OUT OF THE SHADOWS

The Emerging Science of Earthquake Prediction

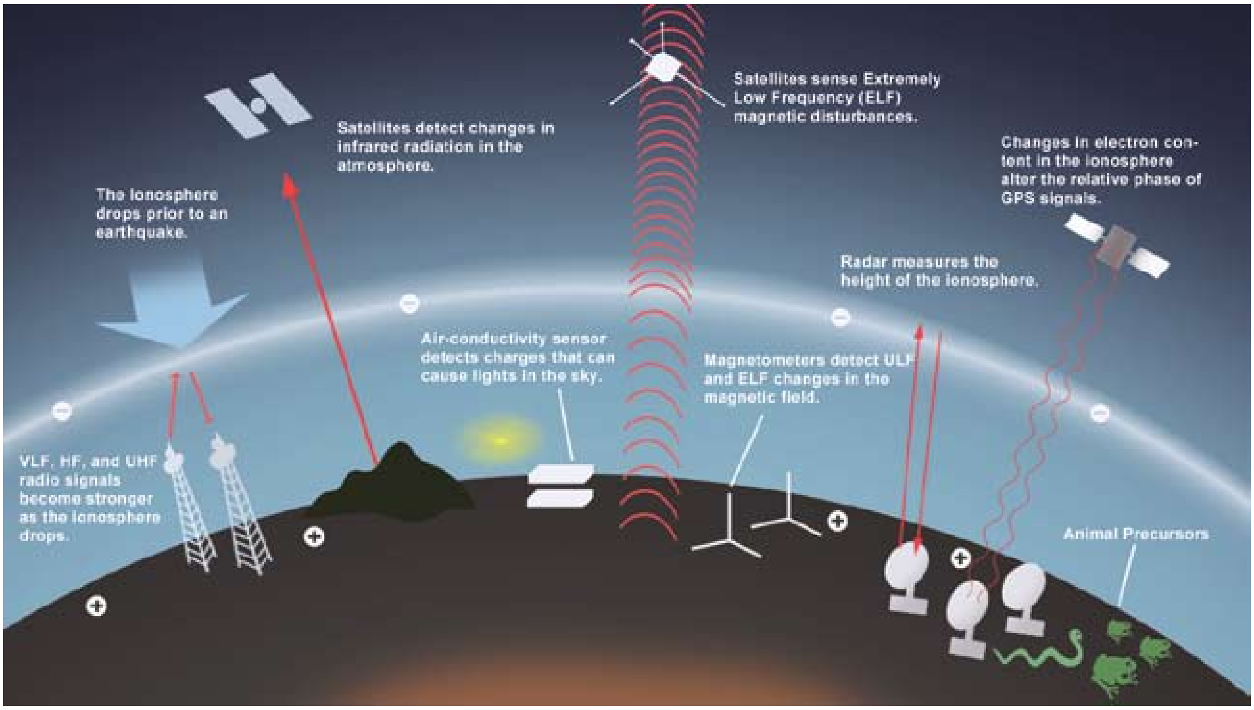
by Oyang Teng

Aerial photo of the San Andreas Fault in the Carrizo Plain, northwest of Los Angeles.

Earthquakes are in some ways the most unsettling of natural disasters. On the one hand, the furies unleashed by tornadoes, hurricanes, and even volcanoes, appear to develop somewhat logically from the action of clouds, winds, and smoking calderas in plain sight. The rumblings of the Earth, on the other hand, seem a betrayal of an almost ingrained trust in the solidity of the ground beneath our feet—and worse, they seem to strike with no warning.

Or do they?

Eyewitness reports going back millennia testify to the existence of aberrations preceding large earthquakes: spooked animals, foggy air, fouled well water. In recent decades, observations with a variety of satellite and ground-based instruments, have expanded the list to include a multitude of transient phenomena outside the range of our normal perception: changes in the electrical conductivity of the air, pulsations in the geomagnetic field, variations in the electron density of the ionosphere, and spikes in electrical ground currents near epicentral zones, among others. These non-seismic signals have been observed on numerous occasions anywhere from weeks to days and hours leading up to an earthquake, speaking to the complexity of the much larger process of physical preparation surrounding the actual rupture of a fault.



EARTHQUAKE PRECURSORS AND THEIR SENSING MECHANISMS

A multi-parameter sensor web can provide the means for earthquake prediction, through the integration of ground and satellite-based measurements of precursor phenomena in the ground, atmosphere, and ionosphere.

In one sense, it should come as no surprise that earthquakes are often preceded by a number of seemingly unrelated, precursory phenomena—not unlike a patient presenting with a range of symptoms, says Chapman University geophysicist Dimitar Ouzounov, a leading scientist in the field of earthquake precursors. Only, in this case, the patient's insides are built from massive blocks of rock tens of kilometers thick, comprised of a variety of minerals under immense pressure, some of which are capable of carrying electric charge, and containing microscopic pores and fracture channels pulsing with high pressure, high-temperature aqueous fluids and gases such as hydrocarbons, carbon dioxide, and radon.

It would be strange if the physical potentials built into such a system under accumulating stress and strain, bringing into play a complex of mechanical, electromagnetic, and geochemical phenomena, *were not* discharged in some detectable form leading up to the final rupture of a fault zone. The bigger the earthquake, the greater the precursor "symptoms."

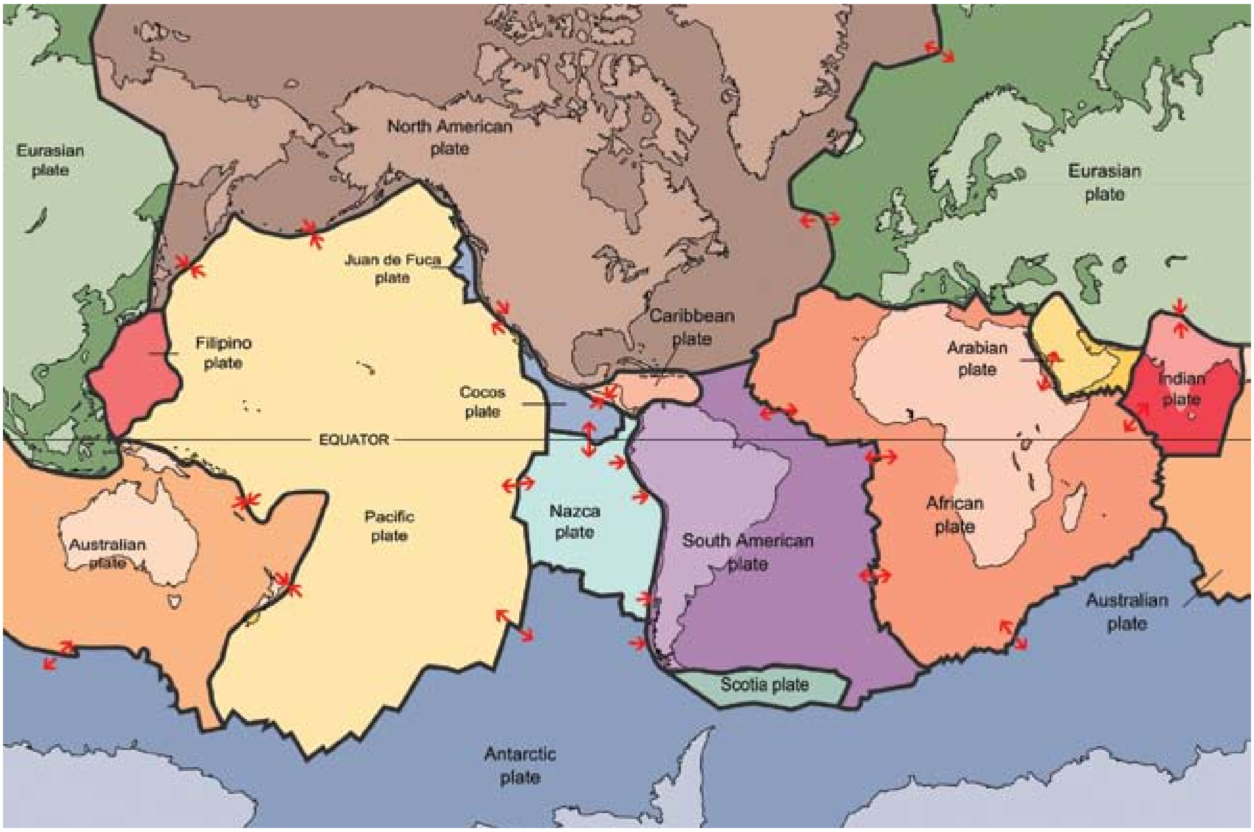
However, the process just described, visualizable in the imagination, is largely a mystery. Earthquake epicenters are located miles below the surface, where we have no direct observations. Our deepest drill holes generally penetrate no more than about 5 kilometers beneath the surface (the record is 10 km) at a very few select spots on the planet; yet, earthquakes classed as "shallow" can extend down to 70 km, with the deepest recorded epicenter at roughly 700 km. Our knowledge of the detailed composition and dynamics of the deep crust, let alone the mantle beneath it, is still conjectural.

The encompassing armature for the geosciences, including seismology, has been provided by the theory of plate tectonics. It gained widespread acceptance beginning in the 1960s as a way to account for matching fossils and landforms on separate continents, seafloor spreading along the mid-Ocean ridges, and—most important for seismologists—the observation that most earthquakes are concentrated within thin geographical bands that are now known to demarcate plate boundaries.

(Intraplate earthquakes, occurring far from any known plate boundaries and, therefore, without any conventional explanation for their cause, have proved to be a particularly deadly exception to this rule. A study published in 2011 showed that, not counting deaths from tsunamis, these intraplate quakes have killed more people in the last 120 years than the more common quakes along plate boundaries).

Because the strongest empirical evidence for plate tectonics pertains to processes occurring on the geological timescales needed for continents to move, it is far too blunt a tool to be applied to earthquake prediction, which must be able to identify both the magnitude and location of a coming quake on a timescale of hours or days.

But despite the fact that we cannot yet directly observe the subsurface crust, its secrets are not so easily contained. As biogeochemist Vladimir Vernadsky was the first to describe, the concentric geospheres of the Earth are closely integrated. Therefore, the 300-km thick shell extending down beneath our feet, containing the majority of earthquake epicenters, can be probed indirectly by examining the transient electromagnetic



15 OF THE LARGEST TECTONIC PLATES

Most earthquakes take place within the narrow geographical bands that demarcate plate boundaries.

Source: USGS

"shadows" projected on the 300-km thick curtain of atmosphere which rises upward from the surface.

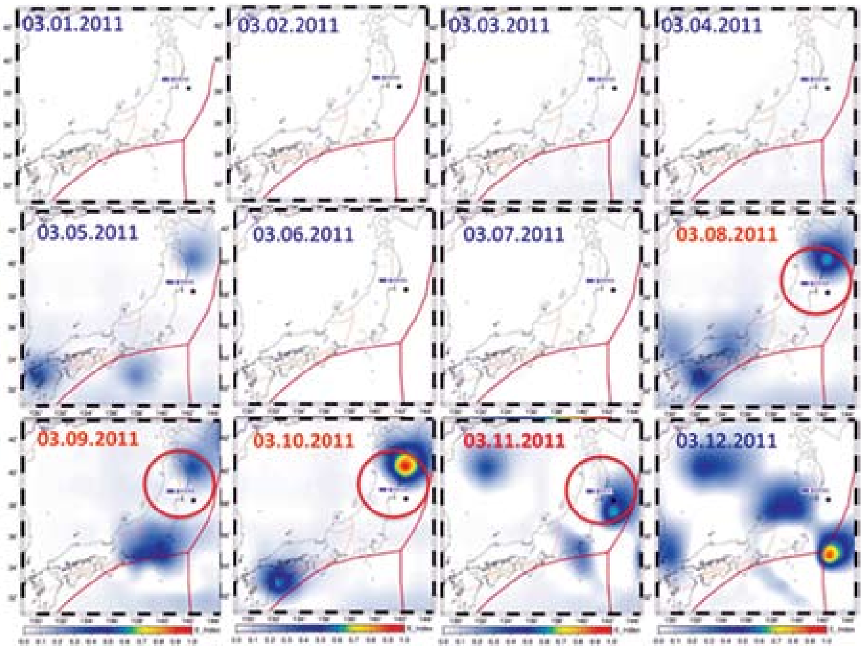
Critics argue that these shadows are too elusive to be reliable. The very diversity and seeming inconsistency of precursor phenomena has been used to argue against their validity; according to traditional seismology, they must be flukes, or artifacts in the data. Moreover, critics argue, there doesn't seem to be any overarching mechanism, like plate tectonics, to tie them all together. Yet, the lack of agreement on a particular theory or mechanism hasn't stopped the continued accumulation of evidence for systemic earthquake precursors by researchers across the world.

The Case of Japan

The urgency surrounding earthquake prediction was put sharply in focus by last year's March 11 magnitude 9.0 Tohoku earthquake and tsunami which killed over 15,000 people in Japan, the world's most disaster-prepared nation. Nine months later, at the Dec. 5-9 Fall conference of the American Geophysical Union (AGU) in San Francisco—the world's largest geophysics gathering—an international group of scientists demonstrated that strong precursor warning signs had, in fact, preceded the megaquake.

Lance Cpl. Garry Welch/U.S. Marine Corps

The March 11, 2011 mega-earthquake in Japan, which killed nearly 20,000 people and left scenes of destruction, as shown here, did have precursor warning signs.



THERMAL ANOMALIES BEFORE THE TOHOKU EARTHQUAKE

Anomalous Outgoing Longwave Radiation (OLR) measured by satellite in the general region above the epicenter (the black star) in the days leading up to the March 11, 2011 Tohoku earthquake in Japan. The infrared thermal anomalies, indicated within the red circle, were determined by comparing outgoing long wavelength measurements on a given day against a reference background field of OLR data for the same day for the seven years between 2004-2011.

Source: D. Ouzounov, S. Pulinets, et. al., "Atmosphere-Ionosphere Response to the M9 Tohoku Earthquake Revealed by Joined Satellite and Ground Observations, Preliminary Results.

Transmission of Very Low Frequency (VLF) and Low Frequency (LF) electromagnetic waves to receivers by way of reflection off the lower layers of the ionosphere (about 60-90 km high), allow scientists to measure changes in the ionosphere by analyzing changes in the signal propagation. Using a worldwide network of such VLF/LF transmitters and receivers, Masahi Hayakawa and Yasuhide Hobara, from the University of Electro-Communications near Tokyo, measured an anomalous drop in the height of the ionosphere in the region above the future epicenter about five days before the main shock.

Hayakawa believes that this precursory phenomenon, which has been measured in other earthquakes they have studied, results from pre-earthquake fractures which send vibrations, called atmospheric gravity waves, up through the air and into the ionosphere. Hobara presented the results of their work in a session devoted to "Monitoring of Mega Earthquake Disasters by Integrating Multi-parameter and Multi-sensors Observations from Ground and Space."

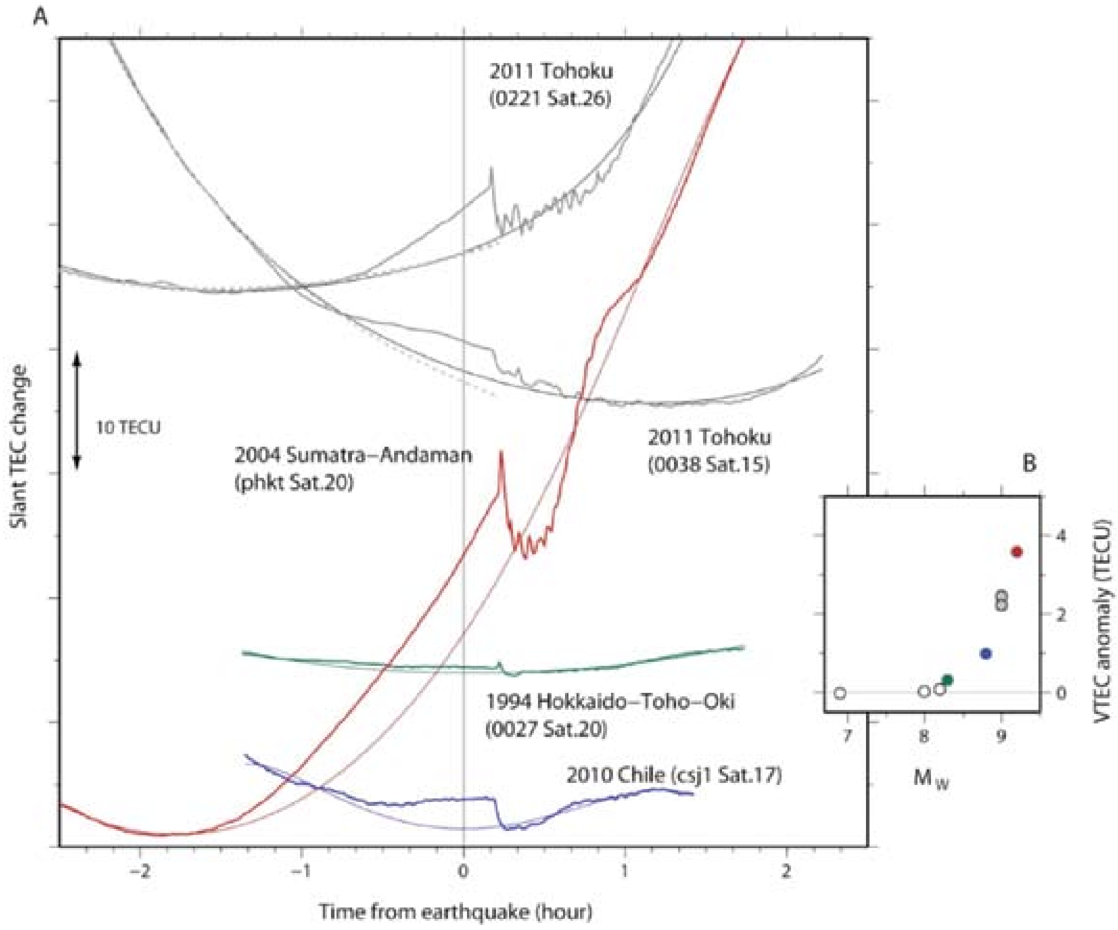
Dimitar Ouzounov, who chaired the session, has found that atmospheric and ionospheric anomalies consistently appear roughly 1 to 5 days before major earthquakes. Among these are satellite-detected long wavelength infrared emissions (in the range of thermal imaging), appearing within the troposphere up to 12 km above the surface. Ouzounov, along with Sergey Pulinets of the Moscow-based Institute of Applied Geophysics, and others, measured such thermal anomalies localized in the general region above the future epicenter in the days before the Tohoku quake, by analyzing deviations from a reference background of satellite-derived atmospheric infrared radiation from the previous seven years.

A rapid increase in emitted infrared emission began on March 8, three days before the main shock. According to the LAIC (Lithosphere-Atmosphere-Ionosphere-Coupling) model developed by Ouzounov and Pulinets, the anomalies are connected to the release of radioactive radon gas within the area of earthquake preparation. Radon ionizes the atmosphere, producing ion clusters which serve as condensation nuclei for atmospheric water vapor, and as the vapor condenses, it releases latent heat in the form of infrared radiation.

They found that this also coincided with anomalous precursory spikes of the total electron content (TEC) of the ionosphere above the epicentral zone, measured by three independent techniques: through GPS satellites transmitting to ground-based receivers; radio tomography, involving radio transmissions from low-orbiting satellites to ground-based receivers; and soundings from four Japanese ionosondes, ground-based radar installations which bounce varying high-frequency signals off different layers of the ionosphere and analyze the time delay of the resulting echoes.

In each case, the measured electron concentration grew to a maximum on March 8, returning to normal within several days following the earthquake. As explained by the Lithospere-Atmosphere-Ionosphere-Coupling model, these ionospheric anomalies are the result of the ionosphere's sensitivity to changes in the conductivity of the lower atmosphere, caused by radon-induced ionization.

Ionospheric anomalies were also detectable within one hour of the earthquake. Delivering the AGU Bowie lecture on "GPS Array as a Sensor of Lithosphere, Troposphere and Ionosphere," Kosuke Heki of Hokkaido University in Japan showed how the total electron content of the ionosphere above the future epicenter markedly increased, beginning about 50 minutes before quake began, and gradually subsided to normal within an hour or so. The measurements were obtained by analyzing phase differences in dual signals sent from GPS satellites to ground stations, utilizing both the dense network of



TOTAL ELECTRON COUNT CHANGES IN SELECTED EARTHQUAKES

Shown are the total electron count (TEC) changes and their models in the 2011 Tohoku earthquake, the 2004 Sumatra-Andaman earthquake, the 1994 Hokkaido-Toho-Oki earthquake, and the 2010 Chile (Maule) earthquake. The horizontal axis shows the time from the earthquakes. Dashed curves in gray for the top two time series show the models derived with data prior to the possible onset of the precursor.

The inset at right shows the vertical TEC anomalies immediately before the earthquakes as a function of their moment magnitudes. Colors correspond to those in the larger figure, and data from three smaller earthquakes (white circles) are included.

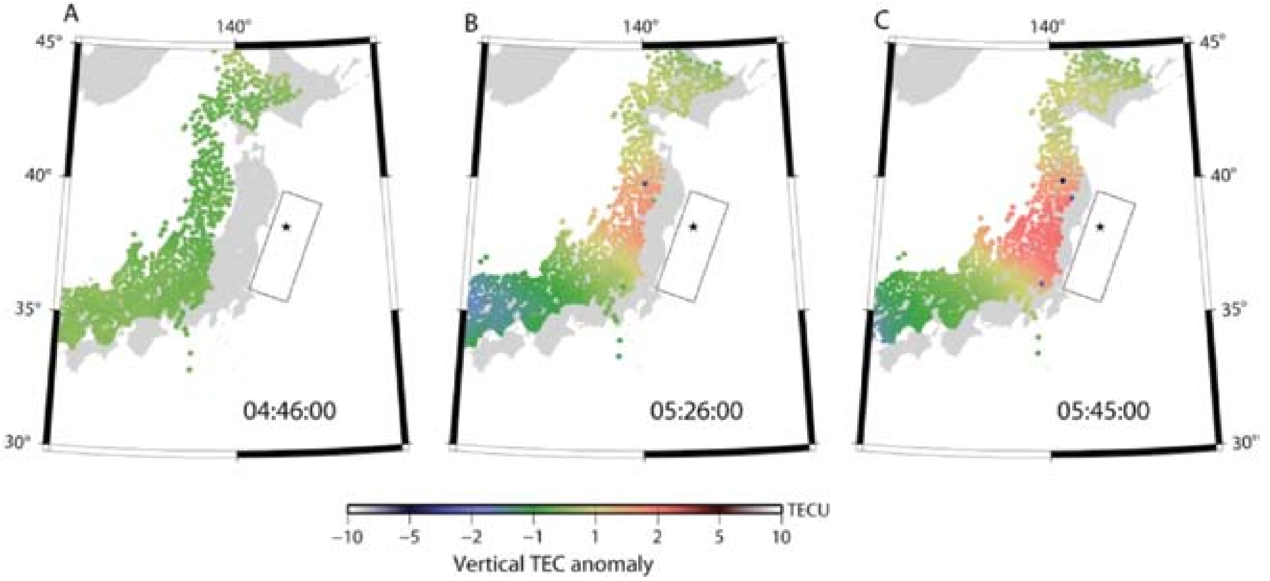
Source: K. Heki, 2011. "Ionospheric Electron Enhancement Preceding the 2011 Tohoku-Oki Earthquake," in *Geophys. Res. Lett.*, Vol.38, No. L17312, doi:10.1029/2011GL047908.

about 1,000 GPS receivers installed within Japan, as well as a global network of 100+ receivers that are used to construct global ionospheric maps.

Heki, whose analysis was published in the Sept. 15, 2011 issue of *Geophysical Research Letters,* also found the same pattern of localized GPS-total electron content increases beginning roughly 50 minutes before the main shock for the two other largest earthquakes of the past decade: the magnitude 9.2 Sumatra-Andaman quake in 2004 and the magnitude 8.8 Chile quake of 2010, as well as the smaller magnitude 8.3 Hokkaido-Toho-Oki quake of 1994. In each case, there was a clear dependence of the size of the anomaly on the magnitude of the earthquake.

While stating that "no conclusive models" have been put forth, Heki points to two possible explanations for the electron count enhancement preceding these large quakes. The first is that proposed by Ouzounov and Pulinets, by which alpha decay of radon changes the resistivity of the lower atmosphere, disturbing the global electric circuit—the diffuse flow of current that flows between the negatively charged ionosphere and the positively charged surface of the planet—and redistributing ionospheric electrons.

The other is a mechanism proposed by NASA physicist Friedemann Freund, involving the production of electric ground currents induced by seismic stress. In this scenario, subatomic alterations in the crystal lattice of igneous or high-grade metamorphic rocks propagate toward the surface as positive charge carriers, leading to the ionization of the near-surface atmo-



INCREASE IN TOTAL ELECTRON CONTENT BEFORE TOHOKU EARTHQUAKE

The total electron content (TEC) in the ionosphere above the epicenter of the Tohoku earthquake increased, beginning about 50 minutes before the quake began. The vertical anomalies in total electron content of the ionosphere are shown at three time periods, (a) 1 hour, (b) 20 minutes, and (c) 1 minute before the 2011 Tohoku earthquake, as observed at Japanese-based GPS stations with GPS satellites in Earth orbit. Positive anomalies (red color) are seen to grow near the focal region.

Source: K. Heki, K. (2011), "Ionospheric Electron Enhancement Preceding the 2011 Tohoku-Oki Earthquake," *Geophys. Res. Lett.*, Vol. 38, No. L17312, doi:10.1029/2011GL047908.

sphere. According to Freund, this not only perturbs the ionosphere by altering the vertical electric gradient, but leads to the thermal infrared anomalies seen by Earth observation satellites, as expanding bubbles of positive ions well up into higher levels of the atmosphere and catalyze water vapor condensation.

A Multi-Parameter Approach

Although particular kinds of precursor measurements have yielded positive results in many of the earthquakes studied, there is no one parameter that has proven consistent across all of them. For this reason, many precursor scientists emphasize that real-time prediction will depend on the integration of a number of different measurements of precursor signals simultaneously.

As Ouzounov pointed out in a presentation on "Utilizing New Methodologies to study Major Earthquakes: Multi-Parameter Observation of Pre-earthquake Signals from Ground and Space," this requires an integrated sensor web of new satellites and ground instruments deployed across the globe, enabling, minimally, constant coverage of the earthquake hotspots around the Pacific Rim and the inland zone stretching from Turkey to Iran, and through to India and China.

In addition to the Tohoku earthquake, multi-parameter hindcasts have been performed for dozens of large earthquakes, including Sumatra-Andaman 2004 (magnitude 9.2), Wenchuan, China 2008 (M 7.9), Haiti 2010 (M 7.0), and Chile 2010 (M 8.8). Precursors were also found for relatively smaller earthquakes such as L'Aquila, Italy 2009 (M 5.8) and the Mineral, Virginia, quake (M 5.8) that took the eastern seaboard of the United States by surprise on Aug. 23, 2011.

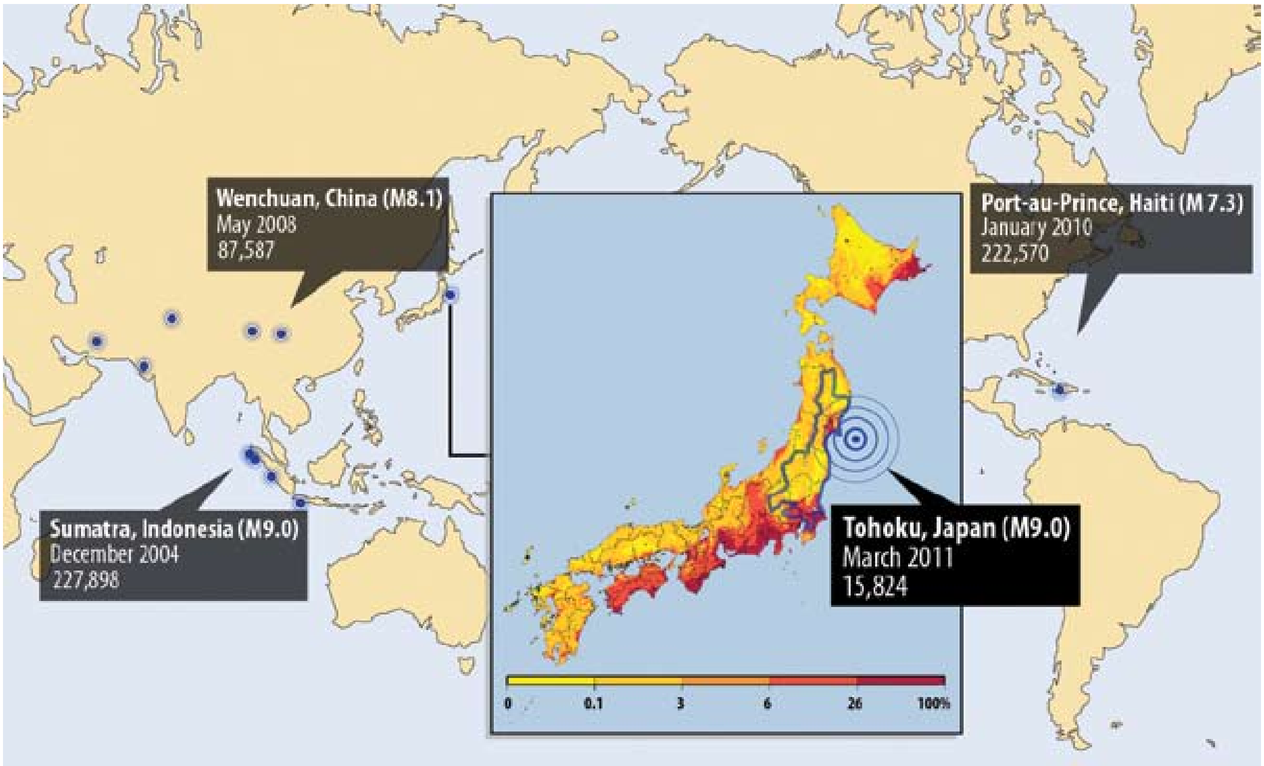
Scientists like Ouzounov are confident that such hindcasts, presented by participants from Russia, Europe, Japan, China, and the United States during the poster and oral sessions in San Francisco, have validated the general program of precursor research as the basis for short-term earthquake prediction.

But such research has been viewed with skepticism, even hostility, by mainstream seismology.

"We are in the absolute minority globally," said geophysicist Seyia Uyeda, a professor emeritus at Tokyo University, during a joint presentation with Greek physicist Panyiotis Varotsos on a panel on "Predicting Extreme Events." "Although I have deep respect for seismologists, seismologists don't like us," Uyeda said.

And because seismologists generally control appropriations for earthquake research, scientists studying non-seismic precursors have operated almost entirely without government support. Despite the heightened interest in earthquake prediction after the Japan disaster, a corresponding level of funding has not been forthcoming. In the United States, the austerity is typified by the Obama Administration's decision in late February 2011 to cancel the planned DESDynI natural hazard monitoring satellite, which would have performed high-fidelity observations in the radar and optical range, and to make cuts to other remote sensing satellite programs on which precursor monitoring depends.

One notable exception to the lack of government sponsorship has been China. Xuemen Zhang of the Beijing-based Institute of Earthquake Science, outlined the Chinese government's



SEISMIC HAZARD MAP

The 12 deadliest earthquakes between 2000-2011 (11 are represented as blue dots) claimed some 700,000 lives. In every case, the actual seismic intensity of the earthquake exceeded the maximum predicted by the Global Seismic Hazard Assessment Program (GSHAP) map published in 1999, which is used as a standard government reference for building codes and emergency response.

On Japan's seismic hazard map (at center), published by the government in 2009, the colored bars indicate the government's predictions of the probability of a high hazard or very high hazard (according the GSHAP seismic intensity criteria) earthquake occurring within 30 years. As can be seen from the blue lines on the map, the region which actually experienced this level of seismic intensity from the March 2011 earthquake was generally assessed as a relatively low-hazard region.

Sources: Vladimir Kossobokov, International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences; Japan Meteorological Agency.

ambitious expansion of the country's precursor monitoring capabilities, with the launch of three dedicated earthquake monitoring satellites planned between 2014-2017, as well as the construction of 50 new ionosondes (up from the current 20 in operation) in the next five years as part of an expanded seismo-ionospheric ground-based monitoring network.

"They're doing this because they realize the technology is affordable, and the science is ready, and needs to be applied," said Ouzounov.

"Why China? Because they have the economic potential to put about $100 million into this project. But also because they're not afraid to test new ideas, new methodologies."

Hazardous Assessments

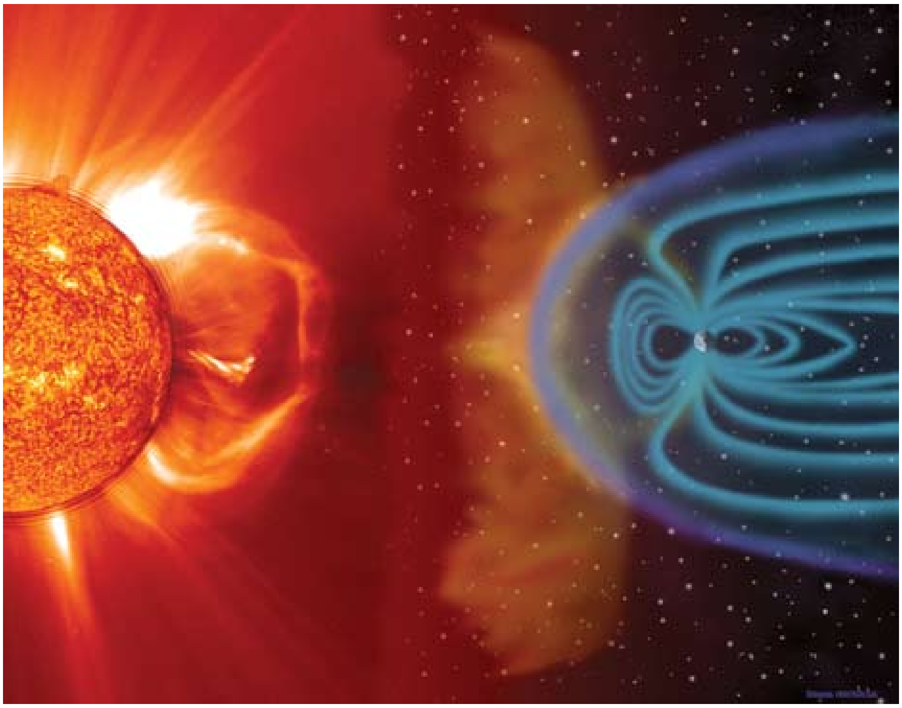
In its starkest terms, the field of earthquake prediction—or lack thereof—is about human lives lost to sudden catastrophe, a point driven home by Vladimir Kossobokov of the Russian Academy of Sciences' International Institute of Earthquake Prediction Theory and Mathematical Geophysics. In a talk with the deceptively dry title "Statistical Validation of Earthquake Related Observations," Kossobokov presented a withering indictment of the status quo in assessing, and therefore preparing for, earthquake hazards.

In its retreat from earthquake prediction, which was once considered the holy grail of the field, seismology has settled on broad forecasts of the probability that certain areas will experience a certain magnitude of seismic risk within a 30- to 50-year timeframe. While short-term prediction relies on precursors, long-term forecasts rely on past events to model risk, based on statistical extrapolations and certain assumptions about the way fault systems build up strain over time.

This has been codified, for example, in the Global Seismic Hazard Assessment Program (GSHAP) map published in 1999, which is used as a standard reference for governments in determining such regulations as building codes. But as a measure of risk for the worst events, it has proven a remarkably consistent failure.

Some 700,000 people have been killed globally in the 12 deadliest earthquakes (and related tsunamis) between 2000-2011. In every case, the actual magnitude of the event was greater than the maximum forecast of the GSHAP map—the Tohoku quake occurred in a region generally assessed as low-hazard, for example—allowing Kossobokov to quantify a surprise factor for each earthquake. The failure, says Kossobokov, is one of methodology, of abstract models of seismic processes accepted without proper validation, and given the stamp of official government sanction.

"Very often people would suggest the seismic hazard assessment maps as an alternative to prediction, as a reliable instrument to reduce disasters," said Kossobokov. But it happened that it's not so. It happened that those maps create disasters, by introducing the wrong estimate of hazards."



NASA

This illustration (not to scale) shows a coronal mass ejection blasting off the Sun's surface toward the Earth (the white dot inside the blue lines on the right). Two to four days later, the CME cloud is shown striking and beginning to be deflected around the Earth's magnetosphere. The blue lines represent magnetic field lines.

One of the most vocal critics of earthquake prediction, University of Tokyo seismologist Robert Geller, also takes issue with the use of hazard maps for risk assessment, but for a different reason. In a commentary in the April 28, 2011 issue of *Nature* magazine, titled "Shake Up Time for Japanese Seismology," Geller argued that the maps should be scrapped, not in favor of greater efforts at prediction, but instead, acceptance that earthquakes are inherently unpredictable on any time scale: We should instead tell the government and the public to "prepare for the unexpected."

But, according to Seyia Uyeda, seismologists simply aren't equipped for earthquake prediction, by the very nature of their current job description.

"Seismology is a science of earthquakes based on seismic records recorded by seismograms. And seismograms only record earthquakes, not precursors," Uyeda said. "Therefore, seismologists never say they can predict short-term. They are honest in that respect. But they think they are the only people who understand earthquakes. That's the trouble with the whole thing, in my view."

A New Geophysics

With earthquake science now swelling with ranks drawn from such fields as atmospheric, ionospheric, and solid-state physics, this institutional prejudice is bound to change, and, Ouzounov hopes, will soon lead to a hybrid system of research between seismologists and precursor scientists working in collaboration.

The strongly interdisciplinary nature of such work also suggests implications that go beyond practical earthquake prediction, but point to the possibility of a new kind of geophysics. For example, the close electrodynamic coupling of the lithosphere, atmosphere, and ionosphere may provide a new framework for studies that have shown strong correlations between solar activity and seismicity, perhaps revealing previously unknown pathways for seismic triggering. This line of investigation overlaps recent decades' developments in climate science, in which solar activity has been found to play a significant role in processes such as cloud formation, through its influence over the electrodynamics of the atmosphere.

The evidence for cosmic influences over the Earth extends even further, into galactic-scale processes whose effects can be read, among other things, in the geological record of long-period cycles of seismic and volcanic activity.

These larger questions, concedes Ouzounov, should not be ignored. But for the moment, he says that he and his colleagues are focussed on validating their methodologies through an actual proof-of-concept prediction, which they hope will bolster their case with the skeptics. If the proper resources were available today, he estimates that real-time monitoring of the United States, for example, could be a reality within a year.

In the meantime, the urgency for such a program is not likely to diminish. Large earthquakes have proven to be more destructive as population densities have increased, and the frequency of megaquakes, such as the Tohoku disaster, appear to have increased in the last decade. The point at which natural disasters become man-made ones, will depend on the choices we make in the coming period.

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