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Anthropocene Geomorphic Change. Climate or Human Activities?

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Key Points:
- Sedimentation rates and frequency of geomorphic disasters show a marked increase worldwide, especially after midtwentieth century
- This points to an intensification of geomorphic processes, which could be one of the characteristics of the Anthropocene
- Land surface change caused by human activities, rather than climate change, is very likely behind the intensification of geomorphic processes

Supporting Information:
- Supporting Information S1

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(continued)

Abstract

An analysis of the evolution of sedimentation rates and disasters caused by surface geologic processes during the last century, at a global scale, is presented. Results show that erosion/sedimentation processes and frequency of such disasters increased substantially, especially after midtwentieth century, coinciding with the period of intense change known as the "Great Acceleration." Increases for this type of disasters are significantly greater than for other disasters related to natural processes, and about 1 order of magnitude in little more than half a century. This implies an important "global geomorphic change." Comparisons and correlations between changes observed in those processes and potential natural (rainfall) and human (degree of land surface transformation) drivers showed a strong relationship with the latter, and not so clear with the former. This suggests that the intensification of surface geologic processes is most likely due to a greater extent to a land transformation/geomorphic processes coupling than a climate/geomorphic processes one.

Plain Language Summary

It is usually assumed that geologic processes change extremely slowly, and this is in general the case when considered within a human time frame. However, geologic activity affecting land surface appears to be changing very rapidly. Data gathered in very different parts of the world show that since the end of the nineteenth century, very especially after midtwentieth century, sediment is accumulating more and more rapidly in very different sedimentation environments. This indicates that erosion (and soil loss) is becoming more intense in all sorts of environments and under very varied climate conditions. Also, the frequency of disasters caused by floods and landslides is increasing in a similar manner. Over tenfold increases seem to have taken place in less than a century. Of course, population growth implies greater exposure and therefore higher probability of disasters, but the magnitude of the increase observed can hardly be explained by this. Results point to an intensification of processes due to the interaction between water and land surface (geomorphic processes), as well as related (not so "natural") hazards. It appears to be one of characteristics of the so called Anthropocene (the age of humans). An analysis of the variations experienced by rainfall and by indicators of the intensity of human activities suggests that this expression of global change (global geomorphic change) is very likely caused mainly by land surface modification, rather than by climate change. If this were confirmed, it would have important implications. It would probably be better to focus mitigation of both undesirable effects not only on climate change (surely necessary) but mainly on land use management and practices. Whereas results on the former require international, global action, in the latter case results could be obtained through national or local policies.

1. Introduction

The objective of this contribution is to analyze data on two indicators of geomorphic processes, in order to determine whether there is a trend toward their intensification, at a global level, during the last century or so. If so, to examine possible causes of that change, including human influence.

The first indicator is the rate of sedimentation, which is the consequence of a variety of geomorphic processes that generate sediment in different environments and climate conditions. Data have been compiled for five large study regions and grouped for analysis by both sedimentary environments and geographical areas. Of course, the relationship between erosion and sedimentation is complex and influenced by many variables, among others connectivity and sediment storage (Rohel, 1962; Dearing & Jones, 2003; Bracken et al., 2014), themselves affected by human activities. For a general approach, we can assume that if

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sedimentation rates increase at a global level, this reflects a global increase of erosion rates, regardless of where in the landscape such erosion is taking place (with possible differences at a local or regional scale). Sedimentation rates (particularly in continental and coastal environments) could thus provide some information on the regular, long-term intensity of geomorphic processes in general, because most of these generate sediment.

The second indicator is the frequency of geomorphic events which cause disasters. The frequency of disasters related to natural processes depends on the frequency of intense (high-energy/area affected) natural events and on human factors related to exposure and vulnerability (Bankoff, 2019), all of which change with time. Thus, disaster frequency could provide some information on the frequency of violent geomorphic episodes.

Rainfall and human activities were considered as possible drivers of changes in the abovementioned processes. The importance of human activities in the modification of natural processes in general and erosion/sedimentation in particular is well known and has been pointed out by different authors (for instance, Marsh, 1864; Stoppani, 1871–73; Vernadsky, 1929; Brown, 1956 [who referred to "technological denudation"]; Judson, 1983; Ter-Stepanian, 1988; Goudie, 1993, 1995; Hooke, 1994, 1999, 2000; Syvitski et al., 2005; Remondo et al., 2005; Walling, 2006; Rivas et al., 2006; Cendrero et al., 2006; Syvitski & Kettner, 2011; Bruschi et al., 2013; Vanmaercke et al., 2015; Forte, 2017; Tan et al., 2017). It is common knowledge that construction, mining, agriculture, or forestry activities contribute significantly to sediment generation (and consequent sedimentation). Due to the relationship between climate and geomorphic processes, climate change also affects sediment generation (e.g., Kemp et al., 2016; Slaymaker et al., 2009).

A complete description of the procedure and information sources used for the analysis presented can be accessed at this site (http://hdl.handle.net/10902/11396). The following two sections present a short description of the approach and data used.

2. Evolution of Sedimentation Rates

To obtain data that could give a global insight on sedimentation rates, a literature survey was carried out. Data presented are part of a systematic review, without excluding any region of the planet. The search was carried out using a set of selected key words, through Web of Science, Scopus, Google Scholar, etc., as well as bibliographic catalogs from universities and research centers from different parts of the world. Over 100 journals were also consulted using the same search criteria.

The keywords/expressions used include the following: erosion rates, sedimentation rates, acceleration of sedimentation rates, human impact on erosion and sedimentation rates, sedimentation rates during the Holocene, sedimentation rates during the late Holocene, sedimentation rates during the human age, geochronology of recent sediments, sediment geochronology, natural and human drivers on erosion and sedimentation, effects of climate and humans on erosion and sedimentation, sedimentation rates in lakes, sedimentation rates in coastal areas, sedimentation rates in estuaries, sedimentation rates in rivers and floodplains, sedimentation rates in reservoirs, geomorphic effects of dam construction, sedimentation rates upstream of dams, sediment transport downstream of dams. A general search was carried out initially and then specifically for continents, regions, or countries. For instance, sedimentation rates in Australia. The database on sedimentation rates presented here has been conceived as a systematic and continuous review work, with the purpose of generating a global database that can be permanently updated, expanded, revised, and made available to interested researchers.

Table S1 in the supporting information summarizes the results for the countries/regions where the highest density of information was obtained, with no other exclusion criteria: China (201 data points, d.p.), India (92 d.p.), USA (415 d.p.), Europe (206 d.p.), and Australia (143 d.p). They cover about 25% of the global continental area, excluding Antarctica. Relevant information has also been obtained from other regions and is presently under analysis. It will be incorporated into the database when greater information density is obtained.

Data on over 1,000 locations were obtained and analyzed. Part of the works consulted included determination of sedimentation rates, but in other cases the objectives were different (ecological analyses, pollution studies, etc.). Thus, some of the contributions did present specific age data and calculated sedimentation rates for different periods. But in others, rates were estimates or had to be calculated from data presented by the original authors.

Part of the works from which information was obtained provided sedimentation rates for a number of time intervals, but in other cases rates were averages for fairly long periods, some of them only for “presettlement” and “postsettlement” times (with a limit around the end of the nineteenth century). Therefore, temporal groups of data could only be established for three time intervals: (A) pre-1900; (B) 1900–1950; (C) post 1950. Limits between the three intervals represented in the figures (Figures 1 and S1) are approximate because, as expected, time limits used for the studies in the different locations vary. Time limits are clearly indicated in the table (Table S1) in each case. Those time lapses happen to reflect three distinct periods from the point of view of activities affecting land use and their effects on geomorphic processes. Prior to 1900 the introduction of agricultural or construction machinery was very limited, and in some regions (USA, Australia) there were vast territories with very low population density (presettlement). Between the beginning and midtwentieth century the use of machinery extended to most countries, and formerly thinly populated territories were colonized. After the midtwentieth, following World War II—the “Great Acceleration” (Steffen et al., 2011; Steffen et al., 2015)—human activities and influence on natural systems grew sharply. In each one of the regions analyzed, data were grouped by both sedimentation environments (lakes, reservoirs, coastal wetlands, and lagoons, estuaries, river channel deposits, flood plain deposits, coastal platforms, etc.) and geographical areas. In both cases results were represented for all points with data as well as only for points with data for the three time lapses considered.

Data above were compared with annual rainfall trends (GPCC; IPCC, 2013). Of course, amount, intensity, and frequency of precipitation determine, to a great extent, the magnitude of erosion, with intensity as the most critical (Blanco & Lal, 2010; Wischmeier & Smith, 1978; Zachar, 1982). We could not obtain adequate time series on rainstorm frequency/intensity for the regions analyzed, but it is not reasonable to expect that they increased in all of them, irrespectively of the considerable differences in annual rainfall trends. According to the IPCC (2013), “There are likely more regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has likely increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most medium.”

It is not easy to identify an indicator of the intensity of human activities with global coverage and long time series (on the order of one century), which could enable meaningful comparisons between very different countries or regions. Population is a possible indicator, but we think that GDP (global domestic product; total, not per capita) could be more appropriate. This might seem, at a first glance, a bit far-fetched, but total GDP of any country or region is the result of population, economy and technology (Cendrero et al., 2006; Kolbert, 2011) and probably reflects better the capacity of any society to transform its environment, as pointed out by Hooke (2000) with respect to the degree of technological advance. Thus, growing GDP implies growing human activities, including those that modify land surface and contribute to sediment generation (urban expansion, infrastructure development, mining, and quarrying, agriculture, forestry, etc.). Surely, it would be better to use indicators more directly linked to land transformation, such as GDP due to construction or mining activities, or area affected by agriculture or forestry activities, but we have not found long time series with global coverage. In some areas (Bonachea et al., 2010; Bruschi et al., 2013; Restrepo, 2015), GDP for such activities was obtained and they followed trends very similar to those of total GDP. Average GDP (Bolt et al., 2018; Bolt & van Zanden, 2013; Madison, 2007) was calculated for the three periods indicated in the five regions for which data on sedimentation rates were obtained.

Results are summarized in Figure 1. Full data, description of the procedure used to obtain rates in each case and existing uncertainties, as well as the complete list of references, are presented in Table S1. A graphic representation of results for the geographical areas and sedimentation environments analyzed in each region is presented in Figure S1.

Almost all the results (Figures 1a and S1) show an increase of sedimentation rates with time. Out of 120 groups of data (taking all and only points with data for the three considered periods), corresponding to sedimentation environments (59) and geographical regions (61), all but one show a clear increase from the initial period (pre-1900) to the third one (post-1950). The exception corresponds to floodplain deposits in the United States, using only points with data for the three periods (5). When all points (35) are considered, the trend is similar to the rest. In the vast majority of cases, rates increase from the first to the second period and from this to the third. There are some exceptions, most of them corresponding to groupings with very

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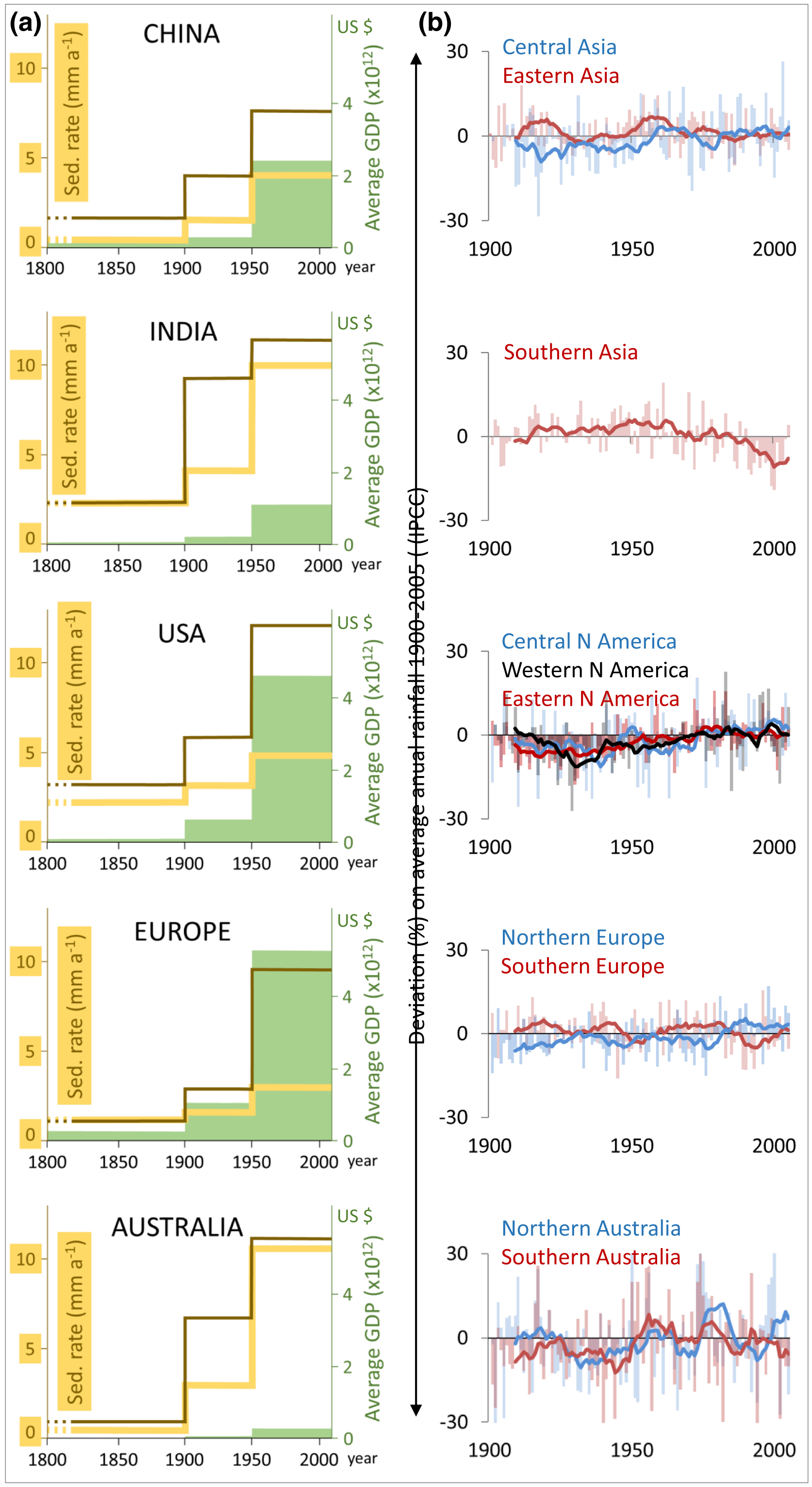

Figure 1. Sedimentation rates and possible drivers: (a) Sedimentation rates (brute averages; yellow: all points with data; brown: points with data for the three periods considered), and GDP (Geary-Khamis dollars, 1990; Bolt & van Zanden, 2013) in the regions analyzed; (b) rainfall evolution (IPCC, 2013; thin lines, annual mean; thick lines, 10-year moving average).

few data. A reduction of sedimentation rates from the first to the second period has been found in two cases, and from the second to the third in six cases. The increase is normally greatest after 1950 (with the exceptions indicated). This general intensification of sedimentation suggests there was a general increase of denudation by all sorts of geomorphic processes in very different geographical areas, especially after midtwentieth century.

Significant increase factors for the whole period covered have been found in quite different environments. Considering only points with data for the three periods considered, factors >3 were found in China in lakes and flood-prone depressions (both not connected and connected to the dynamics of large rivers); >4 in deltas, prodeltas, estuaries, and adjacent coastal sectors; >11 in floodplain deposits. In India, >7 in coastal lagoons. In USA >3 in fluvial channel deposits; around 2.5 in both bays/estuaries and coastal wetlands/lagoons. In Europe, nearly 5 in floodplain lakes/wetlands; >3 in floodplain deposits and about 2.5 in bays/estuaries. In Australia, very high factors were found in flood plain lakes and wetlands (>33), and coastal lagoons (>20). An extremely high (264) but not very significant value, because it corresponds to a single data point, was found for bays/estuaries.

According to works by Dearing et al. (1981), Oldfield and Dearing (2003), Foster et al. (2011, 2012), and Foster and Boardman (2018), very similar patterns have been found in quite different areas. Several reviews on the recent evolution of sedimentation rates in the regions analyzed in this work also show, in most cases, a significant increase in rates, particularly in the second half of the twentieth century (van der Post et al., 1997; Rose et al., 2011; Xu et al., 2017). Van der Post et al. (1997) carried out an analysis of 37 lakes and reservoirs in Great Britain with 210Pb-dated records and found that in 84% of them sedimentation rates increased, especially after 1945, whereas in 11% decreased and in 5% remained stable. Rose et al. (2011), compiled data from cores in 207 European lakes, also dated by means of 210Pb. They found that in 71%, surface (present) rates were higher than basal (nineteenth century) ones, 11% showed no changes and 18% reductions. In all cases present rates were higher than the reference ones (pre-1850), and in general the increase occurred after the midtwentieth century. Xu et al. (2017), in a study of 14 lakes in the middle-low Yangtze basin (China), with records dated using 210Pb and 137Cs, found a significant increase of sedimentation rates after 1900, and especially between 1930 and 1990.

However, numerous contributions have pointed out the sediment load reduction experienced by many rivers as a result of human activities (Chang et al., 2019; Dang et al., 2010; Dearing & Jones, 2003; Golosov & Walling, 2019; Gupta et al., 2012; Hu et al., 2009; Hu et al., 2019; Latrubesse et al., 2017; Li et al., 2016; Miao et al., 2011; Rahman et al., 2018; Shi et al., 2017; Vinh et al., 2014; Wang et al., 2011; Wang et al., 2015; Wu et al., 2018; Yang et al., 2002; Yang et al., 2015; Yu et al., 2013; Zhang et al., 2016; Zhou et al., 2016). Reservoir construction, and other modifications of river courses, considerably reduces connectivity between erosion areas in the basins and channel sectors downstream dams, the latter playing a main role (Kondolf, 1997; Graf, 1999, 2001, 2005, 2006; Magilligan & Nislow, 2001, 2005; Magilligan et al., 2003; Nilsson et al., 2005; Petts, 2009; Dai & Liu, 2013; Magilligan et al., 2013; Petts & Gurnell, 2013; Pal, 2016). The reduction of solid load transported by rivers to the oceans as a consequence of dam construction has been analyzed, among others, by Walling and Fang (2003), Walling (2006, 2008, 2012), Vörösmarti et al. (2003), Syvitski et al. (2005), and Syvitski and Kettner (2011). Vörösmarty et al. (2003) estimated that about 53% of sediment load in regulated rivers was trapped in dams. According to Syvitski et al. (2005), sediment transport due to soil erosion increased by $2{,}3 \times 10^9$ t/year, from pre-Anthropocene to Anthropocene times. During the same period, sediment supply to the oceans decreased by 1.3×10^9 t/year, as a result of sediment trapping in reservoirs. An analysis by Golosov and Walling (2019) showed an 84% average reduction of sediment load in rivers (again reflecting the impact of reservoirs and other regulation works), and a considerable magnitude of erosion in many of the regions analyzed. Walling and Fang (2003), studying sediment load in 145 large river basins for a period >25 years, found that about 70 showed no significant change, 68 showed reductions attributable to reservoir construction, and 7 experienced increases that could be explained by land use changes. Many other contributions (Wang et al., 2007, 2011; Zhang & Lu, 2009; Miao et al., 2011; Du & Shi, 2012; Gupta et al., 2012; Yang et al., 2015; Li et al., 2016; Liu et al., 2017; Wu et al., 2018; Hu et al., 2019; Chang et al., 2019) have attributed the reduction of sediment load mainly to human activities, among which dams appear to be the most important. In particular, Yang et al. (2015) concluded that between 1950–1968 and 2003–2012 the reduction of sediment load observed in rivers could be explained by reservoirs (~88%), other human activities (~7%), and rainfall changes (~5%); and Syvitski et al. (2005)

estimated (eliminating the effects of dams) that sediment generation rates during the Anthropocene increased 16–24% with respect to the previous period. Dearing and Jones (2003) concluded that "… small basins are the most responsive to impacts and show the largest changes in sediment flux". This implies that the increases in sediment flux to the coasts is caused mainly by disturbance of small and medium basins. It must also be borne in mind that dam construction (and consequent sediment trapping) was particularly important well after 1950 (Hossain et al., 2012). Thus, its effects on sedimentation rates have been important in the last few decades and might not be sufficiently reflected in the data we have so far gathered.

The above, according to different authors (Besset et al., 2017; Besset et al., 2019; Syvitski, 2007; Syvitski et al., 2009; Syvitski & Kettner, 2011), is linked to delta retreat. A large number of deltas in the world have experienced erosion and retreat, but many show stability or even accretion. They point out that delta retreat could be attributed mainly to sediment starvation caused by dams but also to sediment compaction and subsidence, sea level rise, or increased storminess.

Being aware of this apparent contradiction, the above-presented results suggest a general increase of denudation rates and sediment generation all over the world and in very different geomorphic environments.

Looking at potential drivers (Figure 1), it can be observed that annual rainfall (only a rough indicator, as mentioned above) presents quite different variation trends (Figure 1b). On the other hand, the shape of the graphs and magnitude of relative GDP increases (Figure 1a) show a much greater similarity with sedimentation rates.

Thus, this coarse grain analysis points to a general increase of sediment generation rates (between late 19th and early 21st centuries) in very different environments in the five regions analyzed, which is compatible with sediment flux reduction in many basins. The increase appears to be more closely related to increasing human activity (and its effects on land surface), than to changes in rainfall. The possibility of a threshold effect (a small rainfall increase leading to a large increase in erosion/sedimentation), cannot be ruled out completely, but it appears unlikely, especially considering the results on disaster frequency presented below.

3. Evolution of Disasters Frequency

The frequency of disasters (EM-DAT) related to natural events is presented in Figure 2a. Although disasters related to the functioning of natural processes can hardly be considered as fully natural at the present time, because in most cases they are influenced to a greater or lesser extent by human factors (e.g., Bankoff, 2019), the distinction made by EM-DAT between "natural" and "technological" disasters, is useful for the present analysis. Not all disasters are included in this database. Inclusion criteria are 10 or more people killed; 100 or more people affected; declaration of a state of emergency; call for international assistance.

"Natural" disasters in the EM-DAT database were grouped into three categories ("Geologic," including volcanism and seismicity; "Climate," including windstorms, droughts, heat and cold waves; "Geomorphic," including those caused by water/land interaction, floods, and landslides). It is very clear that there has been a considerable increase, both at global level and in all continents.

It is well known that the occurrence of disasters is a function of hazard (violent natural event), exposure (persons and human elements potentially affected), and vulnerability (degree to which persons or human elements can be damaged if affected) (UNDRO, 1991). Not all dangerous natural events cause disasters, and the frequency of disasters reported in international databases reflects only in part the frequency of such events. The functional dependence is a multiplication. Therefore, if one of the factors (E, V) is zero, the product will be zero, no matter how big H is. It follows from the relationship above that the number of all kinds of "natural" disasters registered in databases should grow as population plus vulnerable material elements increase (and show a positive relationship with GDP), even if the frequency of dangerous natural events did not increase. This is so because population growth and related increase in the number of material elements will increase exposure. Growth of total GDP (which reflects both per capita increase and population growth) with time has occurred in all countries, with practically no exceptions. This means that there are more persons, buildings, infrastructures, economic activities, and so forth, which imply an increase in exposure. One should also expect, due to better development, that improvement of mitigation measures should lead to a reduction of vulnerability. Mitigation capacity varies widely, of course, depending on the kind of process, but it is logical to assume that it has contributed to the reduction of all disasters. That is, if

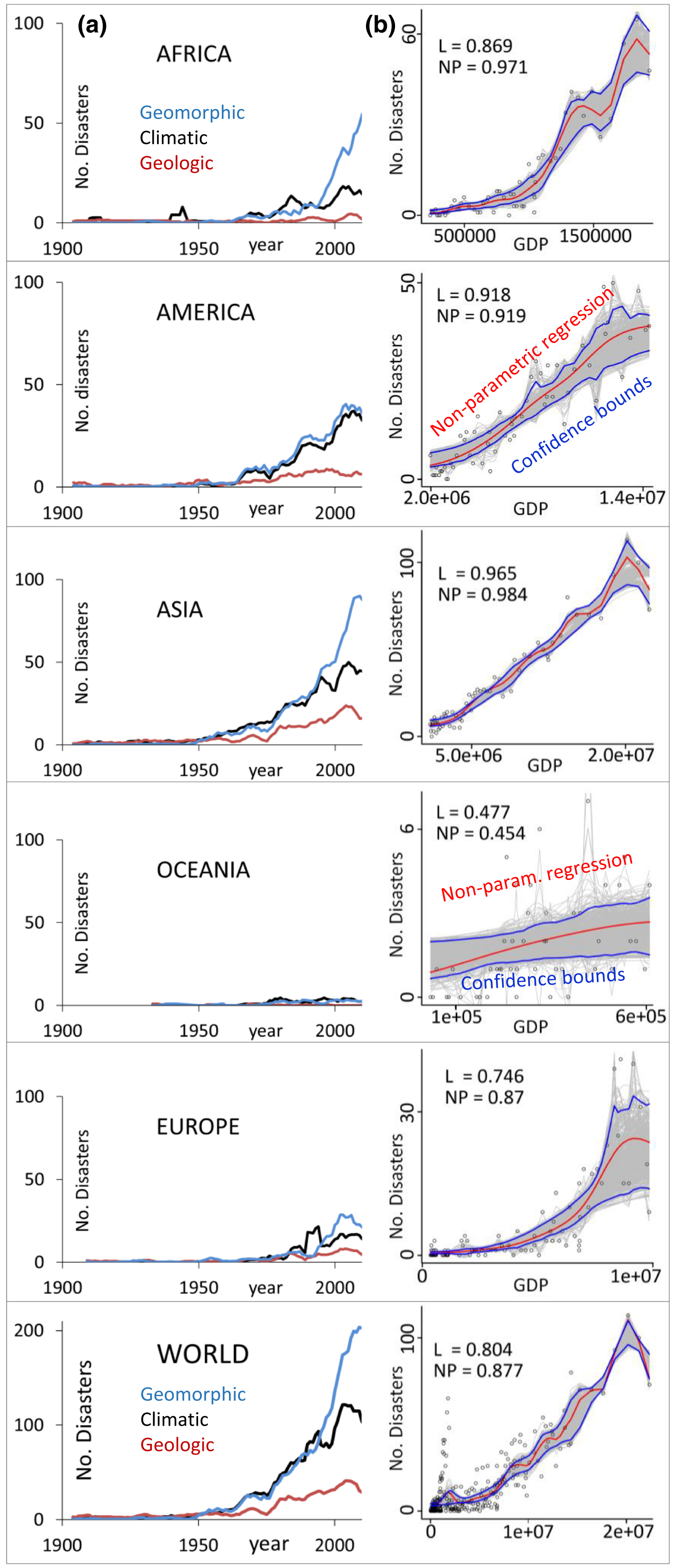

Figure 2. Geomorphic disasters and possible drivers: (a) Disaster frequency (EM-DAT; 5-year moving average); (b) correlation geomorphic disasters frequency/GDP (L, linear; NP, nonparametric).

Table 1
(a) Growth factor of natural disasters' frequency (EM-DAT); (b) linear and nonparametric correlation coefficients GDP/disaster frequency

	Growth factor of natural disasters' frequency[a]						Correlation coefficient GDP/Disaster frequency					
Regions	(2000–2010/1900–2010)			(2000–2010/1950–1960)			Linear			Non-parametric		
	Geologic	Climatic	Geom.	Geologic	Climatic	Geom.	Geologic	Climatic	Geom.	Geologic	Climatic	Geom.
E Africa [b]	2.53	N.A.	**4.22**	5.18	15.15	**67.57**	0.450	0.792	**0.871**	0.781	0.766	**0.956**
Central Africa[a]	N.A.	N.A.	N.A.	2.18	3.09	**12.00**	0.165	0.166	**0.683**	0.000	0.032	**0.649**
N Africa	1.30	N.A.	**2.61**	1.02	3.64	**15.75**	0.176	0.346	**0.686**	0.410	0.413	**0.860**
S Africa	N.A.	N.A.	N.A.	0.55	11.82	**13.64**	0.100	0.433	**0.564**	0.000	0.647	0.573
W Africa [c]	0.00	1.12	**3.24**	0.00	1.25	**27.00**	0.450	0.792	**0.871**	0.781	0.766	**0.956**
AFRICA	2.42	2.54	**2.78**	5.82	5.43	**17.09**	0.521	0.802	**0.869**	0.723	0.849	**0.971**
Caribean	2.30	2.63	**4.27**	5.24	36.61	**79.36**	0.353	0.574	0.567	0.260	0.570	**0.609**
Central America	2.00	8.45	**10.36**	4.67	14.80	**18.14**	0.472	0.621	**0.784**	0.733	0.640	**0.824**
N America	1.35	2.27	**3.36**	3.82	10.70	**19.50**	0.211	0.830	0.775	0.374	0.962	0.770
S America	1.53	2.72	**2.58**	1.85	40.09	17.55	0.523	0.643	**0.812**	0.576	0.621	**0.920**
AMERICA	1.79	3.94	3.75	3.37	25.07	19.05	0.696	0.911	**0.918**	0.768	0.986	0.919
Central Asia[d]	N.A.	N.A.	N.A.	1.82	1.36	**1.87**	0.384	0.024	0.266	0.241	0.000	**0.312**
E Asia	3.10	3.16	**3.70**	10.14	5.75	8.14	0.809	0.812	**0.879**	0.839	0.929	0.918
SE Asia	2.46	2.59	**4.22**	7.22	7.85	**96.00**	0.583	0.836	**0.902**	0.563	0.851	**0.896**
S Asia	2.56	2.13	**3.52**	5.36	7.57	**8.19**	0.679	0.745	**0.933**	0.866	0.853	**0.941**
W Asia	1.43	N.A.	N.A.	2.05	5.72	**14.32**	0.280	0.442	**0.706**	0.529	0.684	**0.756**
ASIA	3.04	3.20	**4.57**	6.20	7.17	**13.29**	0.823	0.860	**0.965**	0.904	0.953	**0.984**
E Europe[b]	2.16	2.58	**2.78**	7.09	14.18	**33.00**	0.593	0.536	0.499	0.565	0.469	**0.705**
N Europe	1.64	1.29	**2.00**	1.60	10.80	8.80	0.136	0.297	**0.484**	0.000	0.220	**0.486**
S Europe	1.02	2.35	**3.44**	2.73	8.18	**9.56**	0.212	0.524	**0.657**	0.739	0.493	**0.869**
W Europe	0.64	1.77	**1.97**	0.30	7.39	4.70	0.138	0.409	**0.498**	0.080	0.861	0.683
EUROPE	2.50	2.89	**4.03**	16.59	51.52	15.97	0.775	0.630	0.746	0.842	0.852	**0.870**
OCEANIA	0.00	1.35	**1.52**	0.00	4.24	**11.64**	−0.291	0.454	**0.477**	0.211	0.616	0.454
WORLD	2.85	3.66	**4.85**	6.05	13.72	**19.04**	0.804	0.801	**0.804**	0.828	0.838	**0.877**

Note: Bold indicates growth factor/correlation coefficient according to prediction.
[a]Factor calculated as frequency for the last decade/average frequency for the period 1900–2010, and frequency for the last decade/frequency for 1950–1960 (or first decade with data). [b]First decade: 1955–1965. [c]First decade: 1966–1976. [d]Data available since 1990.

disaster frequency increases, either exposure, hazard, or both have increased. Greater GDP and development also imply more complete data-gathering procedures. Thus, as time goes by compilation of data on disasters should improve and contain a higher percentage of total event occurrence.

Various types of hazardous events, such as windstorms, cold and heat waves, intense rainstorms, floods, landslides, and so forth are associated to climatic hazards. Although there are different degrees of confidence as well as different trends, depending on the region (IPCC, 2013), climate change seems to be linked to a greater frequency of extreme climate events. Thus, a growing number of such disasters might reflect a growing frequency of extreme climate events (greater hazard). Of course, this would not affect disasters caused by earthquakes or volcanic eruptions.

Disasters associated to the interaction between water and land surface (events such as floods or landslides) are affected not only by the former factors but also by land use change (the extent of which is dependent on the intensity of human activities). Construction and excavation or accumulation of soil and rock for different purposes, as well as forestry and agriculture activities tend to increase runoff and reduce the resilience of the surface layer. A greater frequency of floods or landslides should thus be expected as a consequence. However, this would not affect disasters related to earthquakes, volcanoes, or strictly climatic events.

An axiomatic hypothesis is therefore that the number of the so-called “natural” disasters recorded in databases (such as the EM-DAT) should increase with time, reflecting growing population and economic activities as well as climate change. We would therefore expect (despite the probable effect of improved mitigation) an increase with time of all such disasters recorded in databases. And also a positive correlation with GDP (a rough indicator of the intensity of human activities that modify land surface). The increase should be lowest for disasters related to volcanism or seismicity and greatest for geomorphic disasters. The same should be the case with the correlation disaster frequency/GDP; best for geomorphic disasters and worst for those due to internal earth processes. The evolution of disasters frequency at world and

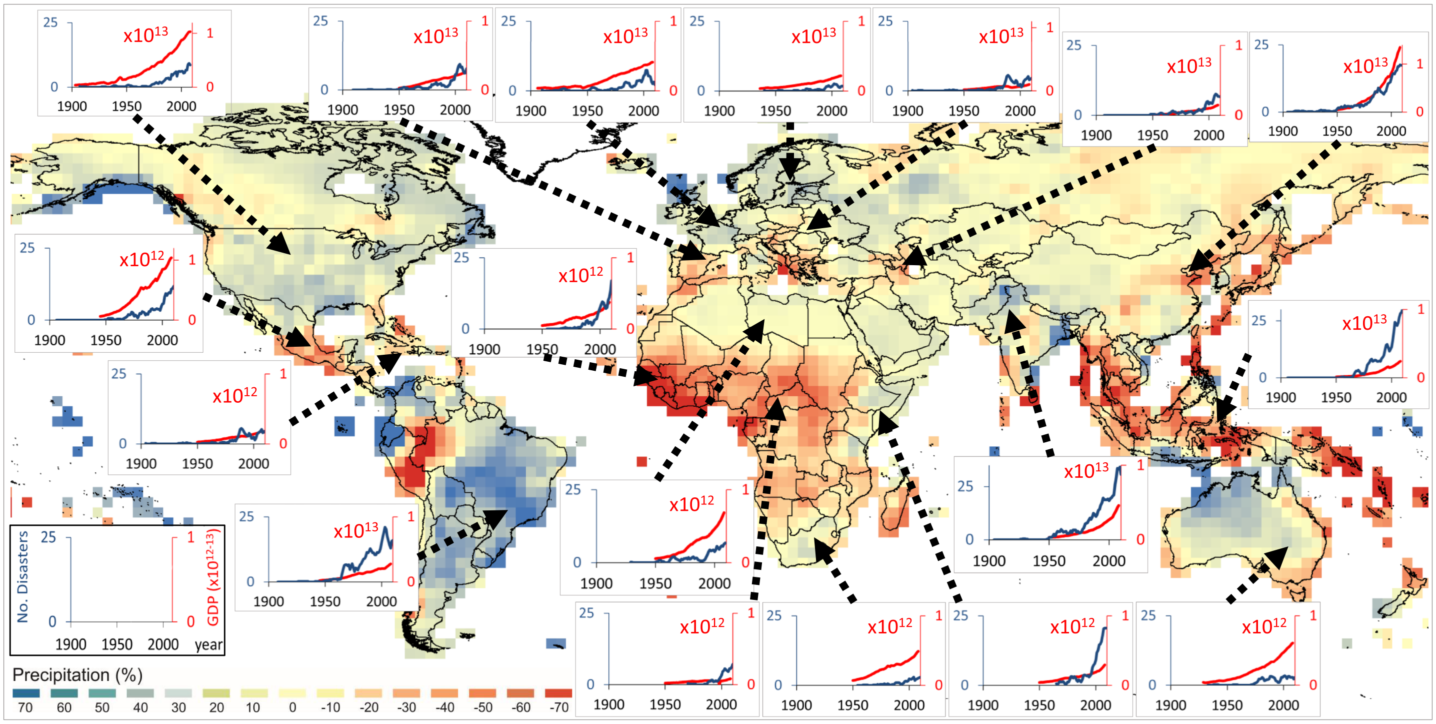

Figure 3. Regional geomorphic disasters, GDP and rainfall. Disaster frequency (EM-DAT). GDP (Bolt & van Zanden, 2013). Annual rainfall 1975–2000 with respect to the 1950–1975 average (after GPCC).

continental level (Figure 2a) shows that in all cases geologic disasters increased least and geomorphic ones most.

Correlations between disaster frequency and GDP can be explored, because both parameters have comparable, long time series with annual resolution (Figure 2b, Table 1). Both linear and nonparametric (Core Team, 2018; Siegel, 1982) correlation coefficients, at world and continental level, are very high, as should be expected from the reasons explained above. The only exception is Oceania, where the number of registered disasters is low. As shown in the table, correlation is best for geomorphic and worse for geologic disasters.

Comparisons between geomorphic disaster frequency and rainfall variations in different regions are presented in Figure 3. It is interesting to point out that the number of annual disasters has grown very significantly in all regions, whereas rainfall has increased in some cases and remained stable or decreased in others. GDP, of course, has also grown in all regions, and with trends similar to those of geomorphic disasters. Again, the results presented suggest that land surface changes caused by human activities are likely to be a more determining factor than climate for the increasing frequency of geomorphic disasters observed. That is, these disasters are not so "natural."

It is very interesting to point out the existence of decreasing trend in GDP/geomorphic disasters frequency in the last few years (Figure 2b). As GDP grows in all cases, the *X* axis in the figure also has a temporal meaning. If the growing frequency of disasters with time during the whole period covered were due to greater frequency of rainstorms (manifestation of climate change), this decrease in the last decade or so would be difficult to explain. A reduction of rainstorm frequency in all continents? However, if the main driver were land surface modification (geomorphic change), there is a logical (but not yet proven) explanation. On the one hand, growing GDP and development normally bring about better implementation of flood and landslide mitigation measures, which favor the decoupling between economic growth and the consequences of land use changes. On the other hand, economic growth in recent years has been linked, to a greater extent than in previous periods, to activities such as information and telecommunication technologies or electronic industry, with very limited impact on land.

4. Conclusions

The results presented indicate that a human-driven, global geomorphic change is taking place, and that this change is particularly intense since midtwentieth century, because human activities are affecting more and more the operation of geomorphic processes, in particular erosion/sedimentation rates. It thus seems that geomorphic change, a consequence of the growing role of humans as geomorphic agents, could be one of the characteristics of the Anthropocene, and that there is a "great geomorphic acceleration" as a part of the "Great Acceleration."

Whereas the change in the indicators analyzed can hardly be disputed, an explanation of the main driving agent is less clear. The data gathered and results obtained through comparison and correlations with the indicators used, point to human-driven changes in land surface (geomorphic change) as a more significant driver than climate change (also human-driven). But this can by no means be considered as firmly established. We feel it should be considered as a reasonable hypothesis worth testing further, better by other researchers using different data and approaches. If the hypothesis were confirmed, it would probably help to better focus efforts toward the mitigation of flood and landslide disasters. As is well known, mitigation efforts directed toward climate change require global action, particularly by countries that are the main generators (whether through production or demand) of greenhouse gases. Thus, results obtained by most countries will rather depend on actions taken by others than by themselves. Actions to mitigate geomorphic change can be implemented at national or even local level, and their effects would also be felt locally, not completely but to a considerable extent independently of actions taken by others.

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