In the tragic aftermath of the Indian Ocean tsunami of December 2004, scientists and warning centers are now better equipped to forecast and model these monstrous waves.

On December 26, 2004, a series of devastating waves attacked coastlines all around the Indian Ocean, taking the largest toll of any tsunami ever recorded. The, surges decimated...
entire cities and villages, killing more than 225,000 people within a matter of hours and leaving at least a million homeless.

This shocking disaster underscored an important fact: as populations boom in coastal regions worldwide, tsunamis pose a greater risk than ever before. At the same time, this tsunami was the best documented in history opening a unique opportunity to learn how to avoid such catastrophes in the future. From home videos of muddy water engulfing seaside hotels to satellite measurements of the waves propagating across the open ocean, the massive influx of information has reshaped what scientists know in several ways.

For one thing, the surprising origin of the tsunami—which issued from a location previously thought unlikely to birth the giant waves—has convinced researchers to broaden their list of possible danger areas. The new observations also provided the first thorough testing of computer simulations that forecast where and when a tsunami will strike and how it will behave onshore. What is more, this event revealed that subtle complexities of an earthquake exert a remarkably strong influence over a tsunami’s size and shape. The improved models that have resulted from these discoveries will work with new monitoring and warning systems to help save lives.

Before the Big One

Researchers have long known that the breeding grounds for nearly all tsunami-generating earthquakes are subduction zones. Marked by immense trenches on the seafloor, such areas form where one of the planet’s outer shell of tectonic plates plunges underneath another. Gravitational forces and the motion of viscous material deep within the earth’s mantle work to keep the plates moving past each other, but friction in the shallow crust temporarily locks them together. As a result, stress builds up across the vast interface, or fault, between the two plates. Sometimes that stress is relieved suddenly in the form of a large earthquake. The bottom plate dives farther down, snapping the top plate violently upward—and the overlying seawater goes along for the ride. The size of the resulting tsunami depends on how much the seafloor moves. Once generated, the tsunami splits in two; one moves quickly inland while the second heads toward the open ocean.

In the eastern Indian Ocean, off the west coast of Sumatra, Indonesia, the India Plate slips below the Eurasia Plate along the Sumatra subduction zone. Southern parts of this fault zone have produced large (magnitude 9) earthquakes in the past, most recently in 1833; Kerry Sieh of the California Institute of Technology and his colleagues have found ancient coral reefs uplifted by these events. Experts were on the watch for another large shock there.

But they were puzzled when the tsunami-producing event of December 2004 originated in the upper part of this region, just northwest of Sumatra. Prior records had shown much slower
motion along the offshore fault there, so it was unclear that stress could ever build up enough

to result in such a violent tremor. Yet later analysis revealed that the magnitude 9 shock
raised a 1,200-kilometer stretch of seafloor by as much as eight meters in some places as it
unlocked a California-size area of the fault zone-displacing hundreds of cubic kilometers of
seawater above normal sea level. As a result, investigators now are considering possible
additional tsunami threats near Alaska, Puerto Rico and other similar subduction zones.

The Sumatra-Andaman shock began at 7:59 A.M. local time, and soon a global network of
seismic stations alerted the Pacific Tsunami Warning Center in Ewa Beach, Hawaii. Although
geophysicists there were some of the first people outside the region to learn of the
earthquake, they had no way to confirm that a deadly tsunami was surging across the Indian
Ocean until they got the first news bulletin of the catastrophe unfolding.

In the Pacific Ocean, where 85 percent of the world's tsunamis occur, remote sensors called
tsunameters can detect a tsunami offshore and warn the Pacific center's scientists and those
at a second center in Palmer, Alaska, before the waves make landfall [see "Tsunami!" by
Frank González; SCIENTIFIC AMERICAN, May 1999]. But no such technology was in place
for the Indian Ocean, and no established lines of communication existed to transmit a warning
to people on the coast. Although the first waves took two hours or more to reach Thailand, Sri
Lanka and many of the areas hardest hit, nearly everyone was taken by surprise.

In the Open Ocean

THAT DECEMBER DAY forever changed the world's appreciation for how much damage
tsunamis can inflict, where they might strike and how utterly defenseless so many
communities are. International groups have been scrambling to rectify the situation ever
since. Meanwhile researchers have been digging through the clues this disaster left behind to
sharpen their understanding of how tsunamis get started, propagate and then crash against
the shores--and to better warn of the next one.

For 15 years, researchers in Japan and the U.S. have been developing computer models that
simulate how a tsunami propagates through the open ocean. Before now, however,
investigators had few observations to compare against their theories. All tsunami-propagation
models require two key starting variables: an estimate of the location and area of deformed
seafloor, which researchers base on the quake's magnitude and epicenter, and a measure of
the height, or amplitude, of the displaced water. The latter can be inferred adequately for
real-time forecasts only after making direct observations of tsunami waves in the open ocean.

But for previous major tsunamis, scientists just had measurements that tide gauges recorded
near the coast or that surveyors later estimated from water damage on land. The main
problem is that near shore, a tsunami's actual size is masked by additional waves generated
as the tsunami bounces off seawalls, wraps around islands, or sloshes back and forth in a bay--all of which make for a very tangled signal.

By sheer coincidence, a trio of earth monitoring satellites gave modelers the pristine, undistorted wave heights they needed for the Indian Ocean tsunami. The satellites happened to orbit over the region between two and nine hours after the earthquake, making the first radar measurements of a tsunami propagating across the open ocean. The results proved for the first time that--as suspected--a bump of water only half a meter high in the open ocean can truly transform into the towering surges that wreak so much destruction on land.

With a ground speed of about 5.8 kilometers a second, the satellites also provided the first continuous transect of tsunami amplitudes--that is, they monitored the waves continuously along their travel path rather than making measurements in a single spot, as tide gauges do. As it turns out, the modeled and measured wave heights match each other quite well, validating general theories about how tsunamis move across the open ocean--and confirming that the current modeling paradigms are a useful tool for public safety, even for the largest tsunami.

**Global Reach**

THE GLOBAL SCOPE of the tsunami further corroborated that the models are sound for forecasting. Because a tsunami in the deep ocean moves along at about the same speed as a jet airliner (from 500 to 1,000 kilometers an hour), the first wave took less than three hours to travel from northern Sumatra and the Andaman Islands east to Myanmar (Burma), Thailand and Malaysia and west to Sri Lanka, India and the Maldives. Within 11 hours it had struck the South African coast 8,000 kilometers away, the farthest point away where a tsunami-related death was reported.

But the waves did not stop there. About the same time the tragedy made the news, scientists started getting records from tide gauge stations around the world. On its westward path, the tsunami curved around the southern tip of Africa and then split as it traveled northward through the Atlantic; one branch headed toward Brazil and the other toward Nova Scotia. On its east: ward path, the tsunami sped through the gap between Australia and Antarctica and into the Pacific as far north as Canada. Not since the eruption of Krakatau volcano in 1883 had a tsunami been known to travel so far.

When the entire path of the tsunami played out on the National Oceanic and Atmospheric Administration's leading computer simulation, called MOST (short for method of splitting tsunami), the simulated wave heights agreed quite well with the measurements at various tide gauge stations. What is more, the model revealed just how a tsunami manages to travel so far. A map of the simulated wave heights for the Indian Ocean event showed that they are...
highest along mid-ocean ridges. These ridges, which connect one ocean basin to the next, appear to channel the wave energy farther than it might otherwise travel. Knowing about this effect is helpful for forecasting because modelers can better estimate where the strongest wave energy is most likely to go.

Immediate Aftermath

FORECASTING HOW a tsunami will behave once it climbs ashore is a much greater challenge. As always occurs in tsunamis, the December event's waves gradually slowed down as they entered shallow water. By the time the ripples reached shore, the distance between crests, which was hundreds of kilometers in the open ocean, had decreased to 15 or 20 kilometers. But with the fast water still pushing from behind, the wave peaks grew higher and higher, to more than 30 meters in Sumatra's Aceh province, the first region hit.

Still moving at about 30 to 40 kilometers an hour, the waves swept inland more than four kilometers in parts of the city of Banda Aceh [see 'PREDICTING TSUNAMI BEHAVIOR']. They receded just as violently, carrying far out to sea anything they picked up on the way in. Along all inundated shorelines, waves pounded the coasts for hours. And with 30 minutes or more between crests, many people haplessly returned to the beaches, only to be attacked by subsequent waves. The cumulative damage to the physical environment was so vast that it was visible to astronauts in space; it was also extremely varied.

Considering the many factors involved, how could models reliably predict such variation? Until the early 1990s, because of unresolved computational complexities, even the best simulations ended their calculations at the water's edge or just offshore. Investigators then used that last height to estimate how far inland a tsunami would climb. But the initial careful surveys of tsunami disasters suggested their estimates were way off. A tsunami that struck Nicaragua in 1992 was the first time scientists made comprehensive field measurements to compare with the model predictions. The flooding levels in some places were up to 10 times higher than what the models had predicted.

A race of sorts soon developed between U.S. and Japanese modelers seeking to describe the inundation more accurately, by calculating the entire evolution of the tsunami on dry land. Through a combination of large-scale laboratory experiments and field measurements from subsequent tsunamis, investigators refined the Japanese TUNAMI-N2 and the U.S. MOST models until they could match the inundation patterns of most past tsunamis quite well—as long as high-resolution data about the coastal and offshore topography were available. These researchers did not know, however, that the models would work as well for the largest tsunamis. As it turned out, the models matched the Indian Ocean flooding better than expected, despite the relative lack of detail about the coastal landscape.
Post-tsunami surveyors in Indonesia and elsewhere quickly noted that predictions of floodwater depth alone could not always foretell the full impact of the tsunami. In many locales in Thailand and Sri Lanka, the tsunami depth on land was less than 4.5 meters, yet the devastation rivaled that in Aceh, where the water was six times deeper. Another shocking reality was that in Banda Aceh, the waves destroyed block after block of reinforced concrete structures that may have withstood the earthquake's shaking.

To account for the magnitude of the wreckage, Ahmet C. Yalciner of Middle East Technical University in Ankara, Turkey, and one of us (Synolakis) are devising new damage metrics—standards that coastal engineers can use to assess the force of tsunami waves on structures—that also consider powerful currents, which are much stronger in tsunami floodwaters than they are in normal tides and storm waves.

**Shaking Surprises**

ARGUABLY THE GREATEST scientific conundrum regarding the Indian Ocean tsunami is the earthquake itself. Even the magnitude of the earthquake is still debated, with some estimates as high as 9.3. Although the seismic shock was the largest since the 1964 Alaska earthquake, it has been a challenge to describe how the Sumatra-Andaman fault produced such a giant tsunami.

By any measure, this earthquake was amazingly complex. Typically the fault slip will be largest right at the start, near its origin. Yet in some cases, the fault break begins with a small amount of slip, suggesting that the earthquake will be small, then hits a weak or highly stressed part of the fault that lets loose violently, resulting in a much larger earthquake and tsunami. That is what happened in the 2004 tsunami. Such cases are challenging to analyze in time to make a useful warning.

NOAA's tsunami forecast models were put to the test for this perplexing event. Running the model with seismic data alone would have underestimated tsunami heights in the open ocean by a factor of 10 or more. Adding the first direct measurement of tsunami amplitude, which reached scientists from a tide gauge station at Cocos Island about three and a half hours after the earthquake occurred, improved the results dramatically. But something was still missing.

In the days following the earthquake, analyses of the shock's strong seismic waves indicated that the initial fault break sped northward from Sumatra at 2.5 kilometers a second. They also pinpointed the areas of greatest slip--and thus of the greatest tsunami generation. The problem for tsunami modelers was that none of these seismic solutions included enough overall fault motion to reproduce either the satellite observations of wave heights in the open ocean or the severe flooding in Banda Aceh.
The critical clue came from land based stations that use the Global Positioning System (GPS) to track ground movements much slower than what seismic waves produce. Those measurements revealed that the fault continued to slip, albeit slowly, after it stopped emanating seismic energy. Although there is a limit to how slowly a fault can slip and still generate a tsunami, it is most likely that this often overlooked phenomenon, called after-slip, accounts for the surprising tsunami heights. If so, incorporating continuous GPS readings may be an important component of tsunami warning systems in the future.

Hit or Miss

THE SPECIFIC FACTORS in any given earthquake clearly exert fearsome controls on tsunamis. As if emphasizing this point, Planet Earth produced another huge temblor along the same fault on March 28, 2005. The initial break occurred an equivalent distance from the Sumatra coastline and at virtually the same depth below the seafloor as the December earthquake, and both shocks are among the top 10 largest recorded since 1900. Yet they produced radically different tsunamis.

Seeing the March earthquake flash on their computer screens as a magnitude 8.7, scientists at the Pacific Tsunami Warning Center and elsewhere expected the worst. Severe damage from strong ground shaking indeed occurred but without immediate reports of tsunami damage. When an international team (including one of us, Titov) surveyed the region two weeks later, they measured tsunami run-up heights as high as four meters—still potentially deadly. Some Indonesians said they learned from their first experience and ran inland when the ground shook. Better evacuation is only one reason the March tsunami did not take more lives.

Analysis of aftershocks from the December earthquake suggested to Andrew Newman of the Georgia Institute of Technology and Susan Bilek of the New Mexico Institute of Mining and Technology that the fault slipped near the deep trench that time and was thus under deeper water than the main part of the fault that slipped in March was. The December tsunami thus had more opportunity to gain height during its trip from deep water to shore. In addition, unlike the December tsunami, fault movement in March occurred below the islands of Nias and Simeulue, thereby limiting the amount of water the uplifting crust could displace.

A slight difference in the fault orientation meant that their tsunami waves proceeded in two different general directions. For the March earthquake, most of its eastbound waves smashed into the island of Sumatra, which blocked much of the wave energy from moving on toward Thailand and Malaysia. The westbound waves shot out into the open ocean to the southwest, largely missing Sri Lanka, India and the Maldives, all of which suffered terribly in December. These examples highlight the critical importance that even small variations in the location of an earthquake can make.
Despite the lingering scientific uncertainties that will probably always surround such complex phenomena, the new tsunami science is ready for implementation. The biggest challenge for saving lives is now applying the scientific findings to proper education, planning and warning.

**Overview/Future Forecasts**

In the wake of the catastrophic December 2004 tsunami in the Indian Ocean, a massive influx of information about the event has reshaped our understanding of such monster waves. From the new data, scientists have learned how to better forecast what areas could spawn a tsunami, where it will go and how far it will climb up on shore. The resulting improved computer models will work with new monitoring and warning systems to help save lives.

**RETHINKING TSUNAMI ORIGINS**

The most notable tsunami-generating earthquakes of the past century occurred where two tectonic plates meet head-on in so-called subduction zones. One plate thrusts atop the other, raising tsunami waves along with it. But the part of the Sumatra-Andaman fault where the Indian Ocean disaster originated had no previous record of shocks larger than magnitude 8. When a magnitude 9 earthquake struck there in December 2004, followed three months later by another nearly as large at magnitude 8.7, scientists began reassessing similar slow-moving faults for their tsunami potential. New areas of concern also include those where bulky features on the seafloor may obstruct subduction, thus adding stress to the fault.

**PREDICTING TSUNAMI BEHAVIOR**

Observations from the December 2004 tsunami confirmed scientists' basic understanding of three keg aspects of tsunami behavior: how large events propagate around the world, what the waves look like in the open ocean, and how far inland the waves will climb. Each image compares direct measurements with values calculated by the leading U.S. tsunami-forecasting model, called method of splitting tsunami, or MOST.

**GLOBAL VIEW** of the tsunami's path shows that the tallest offshore waves modeled correlate well with the tallest waves that tide gauges measured near the coasts. The first wave took nearly 30 hours to reach western Canada.

**WAVE HEIGHTS** in the open ocean--measured by the Jason-1 satellite as it flew over the Indian Ocean two hours after the earthquake that initiated the tsunami--match the model's calculations better than expected. Peaks represent wave crests; dips are wave troughs.

**TSUNAMI FLOODWATERS** in some areas of northern Sumatra's Aceh province attained heights of 30 meters and surged up to 4.5 kilometers inland. Once again, areas that the model predicted would flood agree well with field measurements and satellite images after the event.
Warnings for the Future

Before the December 2004 event, the Indian Ocean had no tsunami-warning system. Since then, several international groups, coordinated by UNESCO's Intergovernmental Oceanographic Commission, have raced to correct the problem. To achieve the monitoring capability that currently exists in the Pacific, the Indian Ocean needs three basin-wide technological components: an improved seismic network to locate large earthquakes, a minimum of five tsunameters to detect tsunami waves as they travel across the open ocean [although 13 are needed to detect a tsunami in less than 30 minutes], and a real-time network of tide gauges near shore.

Key steps took place in the past year. Two seismic networks--one entirely new--now report automatically to the national earthquake centers in Indonesia and Malaysia; the latter will soon make its information available to the entire region. Four tide gauges have already been upgraded for tsunami monitoring--including one near Indonesia, which lies closest to major tsunami-generating faults. More than 20 additional installations and improvements are scheduled for the coming months.

It is unclear how and when the necessary tsunameters can be acquired, and political challenges must be overcome in certain countries before the seismic network can be completed, but UNESCO officials remain optimistic. If all goes well, a basic monitoring system should be operational by July. Computer models must then combine those measurements into accurate warnings.

Once warnings are available, they must still be disseminated to people on the coasts. Along most of the Indian Ocean's 66,000 kilometers of shoreline, the first wave will not arrive for two hours or more--enough time for most people to move inland after an alarm sounds. In places where tsunami waves will strike in an hour or less, an alarm may come too late. Residents must instead recognize natural signs-severe ground shaking and a receding ocean that often precede an incoming surge.

In both cases, swift evacuation to predesignated safe zones is essential. Local officials have already held practice drills in some parts of Thailand, Sri Lanka and Indonesia that were hit hard in 2004.

SHOCKING DIFFERENCES

On March 28, 2005, three months after the tsunami-generating earthquake of December 2004, a second large earthquake rocked the same fault. The initial waves the shocks generated were eight meters in December and 3.5 meters in March; they are exaggerated for comparison's sake in the diagrams. Through detailed studies, researchers have uncovered four main reasons for this unexpected disparity.
First, the March shock released 1/15 the energy of its predecessor [it was a magnitude 8.7 shock; December's was greater than 9]. It struck along a deeper portion of the fault, thereby limiting how much surged upward into the overlying water. It occurred underneath shallow water, so it raised a smaller volume of water; in December, part of the tsunami formed above the deep Sunda Trench. Finally, it struck about 100 kilometers farther south, so most of its eastbound waves struck Sumatra, which shielded Thailand and Malaysia, and its westbound waves headed out to sea; in December, both eastbound and westbound waves attacked nearby landmasses.

MORE TO EXPLORE


A companion article on land use and tsunamis, called "Echoes from the Past," is available at www.sciam.com

National Oceanic and Atmospheric Administration tsunami pages: www.tsunami.noaa.gov/

University of Southern California Tsunami Research Center: http://cwis.usc.edu/dept/tsunamis/2005/index.php


MAP: RETHINKING TSUNAMI ORIGINS

DIAGRAM: TSUNAMETER features a pressure sensor on the seafloor that sends an acoustic signal to a buoy at the surface when it senses a passing tsunami. The buoy then relays the warning via satellite to the officials responsible for sounding an alarm.

DIAGRAM: DECEMBER 26, 2004; magnitude 9

DIAGRAM: MARCH 28, 2005; magnitude 8.7

PHOTO (COLOR): WALL OF WATER; 30 meters high that battered shores in December 2004 has yielded improved computer simulations of tsunami behavior.

PHOTO (COLOR): TWISTED RAILWAY TRACKS near Sri Lanka's southwestern coast community of Sinigame mark where the December 2004 tsunami derailed an eight-car passenger train, killing an estimated 1,500 people.
By Eric L. Geist; Vasily V. Titov and Costas E. Synolakis

ERIC L. GEIST, VASILY V. TITOV and COSTAS E. SYNOLAKIS bring various types of expertise to the study of tsunamis. Geist is a research geophysicist with the U.S. Geological Survey in Menlo Park, Calif. He uses computer simulations to study how the inherent complexity of subduction zone earthquakes affects tsunami generation. Titov developed NOAA's premier computer model for forecasting tsunamis. He is senior modeler for that agency's Tsunami Research Program in Seattle and affiliate assistant professor at the University of Washington. Synolakis directs the University of Southern California Tsunami Research Center, which he founded in 1995. His current work involves field surveys of tsunami destruction, large-scale laboratory models of tsunami waves, and computer simulations of flooding along tsunami-prone Coastlines, including those of California.

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