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2012 EMILIA EARTHQUAKES

ShakeMaps during the Emilia sequence

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1. Introduction

ShakeMap is a software package that can be used to generate maps of ground shaking for various peak ground motion (PGM) parameters, including peak ground acceleration (PGA), peak ground velocity, and spectral acceleration response at 0.3 s, 1.0 s and 3.0 s, and instrumentally derived intensities. ShakeMap has been implemented in Italy at the Istituto Nazionale di Geofisica e Vulcanologia (INGV; National Institute of Geophysics and Volcanology) since 2006 (http://shakemap.rm.ingv.it), with the primary aim being to help the Dipartimento della Protezione Civile (DPC; Civil Protection Department) civil defense agency in the definition of rapid and accurate information on where earthquake damage is located, to correctly direct rescue teams and to organize emergency responses. Based on the ShakeMap software package [Wald et al. 1999, Worden et al. 2010], which was developed by the U.S. Geological Survey (USGS), the INGV is constructing shake maps for $M_L \geq 3.0$, with the adoption of a fully automatic procedure based on manually revised locations and magnitudes [Michelini et al. 2008]. The focus of this study is the description of the progressive generation of these shake maps for the sequence that struck the Emilia-Romagna Region in May 2012.

At its core, ShakeMap is a seismologically based interpolation algorithm that exploits the available data of the observed ground motions and the available seismological knowledge, to produce maps of ground motion at local and regional scales. Thus, in addition to data that are essential to derive realistic and accurate results, the fundamental ingredients for obtaining accurate maps are: the ground-motion prediction equation (GMPE), as a function of distance at different periods, and for different magnitudes; and realistic descriptions of the amplifications that the local site geology induces on the incoming seismic wavefield; i.e., the site effects. In its current version, ShakeMap relies on regional attenuation laws and local site amplifications based on the S-wave velocities in the uppermost 30 m (VS30) to generate its PGM maps.

In this report, we start with a chronicle of the generation of the shake maps for the two strongest earthquakes of the sequence, and we conclude with a comment on the critical aspects of the procedure we adopted.

2. The May 20, 2012, M_L 5.9 earthquake

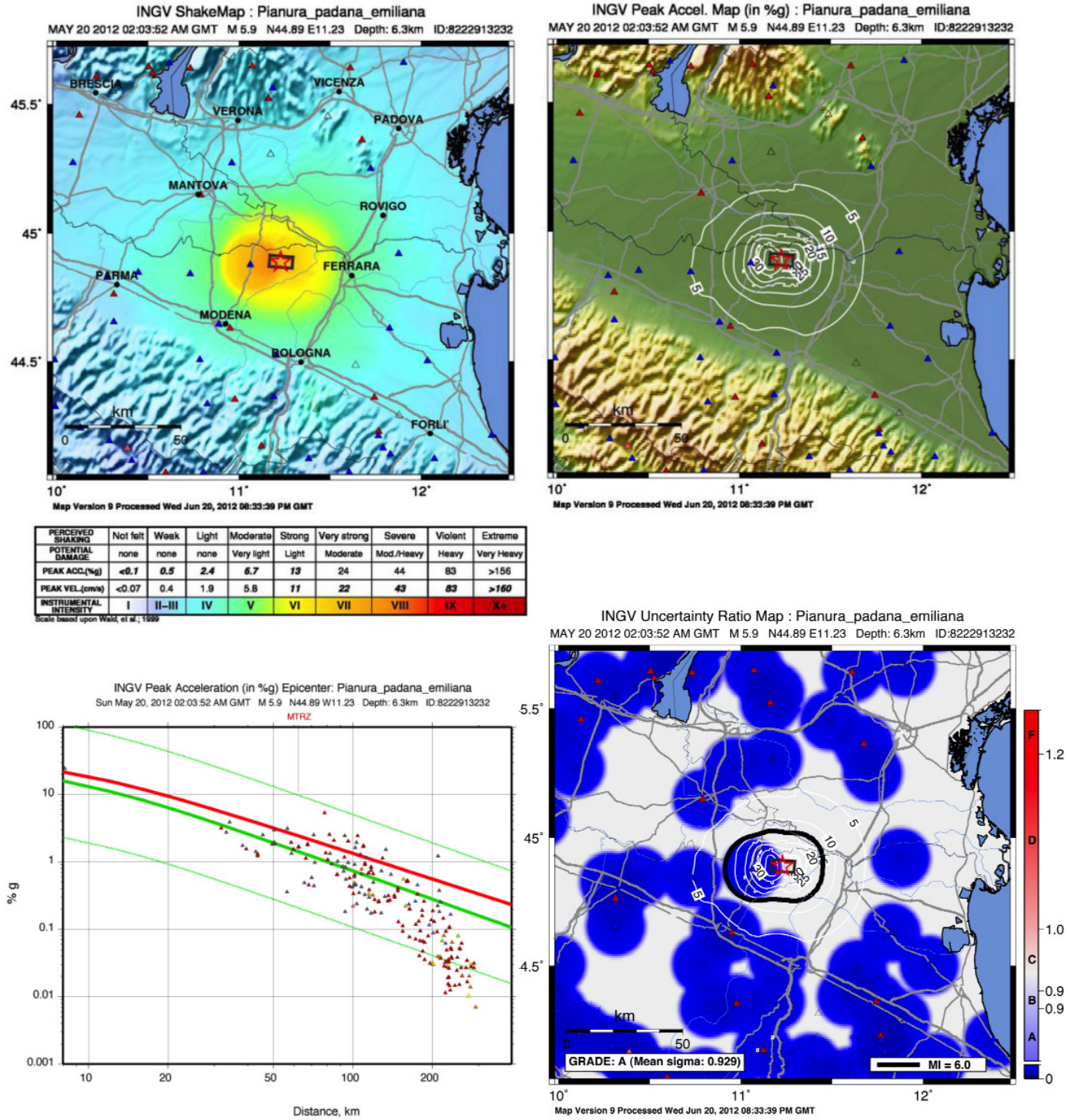
In this section, we present a concise description of the evolution of the ShakeMap determination for the May 20, 2012, M_L 5.9 earthquake.

(i) The automatic final earthquake location (origin time, 02:03:52 GMT; latitude, 44.89°N; longitude, 11.27°E; depth, 4.95 km) was available at 02:07:23; 4 min after the origin time.

(ii) The manually revised location became available 20 min after the origin time, with a similar location, but slightly different depth (6.3 km).

(iii) For the magnitude estimation, the first automatic determination, which became available within about 4 min from the origin time, was M_L 5.9. The manual revision, which was available after 20 min, confirmed the same value. The first moment magnitude was available 1.5 h later, as M_W 5.9.

(iv) The first shake map based on the revised location and magnitude came out a couple of minutes after the final revised location, without any data, as it relied only on the epicentral information, the GMPE and the site effects. For technical reasons, the procedure to download the data failed. Only 50 min from the origin time were the observed data included in ShakeMap. The data availability during the main events suffered from saturation of the near-source broadband recordings, as discussed in Faenza et al. [2011]. Also, Faenza et al. [2011] stressed the importance of availing to the observed data to accurately reproduce the ground shaking experienced. In particular, the importance of the strong-motion data was indicated, which do not saturate at distances close to the epicenter, where source effects on ground shaking, which are hardly predicted by the GMPEs, can strongly influence the near-source shaking. In contrast to what occurred with the L'Aquila mainshock, this time the INGV strong-motion data were available. Unfortunately, the event occurred in an area with poor spatial coverage, and the closest strong-motion station was located at ca. 50 km. Moreover, to prevent errors in the magnitude and/or inter-event variability, ShakeMap



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

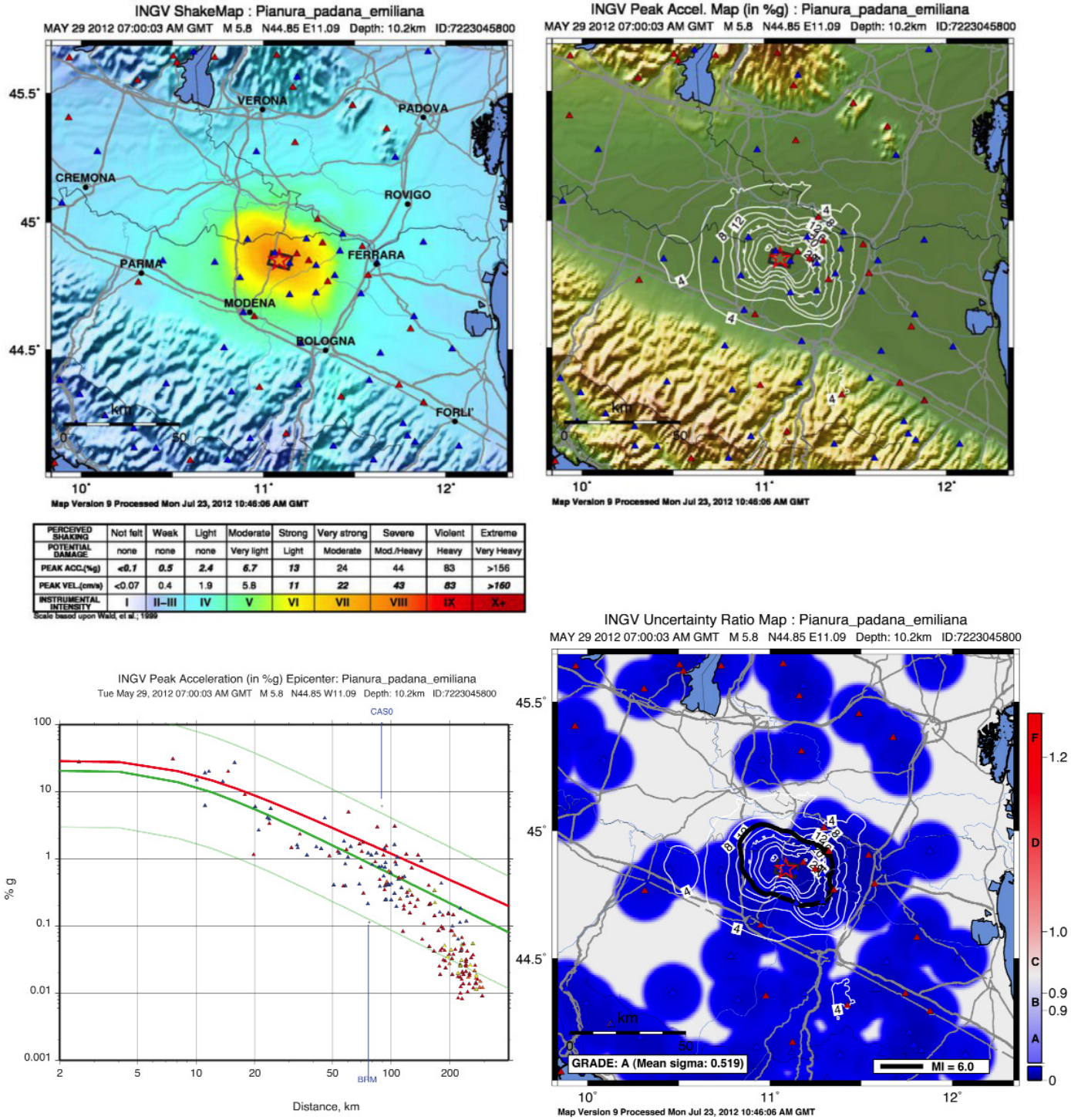
Scale based upon Wald, et al.; 1999

Figure 1. Final ShakeMap for the May 20, 2012, M_L 5.9 earthquake. Event location and magnitude from INGV seismic center, peak ground motion data from INGV (red triangles) and RAN (blue triangles). Intensities expressed in terms of the Mercalli modified scale (top left panel) and PGA (top right panel). Left bottom panel: GMPE as a function of distance. PGA values of Akkar and Bommer [2010] (bottom left panel: solid red line, straight predictions; solid green line, bias corrected predictions). Thin green lines, uncertainties resulting from the adopted relations and used as flagging/unflagging outlier thresholds. The bias factor is -0.47. Other colors are assigned to data obtained from other networks. Right bottom panel: Uncertainty ratio PGA map. The Figure shows how much the map relies on real data (blue) or on estimation (white to red).

adopts a bias correction [Worden et al. 2010] to match the observed data and the predicted ground motion.

(v) Based on the time domain moment tensor solution [Scognamiglio et al. 2012, this volume], the scaling laws [Wells and Coppersmith 1994], and the geology, with the analysis of the active tectonic structures in the area and their orientation, the fault could be included the morning after the event, to better constrain the shaking in the epicentral area (see Figure 1).

(vi) The data of the Rete Accelerometrica Italiana (RAN; Italian Accelerometric Network) maintained by the DPC became available only 10 days after the mainshock. We note that the inclusion of these data is relevant, as they increase the spatial sampling of the ground shaking near the



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INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Figure 2. Final ShakeMap for the May 29, 2012, M_L 5.8 earthquake. As for Figure 1. The bias factor is -0.53.

source – the strong motion station in Mirandola lies ca. 10 km from the surface fault projection (see Figure 1).

3. The May 29, 2012, M_L 5.8 earthquake

Immediately after the May 20, 2012, M_L 5.9 earthquake, a temporary seismic network was installed in the epicentral area. Twenty-four seismic stations were installed by the INGV, and 36 more by others Institutes (the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale [INOGS], the DPC, the Institut de Physique du Globe de Paris [IPGP], and others) [see details in Moretti et al. 2012, this volume]; all but 10 of these stations were stand-alone. These just-mentioned 10 stations were set to transfer the data in real-time to the INGV seismic center in Rome, and six of them were provided with strong-motion recorders. The resulting spatial configuration of the deployed networks greatly increased the spatial coverage in the near-source region, compared to the pre-sequence configuration.

3.1. The ground motion parameters from Earthworm

On May 4, 2012, a new system, Advanced Italian Data Acquisition for Seismology (AIDA) [Mazza et al. 2012, this volume], was implemented at the INGV as the primary tool

to monitor, analyze, save and distribute the Italian National Seismic Network seismograms. This system is based on the Earthworm software [Johnson et al. 1995].

As mentioned above in the description of the ShakeMap for the May 20, 2012, earthquake (Section 2), the procedure used to generate the maps suffered from a temporal delay due to two primary factors. First, the ShakeMap procedure waits until the manually revised event location is ready before starting the waveform download, and secondly, the procedure got intertwined with other procedures that were similarly requesting data.

It was found that while this approach works satisfactory for medium-sized events, for strong events (or during seismic sequences) within the Italian territory, it is severely affected by the slow-down caused by the delayed responses of the data wave server. Thus, while following the experience of the May 20, 2012, earthquake, and while exploiting the Earthworm system, we decided to activate the GMEW (http://www.isti2.com/ew/ovr/gmew ovr.html) module to determine the PGM parameters suitable for ShakeMap in real-time. Specifically, the upgrade of the procedure was implemented in test-mode on a dedicated server, making the publication of shake maps possible a very few minutes from the earthquake occurrence.

The new module prepares the data for the analysis by checking for gaps, and removes the mean, and then processes the traces in the frequency domain using fast Fourier transform, and removes the instrument response. The GMEW module calculates the acceleration, velocity, displacement and spectra responses for the three periods of 0.3 s, 1.0 s, and 3.0 s, with 0.5% damping, for all of the traces, and then it writes an XML file formatted for ShakeMap applications for stations readings.

3.2. ShakeMap evolution of the May 29 M_L 5.8 earthquake

The description of the evolution of ShakeMap for the May 29, 2012, M_L 5.8 earthquake follows.

(i) The automatic final earthquake location (origin time, 07:00:03 GMT; latitude, 44.85°N; longitude, 11.06°E; depth, 8.21 km) was available at 07:04:22; 4 min after the origin time.

(ii) The manual revised location became available 19 min from the origin time, with similar coordinates, but 2 km deeper.

(iii) For the magnitude estimation, the first automatic determination that was available at the same time after the origin time was M_L 5.8. The manual revision confirmed the same value. The first moment magnitude was available was 1 h and 45 min later, as M_W 5.7.

(iv) The first shake map was calculated using the automatic final earthquake location and magnitude, using the new Earthworm module to calculate the PGM parameters; it became available 4 min after the origin time on the dedicated server mentioned above.

(v) The published shake map was calculated using the reviewed final earthquake location and magnitude, and it came out 19 min after the origin time on the public server. In addition, the temporary seismic network guaranteed good spatial coverage in the epicentral area (see Figure 2).

(vi) As for the May 20, 2012, M_L 5.9 earthquake, based on the time domain moment tensor solution [Scognamiglio et al. 2012], the scaling laws [Wells and Coppersmith 1994], and the geology, the fault could be included 2 h after the origin time.

(vii) The RAN data could be included in a shake map only after almost two weeks from the earthquake occurrence, when the data become available (see Figure 2).

4. Discussion

In May 2012, a seismic sequence struck the Emilia-Romagna Region, an area in the Po Valley that had already been hit by moderate-sized earthquakes in the past, and was known for its centuries-old seismic history [Castelli et al. 2012, this volume]. In this study, we describe the progressive determination of ShakeMap as more information became available after the mainshocks of May 20 and 29, 2012.

It is well known that inclusion of observed data is of fundamental importance in the calculation of shake maps. Indeed, accurate quantifications of PGM near the epicenter that avail solely of the PGM prediction equations and the site-effect corrections are difficult and prone to macroscopic errors and bias [Faenza et al. 2011]. Moreover, for larger earthquakes that saturate the recordings of the velocimeters at and near the epicenter, the accuracy of the shake maps depends also on the prompt availability of strong-motion data. The May 20, 2012, M_L 5.9 earthquake certainly did not have enough data to produce accurate maps of the PGM given the very poor station coverage in the epicentral area.

Figure 3 shows the improvement in the quantification of the ground shaking with the inclusion of the source model and new data. The comparison was done following the real temporal evolution of the maps available online, and it was quantified using differential PGA maps. The top panel in Figure 3 illustrates the role of the source model. It was calculated by subtracting the 'preliminary' shake map based on the INGV data without a source model from the one that included the source model. This first preliminary shake map stayed online for 1 day. Figure 3 shows a different pattern in the near-source shaking due to the adoption of the Joyner-Boore distance measure from the fault location. Indeed, the point source approximation leads to an underestimation of the PGA in near source of almost 8%g. The bottom panel of Figure 3 quantifies the role of the near-source stations. It compares the PGA based on the INGV data only (as previously mentioned, for the first weeks, the map relies only on INGV data; Figure 1, red triangles) with the 'final' one available on line at the time. This last map is calculated using both the INGV and the RAN data. Figure 3 illustrates the importance of the near-source stations; in this case, only the RAN station of Mirandola was

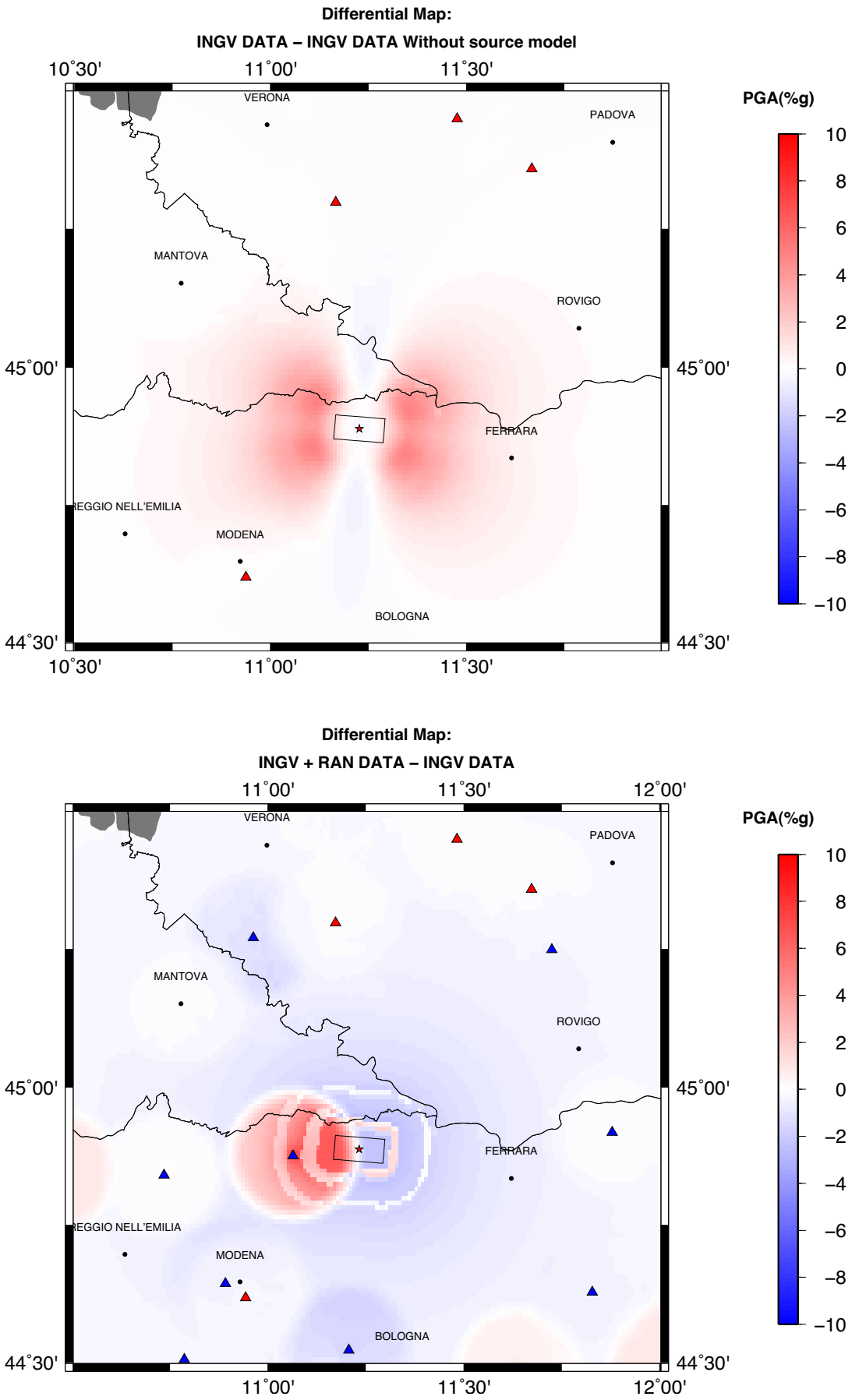

Figure 3. Differential PGA map of the ShakeMap for the May 20, 2012, M_L 5.9 earthquake. Top panel: The map is calculated as the difference between the map based on the INGV data with the source model and the 'preliminary' map calculated without the source model. Bottom panel: The map is calculated as the difference between the map based on the INGV and the RAN data, as the 'final' shake map. with the one based on the INGV data only. The map highlights the importance of the near-source MRN (Mirandola) station, with an increase in the shaking of ca. 10%g in the west fault area.

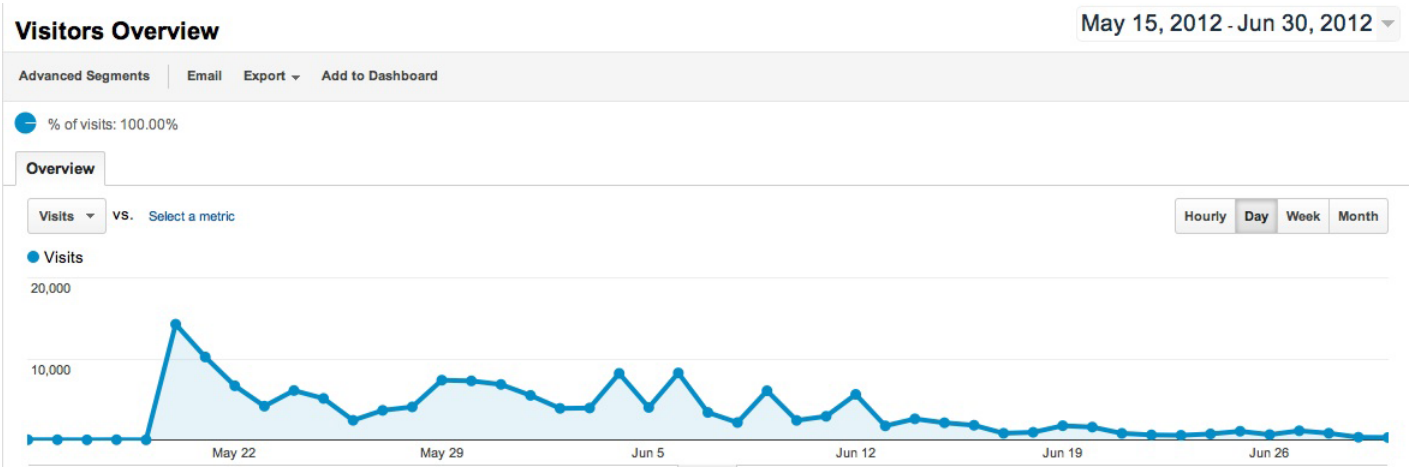

Figure 4. Number of visits to the ShakeMap portal, starting a week before the main event of the sequence. The majority of the visits were from within Italy.

close to the epicenter. This station strongly drives the shaking in the near source, with an increase of almost 10%g in the west fault area, which indicates an underestimation of the ground motion by the GMPE in the near-source area.

Fortunately, the installation of the temporary stations in the epicentral area provided fair coverage for the May 29, 2012, event. This increased accuracy is well expressed by the map of the uncertainties of Figure 2 (bottom-right panel). There are several sources of uncertainties in ShakeMap calculations, including sparse station networks, fault finiteness, and the GMPE [Wald et al. 2008]. The uncertainly map represents the ratio between the actual standard deviation (e.g., the standard deviation of each point of the ShakeMap grid) and the standard deviation of the GMPE. The uncertainties in ShakeMap follow a weight scheme, which depends on the source of the data [see Worden et al. 2010, for details]. The intent of the bottom-right panels of Figure 1 and Figure 2 is to reveal the importance of the station spatial coverage in the calculation of the shake maps, and its improvement after the installation of the temporary stations. The maps follow a color-based scale, where the red areas are poorly constrained, the white areas have the uncertainties represented by the standard deviation of the GMPE, and the blue areas are better constrained and represent the seismic stations [Wald et al. 2008]. Figure 1 (bottom-right panel) shows that the shaking defined for the first event relies almost entirely on the GMPE and source model, while this condition is substantially changed for the May 29, 2012, M_L 5.8 earthquake (Figure 2, bottom-right panel).

A matter of concern remains the persistent unavailability in the short term of the accelerometric data recorded by the RAN. Calculation of the shake maps is important for the emergency response, since they provide the 'first-cut' estimates of the impact of an earthquake. Due to their nature and to the interpolations they rely upon, the shake maps cannot be considered as an instrument to be used much further than the initial estimation of the ground shaking. In this regard, despite many efforts and projects towards almost real-time data sharing, it is still impossible to access the RAN data for fast shake-map estimations. The availability of the data (on request) two weeks after the earthquake occurrence definitely appears to be a little too long in a world where information is spread almost instantaneously through social networks, and there might be something more that should be done to improve this situation.

Comparing the previous experience in 2009 with the L'Aquila sequence, the main changes in the ShakeMap procedure relate to data access, for the accelerometric stations. In addition, during the sequence itself, we were able to modify the procedure to calculate the peak parameters, further reducing the computational time and providing the possibility to disengage from the queues caused by the simultaneous data requests of other procedures. After the first event, the existing procedure that relied on requesting the waveform data as a full SEED volume, which was then processed to extract the relevant PGM parameters, was replaced by the GMEW module of Earthworm. This does not require off-line requests, and the parameters are determined on-the-fly from the incoming data streams and starting from the automatic earthquake location provided by Earthworm.

As a final comment, Figure 4 shows the number of visits to the ShakeMap portal throughout the sequence. The increment in the public interest in ShakeMap during the strong events is clear. During the sequence, more than 200 ShakeMaps were calculated, 28 with $4 \leq M < 5$ and 7 with $M \geq 5$.

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