EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 91 NUMBER 35
31 AUGUST 2010
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Worldwide Integration of Neutron Monitors

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Cosmic rays, high-energy particles that reach Earth's atmosphere from outer space, provide a diagnostic tool to analyze processes of general astrophysical interest, such as the acceleration and transport of highly energetic charged particles in interplanetary space and at the Sun. Cosmic rays also directly affect the terrestrial environment and serve as indicators of solar variability and nonanthropogenic climate changes on Earth at present and in the distant past.

In the 1950s a worldwide network of standardized cosmic ray detectors was developed to examine temporal and spatial variations in the space environment. Despite decades of progress, ground-based neutron monitors (NMs) remain the state-of-the-art instrumentation for measuring cosmic rays with gigaelectron volt energies, which cannot be measured in the same simple, inexpensive, and statistically accurate way by space experiments. Therefore, the worldwide network, which currently consists of about 50 standardized International Geophysical Year (IGY) and NM64 neutron monitors, perfectly complements cosmic ray observations in space. The continuous monitoring of cosmic ray intensity near Earth by neutron monitors since IGY 1957–1958 represents the longest continuous, high-time-resolution series of particle radiation measurements in space science.

Since the coordinated neutron monitor measurements began, the data have been collected in world data centers and are available with a time resolution of 1 hour from these centers for scientific investigations. The media on which the data were stored by the data centers changed during the years, and today the data are available in electronic form via the Internet. A big shortcoming of the data centers for today's demands was the fact that the data were not available in real time and that the time resolution was only 1 hour. Because the analysis of relativistic solar particle events called ground level enhancements (GLEs) and space weather applications such as dose calculations for aircrews and passengers require higher-resolution data, 1-minute measurements were made available from the Web sites of many stations, and several efforts to collect all available data on ftp or Web servers have been recorded through the years. However, these data are often available only with a time delay of hours or days. In addition, the stations often use slightly different data formats and procedures, which make automatic analysis difficult. Currently only a few stations can provide their data in real time, and the data are available only through the respective station's Web site.

eGY
Electronic Geophysical Year

Athens Neutron Monitor Data Processing Center

To improve data availability, in 2005 the Athens NM station initiated an effort to realize a worldwide space weather center, the Athens Neutron Monitor Data Processing (ANMODAP) Center (http://cosray.phys.uoa.gr). The center collects real-time data from many NM stations (see Figure 1) together with satellite data from space missions (e.g., Geostationary Operational Environmental Satellite (GOES) and Advanced Composition Explorer (ACE)) to provide an overall picture of the space environment in real-time or quasi real-time mode.

The implementation of ANMODAP led to the realization of important applications for space weather monitoring and to reliable forecasting products such as the GLE Alert algorithm and the Neutron Monitor Basic Anisotropic Ground Level Enhancement (NM-BANGLE) code. The former algorithm uses ANMODAP to perform preventive prognosis of dangerous solar particle emissions that are heading to Earth. In the case of the December 2006 GLE event (which was recorded as GLE case 70), the Alert algorithm for the first time presented a real-time alert signal 30 minutes prior to the arrival of dangerous fluxes at the face of the Earth; the alert was sent out to various responders.

A European Neutron Monitor Database

In January 2008 a new large European project called the Neutron Monitor Database (NMDB; http://www.nmdb.eu) united all European cosmic ray groups that operate neutron monitors, in a coordinated effort to extend the use of cosmic ray data in cutting-edge applications (e.g., space environment

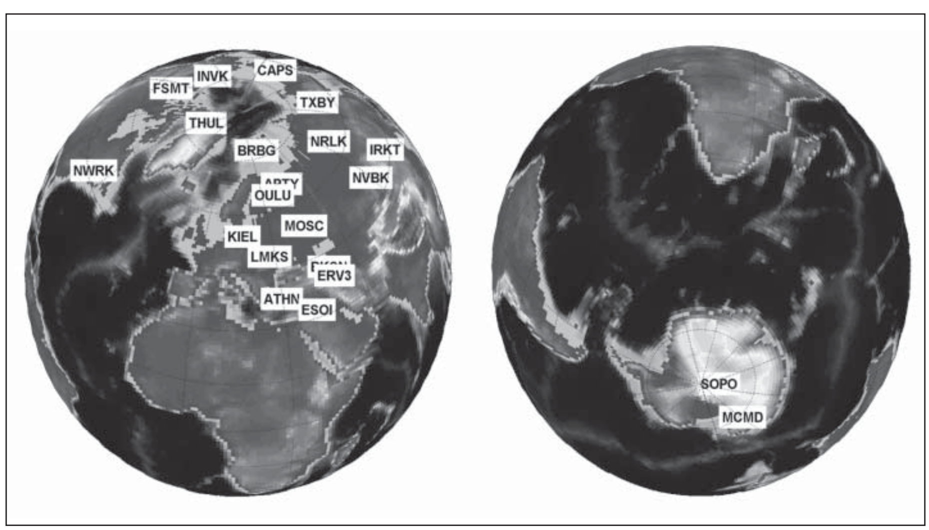

Fig. 1. The 21 neutron monitoring stations of the Athens Neutron Monitor Data Processing (ANMODAP) Center are distributed all over the world.

monitoring and predicting) and make publicly available data sets of NMs. NMDB has created a real-time NM database that holds data with 1-minute and 1-hour resolution. With this database, cosmic ray data have become available for use in a variety of applications, helping to improve space environment research and monitoring.

To reach this point, many of the contributing NM stations upgraded their software and hardware infrastructure and fully modernized their stations. In addition, applications were combined for the first time. For instance, for the 1-minute-resolution NM data, the previously mentioned Alert algorithm was combined with the NM-BANGLE model, which calculates important parameters of GLEs; their combination led to the MAGNETOCOSMICS and PLANETOCOSMICS codes, which calculate the atmosphere's ionization during a GLE event. In this way, the NMDB project offers an overall picture of the space environment and provides important information on the impact of dangerous solar emissions, based solely on NM data in real-time or quasi real-time mode.

In addition, the NMDB holds data sets from NM stations that cover a period of roughly 50 years, resulting in a reference database for NM and space applications. The most important characteristic of the NMDB, though, is its free usability—all of the data are publicly available through the Web site (http://www.nmdb.eu) for noncommercial use. Furthermore, many other applications have been implemented using the 1-hour-format data (e.g., galactic cosmic ray (GCR) anisotropy, daily and monthly GCR spectra, cosmic ray fluctuations, geomagnetic precursor monitoring).

At this point in the digital age, with the NMDB the worldwide neutron monitoring community has been able to secure 50 years of reliable NM measurements and to extend their use in state-of-the-art applications. Neutron monitoring stations and their worldwide networks are stepping into a new era.

Acknowledgments

The author thanks M. Gehmeyer for the invitation to contribute to the Electronic Geophysical Year (eGY) effort. Also, the support of the Special Research Account of the National and Kapodistrian University of Athens (grant 70/4/5803) is gratefully acknowledged. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP/2007-2013) under grant agreement 213007.

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The 2010 Chile Earthquake: Rapid Assessments of Tsunami

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After an underwater earthquake occurs, rapid real-time assessment of earthquake parameters is important for emergency response related to infrastructure damage and, perhaps more exigently, for issuing warnings of the possibility of an impending tsunami. Since 2005, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) has worked on the rapid quantification of earthquake magnitude and tsunami potential, especially for the Mediterranean area. This work includes quantification of earthquake size from standard moment tensor inversion, quantification of earthquake size and tsunamigenic potential using *P* waveforms, and calculation of an archive of readily accessible tsunami scenarios.

For the case of tsunami early warning for coastlines at regional distances (>100 kilometers) from a tsunamigenic earthquake, notification is required within 15 minutes after the earthquake origin time (OT) so that coastal communities can be warned. Currently, rapid assessment of the tsunami potential of an earthquake relies mainly on initial estimates of the earthquake location; depth; and moment, M_0, or the corresponding moment magnitude, M_w.

Recently, *Lomax and Michelini* [2009a] introduced a duration-amplitude procedure for rapid determination of a moment magnitude, M_{wpd}, for large earthquakes using *P* wave recordings at teleseismic distances (30°–90° of distance along a great circle path). M_{wpd} can be obtained within 20 minutes or less after the event origin time, as the required data are currently available in near real time. The procedure determines apparent source durations (T_0) by extrapolating from high-frequency *P* wave records. T_0 is an indication of the time the entire fault took to rupture. The method then estimates magnitudes through integration of broadband displacement waveforms over the interval t_P to $t_P + T_0$, where t_P is the *P* arrival time. *Lomax and Michelini* [2009a] also show that any T_0 greater than about 50 seconds is a reliable indicator for tsunamigenic earthquakes.

This result was used to formulate a direct "duration exceedance" (DE) procedure applied to seismograms located between 10° and 30° of distance along the great circle path of an earthquake source. This helps to rapidly determine if T_0 for any given earthquake is likely to exceed 50–55 seconds and thus be a potentially tsunamigenic earthquake [*Lomax and Michelini*, 2009b].

Case Study: The 27 February 2010 M = 8.8 Chile Earthquake

INGV operates a continuous seismic monitoring center that uses a network of about 250 stations spread over Italian territories to monitor the nation's seismic hazards. A senior scientist is on call and will respond to earthquakes greater than magnitude 4 in Italy and greater than magnitude 6.5 worldwide.

Alberto Michelini, coauthor of this brief report, was on duty in the seismic center as senior scientist at the time of the 27 February 2010 M_w 8.8 Chile earthquake, which was sourced south of Santiago, along the coast. He was able to rapidly assess DE and M_{wpd} through procedures newly established at INGV.

On the morning of 27 February 2010, minutes after the origin time of the Chile earthquake, the senior scientist received the alarm. The display for the real-time DE at INGV (Figure 1; http://s3.rm.ingv.it/warning/warning.html) showed clearly that (1) the event was offshore along a major subduction zone and (2) the DE level was around 3; that is, the rupture duration was very likely greater than 50 seconds, and thus the earthquake was probably tsunamigenic, according to *Lomax and Michelini* [2009b]. This high level of warning was further supported at OT + 16 minutes by M_{wpd} magnitude calculations automatically determined at INGV. These calculations showed that the M_{wpd} was likely 8.8 if the event was a shallow, interplate thrust earthquake, which was likely given the event epicenter. If the earthquake was of a type different than a shallow interplate thrust, the M_{wpd} was likely 8.3 (see *Lomax and Michelini* [2009a] for details on the magnitude calculation). Regardless, it was clear that the M_{wpd} was high, indicating that the earthquake was likely tsunamigenic.

Toward Quicker Detection

Currently, the M_{wpd} calculation is initiated when INGV receives notification from an external agency that a major earthquake has occurred. Thus, time between the initiation of rupture and the conclusion of the M_{wpd} calculation could be reduced to between OT + 8 and OT + 12 minutes using an internal notification procedure.

The great size and likely tsunamigenic nature of this event were thus evident at INGV within 10–15 minutes after the earthquake OT. This additional information complemented the M = 8.3 magnitude and tsunami warning for Chile and Peru issued by the Pacific Tsunami Warning Center at OT + 12 minutes, and further confirmation of a tsunami's likely impact was given by the