EOS

IN THIS ISSUE: Issues in Planetary Chronology, Pg. 199
'Rotators' in the NSF Geosciences Directorate, Pg. 200
Did an Earthquake Trigger the Lusi Mud Volcano?, Pg. 201

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 18 1 MAY 2007

Counting Atlantic Tropical Cyclones Back to 1900

Climate variability and any resulting change in the characteristics of tropical cyclones (tropical storms, subtropical storms, and hurricanes) have become topics of great interest and research within the past 2 years [*International Workshop on Tropical Cyclones*, 2006]. An emerging focus is how the frequency of tropical cyclones has changed over time and whether any changes could be linked to anthropogenic global warming.

The Atlantic is the one tropical cyclone basin that has quantitative records back to the mid-nineteenth century for the whole basin (i.e., North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) [*Jarvinen et al.*, 1984; *Landsea et al.*, 2004]. *Mann and Emanuel* [2006] used this data set to find a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period of 1871–2005. Likewise, *Holland and Webster* [2007] analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both papers linked these changes directly to anthropogenic greenhouse warming. However, both analyses, with no indication of uncertainty or error bars, presumed that tropical cyclone counts are complete or nearly complete for the entire basin going back in time for at least a century. This article will show that this presumption is not reasonable and that improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones.

Reanalysis of Historical Tropical Cyclone Counts

Mann and Emanuel [2006, p. 238] stated that "although wind estimates prior to the 1940s are problematic, detection of the existence of tropical cyclones is less so, because without aircraft and satellites to warn them off, ships often encountered storms at sea, at least peripherally." *Holland and Webster* [2007] likewise make similar arguments. Their assumptions disregarded the recommendations of the original database documentation [*Jarvinen et al.*, 1984] and database extension and reanalysis documentation [*Landsea et al.*, 2004] that tropical cyclones were missed before the mid-twentieth century. In particular, *Landsea et al.* [2004] estimated an undercount bias of zero to six tropical cyclones per year between 1851 and 1885 and zero to four per year between 1886 and 1910. These undercounts roughly take into account the typical size of tropical cyclones, the density of shipping tracks over the Atlantic basin, and the amount of populated coastline. As one goes back further in time, the numbers of ships and shipping lanes decreases and fewer people live in the tropical and subtropical coastal regions. These factors make it increasingly likely that some tropical cyclones would not be counted the farther back in time examined.

Consider the two most active Atlantic hurricane seasons on record (Figure 1): 1933, with 21 tropical cyclones, and 2005, with 28. On the basis of just those cyclones that struck land, 1933 had more impacts (19) than 2005 (17). The difference in frequency between these two years is that there are many more tracks present over the open Atlantic Ocean in 2005 than there were in 1933. Is this evidence of a significant undercount in the historical records?

Here a simple analysis demonstrates the existence of a sizable bias in historical tropical cyclone counts. Figure 2a shows the time series of tropical cyclones going back to 1900, with both multidecadal variations [*Goldenberg et al.*, 2001] and a long-term trend being readily apparent. The data are stratified to indicate which tropical cyclones struck land and which stayed over the open ocean. The former are determined by their center either crossing a coastline or passing within 111 kilometers (60 nautical miles) of a landmass (either island or mainland) as a tropical cyclone.

The year 1900 is chosen as the first in this analysis. It is at about that time that a sufficient number of people lived along the coastline, such that if even a weak tropical storm struck it would likely have been detected and recorded. However, this beginning date of 1900 of having recorded all tropical cyclones that have struck land may be somewhat optimistic, especially for short-lived, relatively weak tropical storms. Consider the detection difficulties of a 1-day tropical cyclone such as Gert, which struck Mexico in 2005 in a sparsely population region of the coast and produced no observed surface tropical storm force winds, caused minimal impact, and was only identified as being a tropical cyclone via satellite imagery and aircraft reconnaissance. Therefore, conclusions from this paper on the number of 'missed' tropical cyclones are likely conservative.

The linear correlation coefficient between the frequency of all tropical storms and those that struck land is a very high 0.87 for 1900–2006. This value might be somewhat surprising given that some years can be quite active yet places such as the continental United States can be relatively untouched (such as what occurred in 2000 and 2001) or seasons that are quiet can have large U.S. impacts (such as 1992 with Hurricane Andrew). The likely reason for such a strong association between the frequency of all tropical cyclones and those that strike land is that taking into consideration all landmasses (i.e., Mexico, Central America, the Caribbean islands, Bermuda, Canada, and the Azores) in addition to the continental United States makes it much more likely that overall busy years will have many landfalls and quiet seasons generally will have fewer tropical cyclone strikes on land.

However, differentiating between the frequency of tropical cyclones that struck land versus those that remained over the open ocean shows that more of the latter were observed in recent decades compared with earlier in the twentieth century (Figure 2a). Figure 2b shows the tropical cyclone data expressed as an annual percentage that make landfall. In the era since geostationary satellite imagery began, in 1966 [*Neumann et al.*, 1999], the average is 59%. While sizable interannual variations are present, this value of slightly more than half is quite stable across the four decades of satellite coverage including periods of both active hurricane seasons (62% from 1995 onward) and a quiet hurricane regime (59% from 1971 to 1994). This value is even steady within the active era between seasons with numerous U.S. landfalling cyclones in 2004 and 2005 (65%) and relative lack of strikes in the United States between 1995 and 2003 (60%). Again, it is likely that the inclusion of tropical cyclones to make landfall in any landmass—in addition to those that just hit the continental United States—minimizes the long-term variability of the percent that strike land caused by genesis location and steering pattern changes.

However, data from the first 66 years, shown in Figure 2b, have a quite different long-term character, with an average of 75% of tropical cyclones striking land. While there were no years with more than 80% striking land from 1966 onward, there were 15 years between 1900 and 1965 in which all (100%) recorded tropical cyclones struck land that season. This difference in the long-term percentage of tropical cyclones that struck land (75% from 1900–1965 versus

Tropical Cyclones cont. on page 202

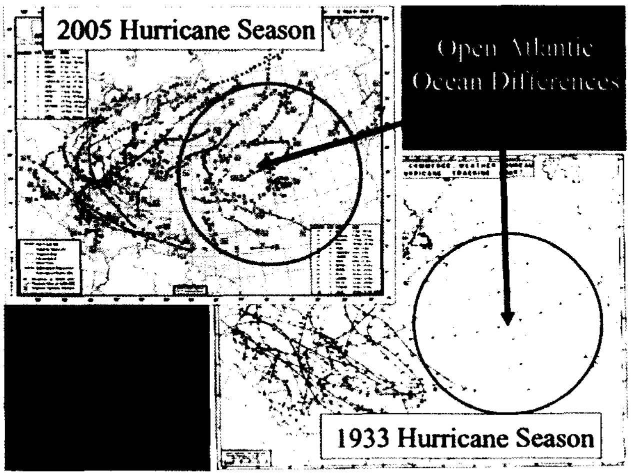

Fig. 1. Track maps of the Atlantic hurricane seasons of 2005 and 1933, the two busiest hurricane years on record for tropical cyclone frequency. The circles highlight large differences in activity that occurred over the open Atlantic Ocean.

By C. W. Landsea

New Borehole Strain System Detects Uplift at Campi Flegrei

Campi Flegrei and Mount Vesuvius are active Italian volcanoes though presently in a quiescent stage. The last eruption of Mount Vesuvius occurred during the spring of 1944. Campi Flegrei last erupted in 1538 but experienced a subsidence trend from the early 1900s to 1970, which was followed by episodes of ground uplift accompanied by seismic swarms [see, e.g., *Aster et al.*, 1992].

Over the past 37 years at Campi Flegrei, about 4 meters of maximum ground uplift has occurred followed by about 1 meter of subsidence, as measured near the center of the caldera in two episodes during 1970–1972 and 1982–1984. This deformation has occurred close to the harbor of the town of Pozzuoli, putting about 400,000 people at heightened risk. From 1985 to 2004, Campi Flegrei's caldera showed gradual subsidence that was interrupted by five mini-uplift episodes in 1976, 1989, 1995, 2000, and, most recently, 2004–2006, each amounting to a few centimeters of uplift [*Pingue et al.*, 2006]. The caldera is generally aseismic during gradual subsidence, but small swarms of microearthquakes are produced during periods of elevated strain rates associated with the mini-uplift episodes [*Saccorotti et al.*, 2001].

These two potentially explosive volcanic systems pose a high risk due to the dense urban population of the Naples metropolitan area where more than 1 million people live within easy reach of either Mount Vesuvius or Campi Flegrei caldera. A new project named Dilatometers Neapolitan Volcanoes (DINEV)—a collaboration involving the University of Salerno (UNISA; Italy), Osservatorio Vesuviano–Istituto Nazionale di Geofisica e Vulcanologia (OV-INGV; Italy), and the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution (CI) of Washington (United States)—has been designed to complement already existing seismic and geodetic instrumentation in the dangerous Campi Flegrei–Vesuvius volcanic region. The project is intended to improve the geophysical monitoring system through the installation of a small network of borehole dilatometers to measure ground deformation and three-component borehole broadband seismometers (Figure 1).

The New Monitoring Network

Since 2004, a network of six borehole Sacks-Evertson strainmeters (dilatometers) has been installed in the Mount Vesuvius and Campi Flegrei region, at depths ranging from 120 to 200 meters. These instruments are provided with air pressure transducers to remove barometric pressure, which influences the ground deformation. Data are displayed at and can be retrieved from the project Web site (http://plinio.ov.ingv.it/dilatometri).

Nominal resolution of the Sacks-Evertson strainmeter, the type used to monitor changes in seismic stress and strain at the

Campi Flegrei cont. on page 203

By R. Scarpa, A. Amoruso, L. Crescentini, P. Romano, W. De Cesare, M. Martini, G. Scarpato, A. T. Linde, and S. I. Sacks

Campi Flegrei

cont. from page 197

Campi Flegrei–Vesuvius volcanic region, is about 10^{-11} strain units, and the nominal dynamic range is 10^{-11}–10^{-3}. The nominal sensitivity is confirmed by comparison with solid Earth tides for the Campi Flegrei dilatometers. The signals are continuously recorded and sampled at 100 hertz. Six channels of 24-bit data logger Kinemetrics Quanterra Q330 and PB14, buffering up to 20 gigabytes of data in MSEED packets, are used as data acquisition systems. Signals from the network are archived at two different data acquisition centers, composed of high-capacity storage units (Hewlett Packard MSA 1500, 2.7TB), through ADSL telephonic lines, allowing almost real-time data access. Real-time signal processing is done with a cluster of Hewlett Packard Proliant DL140 computers consisting of fifteen 3.4-GHz dual processors with 3 gigabytes of RAM each, working with parallel Red Hat Linux software.

Borehole stations are separated by several kilometers, and the network covers critical distances from the crustal magma bodies beneath the Campi Flegrei and Vesuvius volcanoes. An additional 11 borehole seismometers and five surface broadband seismometers are being installed; this project will be completed in December 2007 in complement with the DINEV network.

All drilling operations required for the installation of the borehole equipment were carried out by Geotesting SRL. Drilling commenced in April 2004 at the Quarto (labeled QUAR in Figure 1) site and continued through July 2004 when drilling at Toiano (labeled TOIA in Figure 1) stopped. During drilling operations, PQ (~12 centimeters in diameter) and HQ (~10 centimeters) diamond-coring equipment was used. Where unstable fractured rock has been encountered, the fractures were sealed using concrete grout. Dilatometers were installed in sequence (Quarto, Monteruscello (labeled MRUS in Figure 1), and Toiano) while the drilling equipment was on site; seismometers were installed later. Data acquisition began immediately after the strainmeters were grouted. Strainmeter electronics, the datalogger, and battery arrays for backup power are housed inside local schools with a GPS antenna located on the roof.

Early Results and Evaluations of Future Hazards

When there are changes in the state of a magmatic reservoir, strainmeter data can provide direct information on the structure of the conduit, the physical properties of magma, and the dynamics of magma transport. Borehole strainmeters have been used around the world to obtain these observations [see, e.g., *Ishihara*, 1988; *Linde et al.*, 1993; *Linde and Sacks*, 1995; *Fukao et al.*, 1998; *Mattioli et al.*, 2004; *Voight et al.*, 2006] and have shown very clear deformation signals related to eruptions with a sensitivity much greater than that of GPS. These types of observations have supported modeling of the details of magma transport.

Three of the borehole stations were installed in the Campi Flegrei area at distances ranging from 3 to 8 kilometers from the center of caldera uplift at the harbor of Pozzuoli. An additional three stations were installed near Mount Vesuvius, and a seventh (CHIA, Figure 1) is planned for installation during 2007. This network of borehole strainmeters and broadband seismometers will contribute to the knowledge of the magma feeding system, allowing sampling of seismic and deformation signals from the deep transport, storage, and recharge systems. The network will constitute high-sensitivity short- and middle-term instrument combination with potential for eruption forecasting.

The main goal of DINEV is to improve estimates at Campi Flegrei of the depth of the pressure source in case of unrest and possibly detect ground deformation accompanying small pressure variations due to increased bubble formation, hydrothermal fluid motions, and/or magmatic ascent in the pre-unrest stage. The high sampling frequencies of the installed strainmeters are valuable for identifying the possible occurrence of long-period (LP) or very long period (VLP) volcanic earthquakes, which have important implications for mass transport in the volcanic system. After its installation, the network detected the most recent uplift in Campi Flegrei, which started in November 2004 and included two episodes as of present (+0.6 to +1.6 millimeters per month in 2004 and +2.3 to +3.1 millimeters per month in 2005, as revealed by GPS data [*Pingue et al.*, 2006]). Uplift stopped in January 2007.

The time series of the strainmeter signals, starting from the installation, show overall stable trends, without significant fluctuations at timescales ranging from days to weeks (Figure 2). Data recorded during the first few months are heavily affected by strains associated with curing cement after installation of the equipment. Data interruptions in the first months of operations were due to some problems in the electronics (battery charger, data logger, etc.), mainly at the Quarto and Monteruscello sites.

Strain records at Toiano station, which has the strongest signals and is the closest (about 3 kilometers) to the center of uplift, show some slope changes (10^{-6} strain units per week) that may be related to mini-uplift episodes. Changes in strain rates occurred in October 2004 and May 2005 and preceded the two seismic swarms in March and October 2005 by about 4 months each, consistent with observations of the 1982–1984 significant uplift and the more recent mini-uplift episodes. Another seismic swarm occurred during October 2006 and was followed by an increase in strain similar to that observed at Monteruscello during late June (Toiano was not recording at that time).

Intriguing temperature changes are associated with these stain rate changes at Toiano. Ambient temperature at the strainmeter depth (~120 meters) is very high, close to 60°C, presumably due to influences of the hydrothermal system. Numerous studies [see, e.g., *Battaglia et al.*, 2006, and references therein] have suggested that fluid flow is an integral component of the mechanism for repeated episodes of uplift and subsidence in the Campi Flegrei region.

At Toiano, temperature increased at a rate of about 0.015°C per month over about 100 days. Thermal fluctuations at Quarto and Monteruscello are lower by almost 2 orders of magnitude. These changes provide the potential for novel insight into the source processes.

Work progresses on interpretation of observations and modeling of source mechanisms. The strain and GPS data appear to be consistent with increasing pressure in a source centered under the uplift peak together with a second shallower source located not too distant from Toiano. The temperature increase and the strain changes at Toiano are likely to be direct evidence for magma-chamber-induced fluid migration.

In summary, the network has detected changes that appear to be related to a process originating a new cycle of mini-uplift of the Campi Flegrei volcanic area. Modeling the source or sources responsible for present unrest episodes progresses and is answering the still open question about whether there is a magmatic and/or hydrothermal source causing the Campi Flegrei ground deformations and microgravimetric changes. Answering this question should aid hazard assessment at Campi Flegrei.

Fig. 1. Green dots are the locations of the borehole dilatometers and surface broadband seismometers around Mount Vesuvius and Campi Flegrei. Only a borehole seismometer was installed at site QUAR. Orange circles indicate the permanent network, and small white circles indicate the borehole seismometer network currently under installation. Google Earth imagery © Google Inc., Digital Globe, Terra Metrics, Europa Technologies. Used with permission.

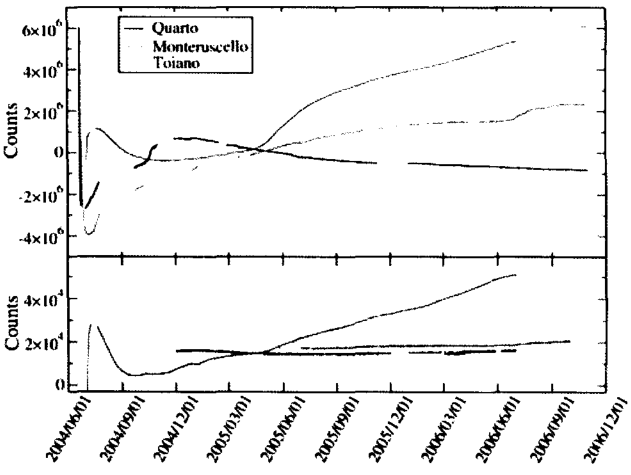

Fig. 2. (top) Time evolution of the strain (low passed at 10^{-2} hertz) recorded at Campi Flegrei dilatometers over the period of 1 June 2004 to 20 November 2006. (bottom) The temperature trend is strong at Toiano station but almost negligible at Quarto and Monteruscello.

Acknowledgments

The project belongs to Centro Regionale di Competenza AMRA and is supported by POR funds, Regione Campania. We also thank Geotesting SRL for their care in the drilling operations. Particular appreciation to Mauro Di Vito for his invaluable help in the site selection and drilling operations. Thanks are also due the many technicians helping in the field project and in particular Marco Capello (OV-INGV), Bernardo Grozea (UNISA), Nelson McWhorter (DTM, CI), Brian Schleigh (DTM, CI), and Mike Acierno (DTM, CI). We appreciate useful comments by David Hill.

References

Aster, R. C., et al. (1992), Seismic investigation of the Campi Flegrei caldera, in *Volcanic Seismology, Proc. Volcanol. Ser.*, vol. III, Springer-Verlag, New York.

Battaglia, M., C. Troise, F. Obrizzo, F. Pingue, and G. De Natale (2006), Evidence for fluid migration as the source of deformation at Campi Flegrei caldera, Italy, *Geophys. Res. Lett.*, *33*, L01307, doi:10.1029/2005GL024904.

Fukao, Y., F. Fujita, S. Hori, and K. Kanjio (1998), Response of a volcanic conduit to step-like change in magma pressure, *Geophys. Res. Lett.*, *25*, 105–108.

Ishihara, K. (1988), Prediction of summit eruption by tilt and strain data at Sakurajima volcano, Japan, in *Proceedings of the Kagoshima International Conference on Volcanoes*, pp. 207–210, Natl. Inst. for Res. Adv., Tokyo.

Linde, A. T., and I. S. Sacks (1995), Continuous monitoring of volcanoes with borehole strainmeters, in *Mauna Loa Revealed: Structure, Composition, History, and Hazards, Geophys. Monogr. Ser.*, vol. 92, edited by J. M. Rhodes and J. P. Lockwood, pp. 171–185, AGU, Washington, D. C.

Linde, A. T., K. Agustsson, I. S. Sacks, and R. Stefansson (1993), Mechanism of the 1991 eruption of Hekla from continuous borehole strain monitoring, *Nature*, *365*, 737–740.

Mattioli, G., et al. (2004), Prototype PBO instrumentation of CALIPSO project captures world-record lava dome collapse on Montserrat volcano, *Eos Trans. AGU*, *85*(34), 317.

Pingue, F., P. De Martino, F. Obrizzo, C. Serio, and U. Tammaro (2006), Stima del campo di spostamento ai Campi Flegrei da dati CGPS e di livellazione di precisione nel periodo maggio 2004–marzo 2006, technical report, Osservatorio Vesuviano, Naples, Italy. (Available at www.ov.ingv.it)

Saccorotti, G., F. Bianco, M. Castellano, and E. Del Pezzo (2001), The July–August 2000 seismic swarms at Campi Flegrei volcanic complex, Italy, *Geophys. Res. Lett.*, *28*, 2525–2528.

Voight, B., et al. (2006), Unprecedented pressure increase in deep magma reservoir triggered by lava-dome collapse, *Geophys. Res. Lett.*, *33*, L03312, doi:10.1029/2005GL024870.

Author Information

Roberto Scarpa, Dipartimento di Matematica e Informatica, Università di Salerno, Italy, and Osservatorio Vesuviano, INGV, Napoli, Italy; E-mail: Roberto.Scarpa@sa.infn.it; Antonella Amoruso, Luca Crescentini, and Pierdomenico Romano, Dipartimento di Fisica, Università di Salerno, Italy; Walter De Cesare, Marcello Martini, and Giovanni Scarpato, Osservatorio Vesuviano, INGV, Napoli, Italy; Alan T. Linde and Selwyn I. Sacks, Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C.