Real-time ground-shaking maps reconstruction of late 2022 Italian earthquakes

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INTRODUCTION

Real-time seismic monitoring provides crucial information for emergency operations after severe seismic events. Ground shaking maps, usually expressed in terms of one of the many ground motion parameters (GMPs) proposed in the literature, are used to evaluate the impact of an earthquake. Traditional approaches, such as ShakeMap (Wald, Quitoriano, Heaton, Kanamori, Scrivner, and Worden, 1999; Wald, Worden, Thompson, and Hearne, 2021), use ground motion prediction equations (GMPEs) constrained by the instrumental GMPs to produce a gridded representation of the ground motion and thus are dependant on the estimate of location and magnitude of the event.

The automated ShakeMap procedure of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) for the Department of Civil Protection (DPC) is triggered, for events of $M \geq 3.0$, when the revised location and magnitude are available, usually several minutes after the event (Margheriti et al., 2021).

ShakeRec (Fornasari, Pazzi, and Costa, 2022) has been developed for the DPC to reconstruct ground-shaking maps in real-time leveraging only the data from the stations, specifically the ones of the Italian Strong Motion Network (RAN, Costa et al., 2022). As such, ShakeRec can fill the temporal gap between the arrival of the seismic data at the data centre and the evaluation of GMPE-based ground-shaking maps providing information during the early stages of emergency management.

The reconstruction capabilities of ShakeRec have been tested for two recent Italian earthquakes: the 22 September 2022 Bargagli earthquake (Genova, North-West Italy, $M_l 4.1$) and the 9 November 2022 Marche earthquake (offshore, Central Italy, $M_l 5.7$).

METHODS

Considering a single GMP, the reconstruction is performed using an ensemble of five convolutional neural networks, as shown in the central panel in Figure 1. The architecture of each ensemble member has been adapted from Fukami et al. (2021) who proposed a data-driven spatial field recovery technique that makes use of Voronoi tessellation to obtain a structured grid representation of sparse data. Each ensemble member is composed of four convolutional layers, with zero-padding, with 12 filters of size 5×5 and a final convolutional layer with a single filter of size 5×5, each using a rectified linear activation function.

The ensemble takes as input (left side of Fig. 1) the Voronoi tessellation of the GMP at the stations, a map of the active station locations, and a normalised VS30 map (Michelini et al., 2020) and produces as output the mean ground-shaking field μ and its uncertainty σ (right side of Fig. 1) with a resolution of $0.05^{\circ} \times 0.05^{\circ}$: the former is computed as the mean of the ensemble members' reconstructions and is comparable to the GMPE expected value at each point; the latter is computed as the combination of an aleatoric and an epistemic term. The offshore area is masked as it is poorly constrained and of little interest for the initial stage of emergency management.

The current ShakeRec implementation is able to update the results every $2\ s$, approximately.

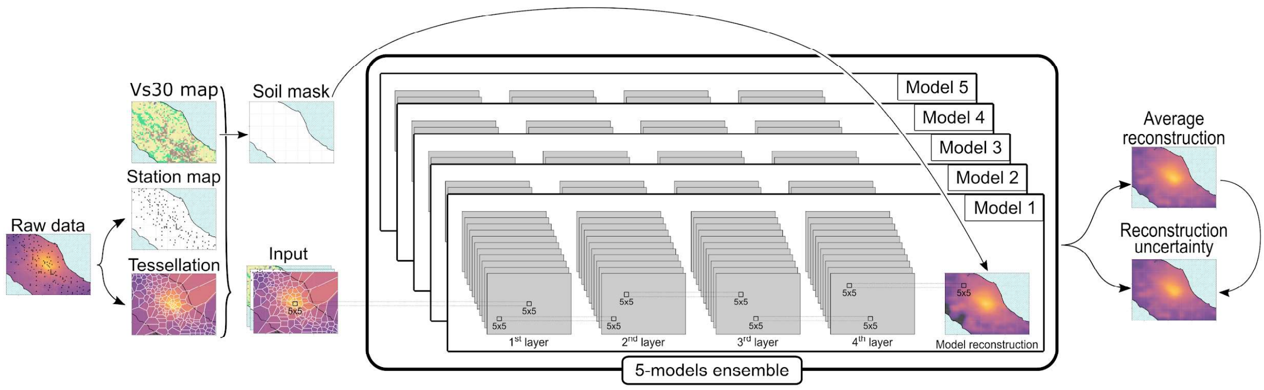

Figure 1. ShakeRec flowchart: real-time and static data are used as inputs to the ensemble that outputs the average reconstructed ground-motion parameters (GMP) field and its associated uncertainty (from Fornasari, Pazzi, and Costa, 2022).

RESULTS

The events analysed have been selected as they represent two interesting study cases with opposite characteristics in terms of position relative to the network: the Bargagli earthquake is a $M_l 4.1$ event with epicentre inland and good azimuthal coverage; the Marche earthquake is a $M_l 5.7$ event with epicentre approximately $30\ km$ offshore and a one-sided azimuthal coverage.

The final peak ground acceleration (PGA) reconstructions obtained with ShakeRec (using the data available after $40\ s$ for the Bargagli event and $35\ s$ for the Marche event) have been compared with the results of ShakeMap computed by INGV and are shown in Figure 2. The stations whose parameters contributed to the reconstructions are indicated on the maps: the black markers indicate stations whose parameters have been used in the reconstruction.

The ground-shaking maps for the Marche event are in overall agreement: the differences, both in the extension of the affected area and in the values on the coast, are imputable to the different distribution of the stations used and the constraints imposed by the site effects (as shown by the small scale variations).

On the other hand, the reconstructions for the Genova earthquake present a noticeable difference in the maximum values: while both reconstructions are constrained to the same area, the maximum value from the INGV ShakeMap is higher than the one obtained by ShakeRec by a factor of 2.6. The cause of this difference is likely the constraint imposed by one station (RNCA) used in the INGV ShakeMap reconstruction that presents much higher values than any of the RAN ones.

The ground-shaking maps for PGA reconstructed with the data available at selected times after each event (namely, $10\ s$, $20\ s$, and $30\ s$) are shown in Figure 3. The coherent evolution of the shaking maps over time can be interpreted as proof of the stability of the model.

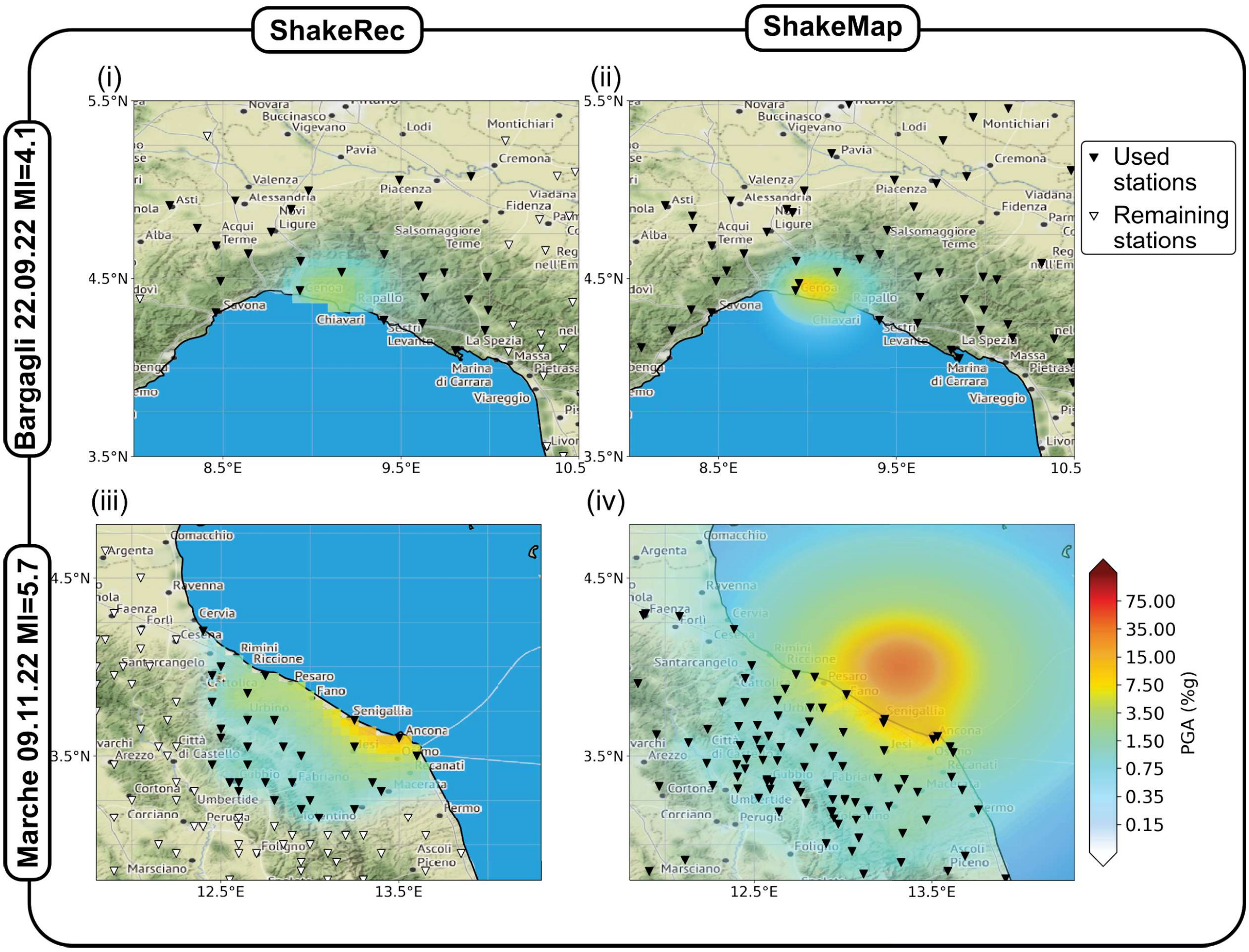

Figure 2. Comparison between the reconstruction from ShakeRec (i and iii) and ShakeMap (ii and iv) for the Bargagli (i and ii) and Marche (iii and iv) earthquakes. The black markers indicate the stations used for the reconstruction and the white marker the remaining stations of the network.

CONCLUSIONS

ShakeRec provides reliable real-time estimates of the ground motion shaking field which can be useful for Civil Protection purposes, especially in the context of post-emergency management. The two proposed scenarios provide an example of both the capabilities and the limits of ShakeRec highlighting the main role that the station distribution plays in the quality of the reconstruction. A natural extension of the obtained results is their use as inputs for ground motion to intensity conversion equations to obtain rough real-time estimates of the macro-intensities for a given seismic event. Even further, ShakeRec results could be integrated with structure vulnerability to assess the potential damages to buildings.

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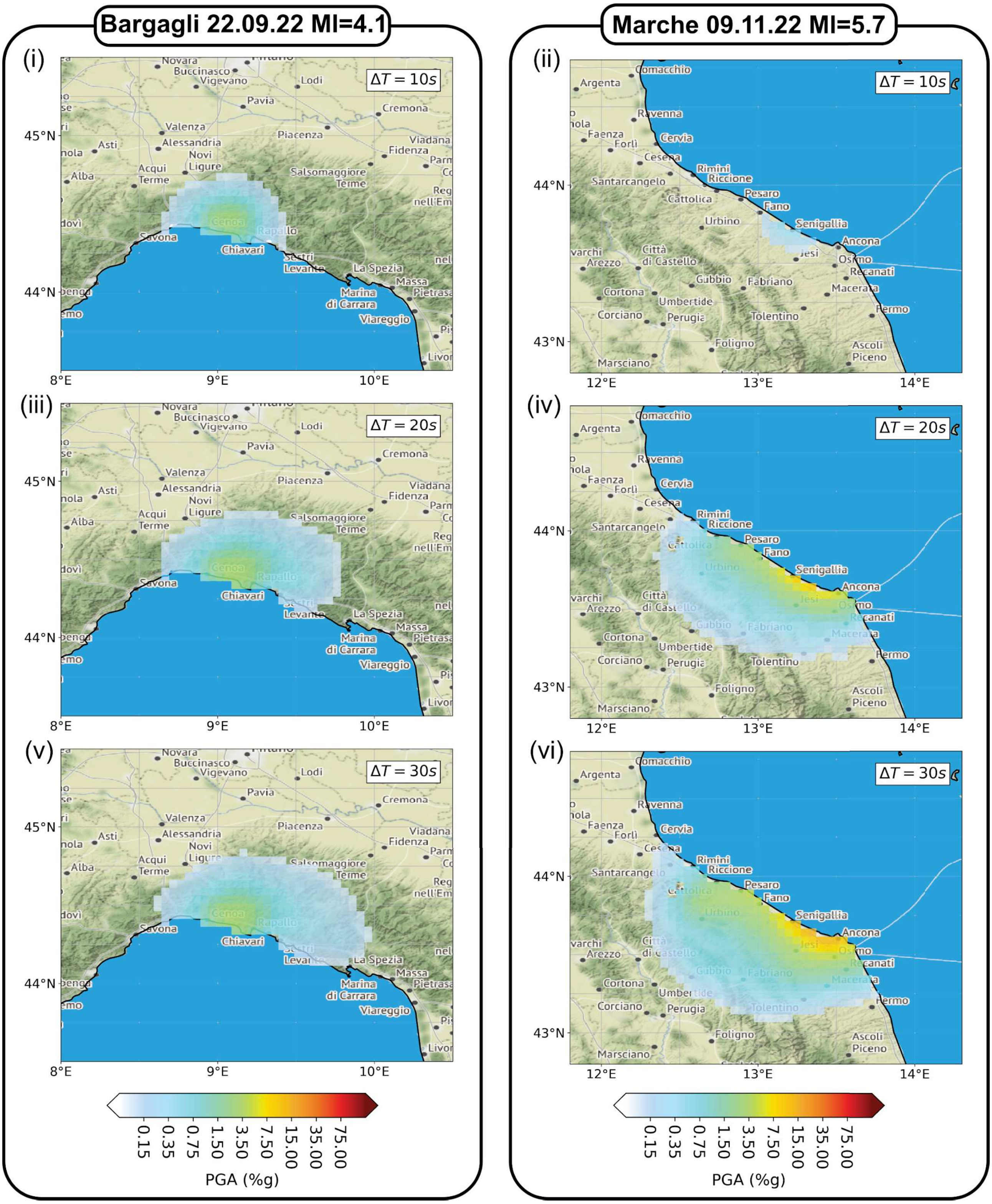

Figure 3. Reconstructions of the ground shaking field in PGA for the Bargagli earthquake (i, iii, and v) and the Marche earthquake (ii, iv, and vi) using the data available at different instants after the events (namely, 10 s, 20 s, and 30 s).

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