



Investigating rupture directivity effects on macroseismic intensity data in Italy

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9 **Abstract.** Macroseismic intensity data represent a fundamental measure of ground shaking, particularly for events lacking
instrumental recordings. Empirical Intensity Prediction Equations (IPEs) are fundamental to relate earthquake source
parameters (i.e., location and magnitude) to site intensities, and have today a broad range of applications. While residual
12 analysis has become a standard procedure in non-ergodic ground-motion studies to isolate source, site and rupture directivity
contributions, similar approaches have not yet been systematically applied to macroseismic intensity data. This study
investigates the potential signature of rupture directivity in macroseismic intensity data of recent Italian earthquakes by
15 adapting the residual decomposition framework commonly adopted in non-ergodic ground-motion studies. The analysis is
based on 213 earthquakes in the period 1907-2020 and more than 18,000 intensity data. Residuals are computed using two
recent IPEs and decomposed into between-event, locality-to-locality, and remaining aleatory variability terms. The spatial
18 distribution of the aleatory residuals is subsequently investigated for the 31 earthquakes which show uniform azimuthal
coverage to identify coherent directional patterns potentially associated with rupture directivity. The results show that the
aleatory component represents the dominant source of residual variability and that 8 out of 31 investigated earthquakes exhibit
21 coherent directional patterns consistent with fault strikes and rupture propagation directions. These results indicate that
intensity residuals preserve measurable source-related directional information and highlight the potential of residual
decomposition as a promising framework for investigating rupture directivity using macroseismic intensity data.

24 1 Introduction

Macroseismic intensity data provide fundamental constraints for investigating long-term seismicity and characterising pre-
instrumental earthquakes. The progressive collection and homogenization of intensity observations have led to the
27 development of several national and regional macroseismic databases (i.e., Locati et al., 2014; 2022; Rovida and Locati, 2015;
Jomard et al., 2021; Fernández-Fraile et al., 2025; Neefs et al., 2025; Rovida et al., 2025), which support the compilation of
long-term parametric earthquake catalogues (i.e., Manchuel et al., 2018; Rovida et al., 2020; 2022; Stucchi et al., 2013). These
30 catalogues underpin current seismic hazard assessment models at national and trans-national scales (e.g., Stucchi et al., 2011;
Woessner et al., 2015; Meletti et al., 2021; Danciu et al., 2024). Beyond their contribution to earthquake cataloguing and



seismic hazard assessment, the availability of large and homogeneous macroseismic datasets supports a wide range of seismological investigations.

In Italy, these datasets have also enabled the development of several Intensity Prediction Equations (IPEs) describing the attenuation of macroseismic intensity with source-to-site distance (e.g., Gasperini et al., 2001; Albarello and D'Amico, 2004; Pasolini et al., 2008; Gomez Capera et al., 2024; Lolli et al., 2024). Traditionally, both IPEs and Ground Motion Models (GMMs) relied on the ergodic assumption, which postulates that ground motion variability can be captured by a single, spatially-averaged model applicable across an entire region. While computationally efficient, this simplification obscures local heterogeneities and complex physical processes, such as rupture directivity and site-specific effects, that are critical for accurate hazard assessment. For this reason, in recent years, the seismological community has shifted towards non-ergodic approaches in ground motion modelling, which relax this stationarity assumption (Anderson and Brune 1999; Al-Atik et al., 2010). By systematically isolating source, path, and locality contributions from the residuals, these non-ergodic frameworks allow for a more accurate and physically meaningful characterisation of seismic attenuation, effectively capturing the azimuthal and spatial patterns often 'smoothed out' by traditional ergodic models. Similarly, macroseismic intensity attenuation also exhibits clear anisotropic spatial patterns (e.g. Carletti and Gasperini, 2003; Sovic and Sariri, 2016; Antonucci et al., 2021), likely related to different physical phenomena, such as finite-fault geometry effects, rupture directivity, site effects, and wave-propagation lateral heterogeneities.

Among these processes, finite-fault geometry and rupture directivity are particularly relevant because they can strongly modulate the spatial distribution of shaking by amplifying ground motion in the rupture area and in the direction of rupture propagation. While directivity effects are well documented in instrumental ground motion records and studies (i.e., Di Luccio, 2010; Convertito et al., 2016; Calderoni et al., 2023; Colavitti et al., 2022; 2026), their signature in macroseismic intensity data remains poorly constrained. Generally, source directivity has mainly been explored indirectly through analyses aimed at retrieving source geometry from the spatial distribution of observed intensities (e.g., Gasperini et al., 1999; 2010; Sirovich and Pettenati, 2004; 2009; Pettenati and Sirovich, 2007). Only a limited number of studies have investigated the role of rupture directivity on the intensity values. Sirovich et al. (2009) analysed the effects of source geometry on the macroseismic intensity distribution of the 29 July 2008 M 5.4 earthquake in the Los Angeles metropolitan region. In Italy, Ameri et al. (2011) analysed the spatial distribution of intensity data from the 6 April 2009 *M_w* 6.29 L'Aquila earthquake to identify and quantify finite-fault and directivity effects.

Starting from these efforts, we investigate the azimuthal variability of macroseismic intensity data in Italy with the aim of identifying possible rupture directivity effects. To this end, we adapt the procedures previously developed to assess spatial variability and directivity effects in the ground-motion parameters (i.e., Sgobba et al., 2021a; Colavitti et al., 2022; 2026). First, we select a dataset of earthquakes from the latest version of the Italian Parametric Earthquake Catalogue (CPTI15; Rovida et al., 2020; 2022), including instrumental locations and magnitudes, with the corresponding macroseismic intensity observations collected in the Italian Macroseismic Database (DBMI15; Locati et al., 2022). We then compute residuals using two different IPEs recently calibrated for the Italian region (i.e., Gomez Capera et al., 2024; Lolli et al., 2024) and analyse the

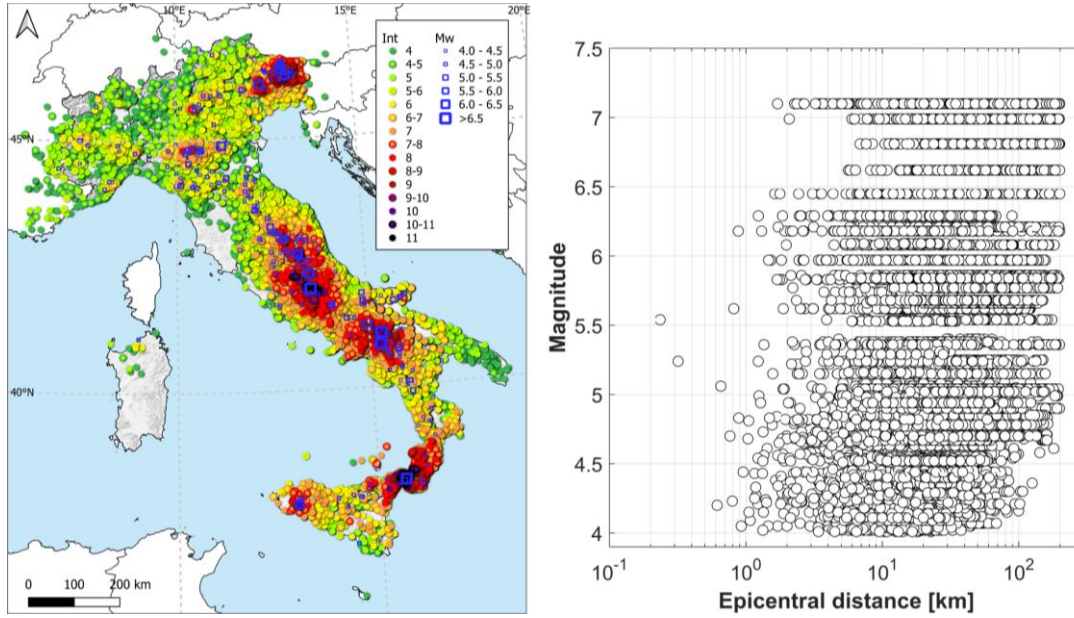


66 spatial distribution of these residuals by comparing the observed patterns with fault orientations reported in the literature for
earthquakes characterised by well-documented directivity effects. By bridging the gap between instrumental observations and
macroseismic data in a non-ergodic framework, this work provides new insights into source-related intensity attenuation and
69 related spatial distribution, establishing a comprehensive methodological approach to characterize directivity effects of
earthquakes in the absence of strong motion recordings.

2 Dataset

72 The dataset selected for the analysis is based on the most recent versions of CPTI15 and DBMI15 (Rovida et al., 2022; Locati
et al., 2022), considering only events with instrumentally determined locations and magnitudes. Following the procedure
adopted in Antonucci et al. (2025), we consider earthquakes that occurred between 1907 and 2020, including only shallow
75 inland mainshocks with $M_w \geq 4.0$ and at least 10 associated Macroseismic Data Points (MDPs). The latter criterion is adopted
to ensure a minimum spatial sampling while preserving a sufficiently large number of earthquakes for the subsequent analyses.
Mainshock identification, necessary to discard intensity data potentially affected by cumulative shaking produced by
78 aftershocks, is performed according to the widely used declustering approach of Gardner and Knopoff (1974). We also exclude
earthquakes occurring in the main Italian volcanic districts (Mt. Etna, Aeolian Islands, and Campanian volcanoes), in the
Calabrian Arc subduction area, as well as events at depths of ≥ 30 km, because their attenuation behaviour differs from that of
81 crustal seismicity. To reduce the influence of incompleteness of the macroseismic data, we apply additional constraints to the
MDPs selection. We consider only macroseismic data with intensity values ≥ 4 MCS and epicentral distances ≤ 200 km. This
is because MDPs with intensity lower than 4 remain significantly underrepresented compared with those characterised by
84 higher intensity, and the macroseismic distributions of most earthquakes are generally well constrained within 200 km from
the epicentre (see Antonucci et al., 2025, for further details). We also discard non-conventional intensity descriptive codes
(e.g., D for damage or HD for heavy damage), as they reflect large uncertainty in the intensity assessment and are generally
87 assigned when the available information is insufficient (see Locati et al., 2022).

The resulting dataset consists of 213 earthquakes with instrumental M_w ranging between 4.0 and 7.1, associated with 18,714
MDPs with intensity values ranging from 4 to 11 MCS across 7655 localities. The spatial distribution of the selected
90 earthquakes and MDPs is displayed in Figure 1a, showing the good spatial coverage across Italy. The selected dataset also
covers a wide range of magnitudes and epicentral distances, as shown in Figure 1b.



93 **Figure 1: Spatial distribution of the selected earthquakes and associated MDPs (a) and distribution of the MDPs as a function of**
 94 **epicentral distance and earthquake magnitude (b).**

3 Methodology

96 In recent years, several authors (e.g., Luzi et al., 2014; 2017; Sgobba et al., 2021a; Colavitti et al., 2022; 2026) have investigated
 97 statistical frameworks designed to decompose source, path, and locality contributions, as well as isolating specific phenomena,
 98 such as rupture directivity effects, that are typically not captured by standard ergodic GMMs (e.g., Bindi et al., 2011; Lanzano
 99 et al., 2019, for Italy). In this context, the shift towards non-ergodic approaches (e.g. Rodríguez-Marek et al., 2011; Kuehn and
 100 Sherbaum, 2016; Landwehr et al., 2016; Sgobba et al., 2021b; 2023) represents the current frontier in applied seismology, as
 101 it allows for a more precise isolation of source, path, and locality contributions by moving beyond the spatially-averaged
 102 assumptions of traditional ergodic models. These methodologies quantify ground-motion variability by analysing residuals
 103 between observed and predicted ground-motion parameters. In this study, we compute the residuals as the differences between
 104 the observed macroseismic intensities reported in the selected dataset (MI_{obs}) and the corresponding predicted values at the
 105 same locality (MI_{pred}). The residual (R_{es}) is defined as:

$$R_{es} = MI_{obs} - MI_{pred} \quad (1)$$

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The predicted intensity (MI_{pred}) at each site is computed using two reference IPEs recently developed for Italy. The first is the
 model proposed by Gomez-Capera et al. (2024), identified by Antonucci et al. (2025) as the best-performing predictive model
 111 for the Italian territory. This model (hereafter GOM24crv) adopts a linear functional form relating the logarithm of



macroseismic intensity to the logarithm of moment magnitude. The second IPE was proposed by Lolli et al. (2024) and is calibrated using a two-step regression analysis (hereafter LOL24all). The comparison between the results obtained with the two IPEs allows us to assess the sensitivity of the estimated residual components to the adopted predictive model and to reduce potential model-dependent biases associated with the functional form and attenuation properties of each IPE.

Following the taxonomy proposed by Al Atik et al. (2010), the total residual (R_{es}) can be decomposed into its two main components: (i) the between-event term (δB_e), which physically represents the average source effect associated with an individual earthquake, and (ii) the within-event term (δW_{es}), which includes the variability remaining after removal of the between-event contribution. Following the partially non-ergodic approach commonly adopted in recent GMM studies, the within-event residual can be further partitioned into a repeatable site-to-site term ($\delta S2S$) and a residual component that remains unexplained (i.e., the aleatory error, δW_0). Since macroseismic data refer to localities rather than instrumental recording stations, in this study, we refer to the repeatable site-to-site term as the locality-to-locality term ($\delta L2L_s$). Although the terminology differs, it represents the same residual component commonly denoted as $\delta S2S$ in the non-ergodic ground-motion literature. In this context, we decompose the R_{es} into three components using a linear mixed-effects regression approach with random-effects analysis, following Stafford (2014) and Bates et al. (2015).

The total residual is expressed as:

$$R_{es} = \delta_0 + \delta B_e + \delta L2L_s + \delta W_0 \quad (2)$$

where δ_0 is the median offset, δB_e is the between-event residual that describes the average misfit between observations and predictions for an individual earthquake, $\delta L2L_s$ is the repeatable locality-to-locality term that represents repeatable site-specific amplification, and δW_0 represents the remaining aleatory variability. The latter reflects the portion of variability that is not explicitly modelled at each locality and may include contributions from directivity and/or path effects. Potential directivity effects can therefore be explored by analysing the azimuthal dependence of these residual terms (e.g., Ameri et al., 2009; Ren et al., 2017; Colavitti et al., 2022; 2026).

In this respect, we analyse the spatial distribution of the aleatory term δW_0 to explore potential directivity effects in the macroseismic data, and we compare the azimuthal distribution of positive residuals with the strike of the earthquake sources proposed in the literature. This approach is motivated by the assumption that rupture directivity may generate larger ground-motion amplitudes at sites located in the forward direction relative to rupture propagation (Aki and Richards, 1980; Somerville et al., 1997).

4 Residual analysis

The results obtained using Eq. (2) for the GOM24crv IPE indicate that the median offset of the model (δ_0) is 0.06, suggesting a negligible systematic bias. The distribution of the between-event and locality-to-locality residuals is shown in Figure 2. Both



random terms follow a normal distribution with a median of zero and standard deviations of τ and ϕ_{L2L} for δB_e and δL_{2L_s} , respectively (Al-Atik et al., 2010; Rodriguez-Marek et al., 2011). The variability values are shown in Table 1, together with the aleatory standard deviation of the event- and locality-corrected residual term, denoted by σ_0 . In the non-ergodic decomposition approach for residuals, the total variability is then calculated as:

$$\sigma = \sqrt{\tau^2 + \phi_{L2L}^2 + \sigma_0^2} \quad (3)$$

and, in this case, $\sigma = 0.78$.

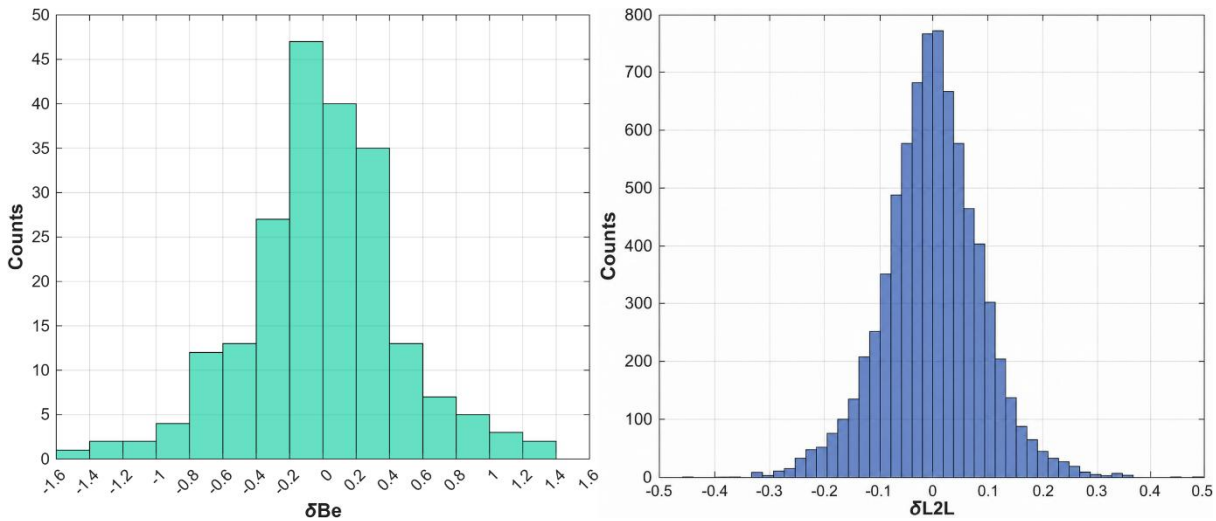


Figure 2: Histogram of the between-event (a) and locality-to-locality residuals (b) estimated for the analysed dataset using the GOM24crv IPE.

Table 1: Random effects covariance parameters (95% CIs).

Parameters	Group	Samples	Standard deviation
τ	Events	213	0.46595
ϕ_{L2L}	Localities	7655	0.20572
σ_0	Aleatory	18714	0.59215



159 The analysis of the between-event distribution (Fig. 2a) reveals that, although the distribution is closely Gaussian, it is characterised by long tails, with several events exhibiting relatively high absolute event error. This is also confirmed by the large value of the corresponding standard deviation, which is approximately 0.47. Among the 213 analysed events, 10 exhibit residuals exceeding $|1|$ intensity degree, with five earthquakes that exhibit large negative residuals (i.e., $\delta B_e < -1$). These cases generally fall into two categories. The first includes earthquake for which the observed macroseismic intensities are substantially low relative to their high instrumental magnitudes (e.g., https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/20121025_2305_000); the second includes events for which the instrumental epicentral location is significantly displaced from the area of maximum observed damage (e.g., https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19280327_0832_000). By contrast, five earthquakes show large positive residuals ($\delta B_e > 1$), indicating an average underestimation of the observed intensities by the predictive model. For these events, the macroseismic effects are high despite their low instrumental magnitudes (e.g., https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19780730_0519_000). These results are consistent with the residual analysis recently carried out on macroseismic intensity data by Antonucci et al. (2025).

171 Aligned with the results reported in Table 1, the contribution of the $\delta L2L_s$ term associated with repeatable site effects at the single locations is lower (0.21). Figure 2b shows the distribution of the locality-to-locality residuals estimated for the 7655 localities of the dataset. The histogram exhibits a zero-mean Gaussian distribution, with most residuals falling within the range $-0.5 \leq \delta L2L_s \leq 0.5$, significantly lower than that of the between-event term (± 1.6 intensity degrees). This behaviour suggests that only a limited number of localities exhibit persistent amplification or de-amplification effects relative to the average predictions provided by the adopted IPE. This result is significant because it differs markedly from what is observed in the analysis of seismic records, where systematic station error generally accounts for most of the variability, particularly at short periods (see Lanzano et al., 2019 for Italy). The low variability observed in the $\delta L2L_s$ term could be due to the following factors. The analysis dataset is designed to study directivity effects, starting from the selection of recent events with instrumental location and magnitude; as a result, the number of MDPs per locality is not enough to estimate the repeatability of the site effect using the residual decomposition method. In addition, the macroseismic intensity represents the overall level of shaking experienced across an inhabited locality and may therefore smooth out small-scale geological heterogeneities (i.e., site effects). A more targeted analysis, based on dedicated datasets, would be required to better characterize this source of variability.

186 Finally, the event- and locality- corrected standard deviation, i.e., the aleatory variability, is found to provide the largest contribution to the total variability (0.59 units in Table 1), thus indicating that there remain relevant effects (e.g., anisotropy of attenuation) not captured by the model even after the residual decomposition. In the following section, we focus on this term to identify if source directivity effects can contribute to explaining this leftover variability.



189 5 Directivity Analysis

To detect potential rupture directivity effects, we analyse the spatial distribution of the aleatory error δW_0 for the earthquakes selected in Section 2. From the initial dataset of 213 events, we remove those with incomplete azimuthal sampling, retaining
192 only events with at least five MDPs in each 45° azimuthal sector. This criterion ensures a sufficiently uniform azimuthal coverage around the instrumental epicentre, thereby reducing potential biases associated with gaps in the macroseismic intensity distribution and poor azimuthal coverage.

195 For instance, the M_w 6.45 earthquake that occurred in Northeastern Italy on 6 May 1976 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19760506_2000_000) and the M_w 6.09 event that occurred on 20 May 2012 in the Po Plain region (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/20120520_0203_000) do not satisfy this criterion and are therefore excluded
198 from the analysis; the first because it is a cross-border earthquake and macroseismic observations are available only for Italian localities, the second because it has only few scattered MDPs. As a result, only 31 out of 213 events satisfy the above-mentioned selection criterion.

201 We then focus on the δW_0 values obtained from sites located within 80 km of the instrumental epicentre for the 31 events. This distance is chosen to minimize the contribution of anelastic attenuation (intrinsic absorption and scattering) that increases with increasing propagation path, while preserving a sufficiently large number of observations around each epicentre. The
204 Supplementary Material includes figures showing the spatial and azimuthal distributions of δW_0 values estimated with GOM24cerv and LOL24all IPEs, for all 31 earthquakes.

Unlike instrumental datasets, for which statistical methods based on ground-motion residuals allow a more objective
207 identification of directional patterns and quantification of the power of directivity (Colavitti et al., 2022; 2026), no equivalent statistical metric is currently available for macroseismic residuals. Consequently, the identification of events with directivity effects is based on the visual inspection of the azimuthal distribution of δW_0 values. In detail, we focus on earthquakes
210 exhibiting azimuthal patterns characterised by clusters of systematically positive δW_0 values (i.e., > 0.5 intensity degrees) within a given azimuthal sector. As an example, Figure 3 shows the results for two events occurred in Northeastern Italy on:
(i) 27 March 1928 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19280327_0832_000) and (ii) 13 September 1989
213 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19890913_2153_000).

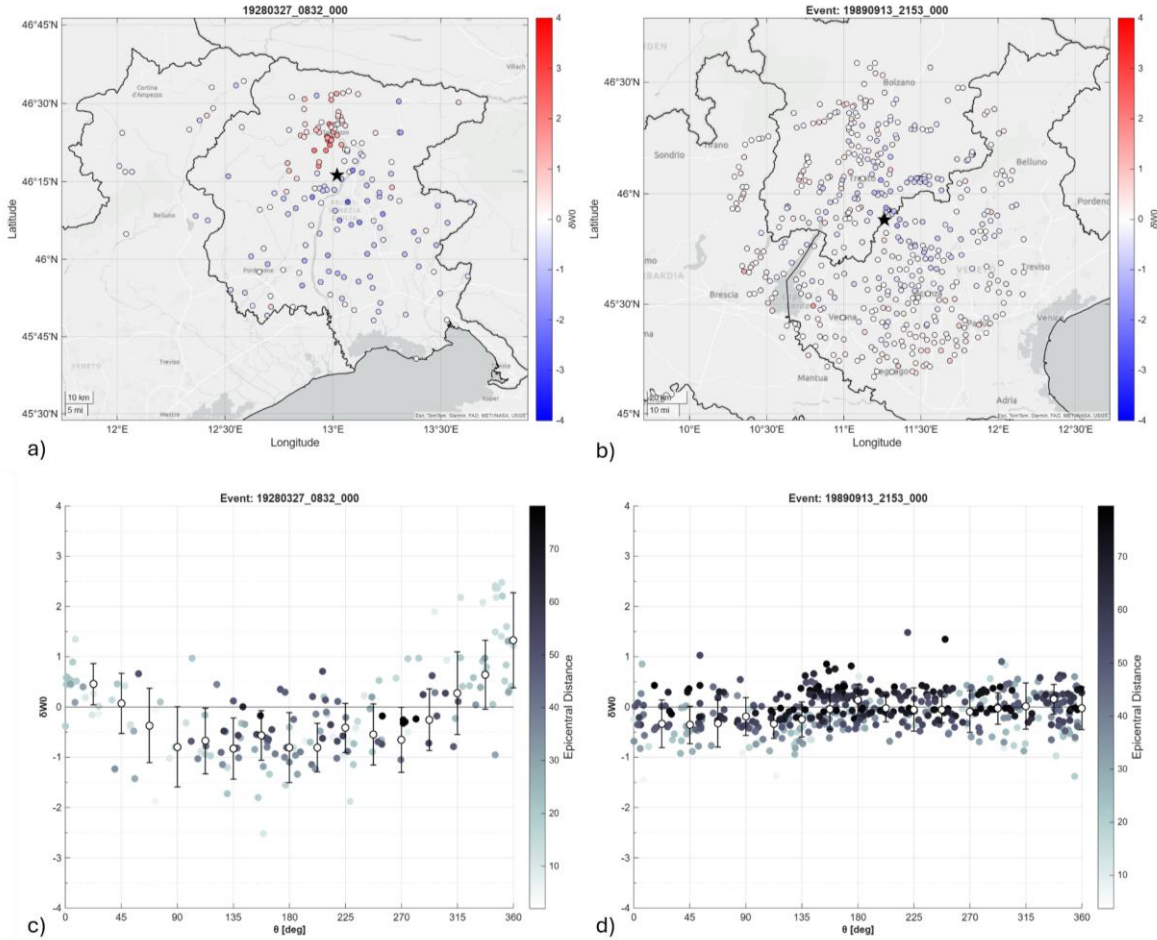


Figure 3: Spatial (top) and azimuthal (bottom) distribution of the aleatory residuals δW_0 estimated with GOM24crv at each site for the events that occurred on 27 March 1928 (a, c) and 13 September 1989 (b, d).

The 1928 event shows a spatial pattern characterised by positive δW_0 values north-northwest of the epicenter and a well-defined azimuthal distribution (Fig. 3a and 3c). In particular, predominantly positive residuals (i.e., ≥ 1) are observed at sites located within $330^\circ - 20^\circ$. The azimuthal distribution of these localities is aligned with the strike of one nodal plane of the focal mechanism reported by Sukan et al. (2024) and is consistent (i.e., strike = 20°) with the residual results (see Saraò et al., 2021 for further details). In contrast, the spatial and azimuthal distributions of the δW_0 values for the 1989 event (Fig. 3b and 3d) do not reveal any preferred azimuthal direction.

According to the adopted criterion, 8 out of the 31 investigated earthquakes (see list in Table 2) show evidence of potential directivity effects (i.e., about 26%). These results are consistent with a recent study based on instrumental ground motion records, which found that approximately one-third of the events in a Central Italy dataset exhibited directive behaviour (Colavitti et al., 2022; 2026). In the following, we investigate a set of case studies in terms of the spatial distribution of δW_0 , analysing the results as a function of the associated fault geometry. The discussion refers to the results obtained using the



GOM24crv model. Since the LOL24all model provides essentially identical patterns, its results are reported only in the Supplementary Material.

Table 2: Identification code, date, epicentral area, and instrumental locations and magnitudes as reported in CPTI15 for the investigated earthquakes that show directivity effects. *Italic bold records indicate the case studies discussed below.*

EqID	Date	Ep. Area	LatIns	LonIns	MwIns
19280327_0832_000	27/03/1928	Carnia	46.270	13.020	6.02±0.08
<i>19300723_0008_000</i>	<i>23/07/1930</i>	<i>Irpinia</i>	<i>41.070</i>	<i>15.360</i>	<i>6.62±0.16</i>
<i>19500905_0408_000</i>	<i>05/09/1950</i>	<i>Gran Sasso</i>	<i>42.508</i>	<i>13.350</i>	<i>5.68±0.14</i>
19750116_0009_000	16/01/1975	Stretto di Messina	38.137	15.711	5.18±0.08
<i>19801123_1834_000</i>	<i>23/11/1980</i>	<i>Irpinia-Basilicata</i>	<i>40.724</i>	<i>15.414</i>	<i>6.81±0.10</i>
19840429_0502_000	29/04/1984	Umbria	43.204	12.585	5.62±0.10
<i>20090406_0132_000</i>	<i>06/04/2009</i>	<i>L'Aquila</i>	<i>42.342</i>	<i>13.380</i>	<i>6.29±0.07</i>
<i>20160824_0136_000</i>	<i>24/08/2016</i>	<i>Central Italy</i>	<i>42.698</i>	<i>13.233</i>	<i>6.18±0.07</i>

24 August 2016 - Central Italy

Figure 4 shows the distribution of the aleatory error estimated at each locality for the 24 August 2016 Central Italy earthquake, M_w 6.18 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/20160824_0136_000). In particular, the azimuthal distribution shows a peak of positive δW_0 values between 130° and 160° , with some localities characterized by $\delta W_0 \geq 1$ (Fig. 4b). Despite the relatively complex azimuthal pattern, these results are broadly consistent with the strike direction of the causative fault proposed by several studies, which ranges between approximately 155° and 160° (i.e., Lavecchia et al., 2016; Tinti et al., 2016; Chiaraluce et al., 2017; Pizzi et al., 2017; DISS Working Group, 2025). In addition, Figure 4a highlights positive δW_0 values at sites located southeast of the instrumental epicentre, which may reflect rupture directivity effects consistent with the southeastward rupture propagation inferred by Tinti et al. (2016) and also in line with several previous studies on recorded ground motion (e.g. Spagnuolo et al., 2016; Ren et al., 2017; Luzi et al., 2017).

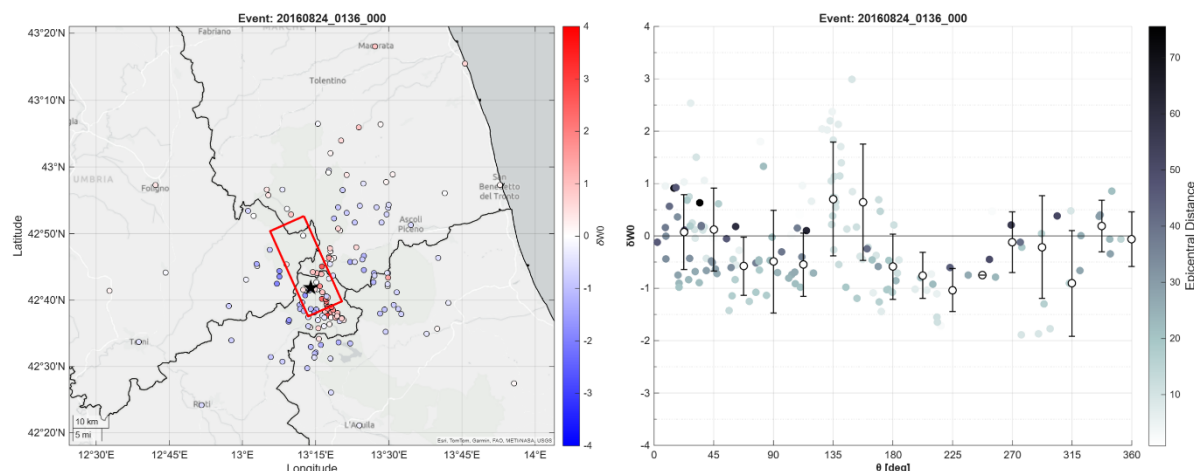
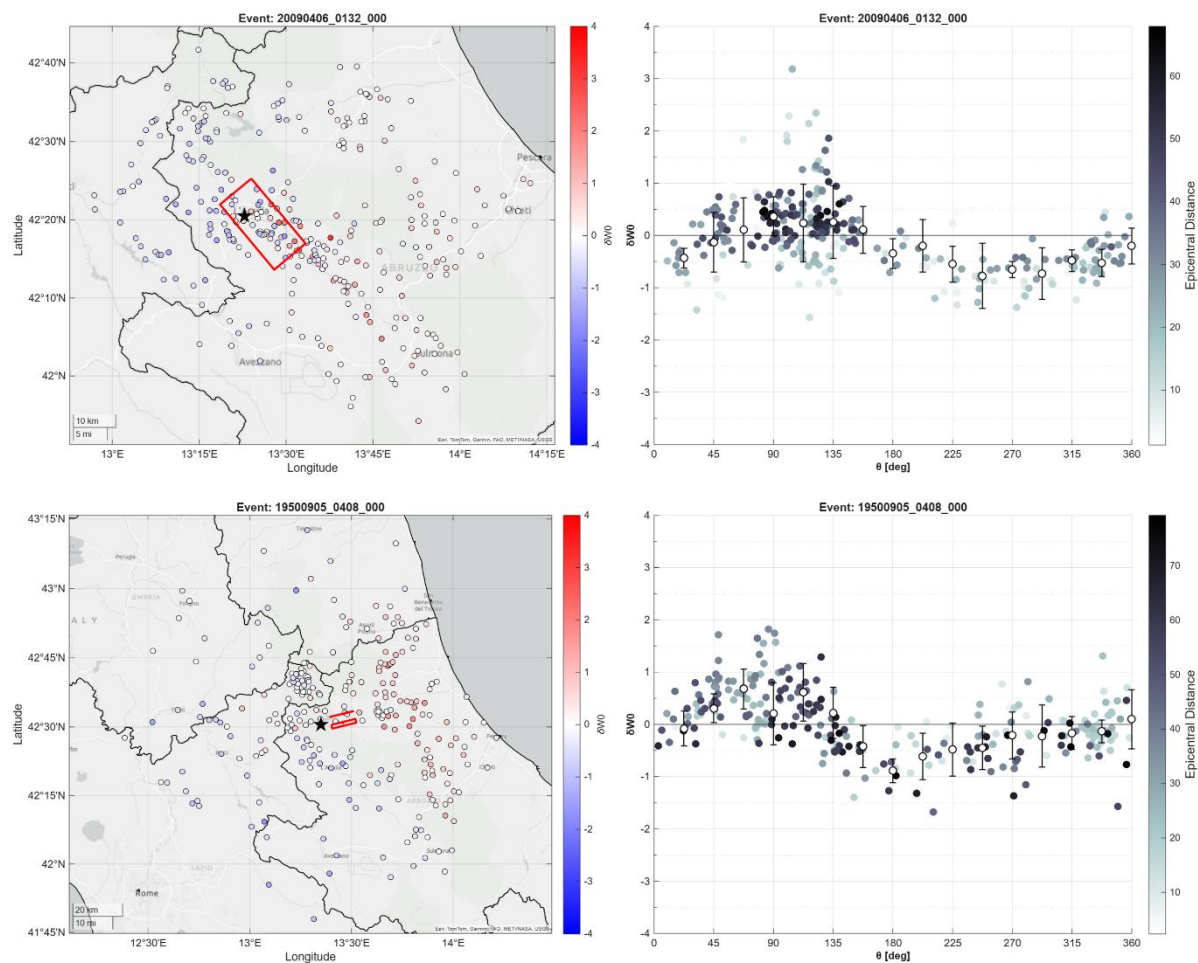


Figure 4: Spatial (left) and azimuthal (right) distribution of the aleatory error δW_0 estimated with the GOM24crv model for the 24 August 2016 Central Italy earthquake. In red is reported the projection of the causative fault as proposed by Tinti et al. (2016).

6 April 2009 - L'Aquila and 5 September 1950 - Gran Sasso

Figures 5a and 5b show the distribution of δW_0 values for the 6 April 2009 L'Aquila earthquake, M_w 6.29 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/20090406_0132_000). In this case, the azimuthal analysis reveals predominantly positive δW_0 values concentrated between 100° and 135° , with a peak around 130° , which is consistent with the strike of several proposed source models (i.e., Atzori et al., 2009; Anzidei et al., 2009; Cirella et al., 2009). These studies consistently infer a similar fault geometry, with strike directions ranging between 133° and 137° , in agreement with geological observations along the Paganica fault (Falcucci et al., 2009). Consistent with these findings, several authors (i.e., Calderoni et al., 2015; Akinci et al., 2010; Ameri et al., 2009; Pino and Di Luccio, 2009) identified rupture directivity effects from instrumental data, highlighting a systematic amplification of ground motions southeast of the epicentre. A similar pattern is observed in the macroseismic data, where sites located southeast of the instrumental epicentre exhibit high positive δW_0 values (Fig. 5a). Our results are also consistent with those proposed by Ameri et al. (2011), who investigated macroseismic intensity residuals using a different approach with a specific non-parametric attenuation model.

Focusing on another event that occurred near the area affected by the 2009 earthquake, Figures 5c and 5d show the distribution of the variability errors estimated at the localities for the 5 September 1950 Gran Sasso earthquake, M_w 5.68 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19500905_0408_000). In this case, the strike direction (i.e., 74°) inferred from regional geological data proposed by the DISS Working Group (2025) is consistent with the peak of positive δW_0 values observed at sites around 70° - 80° (Fig. 5d).



270 **Figure 5: Spatial (left) and azimuthal (right) distribution of the variability error δW_0 estimated with the GOM24crv model for the**
 273 **6 April 2009 Central Italy (top) and for the 5 September 1950 (bottom) earthquakes. In the top left panel is reported the projection**
of the causative fault as proposed by Cirella et al. (2009), and in the bottom left panel by the DISS Working Group (2025).

23 November 1980 and 23 July 1930 - Irpinia

The Irpinia earthquake that occurred on 23 November 1980 in Southern Italy (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19801123_1834_000) is the largest event recorded by strong-motion instruments in Italy (Ameri et al., 2011). This earthquake caused destructive effects in numerous localities (Guidoboni et al., 2018; 2019) associated with the rupture of three fault segments, activated with a time lag of about 20 seconds (i.e., Bernard and Zollo, 1989; De Landro et al., 2022). In particular, the main shock was related to the rupture of a normal fault oriented along the NW-SE Apennine direction, with strike values generally ranging between 310° and 315° (Westaway and Jackson, 1987; Bernard and Zollo, 1989; Pantosti and Valensise, 1990; DISS Working Group, 2025). Analyzing δW_0 values at the considered localities, Figure 6a suggests possible

279
282 directivity effects at the localities distributed along the NW-SE direction, with a peak of positive values between 290° and



320°, consistent with the strike of the causative faults (Fig. 6b). However, this interpretation is only limited to the main rupture segment, since the available macroseismic intensity distribution (Guidoboni et al., 2018) reflects the combined effects of the three sub-events, which occurred within a very short time interval.

Together with the 1980 earthquake, in the last 100 years two other strong events hit the Irpinia area, in particular those that occurred on: (i) 21 August 1962 (https://emidius.mi.ingv.it/ASMI/event/19620821_1819_000) and (ii) 23 July 1930 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19300723_0008_000). For the 1962 event, the figures reported in the Supplementary Material do not show any clear directivity effects. Indeed, the azimuthal distribution does not reveal any preferential orientation of the positive δW_θ values, in particular in the direction of the causative fault of this event, likely having a strike of approximately 278° (Vannoli et al., 2016). This suggests that source directivity is not completely reflected in the macroseismic intensity distribution. Conversely, the 1930 event shows positive δW_θ values concentrated along two preferred azimuthal ranges: (i) between 90° and 130° and (ii) between 250° and 290° (Fig. 6c, 6d). Several authors proposed focal mechanisms for the 1930 Irpinia earthquake characterised by strike directions around 280°–290° (e.g., Emolo et al., 2004; Pino et al., 2008). In particular, Fig. 6d highlights a possible directivity effect aligned with the proposed strike direction, with sites located around 270° exhibiting predominantly positive δW_θ values.

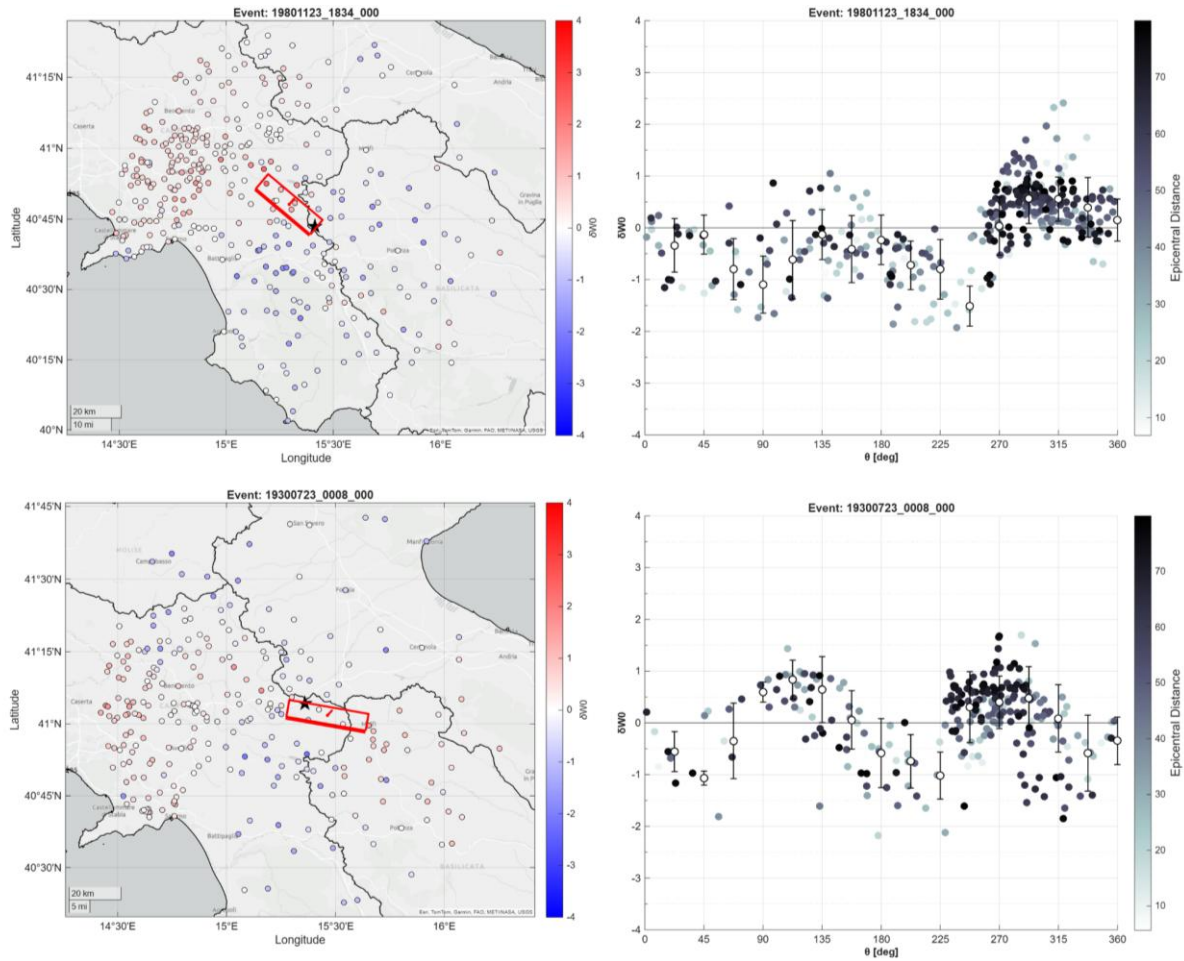


Figure 6: Spatial (left) and azimuthal (right) distribution of the variability error δW_0 estimated with the GOM24crv model for the 23 November 1980 (top) and for the 23 July 1930 (bottom) earthquakes. The projection of the causative faults is from the DISS Working Group (2025).

6 Conclusions

In this study, we investigated the potential signature of rupture directivity effects in the Italian macroseismic data by adapting a residual decomposition framework commonly adopted in non-ergodic ground-motion studies. This approach represents an innovative application of residual decomposition to macroseismic intensity data. Starting from a dataset of 213 instrumental earthquakes and more than 18,000 macroseismic observations, we decomposed the total residual into between-event, locality-to-locality, and remaining aleatory variability components. The results show that the aleatory component (δW_0) remaining after the residual's decomposition represents the largest source of variability among the other residual terms. We analysed the spatial distribution of the aleatory error δW_0 for 31 earthquakes characterized by sufficiently uniform azimuthal coverage of MDPs to explore potential directivity effects in the macroseismic data, by investigating the azimuthal distribution of positive residuals.



We then identified a subset of 8 earthquakes (i.e. 26% of the total) exhibiting spatial patterns compatible with source directivity. Overall, the analysed case studies show that, for several well-documented Italian earthquakes, the azimuthal distribution of positive δW_0 values is broadly consistent with the strike of the causative faults and, where independently constrained, with the preferred rupture propagation direction inferred from instrumental and geological investigations. In addition, these results are in line with several recent studies based on instrumental ground motion records, which found that approximately one-third of the events in a Central Italy dataset exhibited directive behaviour (Colavitti et al., 2022; 2026). This agreement suggests that macroseismic intensity observations preserve measurable signatures of source directivity despite their nature (i.e., ordinal and discrete data) and their different approach to collecting data.

The results obtained in this study indicate that residual decomposition provides a promising and, to date, largely unexplored framework for investigating source directivity using macroseismic data. Beyond identifying potential directivity effects, the proposed methodology may provide additional constraints on the orientation of causative faults reconstructed from macroseismic data. In this respect, this approach could complement existing macroseismic techniques for finite-fault reconstruction and contribute to better constraining the strike direction of the fault rupture related to historical events (i.e., Gironelli et al., 2023; 2026).

Such findings could also contribute to improving attenuation models by developing a new generation of non-ergodic IPEs capable of overseeing the isotropic decay of macroseismic intensity. Future developments should focus on quantifying the contribution of the locality-to-locality term along with systematic propagation terms by extending this framework to historical earthquakes.

Data availability

DBMI15 is available at https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/ (Locati et al., 2022). CPTI15 is available at https://emidius.mi.ingv.it/CPTI15-DBMI15/query_eq/ (Rovida et al., 2020; 2022).

Author contribution

AA and GL performed the analysis. All the authors equally contributed to the analysis of the results and the writing of the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.



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