but the number of muons that can be detected depends on the density and thickness of the seawater directly above the underwater tunnel which contains HKMSDD (Figure 1). Therefore, by counting the number of muons at HKMSDD, sea level variations can be detected.

Although the mechanism of meteotsunami is not yet entirely understood, prior works suggest that this phenomonen is caused when two factors occur at the same time: 1. atmospheric energy is transferred to a body of water and 2. the propagation speed of the atmospheric disturbance is approximately equal to the local free wave speed. When these two events happen concurrently, the energy transfer is more efficient and concentrated, which is a condition that tends to develop into meteotsuami.

Figure 2 shows the meteorological history of Typhoon-16, 2021 as it passed near coastal cities in Japan: Irozaki, Yokohama and Mito. Since the linear distance between Irozaki and Yokohama and that between Yokohama and Mito are both 120 km, we can calculate that the average speed of the typhoon between Irozaki and Yokohama and that between Yokohama and Mito were 40 kmh^{-1} and 60 kmh^{-1}, respectively. Considering the depth of Tokyo Bay ranges from 15 m -20 m, the free wave speed would be 44 kmh^{-1}-50 kmh^{-1} in Tokyo Bay. Therefore, the movement speed of the pressure drops was similar to the local free wave speed, increasing the probability that a meteotsunami would be generated in Tokyo Bay.

Figure 3 shows the muographically measured time series of the abnormal tides. This data showed that the meteotsunami's damping coefficient for Tokyo Bay was in agreement with prior studies (orange lines). The currently observed decay time in Tokyo Bay was much shorter than the decay time (green lines) that was observed in Lake Geneva which has a larger water depth (150 m). This shorter decay time matches the meteotsunami damping model proposed in prior studies.

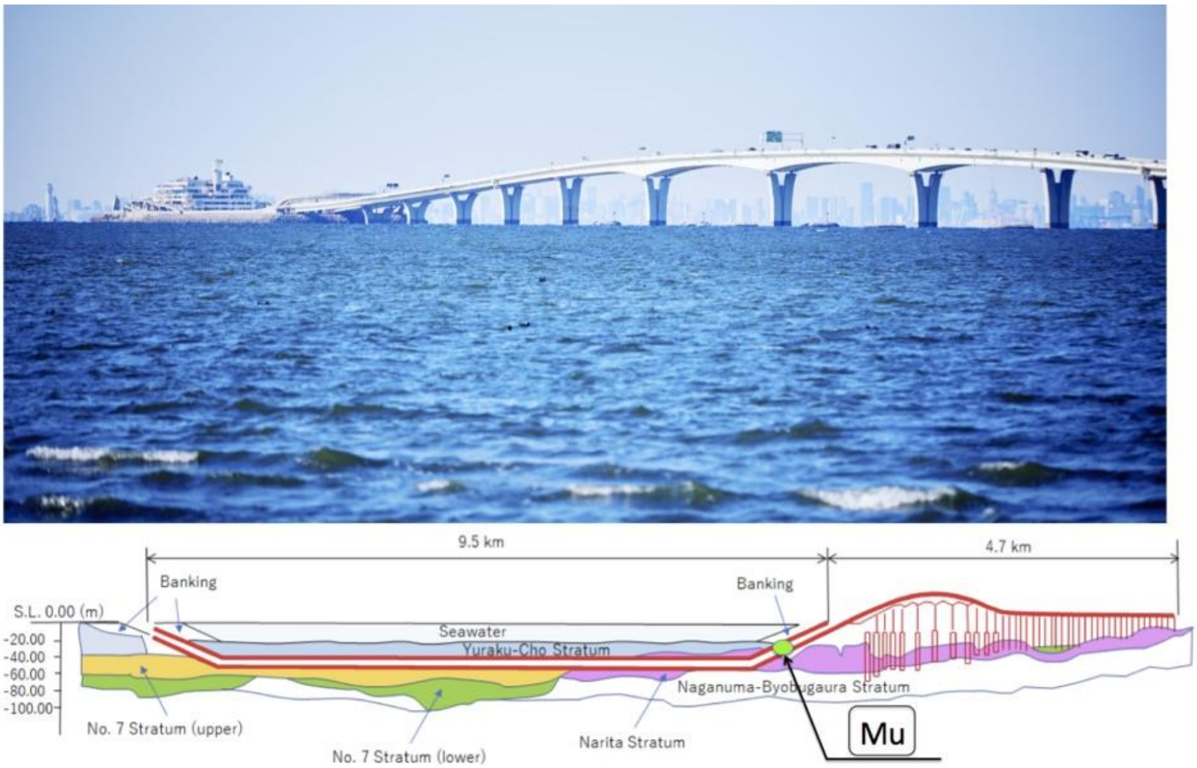

Figure 1: Photograph of Tokyo Bay Aqua-line and the location of TS-HKMSDD

The label Mu indicates the location of TS-HKMSDD.

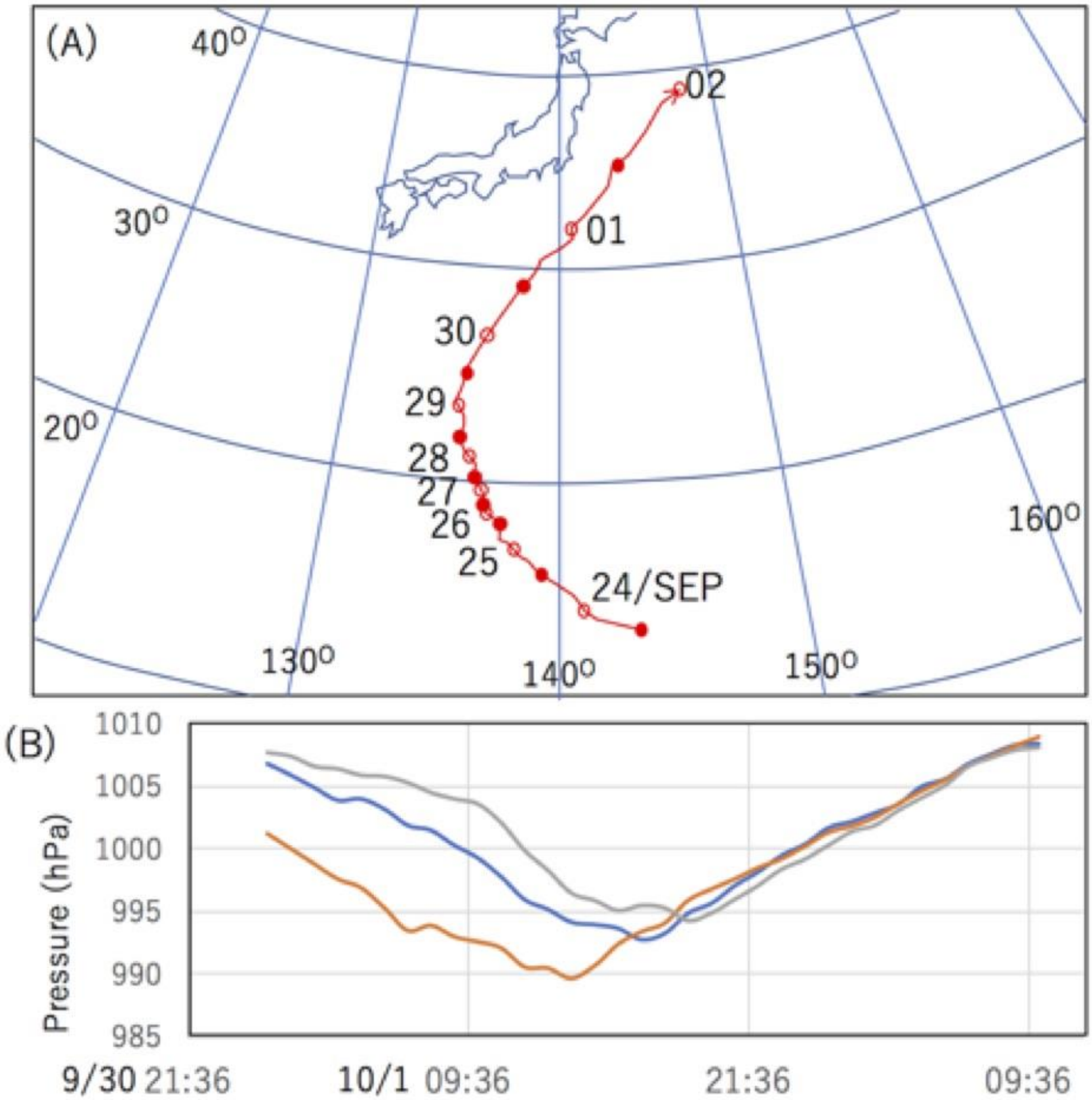

Figure 2: Meteorological history of Typhoon-16 and the sequence of the pressure drops.

The passage of Typhoon-16 (A) and the sequence of the pressure drops observed in the cities Irozaki (orange), Yokohama (blue), and Mito (grey).

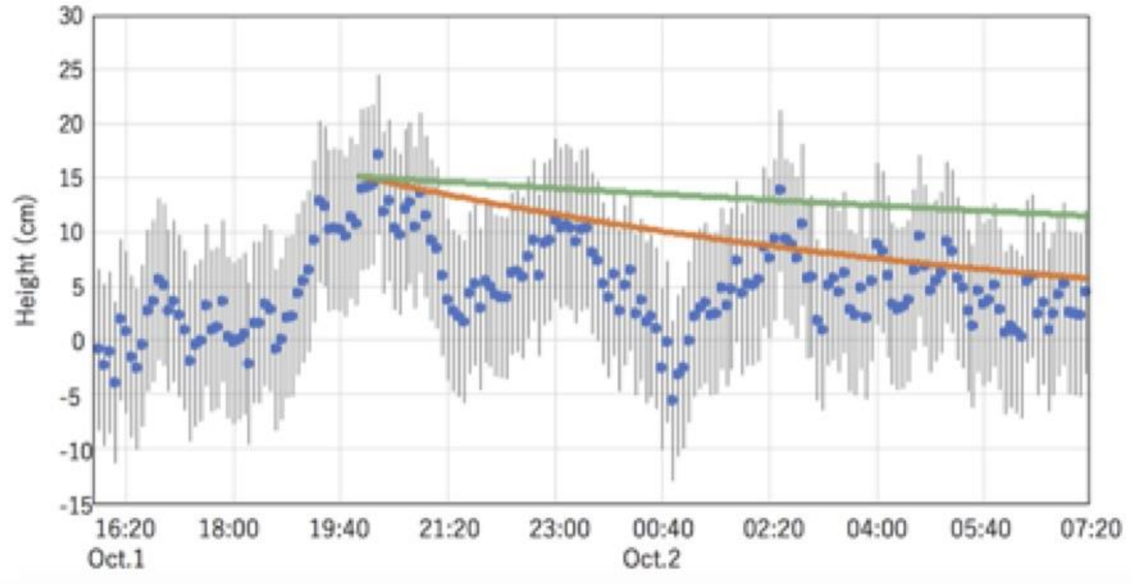

Figure 3. Muographically measured time series of the abnormal tides

The decay curves calculated for Tokyo Bay (orange) and Lake Geneva (green) are overlaid. Vertical bars indicate the standard deviation error bars.

Future Prospects. Owing to the ubiquitous nature of atmospheric disturbances, associated meteotsunamis can add to the risk posed by seismic tsunamis or can increase the risk to regions not traditionally recognized as seismic-tsunami-prone. Other meteotsunami events have taken place, for example, in the English Channel and the Gulf of Finland. These two regions also have the potential to be future HKMSDD sites. The Channel Tunnel connects the UK to France and could be used for similar measurements. Similarly, if the planned underwater tunnel project is constructed across the Gulf of Finland to connect Finland and Estonia, this could also be a good candidate location for HKMSDD. If these future United Kingdom (UK-HKMSDD) and Finland (FI-HKMSDD) array projects are realized, they could be utilized to (like TS-HKMSDD) collect data on sea level/oceanographic phenomenon both locally and also sharing data as part of a larger global network which would have the potential to increase and improve our understandings about meteotsunamis as new hubs are added.

4. Contact:

Professor Hiroyuki K.M. Tanaka Director, International Muography Collaborative Research Organization, The University of Tokyo
1-1-1, Yayoi, Bunkyo-ku, Tokyo 113-0032
Email: ht”at”muographix.u-tokyo.ac.jp
ht”at”eri.u-tokyo.ac.jp
ht”at”virtual-muography-institute.org

* Please send to all three addresses. International Muography Research Organization
Website: www.muographix. u-tokyo.ac.jp

5. Journal information:

Journal title: Scientific Reports
Article title: Periodic sea-level oscillation in Tokyo Bay detected with the Tokyo-Bay Seafloor Hyper-Kilometric Submarine Deep Detector (TS-HKMSDD)

Authors：Hiroyuki K. M.Tanaka*, Masaatsu Aichi, Szabolcs József Balogh, Cristiano Bozza, Rosa Coniglione, Jon Gluyas, Naoto Hayashi, Marko Holma, Jari Joutsenvaara, Osamu Kamoshida, Yasuhiro Kato, Tadahiro Kin, Pasi Kuusiniemi, Giovanni Leone, Domenico Lo Presti, Jun Matsushima, Hideaki Miyamoto, Hirohisa Mori, Yukihiro Nomura, Naoya Okamoto, László Oláh, Sara Steigerwald, Kenji Shimazoe, Kenji Sumiya, Hiroyuki Takahashi, Lee F. Thompson, Tomochika Tokunaga, YusukeYokota, Sean Paling & Dezső Varga

DOI：10.1038/s41598-022-10078-2

URL：https://www.nature.com/articles/s41598-022-10078-2

6. Glossary:

(Note 1) Meteotsunami, Meteotsunamis or meteorological tsunamis are tsunami-like sea-level oscillations that take place in closed or semi-closed water bodies in bays, lakes or channels with periods ranging from minutes to several hours. The temporal and spatial characteristics of meteotsunamis and seismic tsunamis are similar. While meteotsunamis are generally associated with frontal passages and cyclones, other causes are possible such as the recent air shock associated with the 2022 Hunga Tonga–Hunga Ha'apai eruption that generated a global meteotsunami event.

(Note 2) Tokyo Bay Seafloor Hyper KiloMetric Submarine Deep Detector (TS-HKMSDD): Muographic modules that can detect elementary particle muons (Note 3) are arranged at regular intervals. Whenever a muon is detected, a signal is collected and recorded at a data acquisition center located in the center of the TS-HKMSDD. TS-HKMSDD was installed inside the Tokyo Bay Aqua-Line undersea tunnel (over 100 meters long), but further expansion and installation of new muographic arrays are planned in Tokyo Bay as well as in locations worldwide, such as the North Sea, the British-French Strait, and the Gulf of Finland.

(Note 3) Muography: Similar to x-ray technology, muography takes advantage of the strong penetration of cosmic-ray muons (Note 4) (high energy muons can travel through 1 km or more on rock before decaying), and this characteristic has been utilized for imaging the internal structure of gigantic objects on land. X-rays generate medical radiographic images since most x-rays can travel through the soft tissue within a human body without interacting and decaying. Due to the penetration power of high energy muons, they can travel through deep seawater and beyond without interacting and decaying, therefore it is possible to create images with this method (similar to X-ray photographs) to discover, for example, the density distribution and/or depth of the ocean and seafloor using muography.

(Note 4) Cosmic-ray muon: When particles called cosmic rays, which are accelerated to nearly the speed of light by high-energy events (such as supernovae) reach Earth, they react with the atomic nuclei of nitrogen and oxygen that make up the atmosphere to generate high-energy secondary particles. One of these generated particles is an elementary particle called the muon, which has strong penetrating power.