EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 20

15 MAY 2007

PAGES 217–224

Natural Radioactivity, Earthquakes, and the Ionosphere

PAGES 217–218

Air ionization produced by natural ground radioactivity, mainly by radon emanating from the Earth's crust, is a primary source of ions in the planetary boundary layer (PBL) of the atmosphere over land [*Hoppel et al.*, 1986]. These ions provide the air conductivity responsible for fair weather vertical electric current in the global electric circuit (GEC), a system of stationary electric currents between the ground and ionosphere driven by global thunderstorm activity. This activity is considered an electric generator of the potential difference between the ground and ionosphere (200–600 kilovolts), and the return downward current closes the circuit in the areas of fair weather [*Roble and Tzur*, 1986]. The upper closing limit of this circuit is of the altitude of 60 kilometers. At altitudes higher than 60 kilometers, cosmic rays and solar radiation also contribute to air ionization. The processes in the PBL are important for atmosphere-ionosphere electrodynamics because more than 70% of atmosphere columnar resistance is provided by the PBL. This resistance determines the total current between the ground and ionosphere, and it should correspond to the current generated by thunderstorms.

Calculations of ionosphere potential (which averages 280 kilovolts) within the frame of the GEC model [*Roble and Tzur*, 1986] try to take into account the orography (influence of the relief and local irregularities) and other factors, but these calculations do not take into account the local variations of air conductivity that may affect the ionosphere. It is well known that air pollution or other high aerosol concentrations in the atmosphere (dust storms, volcano eruptions, polluted cities, fog) can increase the columnar electrical resistance up to several hundred percent [*Gringel et al.*, 1986]. An attempt to calculate the effects in the ionosphere from such events was made by *Pulinets et al.* [2000]. Seismically active areas were considered as one of the possible sources of the anomalous ionospheric variations, and radon emanation was named as a principal source.

Here we intend to demonstrate how the large-scale local irregularities of air conductivity produced by natural radioactivity can create irregularities within the ionosphere through coupling within the frame of the GEC model.

Effect of Radon Emissions on the Atmosphere

Hundreds of publications have noted increased radon concentration in the vicinity of active tectonic faults a few weeks before strong seismic events. Ionization of the near-ground layer of the atmosphere produced by radon has two major consequences [*Pulinets et al.*, 2006a]. First, after a series of chemical reactions, newly formed ions become the centers of water condensation. The process is very effective; more than 100 water molecules may attach to a single ion. During attachment, the latent heat of evaporation is released, leading to an increase in surface temperature and the so-called thermal anomalies that have been observed before earthquakes. The second consequence is that due to the presence of many centers of condensation, the chemical potential of the formed ion clusters changes. This change increases the work function for the water molecules, which prevents them from evaporation and keeps large clusters stable for a longer time. Thermal convection (due to increased temperature) spreads the large clusters throughout the PBL, and the atmosphere columnar resistance sharply grows due to the low mobility of the cluster ions.

What are the practical consequences of these two effects? First, the thermal anomalies can serve as tracers of increased radon emanation. Using a remote sensing technique developed by several groups, one can see radon distribution, the spatial size of any anomaly, and temporal variations [*Ouzounov et al.*, 2006, and references therein]. From the satellite data it becomes clear why ground radon measurements failed to serve as an earthquake precursor. Satellite monitoring shows the migration over time and space of variations in radon, and its presence will not necessarily be close to the epicenter of an earthquake. However, with satellites, an anomaly can be observed within a much larger area (earthquake preparation area) that for large earthquakes is of the order of several hundred thousand square kilometers. Most important, the thermal anomalies for all recent major earthquakes were registered before the seismic shocks, which proves that radon variation is a real precursor to an earthquake. Of course, the lithology creates the difference in radon emission intensity for different areas of the globe.

Nonetheless, these thermal anomalies are equivalent in size to the air ionization and ions' hydration area, and hence to columnar resistance anomalies that cannot be 'unnoticed' within the ionosphere because of size. The local conductivity anomaly of the order of an individual cloud or even a volcano

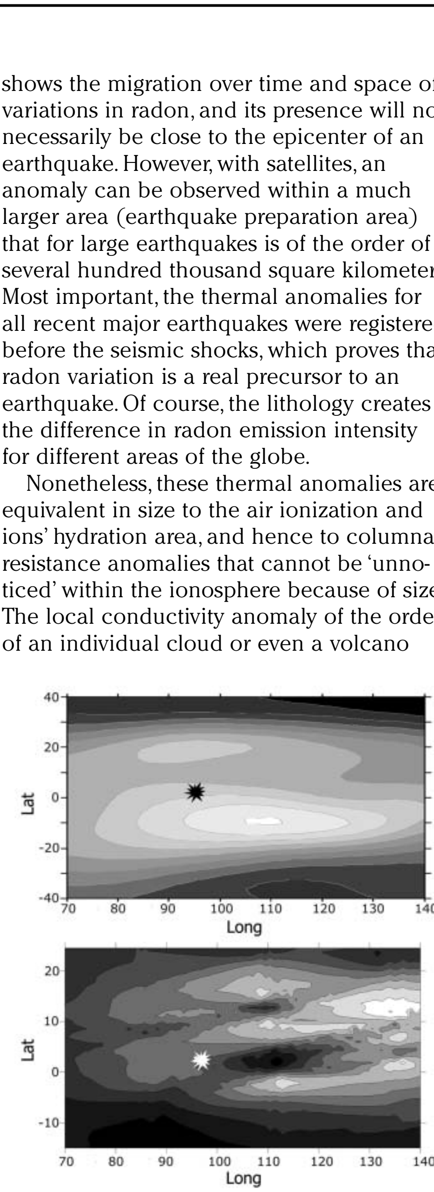

Fig. 1. (top) IONEX total electron content (TEC)—a special code that generates global maps of the vertical TEC using data from 150 GPS receivers distributed globally—as measured 2 days before the Sumatra earthquake of 26 December 2004 (modified after Zakharenkova et al. *[2006]). (bottom) In situ ion density distribution measured onboard the DEMETER satellite 6 days before the Sumatra earthquake of 28 March 2005. Lower plasma concentration is indicated by darker shading. Bursts indicate the position of the epicenter of the impending earthquake.*

By S. A. Pulinets

eruption is not sufficient in size to produce noticeable changes within the ionosphere, but irregularities of the order of 10 degrees in latitude and longitude create the essential difference in vertical current of GEC. The ionosphere potential will grow over the earthquake preparation area and create a horizontal potential difference with undisturbed ionosphere outside the modified area. For example, close to the geomagnetic equator, an east directed electric field will be created to the east of the epicenter of an impending earthquake, and a west directed electric field will be created to the west of the epicenter. Such a configuration will increase the development of an equatorial anomaly to the east from epicenter and inhibit its development to the west from it because the upward **E** × **B** drift of the plasma near the geomagnetic equator is created by the Earth's general east directed electric field (keeping in mind that the geomagnetic field on the geomagnetic equator is directed north).

Such a situation was observed for the Sumatra mega earthquakes of 26 December 2004 [*Zakharenkova et al.*, 2006] and 28 March 2005 [*Pulinets et al.*, 2006b] (see Figure 1). Though the 26 December 2004 earthquake occurred under water, radon signatures were developed by the land within the earthquake's preparation area, which for a magnitude 9 earthquake has a diameter of 7000 kilometers. One can expect also the radon exhalation through the ocean with gas discharges accompanying the earthquake preparation process. Figure 1 (top) demonstrates the enhanced equatorial anomaly observed 2 days before the 2004 Sumtatra earthquake as registered by the network of continuous GPS receivers in the area. Figure 1 (bottom) shows the spatial distribution of the ion concentration as registered by the French satellite DEMETER 6 days before the 2005 Sumatra earthquake. Both figures demonstrate the enhanced development of the equatorial anomaly to the east of the earthquake epicenter, with the southern crest of the anomaly being more developed. In Figure 1b, the plasma bubbles within the crest, which are another indicator of the increased development of equatorial anomaly, can be seen.

In the middle and high latitudes, the area of ionosphere modified by the electric conductivity effects due to earthquake preparation is more circular. (The main morphological and statistical characteristics of the ionospheric anomalies associated with earthquakes in these regions are explained in detail by *Pulinets and Boyarchuk* [2004].)

Because geological structure varies, radon concentrations also vary according to location. Sometimes the concentration of radon is not sufficient to create the pronounced, large-scale variations within the ionosphere. Instead, 'scintillations' of the columnar resistance and correspondent regional variability will be observed in the ionosphere.

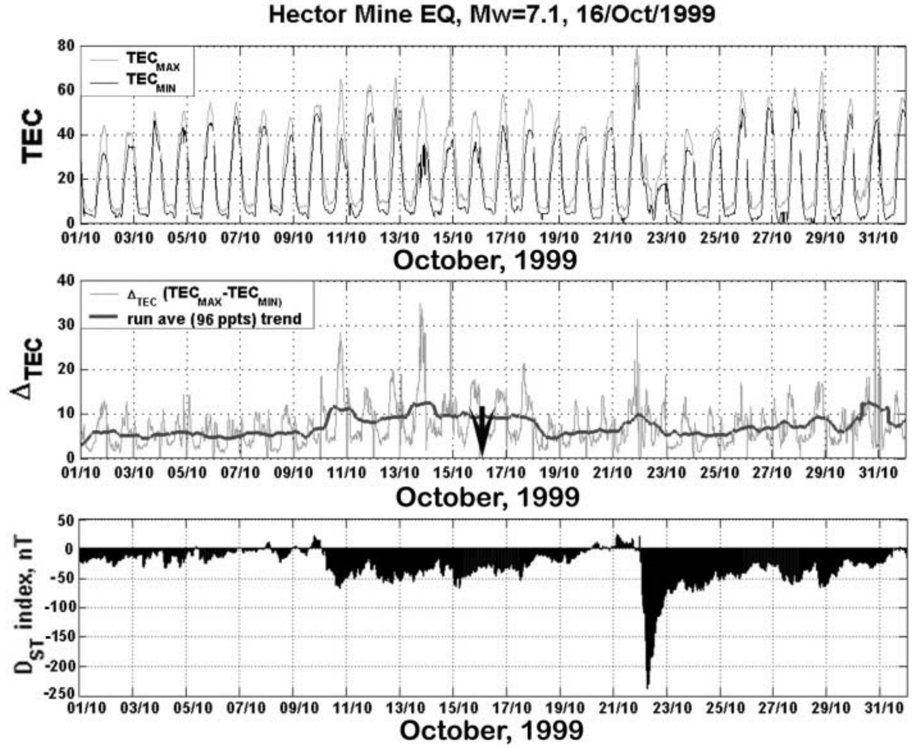

*Fig. 2. Analysis of GPS TEC data for a network of GPS receivers in California for the period of October of 1999. (top) The grey curve indicates maximal TEC values for the set of stations under analysis. The solid curve indicates minimum TEC values for the set of stations under analysis. (middle) The thin grey curve is the variability index, the difference between the maximum and minimum values presented in the top panel. The solid curve is the running (96 points) average. Arrow indicates the moment of seismic shock. (bottom) Global equatorial index of geomagnetic activity (*Dst *index) for October 1999. Note the increase of the variability index (middle panel) on 10 October, 6 days before the seismic shock. The index does not grow after strong geomagnetic storm (near -250 nanoteslas) on 22 October (*Dst *index, bottom panel).*

Detecting Earthquake-Induced Ionospheric Variability

Ionospheric variability can be detected through correlation analysis [*Pulinets et al.*, 2006c]. We studied correlations between the records of GPS receivers in different areas and discovered that in a majority of cases the correlation coefficient grows during magnetic disturbances. However, before earthquakes, the correlation coefficient drops to within about a 700-kilometer diameter around the earthquake epicenter. This allowed us to formulate for the first time a special index of ionosphere variability, which is sensitive to the pre-earthquake variations and much less sensitive to the magnetic storm variations. Figure 2 demonstrates one of the cases considered in the paper [*Pulinets et al.*, 2006c] and shows that a few days before California's 16 October 1999 Hector Mine earthquake (M_w = 7.1) the variability index (middle panel of Figure 2) was higher than during a strong (*Dst* ~ -250 nanoteslas) eomagnetic storm.

Similar results were obtained for all recent major earthquakes in California, Mexico, and Sumatra. The presence of thermal anomalies for all of these earthquakes supports the presented mechanism of observed ionospheric variations.

Satellite technologies have allowed a greater understanding of the physics of seismoionospheric coupling. Ionospheric mapping with the use of topside sounding, GPS total electron content (TEC), and remote sensing of the thermal anomalies have allowed the main morphology and statistical characteristics of the ionospheric precursors to be established. An increasing number of scientists have become involved in these studies recently, and many countries (China, France, Italy, Mexico, Russia, Ukraine, United States) are launching the satellites necessary to find ionospheric precursors to earthquakes. Short-term earthquake prediction based on ionospheric data may one day become as routine a technique as seismographs.

Acknowledgments

The author thanks Dimitar Ouzounov (NASA Goddard Space Flight Center, Greenbelt, Md.) for valuable cooperation in the thermal precursors studies, and Michel Parrot (LPCE/CNRS) for providing the data of DEMETER satellite.

References

Gringel, W., J. M. Rosen, and D. J. Hofmann (1986), Electrical structure from 0 to 30 kilometers, in *The*

Earth's Electrical Environment, pp. 166–182, Natl. Acad. Press, Washington, D. C.
Hoppel, W. A., R. V. Anderson, and J. C. (1986), Atmospheric electricity in the planetary boundary layer, in *The Earth's Electrical Environment*, pp. 149–165, Natl. Acad. Press, Washington, D. C.
Ouzounov, D., N. Bryant, T. Logan, S. Pulinets, and P. Taylor (2006), Satellite thermal IR phenomena associated with some of the major earthquakes in 1999–2003, *Phys. Chem. Earth, 31*, 154–163.
Pulinets, S. A., K. A. Boyarchuk, V. V. Khegai, V. P. Kim, and M. Lomonosov (2000), Quasielectrostatic model of atmosphere-thermosphere-ionosphere coupling, *Adv. Space Res.*, *26*, 1209–1218.
Pulinets, S. A., and K. A. Boyarchuk (2004), *Ionospheric Precursors of Earthquakes*, 315 pp., Springer, New York.
Pulinets, S. A., D. Ouzounov, A. V. Karelin, K. A. Boyarchuk, and L. A. Pokhmelnykh (2006a), The physical nature of the thermal anomalies observed before strong earthquakes, *Phys. Chem. Earth, 31*, 143–153.
Pulinets, S. A., M. Parrot, and D. Ouzounov (2006b), Conjugated near-equatorial effects registered by DEMETER satellite before Sumatra earthquake M8.7 of March 28, 2005, paper presented at the International Symposium: Results of the DEMETER Project and of the Recent Advances in the Seismo-Electromagnetic Effects and the Ionospheric Physics, Toulouse, France, 14–15 June.
Pulinets, S. A., A. N. Kotsarenko, L. Ciraolo, and I. A. Pulinets (2006c), Special case of ionospheric day-to-day variability associated with earthquake preparation, *Adv. Space Res.*, in press, doi:10.1o16/j.asr.2006.04.032.
Roble, R. G., and I. Tzur (1986), The global atmospheric-electrical circuit, in *The Earth's Electrical Environment*, pp. 206–231, Natl. Acad. Press, Washington, D. C.
Zakharenkova, I. E., A. Krankowski, and I. Shagimuratov (2006), Modification of the low-latitude ionosphere before the 26 December 2004 Indonesian earthquake, *Nat. Haz. Earth Syst. Sci.*, *6*, 817–823.

Author Information

Sergey Alexander Pulinets, National Autonomous University of Mexico, Mexico City; E-mail: pulse@geofisica.unam.mx; on leave from IZMIRAN (Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russian Academy of Sciences).

A Strategy for Climate Change Stabilization Experiments

PAGES 217–219, 221

Climate models used for climate change projections are on the threshold of including much greater biological and chemical detail than previous models. Today, standard climate models (referred to generically as atmosphere-ocean general circulation models, or AOGCMs) include components that simulate the coupled atmosphere, ocean, land, and sea ice. Some modeling centers are now incorporating carbon cycle models into AOGCMs in a move toward an Earth system model (ESM) capability. Additional candidate components to include in ESMs are aerosols, chemistry, ice sheets, and dynamic vegetation [e.g., *Cox et al.*, 2000; *Friedlingstein et al.*, 2006].

In this article, we discuss a new strategy for using climate system models as part of a coupled biophysical-climate and integrated model assessment approach. The motivation is to develop a next-generation experimental design that follows on the scenario approach where concentrations and their derived emissions based on story lines were used in the development of the Intergovernmental Panel on Climate Change (IPCC) third and fourth assessment reports. We specifically address recent developments in climate system models that can shed light on greenhouse emissions scenarios. Complementary aspects of ongoing model development (e.g., observations and paleoclimate experiments) are important components of a much larger research strategy of which the modeling approach proposed here is one part.

Modeling groups are now making decisions as to what form their next-generation climate models will take with the consideration of how new climate change experiments may be evaluated in a next IPCC assessment. The experiments proposed in this article regarding stabilization scenarios warrant community experiments to address this issue even if there is not another IPCC assessment. Additionally, new emissions scenarios developed by the integrated assessment community reflect recommendations of the 25th IPCC session (held in April 2006 in the Republic of Mauritius). These advances in both the climate modeling and scenarios communities provide an opportunity for increased communication and collaboration that could recommend plausible action toward assessing human mitigation of changing climate.

By K. A. Hibbard, G. A. Meehl, P. M. Cox, and P. Friedlingstein.

This confluence of activities in model and scenario development needs to be communicated and coordinated across various groups and scientific communities. To this end, a strategy for the next-generation climate simulations should (1) identify new components in preparation for inclusion in AOGCMs;
(2) establish communication for coordination through the World Climate Research Programme (WCRP), the Integrated Geosphere-Biosphere Programme (IGBP), and the Integrated Assessment (IA) modeling teams such as those involved with IPCC Working Group III (WGIII); (3) propose an experimental design for 21st-century climate change experiments; and (4) specify the requirements for new stabilization scenarios (particularly with regard to impacts, mitigation, and adaptation).

Empirical evidence and first-generation coupled carbon cycle model results indicate the possibility of a large positive carbon cycle feedback to the climate system, which challenges any particular stabilization target [*Cox et al.*, 2000; *Fung et al.*, 2005; *Friedlingstein et al.*, 2006]. While some models include a carbon cycle, none has consistently incorporated nutrient and/or micronutrient limitations, land use, fire, succession, ocean bottom chemistry, and tropospheric ozone dynamics. Taking into account the state of the art of these new components, a strategy involving an experimental design addressing two timescales is proposed for community coordinated climate change projection experiments.

Near-Term Experimental Design (2005–2030)

A major goal for 25-year model projections is to provide better guidance about the likelihood of changes in climate extremes at regional scales. Meeting this challenge will depend on scientific questions that address understanding the processes that produce extremes related to the hydrological cycle,

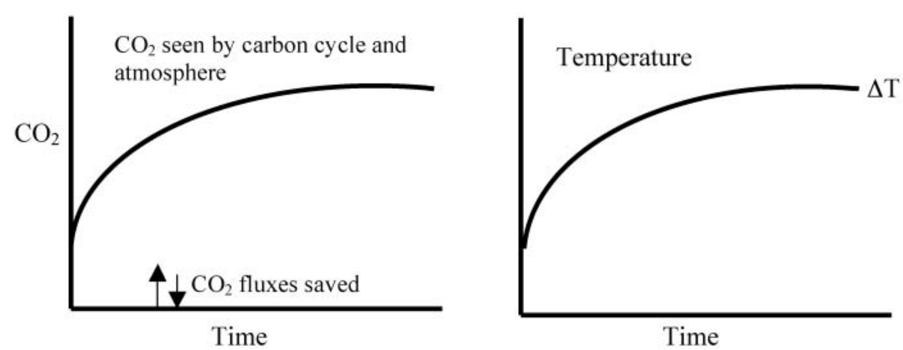

Fig. 1. Schematics of experiment 1. The carbon cycle responds to (left) increasing CO_2 concentrations and (right) changes in temperature. The land and ocean CO_2 fluxes are saved to derive emissions for Integrated Assessment (IA) modeling teams such as those involved with IPCC Working Group III (WGIII) scientists. The land and ocean CO_2 fluxes are not radiatively interactive with the atmosphere.