Observations on the connection between glacial phases, natural catastrophes and economic trends of the last millennium in Italy

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Abstract
Humanity has often faced critical phases determined by climate changes combined with other natural catastrophes that implied significant socio-economic consequences. In this article, we present an observational study on the possible systematic connection between these factors for the specific case of Italy, comparing the occurrence of pandemics, earthquakes, and volcanic eruptions with the glacial history of the last millennium. We have found that the natural catastrophes concentrate in the periods of ice expansion in Europe, whereas the phenomena are in attenuation in the current phase of global warming. Such a behavior has influenced the economy of the country: in fact, a comparison with a reconstruction of the per capita Gross Domestic Product since 1310 shows that the periods of maximum economic expansion occurred during the deglaciation phases. This study has confirmed the general connection of the climate with a number of Earth processes and the difficulty to foresee its changes. Furthermore, the extension of the analysis at the world level for the last 2500 years has evidenced that different types of pandemics (plague, cholera and influenza) almost exclusively spread during the phases of glacial expansion.

Keywords
earthquake, Italy, Little Ice Age, pandemic, volcanic eruption

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Introduction
There were periods in the history when different natural and social phenomena combined, leading to extremely negative consequences for humans. For example, a well-documented adverse period was the 17th century (Parker, 2013), when particularly cold climate conditions occurred in coincidence with a dreadful plague pandemic, increased global volcanism and a series of conflicts, including the devastating Thirty Years’ War (1618–1648). Locally, in southern Italy, in the 34 years between 1626 and 1659, the Kingdom of Naples experienced seven destructive earthquakes (Rovida et al., 2016), the largest eruption of Mt. Vesuvius since the Roman age (1631, about 4000 casualties (Rosi et al., 1993)), the revolt of Masaniello (1647) and the plague of 1656, killing the 50% of population in Naples (Alfani and Melegaro, 2011). Scholars have wondered if similar negative combinations can be simply attributed to chance or if any systematic relationship exists. Some historians have recognized the climatic conditions related to glaciations to be common factors characterizing the 17th century and other critical time periods (Behringer et al., 2005). During the last millennium, these phases were related to the evolution of the ‘Little Ice Age’ (LIA), a broadly defined period of cooling most evident in Europe and Asia between the 17th and the 19th centuries. The origin of the term LIA, as well as its uncertain and controversial nature, were extensively discussed by Grove (2004) and reviewed by Matthews and Briffa (2005), referred as MB2005 hereafter. In particular, there are several evaluations of the spatio-temporal extent of the LIA: the largest proposed limits go beyond Europe to embrace the entire northern hemisphere (although with significant regional differences) between the 14th century and the first half of the 20th century, whereas it is in doubt if it involved the southern hemisphere. There is also no consensus on what are the climate parameters that better characterize the LIA (summer/winter temperature or precipitations). Interesting for the following analysis, MB2005 distinguish between the LIA glacierization, most evident in the European Alps for about 650 years (1300–1950) and the LIA climate, lasting for a shorter period of 330 years (1570–1900) and characterized by a low summer temperature of land areas north of 20° N. MB2005 summarize different hypotheses concerning the cause of the LIA. They involve the reduced solar radiation, the increased volcanic activity, the changes in the oceanic circulation and the orbital forcing. Ruddiman (2003) has also suggested the indirect influence of the decrease of human population (through the reduction of the greenhouse effect) that followed the Black Death of the 14th century. Other hypotheses look at the natural
variability of the climate, caused by interactions and feedbacks between its components (temperature, pressure and precipitations), without the intervention of an external forcing. Within the LIA, Wanner (2000) has recognized three phases of maximum glacial extension in the Alps (17th century and the middle of the 14th and 19th centuries), named ‘Little Ice Age’-type events (LIATEs). By analyzing the second LIATE (1570–1630), Pfister (2005) traces the chain of the phenomena (LIA-type impacts), that, starting from the climatic conditions (possibly triggered by volcanic eruptions), negatively affect the human societies, reducing the available resources and facilitating the diffusion of the diseases. According to such an analysis, the main negative factor is not the peak of cold in winter but, rather, the combined presence of water (through precipitations or prolonged snow coverage) and cold during the months that are most critical for the yearly agricultural cycle, with a direct effect on the volume and the quality of the final product: March to April (sowing), July to August (main maturation) and September to October (harvest). In the present work, we further investigate on the combination of natural processes and on their consequences by exploiting the large historical documentation available for Italy. We examined the occurrence of pandemics, earthquakes and volcanic activity in comparison with the glacial history of the last millennium in order to assess the possible occurrence of a systematic connection among these factors. Part of the story (namely, the correlation at a large spatial scale between seismic and volcanic activity in Italy and its possible relationship with the climate changes) was discussed in previous papers (Bragato, 2017a, 2018). In those works, the main result (supported also by formal statistical tests) was the recognition of the time correspondence between a transient of increased volcanic and seismic activity with the occurrence of the LIA. Recalling the previous distinction introduced by MB2005 between LIA glacialization (1300–1950) and LIA climate (1570–1900), the seismic-volcanic activity was compared with both glacier extension and surface temperature (Bragato, 2018), reaching the conclusion that it was best correlated to the longest period of the LIA glacialization. This analysis is herein completed considering detailed data about the evolution of glaciers in Switzerland during the last century. Furthermore, it is extended performing a systematic comparison of the geo-glaciological trends with the occurrence of pandemics and with the economic development of Italy.

Glacial phases and natural catastrophes through the history

Glacial evolution in the European Alps

Here, we summarize concepts, methods and results in the reconstruction of the glacial evolution of the last millennium in the European Alps. What we describe is just a spatio-temporal fragment of the glacial history of the Earth, which was extremely variable. For a short introduction to this history, we refer to textbook by Earle (2015), who presents a reconstruction of the global temperature for the past 5 million years based on oxygen isotope of forams (Lisiecki and Raymo, 2005). His graph, here reproduced (modified from Earle (2015), originally produced with data from Lisiecki and Raymo (2005)): (a) entire time series with the indication of the MPT (Clark et al., 2006) and (b) details of the last 500,000 years showing the five most recent glacial phases and the LGM. MPT: mid-Pleistocene transition; LGM: Last Glacial Maximum.

Figure 1. Reconstruction of the average global temperature for the last 5 million years based on oxygen isotope of forams (modified from Earle (2015), originally produced with data from Lisiecki and Raymo (2005)): (a) entire time series with the indication of the MPT (Clark et al., 2006) and (b) details of the last 500,000 years showing the five most recent glacial phases and the LGM. MPT: mid-Pleistocene transition; LGM: Last Glacial Maximum.

with the Holocene. In this view, the entire LIA and the LIATEs comprising it appear to be minor episodes of the long-term glacial evolution of the Earth.

Returning to the glaciers of the European Alps, their behavior reflects the interaction of various elements, like the temperature, the precipitation, the solar radiation, the wind and the topography (Haebeler, 1994; Hoelzle et al., 2003; Hoinkes and Steinacker, 1975; Kuhn, 1980; Oerlemans, 2001). The optimal conditions for their growth are as follows: a cool and humid winter, the relapse of cold water in spring melting, a cool and wet summer and the occurrence of pronounced and long-lasting high-pressure situations in summer and autumn (Ivy-Ochs et al., 2005, 2009; Kellner-Pirklbauer et al., 2012; Nussbaumer et al., 2014). The long-term evolution of glaciers can be estimated using various methods (Holzhauser, 1997; Holzhauser and Zumbühl, 1996): glaciological (direct size measurements), historical (collection of data from written and pictorial historical records), glacio-archaeological (human traces such as foundations) and glacio-geomorphological (use of dateable organic material from overgrown soils and crushed trees). The parameter considered in these reconstructions is the length of the glacier. The length variations are delayed, and filtered responses to the climate changes: snow accumulates at high altitude, which subsequently turns into firm and then glacier ice that slowly flows downstream. After some years (reaction time), the glacier shortens in length if the temperature increases and the precipitation decreases or; on the other hand, it advances if the temperature decreases and the precipitation increases. Finally, the glacier reaches a new equilibrium after a certain time (response time: Haebeler, 1991; Johannesson et al., 1989; Oerlemans, 2007). In general, the larger the glacier, the longer the reaction and response times, with increased insensitivity to the short-term climatic changes.
Here, we look at the behavior of the Great Aletsch glacier (Holzhauser and Zumbuhl, 1996) located in the Alps of Valais (Switzerland, black diamond in Figure 2). With its length of 22.5 km and surface of 78.4 km$^2$ in 2011 (Fischer et al., 2014), it is the largest glacier in the European Alps, characterized by a reaction time of about 24 years (Müller, 1988) and a response time between 50 to 100 years (Haeberli and Holzhauser, 2003). According to comparative analyses (Holzhauser et al., 2005), it is representative of the general trend of glacier and lake-level variations in the western and central Europe, working as an indicator of continental water accumulation. Figure 3(a) depicts the evolution of the glacier since 1100 AD: the initial phase (up to 1300) is part of the ‘Medieval Warm Period’, started in the 8th century and characterized by a general ice retreatment with a few weak advances, including one, visible in Figure 3(a), occurred in the 12th century. During the subsequent LIA, the glacier evolved through three main peaks (maximum extensions around 1370, 1678 and 1859/60), the same peaks that led Wanner (2000) to the definition of LIATE. The peak of extension of 1859/60 was followed by the continuous retreatment of the Great Aletsch glacier, insensitive to the short-term climate fluctuations of the 20th century. Such fluctuations had effects on smaller glaciers, characterized by quicker reaction times. For a quantification, we looked at the overall glacial evolution of Switzerland, summarized by the percentage of advancing glaciers in each year (Figure 4(a)) available in (Glaciological Reports, [1881] 2017). According to Figure 4(a), there were two periods of partial ice restoration with maxima on 1919 and 1980, as well as a possible weak reactivation around 2013.

**Pandemics with effect in Italy**

For a systematic and exhaustive account of the pandemics that struck also Italy, we referred to a study by Alfani and Melegaro (2011), from which we drew the times of occurrence of pandemics (continuous vertical lines in Figures 3 and 4). The historical reconstruction indicates that after the Justinian plague of 541–542 AD, pandemics were absent and almost forgotten for eight centuries. They suddenly reappeared at the maximum degree of mortality with the Black Death of 1347–1349, which killed at least 30% of population (60% in large cities like Florence and Siena). Plague stayed in Italy for about four centuries but, in general, with much smaller effects than during the Black Death. The epidemics, although frequent, had mainly local or regional character, with extreme sparse distribution even within the same region. Cipolla (2002) reports the series of epidemics occurred in Venice and Florence (about 20 in both cities) and evidences how the plague hit more severely the urban areas than the countryside, perhaps due to the higher density of inhabitants and the worse hygienic conditions of the cities. According to Alfani and Melegaro (2011), who discuss the particular case of the plague of 1574–1577 (the strongest of the 16th century), such an urban character, combined with the fact that 80% of the Italian population lived in the countryside, contributed to keep low the overall mortality of the disease. Only two outbreaks had demographic effects similar to the Black Death, with a mortality rate near to 30%: that of 1629–1631 in northern Italy (about 2 million deaths) and that of 1656–1657 in southern Italy (about 1 million deaths). Later, pandemics reappeared with the cholera of the 19th century. Worldwide, there
were five pandemics between 1817 and 1896 (Colwell, 1996), cumulatively represented by the gray band in Figure 3. They struck Italy with three peaks of mortality (thin vertical lines in Figure 3): 1835–1837 (146,000 deaths), 1854–1855 (120,000 deaths) and 1865–1867 (160,000 deaths). The 20th was the century of influenza (thin vertical lines in Figure 4), with the main pandemic of 1918–1920 (Spanish flu, 400,000 victims) and two minor, causing a few thousands of deaths in total (Asian flu, 1957–1958; Hong Kong flu, 1968–1969). The World Health Organization declared the swine flu of 2009 to be the first influenza pandemic of the 21st century, although the number of victims was relatively low (near to 250 in Italy). In the same time period, two cholera pandemics occurred worldwide (Colwell, 1996): one between 1899 and 1923 and the other one between 1961 and 1991 (gray bands in Figure 4). According to the World Health Organization (2018), after 1991, the incidence of cholera
The worsening was mainly due to two outbreaks that are still ongoing on 2018: that of Haiti, started on 2010, and that of Yemen, started on 2016. The latter is perhaps one of the worst outbreaks ever recorded, with more than 1,000,000 new cases and 2261 deaths on 2017. In Italy, the cholera pandemics of the 20th century had much lower effect than those of the previous century, with two outbreaks (thick vertical lines in Figure 4) occurred on 1910–1911 (7,000 deaths) and on 1973 (24 deaths).

The pandemics of sexual transmitted diseases, which are apparently related to social rather than to environmental factors, have not been represented (Figures 3 and 4). In the reconstruction of Alfani and Melegaro (2011), they are syphilis and AIDS. Syphilis reached Italy from America on 1494, remained at the pandemic level for about one century, to become endemic, with low mortality rates in the following centuries. Concerning AIDS, the pandemic is still ongoing: in Italy, the first case was diagnosed on 1982, with a peak of mortality on 1995 (4582 casualties).

Seismic and volcanic activity in Italy

Seismically, Italy is one of the most hazardous areas in Europe. The country is placed at the collisional boundary between the Eurasian and the African plates, with the interposition of the Adriatic microplate (Figure 2), which, accordingly with different
geodynamic studies, is either a promontory of the African plate (Channell et al., 1979; Chiarabba et al., 2015; Mantovani et al., 1990; Marsella et al., 1995; Rosenbaum et al., 2002), or is composed by one or two independent detached blocks (Battaglia et al., 2004; D’Agostino et al., 2008; Oldow et al., 2002; Viti et al., 2011). The complex dynamics related to the plate collision causes earthquakes that are mainly located along the Apennine chain and on northeast of the country, at the junction between the Alps and the Dinarides. Thanks to its enormous historical heritage and to the long tradition of systematic collection of earthquake data, nowadays the country has a highly reliable seismic catalog covering the last millennium (Rovida et al., 2016). Since 1100, the catalog reports 82 strong earthquakes with estimated moment magnitude $M_w$ between 6 and 7.3 (circles in Figure 2), the latter value reached for the earthquake of 1693 in eastern Sicily. The data about the earthquake mortality have been reported by Guidoboni et al. (2018). Although with significant exceptions, the number of victims ranges from a few people for earthquakes of magnitude around 5.5 to tens of thousands for earthquakes of magnitude near to 7. In some cases, the fatalities were caused by sequences of strong earthquakes rather than by a single mainshock. Table 1 reports the seismic sequences with at least 10,000 fatalities: the maximum (80,000 deaths) was reached for the Calabria–Messina earthquake occurred on 1908 ($M_w$ 7.1), when the effect of the shaking combined with that of a tsunami. Concerning the time distribution of the earthquakes, Bragato (2017a, 2018) has evidenced a marked transient of seismic activity between 1600 and 1900, followed by a significant decrease during the last century. Such a features are homogeneous from northern to southern Italy and persist after considering the possible incompleteness of the catalog and the mistakes in the magnitude estimation. The results of the previous study are summarized in Figure 3(b), where dots represent the occurrence of earthquakes of magnitude at least 6, and the curve is the corresponding time density estimated by Gaussian kernel smoothing (smoothing parameter $h = 40$ years): it has three peaks centered on 1339, 1714 and 1854. Figure 4(b) shows the details of seismicity since 1900. It evidences an overall decreasing trend with three large oscillations: the last one comprises the recent destructive earthquakes of L’Aquila (2009), Emilie (2012) and Central Italy (2016) with more than 600 casualties in total. Such oscillations are part of a statistically significant cyclic behavior with a period of about 50 years that is observable since 1600 (Bragato, 2017b).

Italy has dangerous volcanoes. They are among the most studied in the world, being the object of a wide scientific literature produced at least since the 17th century (Borelli, 1670). An up-to-date view of the state of the research on the Italian volcanoes and on their interaction with the human life is available (AA VV, 2018). Their systematic, institutional surveillance started on 1841 at Mt. Vesuvius, with the foundation of the Osservatorio Vesuviano, the oldest volcano observatory in the world. Nowadays, the Italian volcanoes are continuously monitored by multi-parametric networks of physical and chemical sensors, mainly managed by the Istituto Nazionale di Geofisica e Vulcanologia at its sections of Naples (Osservatorio Vesuviano, http://www.ov.ingv.it) and Catania (Osservatorio Etneo, http://www.et.ingv.it). For a comprehensive history of the eruptions in Italy, we refer to the database of the Smithsonian’s Global Volcanism Program (Siebert et al., 2010). For the time period 1100–2018 AD, the catalog reports 267 eruptions with Volcanic Explosivity Index (VEI; Newhall and Self, 1982) up to 5 attributed to eight volcanoes (triangles in Figure 2). The largest and most active volcano is Mt. Etna, in Sicily, with 116 major eruptions (VEI between 2 and 4) since 1100 AD, the last of which started on 2013 and is still ongoing. The eruptive history of the volcano was reconstructed using historical sources as well as geological and geophysical methods (Coltellii et al., 2000; Tanguy et al., 2007). According to such a data, the volcano accelerated its activity in the 17th century and since then has continuously increased the frequency of the eruptions (Branca and Del Carlo, 2005), reaching its maximum activity in the last century (70 eruptions, 41 of which with VEI between 2 and 3). Despite its intensified activity and the destructive potential, the volcano has been not so dangerous for the human life. Mt. Etna is capable of both effusive and explosive eruptions (Moretti et al., 2018), but the worst eruptions of the last millennium were mainly effusive with relatively slow lava flows, so that people had enough time to evacuate. This happened for what is considered the largest eruption of the last millennium, occurred on 1669 (Branca et al., 2015). In that case, the lava flow destroyed a number of small villages, reached the city walls of Catania but caused no victims. It was the same for the eruption of 1928 that destroyed the town of Mascali (Branca et al., 2017). On 1992, it was also possible to respond actively to the volcano by diverting the lava flow (Barberi et al., 1993). In the following, we focalize on what is perceived as the main eruptive risk in Italy. It is located around the Gulf of Naples, with the three volcanoes Mt. Vesuvius, Ischia and Campi Flegrei (Scandone et al., 1991), threatening a densely populated area (2600 inhabitants per km², 3 millions in total in the Metropolitan City of Naples). Mt. Vesuvius is the most famous, mainly for the eruption of 79 AD that buried Pompeii (Scandone et al., 1993) and the one of 1631, killing at least 4000 people (Rosi et al., 1993), both eruptions with $VEI = 5$. The volcano had both effusive and explosive eruptions (Cioni et al., 2008), but the worst consequences came from the latter ones. The explosiveness combined with the presence of large residential areas just under its cone, gives short reaction time after the beginning of an eruption. As a consequence, researches have investigated the precursors that, in the very first phase of activity, could indicate the evolution toward a large eruption (Pappalardo et al., 2014; Scandone and Giacomelli, 2013). Models of the volcano have been developed in order to generate eruptive scenarios and to construct emergency plans (Macedonio et al., 2012). For our analysis, we have taken into consideration the eruptive history of the volcano, which is particularly well known thanks to the rich historical documentation and to recent geophysical investigations on the lava flows of the past (Guidoboni and Boschi, 2006; Principe et al., 2004; Scandone et al., 1993, 2008). According to (Siebert et al., 2010), since 1100 Mt. Vesuvius had 30 eruptions with VEI $\geq$ 2 (dots in Figure 3(c)). The bulk of the eruptive activity occurred between 1631 and 1944 (Figures 3(c) and 4(c)) with two maxima on 1710 and 1842. At present, the main concern is for the Campi Flegrei caldera, a volcanic structure that was formed about 40,000 years ago as a consequence of a supereruption rated $VEI = 7$ (Chiodini et al., 2016; Mastrolorenzo et al., 2017) that possibly had large-scale effects on the climate and on the human evolution (Fedele et al., 2008). The last eruption within the caldera occurred on 1538 ($VEI = 2$) and formed the new volcano Monte Nuovo.

Table 1. Seismic sequences with at least 10,000 fatalities occurred in Italy since 1100 AD (Guidoboni et al., 2018). The moment magnitude $M_w$ of the strongest earthquakes is also reported (Rovida et al., 2016).

| Year     | Area              | $M_w$ | victims |
|----------|-------------------|-------|---------|
| 1169     | Eastern Sicily    | 6.5   | 15,000  |
| 1456     | Sannio–Irpinia    | 7.2   | 27,000  |
| 1638     | Calabria          | 7.1   | 6,800   |
| 1688     | Sannio            | 7.1   | 10,000  |
| 1693     | Eastern Sicily    | 7.3   | 54,000  |
| 1783     | Calabria          | 7.1   | 7.7, 7.0 | 35,170 |
| 1857     | Basilicata        | 7.1   | 19,000  |
| 1908     | Calabria–Messina  | 7.1   | 80,000  |
| 1915     | Marsica           | 7.1   | 32,610  |
level from ‘green’ (ordinary activity) to ‘yellow’ (the second of 2011 and is still ongoing. It led the authorities to increase the alert 1983, respectively. A further, more smoothed rise started around 1980, roughly 133-m high). After a quiet period of about 500 years, the caldera reactivated in the middle of the 20th century with a series of uplift episodes threatening an eruption. Such a behavior has induced the intensification of monitoring and studies concerning the source of deformation (Amoruso et al., 2014, 2017) and the management of the volcanic hazard (Mastrolorenzo et al., 2017). Here, we consider the data on ground deformation, which have been monitored since 1905, initially through irregular geodetic leveling (Del Gaudio et al., 2010) and, since 2000, through a permanent network of GPS receivers (De Martino et al., 2014). The measured vertical movements (Figure 4(d)) indicate an overall uplift of about 3.5 m mainly concentrated in three periods starting on 1950, 1968 and 1983, respectively. A further, more smoothed rise started around 2011 and is still ongoing. It led the authorities to increase the alert level from ‘green’ (ordinary activity) to ‘yellow’ (the second of four alert levels), requiring a frequent evaluation of geophysical and geochemical data, with the consequent production of weekly bulletins.

Discussion

The long-term time correlation among the various natural processes is shown in Figure 3. The three peaks of seismicity are almost coincident with the maximum extensions of the Great Aletsch glacier (although with a major lag of about 35 years for the peak around 1700). There is also some similarity on the minor fluctuations of 1100–1200 and 1450–1550. The eruptive behavior of Mt. Vesuvius follows a similar trend, although the eruptive accelerations before 1600 are rather weak. A formal statistical test has shown a significant time correlation between the Italian seismicity and the Vesuvius’ eruptions since 1600 (Bragato, 2017a, 2018). Altogether, the phases of enhanced glacial, seismic and volcanic activity correspond to the occurrence of pandemics in Italy (vertical bars in Figure 3). Figure 4 shows the details since 1900. The seismicity has three cycles of increased activity: the first and second ones took place during the phases of partial ice restoration, when also influenza and cholera pandemics verified; the last seismic cycle started contemporaneously with the swine influenza of 2009 but, so far, has only a weak glacier counterpart started on 2013. Looking at the volcanic activity, the last eruptive phase of Mt. Vesuvius (1913–1944, Figure 4(c)) coincided with the first cycle of seismicity and glacial expansion. After a short pause around 1950 involving the glacial, geological and biological processes, the entire system reactivated quite synchronously. The new common phase opened in the Neapolitan volcanic district, when the magmatic activity moved from the eruption of Mt. Vesuvius to the uplift of Campi Flegrei (Figure 4(d)). Such a shift is not unusual and has precedents in the alternating behavior of the two volcanoes in the last 2000 years (Walter et al., 2014). The two largest uplifts of Campi Flegrei (around 1970 and 1984) roughly occurred in correspondence with three strong earthquakes (Belice, 1968; Friuli, 1976 and Irpinia, 1980, more than 3000 casualties in total) as well as to the last expansion of glaciers. After a pause of about 25 years, the last, weak uplift episode started around 2011, clearly superimposed to the seismic cycle of 2009–2016.

Our observations suggest a systematic connection between environmental processes of different nature. At present, we miss a valid overall explanatory theory. Some possible causal links have been suggested and modeled in the literature, but, at present, the results are still partial and largely hypothetical. The largest part of the studies is centered on the climate, given its potential to affect all the other elements, mainly through the combined action of temperature and water accumulation or flow. We summarize some of these works in the following.

A general explanation for the increased onset of the diseases is that the bad weather induced harvest failure and malnutrition and reduced the resistance to the diseases. For the specific case of plague, a systematic study based on biological elements (Ben Ari et al., 2010) has demonstrated that the water accumulation in the soil, the prolonged snow coverage in spring and cool summers are all environmental factors favorable to the spread of the disease. Such factors are typical of the LIATEs and are almost the same that, as seen in the introduction, negatively affect the quantity and the quality of the agricultural production (Pfister, 2005). The presence of water had also an important role for the spreading of cholera, either through the reservoir fluctuations or the rainfall events (Righetto et al., 2012, 2013). According to various works collected by McGuire and Maslin (2013), the climatic processes were able to control the seismicity and the volcanism at different time and space scales by re-distribution of the water load on the earth’s surface (sea level, ice, snow and surface hydrology). Similar works have been stimulated mainly by the tentative to foresee the geological consequences of the current global warming and, consequently, they tried to model the tectonic effect of deglaciation (Hampel et al., 2010). A more general and long-term perspective is furnished by Fischer (1964), who has investigated the interactions between the tectonic processes and the sea level changes evidenced by the cycles of sedimentation in the Northern Alps (region of Salzburg, Austria). Fischer has recognized stratigraphic sequences (cyclolhems) that have been attributed to low-amplitude eustatic fluctuations with a periodicity ranging between 20,000 and 100,000 years. The cyclolhems group in megacycles in sets of 5 to 8, possibly due to the rhythmic variations in the rate of tectonic subsidence. Later, Goldhammer et al. (1987) have revised the length of Fisher’s megacycles to 100,000 years and related them to the aforementioned Milankovitch cycles, of astronomical origin. By combining these elements, it is possible to speculate about a causal chain, in which the astronomical factors influence the rate of tectonic subsidence and the related phenomena (e.g. earthquakes) through surface load changes caused by climate processes.

There are also other possible paths of interaction, not starting from the climate. For example, the eruptions and the earthquakes can trigger one to each other through stress transfer (Nostro et al., 1998), while it is well known that the volcanism affects the climate: the large eruptions, through their emissions, can induce a few years of global cooling (Bethke et al., 2017; Cole-Dai et al., 2013; Courtillot, 2005; D’Arcy Wood, 2014; Kelly et al., 1996; Viner and Jones, 2000). According to Miller et al. (2012), sequences of large eruptions, if enough close in time, might trigger long-lasting climate changes. This study has suggested that an unusual, 50-year-long episode of four massive tropical volcanic eruptions had triggered the LIA between 1275 and 1300 AD. The persistence of cold summers following the eruptions is best explained by a subsequent expansion of sea ice and a related weakening of Atlantic currents, according to computer simulations conducted for the study. This research, which has used analyses of patterns of dead vegetation, ice and sediment core data and computer climate models, has provided new evidence on the onset of the LIA. Scientists have theorized that the LIA was caused by a decreased summer solar radiation, with erupting volcanoes which cooled the planet by ejecting sulfates and other aerosol particles, which reflected the sunlight back into the space or by a combination of the two processes. The specific onset of the cold times marking the starting point of the LIA has been clearly identified for the first time, providing an understandable climate feedback system that explains how this cold period could be sustained for a long period of time. If the climate system is hit again and again by cold conditions over a relatively short period, in this case from the volcanic eruptions, there appears to be a cumulative cooling effect. The simulations constructed in this study have shown that the volcanic eruptions had a strong cooling effect. The eruptions could have triggered a chain reaction, affecting sea ice and ocean currents in a way that lowered temperatures for centuries.
The puzzle of the overall interaction between humans and the physical/biological environment is further complicated by the ability of the former to affect the latter. For the phenomena of our interest, the most evident cases are that of urbanization and trade routes that have contributed to the spread of pandemics and that of the progressive industrialization since the end of the 18th century, which has increased the emission of the greenhouse gases and contributed to the current global warming. Some researchers have proposed that the human influences on climate began earlier, starting from the development of agriculture about 8000 years ago. Ruddiman (2003) has suggested that deforestation for food production has significantly contributed to the increase of carbon dioxide in the atmosphere in the last few millennia. This author has gone ever beyond and hypothesized that the rapid and temporary decrease of carbon dioxide observed in the 15th and 17th centuries might have been a consequence of large epidemiics and pandemics (mainly the Black Death, the plague of the 17th century and the high mortality in the Americas due to the various diseases arrived from Europe). According to this hypothesis, the reduced population of the Earth caused a decrease in agricultural activity. As a consequence, reforestation took place, allowing more carbon dioxide uptake from the atmosphere, which was a control factor in the cooling noted during the LIA. Our analysis offers elements that are complementary to those of Ruddiman (2003). In particular, Figure 3 shows that the occurrence of pandemics in Italy has systematically followed the starting of the LIA. It follows that the reduced population and the reforestation might have been at most an aggravating factor but not the origin of the climate worsening.

Despite the lack of explanation, the combination of catastrophes had significant effects on the Italian society. The first one clearly was the increase of mortality. Previously, in this paper, we reported the estimate of the number of victims for the various pandemics (up to some millions for the three plague outbreaks). For the volcanic eruptions, the worst case (considering all the volcanoes of Italy, including Mt. Etna) was that of the eruption of Mt. Vesuvius of 1631 AD, with at least 4000 victims. We drew data on the mortality due to earthquakes from a study by Guidoboni et al. (2018). We counted at least 100 earthquakes with victims in the last millennium. Nine of them caused 10,000 or more victims (Table 1), with the peak of 80,000 deaths for the Calabria–Messina earthquake of 1908 (Pino et al., 2009). Taking into account the uncertainty on such a data, we can estimate a total of about 400,000 victims by earthquakes in the last millennium. According to the trend of population in Italy reconstructed by Lo Cascio and Malanima (2005) and represented by the dotted line in Figure 3(a), the only events with significant and persistent demographic effect at the national level were the plague pandemics of the 14th and of the 17th centuries. The plague of 1347 caused a reduction of the number of inhabitants from about 12.5 million to 9.5 million and started a demographic crisis that concluded a century later (7.5 millions of inhabitants around 1450). The crisis was followed by a period of demographic development, stopped by the plagues of 1629 and 1656. Later, the population started a continuous increase, almost insensitive to the climate oscillations as well as to the cholera outbreaks and to the intense seismo-volcanic activity of the 19th century.

Malanima (2011) has reconstructed the evolution of the per capita Gross Domestic Product (GDP) between 1310 and 1913 for northern and central Italy. We exploited such a work in order to compare the occurrence of the catastrophes with the economic trends. The reconstruction of the per capita GDP can be considered as representative for the entire country up to 1880, when the northern Italy accelerated its industrialization and strongly differentiated its economy from that of the southern Italy (Daniele and Malanima, 2007). The time series of the per capita GDP is shown in Figure 3(d) (thin line). It proceeds with a series of fluctuations of different duration and amplitude. The main trend, evidenced by the smoothed curve (thick line in Figure 3(d), obtained by kernel smoothed regression using a smoothing bandwidth of 40 years) has three oscillations with maxima in the 15th century (during the Renaissance), around 1730, and in the second half of the 19th century, after the unification of the country in the Kingdom of Italy in 1861. These maxima occurred during the three deglaciation phases within the LIA. For the first two, the dominant role of the agriculture in the economy immediately suggests a strong positive impact of better climate conditions. Differently, the growth in the second half of the 19th century was mainly driven by the technical progress and the industrialization, especially of northwestern Italy. Nonetheless, according to Toniolo (2013: 15) in the first 20 years after the unification (1861–1882), the development of the country had the largest contribution from the increased productivity in the agricultural sector, which attracted more capital and workers (the number of employees in agriculture grew faster than the overall population). Although the reasons of such an improvement were largely dependent on the changed political and economic situation in Italy and abroad, it appears realistic to think that it was at least favored by the changing climate. Anyway, it was in this early stage of agricultural-driven development that Italy regained the per capita GDP of the Renaissance. Another important relationship involves the economy and the pandemics. In general, such a relationship applies in both directions: poverty, with the consequent malnutrition, physical weakness and lack of hygiene, helps the spread of the diseases; on the other hand, a pandemic reduces the overall productivity of the country by killing people or making them unable to work for long time periods. Furthermore, a pandemic may curb the circulation of people and goods, so reducing the gains from trades. Figure 3(d) gives some indications from the point of view of the per capita GDP. The plague of 1347 occurred during a crisis started at the beginning of the 14th century, testified by the decreasing of the per capita GDP. Among the causes of the crisis, the worsening of the climate conditions with two heavy famines in 1317 and 1346 (Cipolla, 2002: 313). The plague contributed further to diminish the overall GDP but, in the short term, it originated a growth of the per capita GDP. The explanation of Malanima (2012) is that the Black Death destroyed men but not capital or resources (including the arable land), so that the survivors could become singularly more productive. In addition, the two plague outbreaks of the 17th century worsened a pre-existing crisis, and induced a similar short-term positive rebound of the per capita GDP just after their occurrence. In this case, the crisis originated in the previous century as a consequence of different factors, including numerous famines and a long series of wars for the control of the peninsula fought by Italian and foreign powers (Alfani, 2013). Finally, we observe that the per capita GDP is rather insensitive to the occurrence of seismic and volcanic events, with phases of economic improvement placed both in quiet periods (around 1420) and at the height of seismic-volcanic crises (around 1730 and 1850).

**Conclusion**

We have observed an overall time correlation between the environmental processes having a different nature. Some of the relationships have been tentatively explained in the literature, sometimes based on accurate theoretical models. Nonetheless this, so far, they are neither reliable nor complete, so that we limit ourselves to consider the continental glaciation in Europe as a risk factor increasing the probability of natural catastrophes in Italy. Coherently with this view and despite recent and strong earthquakes, the geological and biological phenomena here analyzed have been attenuated in the current period of global warming. From the social point of
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We observed that the pandemics drove the demographic crises, while the long-term trend of the per capita GDP is mostly correlated to the glacial phases, suggesting a dependence on the climate. The plague pandemics of the 14th and 17th centuries surely had a strong impact on the economy (e.g. a significant decrease of the overall GDP of the country), but they entered as an aggravating factor in pre-existing crises. Furthermore, in the short term, they had a positive effect on the per capita GDP by leaving relatively more resources to the reduced population. Both the demographic and economic trends at a national level appear not dependent on the occurrence of earthquakes and volcanic eruptions, which have mainly local consequences.

We wonder if what observed for Italy has a general validity. It is possible that the synchronous variations of geo-hazards are related to the particular tectonic setting of the country, with the thin Adriatic microplate nestled between the Eurasian and African plates (Figure 2), making it extremely reactive to the surface phenomena. The lacking of a rich historical documentation similar to that one available for Italy prevents for a large-scale extension of this study. Nonetheless this, an analysis of the global seismicity restricted to the last century (Bragato and Sugan, 2014) indicates that the current decreasing trend of the Italian seismicity has correspondence in the entire northern hemisphere as well as in more restricted and well monitored areas, like California. The Italian seismicity is also characterized by a marked periodicity. The analysis by Bragato and Sugan (2014), which is performed in terms of seismic rates (number of earthquakes per year), shows no similar behavior at the global level. Differently, a strict relationship emerges by looking at the mortality due to the earthquakes. In Figure 4(e), we reported the global data of Ambraseys and Bilham (2011) completed for the last decade with values drawn from press news (BBC News, 2018). The incidence of the earthquake mortality in each decade since 1900 (number of deaths per million of the mean global decadal population) oscillates almost synchronously with the Italian seismicity, showing three similar peaks around 1910, 1970 and after 2000, as well as two clear minima around 1950 and 1990. We can conclude that, at least from 1900, the global and the Italian seismicity have shared a common social impact, although such a similarity is not explained by the simple comparison of the seismic rates.

Our analysis opens a new view on the worldwide relationship between the climate and the past pandemics. In Figure 5, we extended the comparison of glaciations to the known pandemics of the Euro-Mediterranean region back to the antiquity (Harper, 2015), including the plague of Athens of 430 BC, the Antonine plague of 165 AD and the Cyprian plague of 249 AD as well as the Justinian plague of 541 AD. Figure 5 also reports the occurrence of the Third Plague Pandemic (Frith, 2012) that expressed its maximum virulence and mortality between 1855 and 1900, roughly in parallel with the third LIATE and the cholera pandemics of the 19th century. Figure 5 shows that different types of pandemic were absent in warm periods (the Roman and the Medieval climate optima) and concentrated near the extreme of the glacial phases, especially in the last 1500 years. Such a result should be of interest for the ongoing debate on the consequences of the climate change for the human health. Our Figure 5 has similarities with a graph reported by Ruddiman (2003), here reproduced in Figure 6. Such a graph compares the occurrence of epidemics and pandemics with the trend of various climate-related quantities like the concentration of carbon dioxide in the atmosphere, the mean temperature in the northern hemisphere and the solar and volcanic radiative forcing. The difference is that, whereas Ruddiman (2003) tends to demonstrate the consequences of the diseases on the temporary reduction of the carbon dioxide with consequent cooling, our Figure 5 indicates clearly that the insurgence of pandemics follows in time the starting of the LIATEs. This relationship is extended also to the LIATE occurred around 1850, which is missing in the work by Ruddiman. Furthermore, by connecting the occurrence of the diseases to the ice expansion rather than to the decrease of temperature, we stress the importance of the water factor.

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Figure 5. Large-scale view of glaciations versus diseases: length of the Great Aletsch glacier since 1500 BC (copyright H. Holzhauser, modified after Holzhauser et al. (2005)) with superimposed the time of occurrence of the pandemics (arrows, in red those affecting Italy).
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