



Image credit: NOAA

# The science behind tsunamis

**Focus areas:** Ocean & Coasts **Topics:** tsunamis

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## What is a tsunami?

A tsunami is a series of waves generated by a large and sudden displacement of the ocean. Large earthquakes below or near the ocean floor are the most common cause, but landslides, volcanic activity, certain types of weather and meteorites can also cause tsunamis.

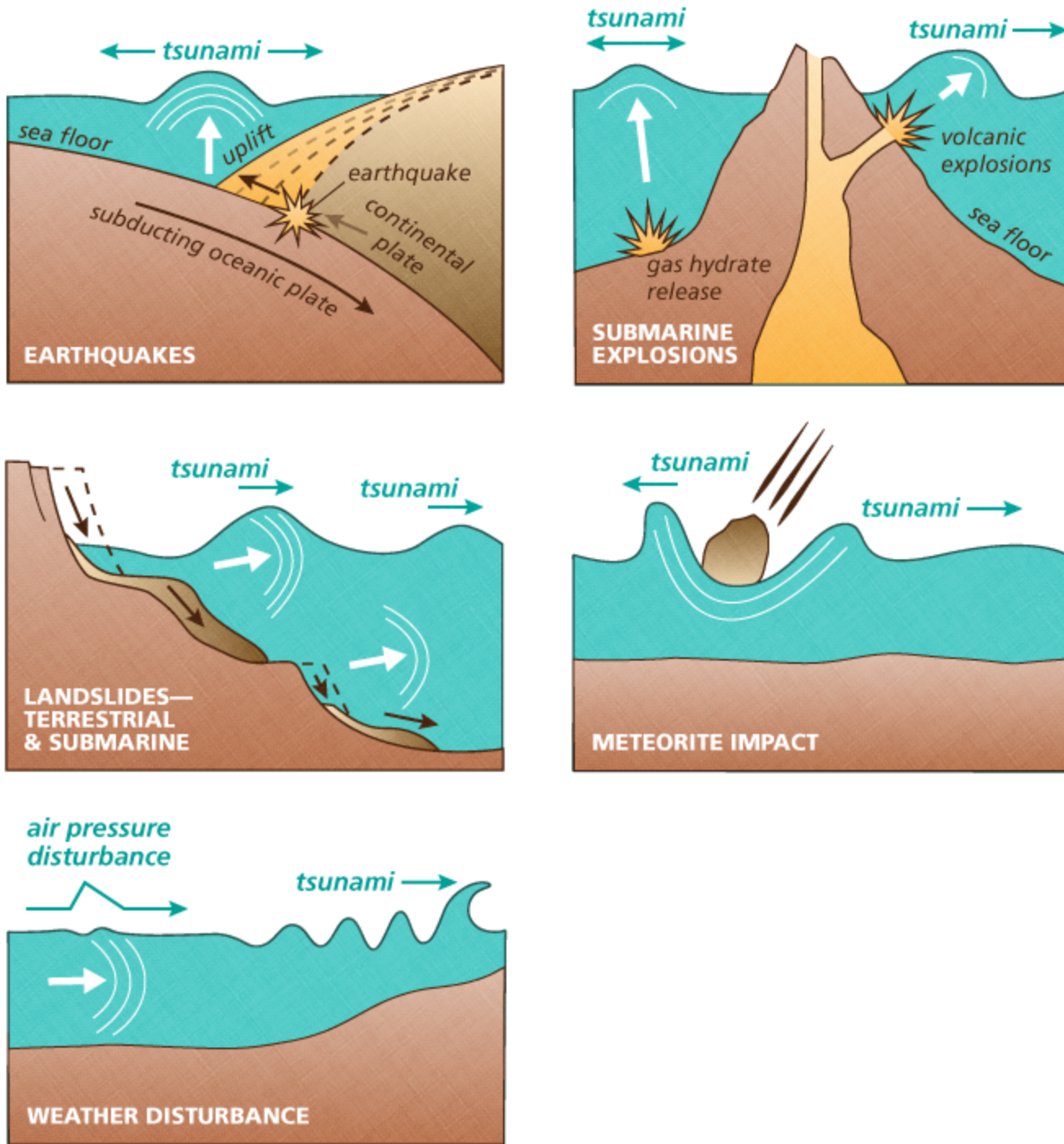
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Indonesia 10 Years After Devastating Indian Ocean Tsunami in December 2004 - A composite image showing a comparison between a coastline in Aceh, Indonesia, in 2004 (left) and again in 2014 (right). Aceh was the worst hit location, being the closest major city to the epicentre of the 9.1 magnitude quake on December 26, 2004. It suffered a huge hit from the following tsunami which resulted in around 130,000 deaths. Throughout the affected region of eleven countries, nearly 230,000 people were killed, making it one of the deadliest natural disasters in recorded history. (Image credit: Getty Images)

Tsunamis radiate outward in all directions from their source and can move across entire ocean basins, around islands and into bays, sounds and up rivers. When they reach the coast, they can cause dangerous coastal flooding and powerful currents that impact marine operation and navigation, and can last for several hours or days.

# TSUNAMI GENERATION SOURCES



Tsunami generation sources. Credit: Washington Geological Survey, Department of Natural Resources partially modified from a diagram by Adam Switzer.  
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Tsunamis are infrequent but can pose a serious threat to life and property when they occur. Tsunamis have claimed hundreds of thousands of lives and caused hundreds of billions of dollars in damage around the world.

In deep ocean water, tsunami waves may go unnoticed. But as the waves travel closer to the shore, they build in height as the water becomes more shallow. The speed of tsunami waves depends on ocean depth: The deeper the water, the faster the wave travels. Tsunami waves may travel as fast as jet planes through deep waters, only slowing down when reaching shallow waters. While tsunamis are often referred to as tidal waves, this name is discouraged by oceanographers because tides have little to do with these destructive waves — though a tsunami at high tide may cause more damage and flooding.

## **What causes a tsunami?**

About 80% of all known tsunamis are triggered by earthquakes. These seismic events move Earth's surface, displacing the water above and generating waves that rapidly travel in all directions across the ocean or body of water.

Not all earthquakes create tsunamis. An earthquake must be big enough and close enough to the ocean floor to cause the vertical movement of the ocean floor that typically sets a tsunami in motion. As the ocean floor rises or drops, so does the water above it. As the water moves up and down, seeking to regain its balance, the tsunami radiates in all directions. The amount of movement of the ocean floor, the size of the area over which it occurs (which may be reflected in how long the earthquake lasts) and the depth of the water at its source are all critical factors in the size of a resulting tsunami. Earthquakes can also cause landslides that generate tsunamis.

## **How landslides generate tsunamis**

Tsunamis can be generated when a landslide enters the water and displaces it from above (subaerial) or when water is displaced ahead of and behind an underwater (submarine) landslide. Tsunami generation depends on the amount of landslide material that displaces the water, the speed it is moving and the depth it moves to. Landslide-generated tsunamis may be larger than seismic tsunamis near their source and can impact coastlines within minutes with little to no warning, but they usually lose energy quickly and rarely affect distant coastlines.

Most landslides that generate tsunamis are caused by earthquakes, but other forces (like gravity, wind and increased precipitation) can cause overly steep and otherwise unstable slopes to suddenly fail. Earthquakes that are not large enough to directly generate a tsunami may be large enough to cause a landslide, which can in turn generate a tsunami. A landslide-generated tsunami may occur independently or along with a tsunami directly generated by an earthquake, which can complicate the warning process and compound the losses.

# What is a meteotsunami?

Large storms over the ocean or large water bodies can cause meteotsunamis, which, like tsunamis, can also be destructive.

Meteotsunamis are driven by air-pressure disturbances often associated with fast-moving weather events, such as severe thunderstorms, squalls and other storm fronts. The storm generates a wave that moves towards the shore, and is amplified by a shallow continental shelf and inlet, bay or other coastal feature.

Meteotsunamis have been observed to reach heights of 6 feet (1.82 meters) or more. They occur in many places around the world, including the Great Lakes, Gulf of Mexico, Atlantic Coast and the Mediterranean and Adriatic Seas.

Identifying a meteotsunami is a challenge because its characteristics are almost indistinguishable from a seismic tsunami. Meteotsunamis can also be confused with wind-driven storm surge or a seiche. These uncertainties make it difficult to predict a meteotsunami and warn the public of a potential event. However, NOAA scientists have identified atmospheric conditions that are likely to generate meteotsunamis and continue to research them.

## Where do tsunamis occur?

Although tsunamis occur relatively infrequently, they can be a serious threat to life and property. Tsunamis have claimed hundreds of thousands of lives and caused hundreds of billions of dollars in damage around the world.

A tsunami can strike any coast (ocean, lake or even river) at any time. There is no season for tsunamis. This is quite evident when we look at records of past tsunamis. Tsunamis typically happen where there are large faults that can generate large earthquakes. Most of these large faults are around the Pacific Ring of Fire. However, any active fault that crosses water may be capable of generating a tsunami. As mentioned above, other causes of tsunamis include landslides and volcanic eruptions which can happen far away from any ocean coastline.

Tsunamis are sometimes referred to as "tidal waves," but this is very misleading as they are not related to tides.

# Tsunamis throughout history

## What information do we have about tsunamis that happened in the past?

The NOAA/World Data Service (WDS) tsunami database is a listing of historical tsunami source events and runup (inland flooding extent) locations throughout the world that range in date from 2000 BCE to the present. The natural hazards datasets for tsunamis are available through the HazEL (Hazardous Event Lookup) interface, developed by NOAA's National Centers for Environmental Information (NCEI).

The events were gathered from scientific and scholarly sources, regional and worldwide catalogs, tide gauge data, deep ocean sensor data, individual event reports and unpublished works. One example, [published on the USGS website](#), demonstrates how old records in Japan helped unravel what happened during the “orphan” tsunami of 1700.



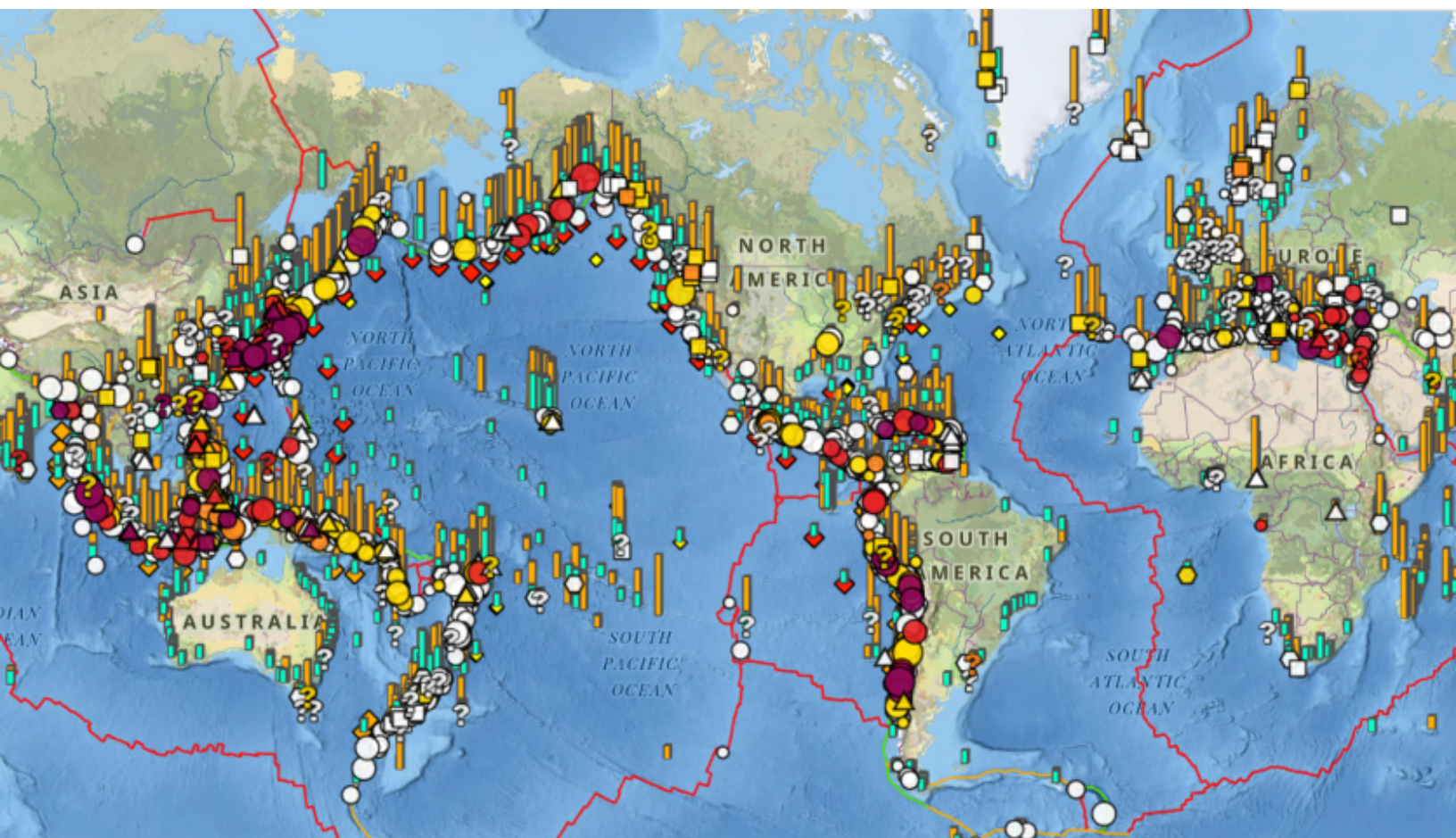
View of Krakatoa during the earlier stage of the eruption, from a photograph taken on Sunday, 27 May 1883. (Image credit: Published in the Report of the Krakatoa Committee of the Royal Society.)

Of the approximately 2,800 events in the [NCEI Global Historical Tsunami Database](#), more than 1,400 are confirmed tsunamis. Over 270 confirmed deadly tsunamis have resulted in over 544,000 known (or confirmed) deaths. It is important to note that this number may include deaths from the generating event (e.g., earthquake) as it is not always possible to separate deaths from the different causes. It is likely that these figures should be much higher, but in many events the actual number of fatalities is not known. Tsunamis have not always been reported the same way throughout history, and the way that deaths resulting from them has not always been counted in the same manner. The tsunamis prior to the 1900s were especially recorded in ways very different from modern methods.

For example, many Indigenous communities have [oral histories](#) of tsunamis that impacted coastlines and damaged or destroyed their communities. By listening to these histories and documenting where similar stories exist along stretches of coastline, researchers are able to better understand and unravel details about tsunamis that happened before there was monitoring equipment or written record of such events.

Between 1900 and 2015, a total of 754 confirmed tsunamis have occurred, with 78% of those events in the Pacific Ocean and 5% in the Indian Ocean, according to the Global Historical Tsunami Database. The highest percentage of tsunamis generated since 1900 are off of Japan (21%) and Indonesia (8%). In the U.S., tsunamis occur about twice a decade. The risk is greatest for states and territories with Pacific and Caribbean coastlines.

# How does NOAA get information about ancient tsunamis?



This map from NCEI's [Natural Hazards Viewer](#), shows the overwhelming number of datapoints that are useful when cataloging historic tsunami information. The map in this figure is displaying significant earthquakes (circles), tsunami events (color, size, and shape coded by tsunami generating source and number of fatalities if known), tsunami observations (shown by bars with heights associated with runup values), DART deployments (diamonds), and major plate boundaries (red lines). (Image credit: NOAA)

[Download Image](#)

The events and observations in the NCEI Global Historical Tsunami Database were gathered from the NOAA Tsunami Warning Centers, NOAA National Data Buoy Center, NOAA National Ocean Service, UNESCO/IOC-NOAA International Tsunami Information Center, NOAA Pacific Marine Environmental Laboratory, U.S. Geological Survey, national and government databases and reports, tsunami catalogs, post-event reconnaissance reports, journal articles, newspapers, internet sources, email and other written documents.

A historical tsunami means it was documented in the written records, or by scientific instrumentation, near the time of the event.

NCEI has archived over 8,000 documents that describe damage and effects from tsunami, earthquake and volcano events. The NCEI historical tsunami database is focused on documented historical tsunamis, as such it does not include sources only inferred from the study of tsunami deposits or other geologic and archeological evidence.

Tsunami deposits are the physical evidence left behind when a tsunami impacts a shoreline or affects submarine sediments. NCEI maintains a list of publications that characterize global tsunami deposits.

## What can we learn from studying historical tsunami records?

Historical tsunami data is critical for a basic understanding of tsunami generation, wave characteristics and coastal impacts.

Historical tsunami records support:

- Calibration and validation of tsunami models, which are needed for forecasts as well as inundation and evacuation mapping.
- Tsunami hazard assessments require historical records since it provides insight into tsunami behavior and what might happen during future events. Risk assessments are needed by emergency managers and coastal zone managers for tsunami hazard mitigation and planning.
- Tsunami Warning Centers may use historical records to evaluate the likelihood of tsunami generation following an earthquake and develop the thresholds of tsunami warning products.
- Land use planners and engineers may use the data to develop safer building codes, zoning and other guidance.
- Media use the information when reporting about hazard response and to increase public awareness.
- Historical tsunami data supports key concepts in Earth Science curriculums for grades K-12 and beyond.
- Public education for life-safety actions. For example, historical records have documented that the following “natural warning signs” may precede tsunami waves: (1) strong or long ground shaking; (2) unusual disappearance of water; (3) the roaring sound of the water.

## 2004 Indian Ocean tsunami

On December 26, 2004, the third-largest earthquake recorded in the world (since 1900) occurred off the west coast of the Indonesian island of Sumatra. One of the most devastating and catastrophic tsunamis recorded, it spread outward throughout the Indian

Ocean and struck the coastlines of 17 countries in southeastern and southern Asia and eastern and southern Africa.

In total, just over a quarter of a million people lost their lives from this tragic event, with another 1.7 million people displaced. In 2017, the cost and damage from the tsunami was estimated to be approximately \$13 billion.



BANDA ACEH, SUMATRA, INDONESIA - JANUARY 4, 2005: A lone mosque remains standing among the damage of a coastal village near Banda Aceh, Sumatra, Indonesia following the 2004 Indian Ocean tsunami. (Image credit: Getty images)

The 9.1 magnitude earthquake in the Indian Ocean was about 19 miles below the ocean floor, and the length of the rupture was roughly 800 miles — basically the size of California's coastline. The quake displaced a massive volume of water to generate a global tsunami, which reached some areas within 20 minutes and others in 7 hours. The tsunami was observed by more than 100 coastal water-

level stations in the Atlantic and Pacific ocean basins. One of the hard-to-grasp statistics from the tsunami were wave heights that reached 167 feet in Indonesia's Aceh province in northern Sumatra, which resulted in flooding up to 3 miles inland.

Once the tsunami reached portions of Asian and African coastlines, the waves advanced inland, carried debris, destroyed once-thriving communities and ruined many livelihoods. Imagine: No more homes, basic services, and critical infrastructure such as roads, power lines, bridges, clean water, gasoline/fuel — essentially all the things we rely on in our modern world. The economies of many countries were devastated. The saltwater from the tsunami damaged soils, crops and vegetation, while completely changing the overall environmental landscape of many Indian Ocean coastal communities.

## **An order of magnitude hard to imagine**

Since 1900, about 5% of all tsunamis have occurred in Southeast Asia, but the scope and magnitude of the 2004 tsunami set it apart from others.

Since this catastrophic event, NOAA has made significant improvements to its tsunami detection, forecasting, warning and preparedness capabilities, including:

- [U.S. Deep-ocean Assessment and Reporting of Tsunamis \(DART\)](#) buoys increased from 6 to 39.
- Installed or upgraded [188 coastal water-level stations](#) to support tsunami warning operations.
- Upgraded the [Global Seismographic Network](#) to transmit 100% of its seismic data in real time.
- Developed [forecasting models](#) to predict the arrival time, duration, height and extent of flooding.
- Expanded the [Tsunami Warning Centers'](#) responsibilities.
- Started the [TsunamiReady](#) program to help communities minimize risk through better hazard assessment, planning, education and warning communications.
- In 2007, the U.S. Congress Established a new Act of Law, the Tsunami Warning and Education Act, which was later revised and reauthorized in 2017 as the Tsunami Warning, Education, and Research Act ([TWERA](#)), which outlines the responsibilities and goals for NOAA and a successful U.S. Tsunami Warning System and Program. TWERA formally established the [National Tsunami Hazard Mitigation Program](#), a program led by NOAA to advance tsunami preparedness at the local level through partnerships and grant funding for at-risk states and territories.

# Monitoring and alert systems

## Where do tsunamis strike?

Tsunamis can strike any U.S. coast and territory any time. The coastlines most at risk are in the Pacific Ocean basin and the Caribbean Sea.

NOAA has two tsunami warning centers in the U.S. that are staffed 24 hours a day, 7 days a week, to monitor and alert for tsunamis from earthquakes. Scientists detect the earthquake, observe the tsunami, forecast tsunami impacts, issue tsunami alert messages, conduct public outreach and coordinate with partners to continually improve warning operations with the main mission in protecting life and property from tsunamis.



Tsunami buoy systems quickly provide critical information to warning centers. (Image credit: NOAA)

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The [National Tsunami Warning Center](#), located in Palmer, Alaska, serves the continental U.S. (East, West and Gulf Coasts), Alaska and Canada. In Ford Island, Hawaii, the [Pacific Tsunami Warning Center](#) (PTWC) serves the Hawaiian Islands and the U.S. Pacific and Caribbean territories, including American Samoa, Guam, Northern Mariana Islands, Puerto Rico, U.S. Virgin Islands and the British Virgin Islands. PTWC also serves as the Pacific Tsunami Warning System's main tsunami service

provider. In this role, PTWC works closely with other international, subregional and national centers to monitor seismic and sea level stations around the Pacific Ocean for large earthquakes and tsunami waves.

Both tsunami warning centers are part of NOAA's National Weather Service (NWS). NWS also leads the [National Tsunami Hazard Mitigation Program \(NTHMP\)](#) and the [International Tsunami Information Center](#) [↗](#) (ITIC). The NTHMP is a coordinated U.S. national effort to mitigate the impact of tsunamis through public education, community response planning, hazard assessment and warning coordination.

## How does NOAA monitor and detect tsunamis generated by earthquakes or volcanic eruptions?

NOAA has a suite of [coastal water-level stations](#) along the West, East and Gulf Coasts and surrounding Alaska, Hawaii, Puerto Rico and U.S. Territories. These stations collect important data about the height of the ocean at specific coastal locations and monitor tides. The data is then relayed by satellite to NOAA's warning centers, where it is used to confirm tsunami height and arrival time, and is incorporated into tsunami forecast models.

In addition to vast coastal water-level stations, NOAA has 39 [Deep-ocean Assessment and Reporting of Tsunami \(DART®\)](#) sea-level systems located strategically throughout the Pacific and Atlantic Ocean basins, the Gulf of Mexico and the Caribbean Sea. The DART systems help identify early detection, measurement and real-time reporting of tsunamis in the open ocean waters.

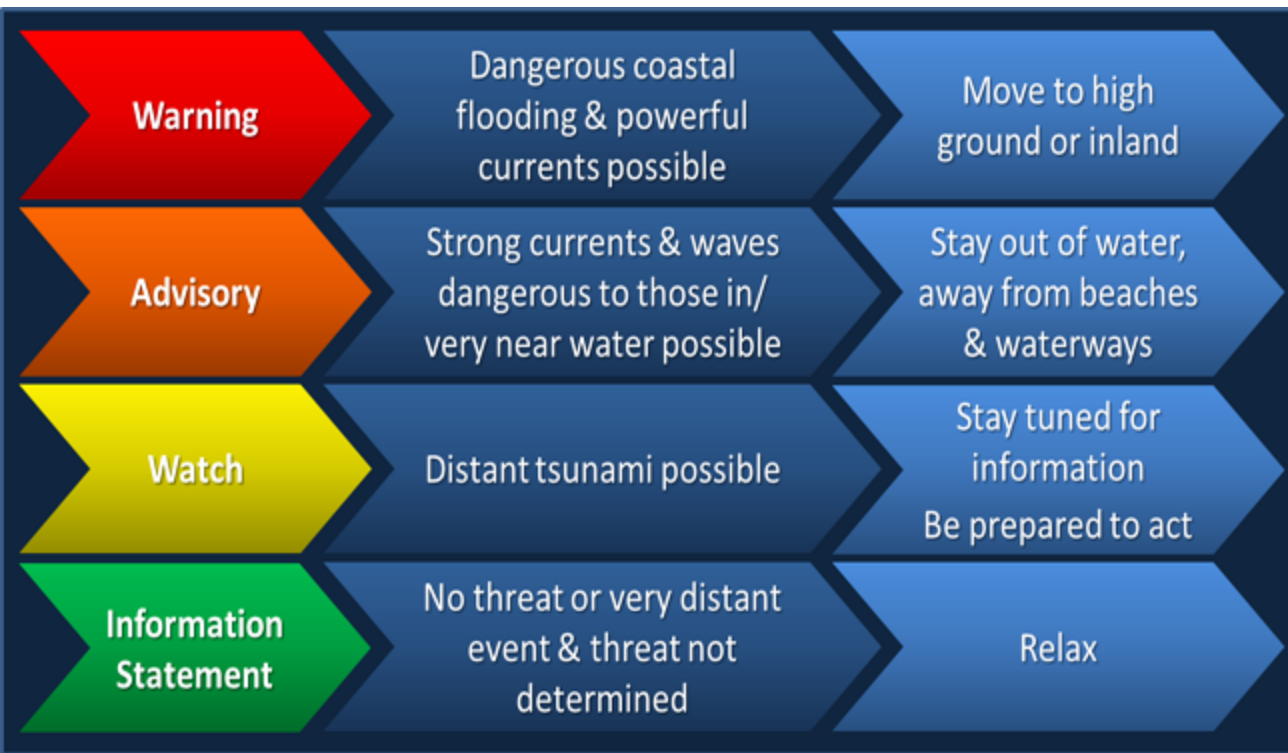
Data from these coastal and DART stations are then relayed via satellite to the warning centers, where they are used to confirm tsunami height and arrival time and incorporated into tsunami forecast models.

A constellation of satellite [radar altimeters](#) — including NOAA's partnered missions ([Jason-3](#) and [Sentinel-6](#)) — measure sea surface height and roughness. Those measurements provide subtle but detectable signals as tsunamis cross the deep ocean: A small, rapid change in sea level paired with altered surface roughness. The data can support and refine tsunami propagation models, allowing for more accurate predictions of wave travel times and coastal impacts. Additionally, altimeter data can enhance bathymetric models by providing information on ocean bottom topography, which affects tsunami wave speed and direction. This approach is not yet operational at NOAA's Tsunami Warning Centers.

# When NTWC and PTWC issue tsunami alerts, what do they mean?

The National Tsunami Warning Center (NTWC) and Pacific Tsunami Warning Center (PTWC) issue four different messages and alerts to notify the public, emergency managers and other local officials and partners about the potential for a tsunami following a possible tsunami-generating event.

Below are the four types of messages and their definitions:



Tsunami alerts for U.S. and Canada: what they mean and what you should do (full tsunami alert definitions).

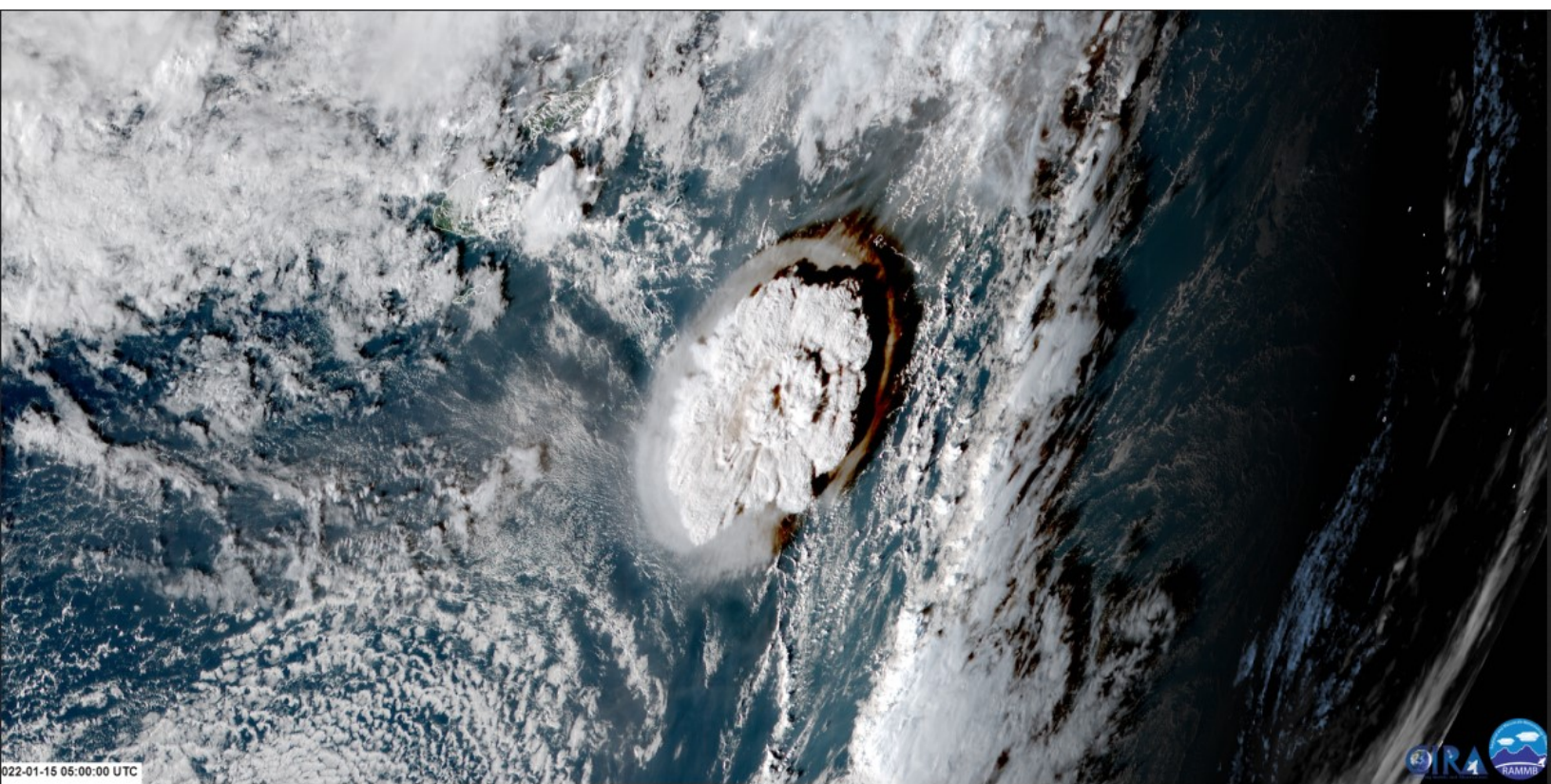
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## Tsunami mitigation and research: What's next?

NOAA's National Weather Service (NWS) is currently going through a transformation throughout the agency, as outlined in its Priorities & Action Strategies for the Future. One of the actions is to revamp the tsunami program, primarily the operational alignment of

the two NWS Tsunami Warning Centers (TWC), the National Tsunami Warning Center (NTWC) in Palmer, Alaska and the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii.

This action aims to provide consistent tsunami forecasting, alerting, decision-support services and seamless, comprehensive service backup. Substantial progress has been made in recent years, solidifying the requirements for new common analytical software to common operating systems and technical support. The most critical component of the effort to establish a common operating platform is to provide service backup between the two Tsunami Warning Centers if one Tsunami Warning Center becomes inoperable or requests back-up.



Satellite imagery of the Tonga-Hunga Ha'apai volcano in the South Pacific Ocean on January 15, 2022. (Image credit: CSU/CIRA and JAXA/JMA)

NOAA's Tribal Relations Team works to strengthen and build relationships with tribes, Alaska Native communities and Native Hawaiian and Pacific Islanders, and works to ensure accountability (by integrating tribal treaties and reserved rights into agency decision-making processes, and upholding Executive Orders), maintain and establish relations and promote awareness of the policies, activities and concerns related to these vital partners.

Congress has authorized NOAA to lead the National Tsunami Hazard Mitigation Program (NTHMP) through NWS's Tsunami Program. Tasked with reducing the impact of tsunamis on the nation, the NTHMP is a unique and effective partnership between the NOAA, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS) and 28 U.S. coastal states and

territories. One of the greatest strengths of the NTHMP is the extraordinary commitment each member brings to the program and the high level of cooperation between federal, state and territory emergency management and scientific partners. This collaboration enhances cost-effectiveness and improves the program's ability to implement consistent national policies and projects at the local level. The NTHMP has four strategic overarching priorities or themes:

1. Hazard and Risk Assessment
2. Education and Preparedness
3. Mitigation and Recovery
4. Alert, Warning, and Response

The themes are supported by goals and strategies, which the NTHMP will strive to meet through collaboration between partners and stakeholders.

## **New frontiers in tsunami research**

The scientists at [NOAA's Pacific Marine Environmental Laboratory \(PMEL\)](#) in Seattle are working with NWS staff to develop new tsunami detection and modeling methods. The [NOAA Center for Tsunami Research](#) at PMEL aims to translate new science into a more accurate, fast and actionable tsunami forecast capability for NOAA's Tsunami Warning Centers.

PMEL tsunami research mainly focuses on providing accurate inundation forecasts in real-time before flooding from a tsunami reaches threatened coastlines. If timely and accurate, the tsunami inundation estimates are critical for saving coastal residents' lives during a tsunami event. Modeling, real-time tsunami detection and data assimilation are central to PMEL's tsunami research.

About 80% percent of all known tsunamis are triggered by earthquakes. That is why the current tsunami warning system is focused on earthquake-generated tsunamis. However, landslides, volcanic eruptions and asteroid impacts have caused catastrophic tsunamis. Large storms over the ocean or large water bodies can cause meteotsunamis, which can also be destructive. Specialized models developed by [NOAA's National Center for Tsunami Research](#) can predict coastal inundation from these other tsunamis, too, provided they get accurate information about the size and location of the triggering event.

Data from atmospheric and weather observations combined with real-time coastal and deep-water tsunami detection, as well as AI-assisted analytics, could provide enough information for models to forecast wave heights before a non-seismic tsunami arrives onshore.

Additionally, NOAA is working with emergency managers to assess long-term tsunami hazards by modeling hypothetical events and to prepare tsunami inundation maps under different scenarios to build tsunami-resilient communities.

NOAA is collaborating with the [American Society of Civil Engineers](#)  to develop the world's first probability-based tsunami design provisions. Among their goals:

- Establishing building codes requiring structures in inundation zones to be able to withstand wave forces.
- Assessing tsunami debris hazards. One of the most destructive elements of a tsunami results from the debris that is swept up and propelled shoreward, then seaward, by powerful waves.
- Creating new tsunami inundation (flooding) maps that are based on probabilities of occurrence for different size earthquakes which can be tailored to a given location and take into account hazards amplified by sea level rise and changing coastlines.

## Beyond alerts: Learn the signs of a tsunami

Feeling an earthquake or hearing a loud roar coming from the ocean could be your only warning for an incoming tsunami. If you feel an earthquake, drop, cover and hold on to protect yourself from earthquake shaking, then evacuate to high ground as soon as it is safe to do so. Visit the [Check out the NTHMP website](#) to find the tsunami hazard and evacuation maps for your state or territory.

NOAA's [National Weather Service \(NWS\)](#) has a few programs to help you prepare before, during and after a potential tsunami that could save your life and the lives of your family and friends.

The NWS [TsunamiReady](#) program, which started in 2001 and is modeled after the NWS [StormReady](#) program, helps communities minimize the risk posed by tsunamis through better risk assessment, planning, education and warning communications. The main goal of the program is to improve public safety by establishing [guidelines](#) for a standard level of capability to mitigate, prepare for and respond to tsunamis. TsunamiReady works with communities to help them meet these guidelines, and ultimately become recognized as TsunamiReady by NWS.

Coastal communities should consider conducting a tsunami hazard assessment. This assessment should include computer models and information from past tsunamis to identify and map the areas likely to be flooded, and by how much, during a tsunami. Communities can use the resulting tsunami hazard maps to determine where people and other important community assets (e.g., buildings, facilities, bridges, schools and hospitals) are at risk, so that they can decide where to focus preparedness, response and mitigation efforts.

Communities that understand their tsunami risk are better prepared to protect the public in the event of a tsunami.

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