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Long-term impacts of tropical storms and earthquakes on human population growth in Haiti and the Dominican Republic

Klose, Christian D.[1] **and Webersik, Christian**[2]

[1]Think GeoHazards, New York, USA
[2]University of Agder, Kristiansand, Norway

Abstract. Since the 18th century, Haiti and the Dominican Republic have experienced similar natural forces, including earthquakes and tropical storms. These countries are two of the most prone of all Latin American and Caribbean countries to natural hazards events, while Haiti seems to be more vulnerable to natural forces. This article discusses to what extent geohazards have shaped both nation's demographic developments. The data show that neither atmospheric nor seismic forces that directly hit the territory of Haiti have significantly affected the country's population growth rates and spatial population densities. Conversely, since the 1950s more people were exposed to atmospheric hazards, in particular, in regions which historically experienced higher storm frequencies.

Keywords. Natural Hazards, Risk, Urbanization, Haiti, Earthquake, Hurricane, Population, Growth, Artificial Intelligence, Machine Intelligence, Self-Organizing Maps

1 Introduction

Haiti and the Dominican Republic are situated on Hispaniola island and have experienced similar natural forces since the 18th century, including tropical storms, hurricanes, and earthquakes. Both countries are highly prone to extreme natural hazard events. They seem to be the most prone of all Latin American and Caribbean countries (IBDReport , 2009). Historically, Haiti tends to be more vulnerable to natural forces with more human fatalities and socio-economic damages, although in both countries about the same human population size of 10 million inhabitants are exposed to geohazards (see Table 1 and Figure 1). In fact, Haiti's prevalent vulnerability index (PVI) ranges between 20-40% lower than the index for the Dominican Republic (IBDReport , 2009). Appendix A and Tables 2 give a brief overview on the histroical development trajectories of both nations.

Many tropical storms and hurricanes pass Hispaniola island from a distance, while storm tracks do not directly hit the island's territory. These natural forces, however, may still affect Haiti or the Dominican Republic. The 2004 hurricane Jeanne, for example, killed about 3,000 people in Haiti and caused damages in the city of Gonaïves in the Artibonite department. For three days, more than three-quarters of the city's area were flooded. In such situations, Haitian municipalities tend to rely on foreign humanitarian aid and the presence of armed forces of the United Nations Stabilization Mission in Haiti (MINUSTAH). Natural hazard events that directly occur on a country's territory can be even more destructive with impacts on a) the national economy and b) the work of international aid organizations. For example, in 1998, Hurricane George destroyed more than three-quarters of Haiti's crops. This, in turn, affected the food supply of the country. Furthermore, the 2010 M7 earthquake resulted in over 230,000 fatalities, including about 100 staff members who worked for the United Nations. Given these facts, one could anticipate that natural forces which made landfall in Haiti and the Dominican Republic would have more long-term effects on the countries' human population growth rates. The objective of this research study is a) to delineate spatio-temporal relationships between the development of the human population and natural forces (e.g., tropical storms, hurricanes, and earthquakes) between 1850-2009 in both countries and b) to identify patterns and significant inter-relationships between the nature-system and human-system in space and time.

The following section describes the data sets of the occurrence and intensity of seismic and atmospheric forces which determine the hazard levels that Haiti and the Dominican Republic have historically been exposed to. The third section of the second chapter outlines the methods that were utilized for

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Correspondence to: Klose, Christian D.
(christian@cdklose.com)
Senior Research Scientist at Think GeoHazards

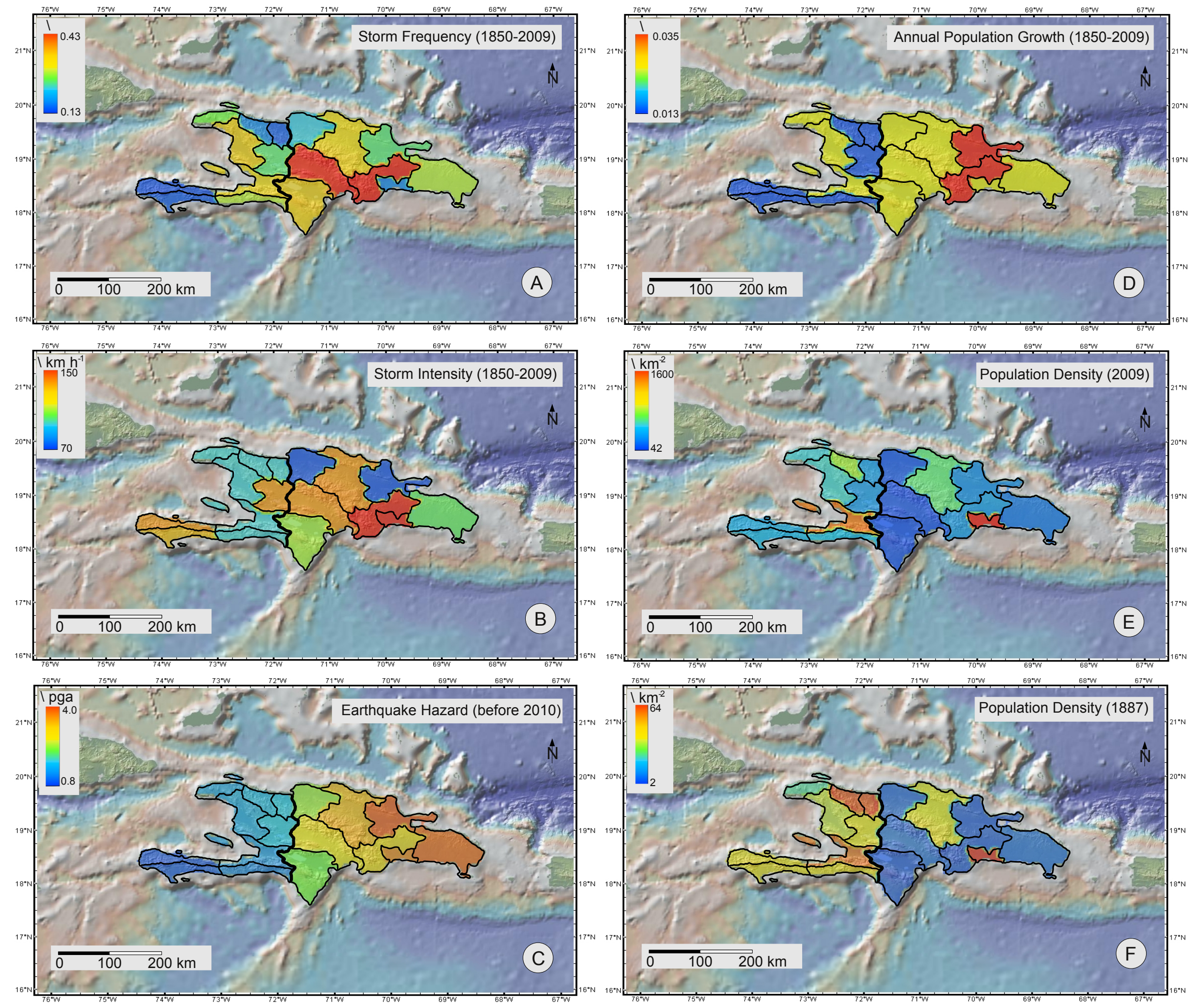

Fig. 1. Spatial distribution of atmospheric and seismic hazard components (A-C) and vulnerability components of the population in Haiti and the Dominican Republic: A) frequency of storms and hurricanes between 1850-2009 that made landfall in each department, B) maximum observed intensity of storms and hurricanes, C) percentage of the peak ground acceleration of earthquakes with 2% probability of exceedance in 50 years, D) annual population growth between 1850-2009, E) population density in 2009, F) population density in 1887. The data sources and actual numbers that were visualized in each sub-figure are summarized in Table 1.

the analysis of the spatio-temporal data. The last section provides a discussion of the results followed by a conclusion.

2 Data and Methods

Almost every year, natural forces make hundreds and thousands of Haitians homeless and claim lives. Spatial and temporal data of these storms and earthquakes that directly hit Hispaniola island between 1850-2009 were analyzed in this study (Tables 2 and 1). The spatial data are categorized with respect to nine departments/regions in Haiti and eight in the Dominican Republic. Figure 2 visualized the departments that are named and summarized as follows:

Departments and labels of Haiti:

North (H_N):	Nord
North-West (H_NW):	Nord-Ouest
North-East (H_NE):	Nord-Est
East (H_E):	Centre
West 1 (H_W1):	Ouest
West 2 (H_W2):	Artibonite
South (H_S):	Sud
South-West (H_SW):	Grand'Anse and Nippes
South-East (H_SE):	Sud-Est

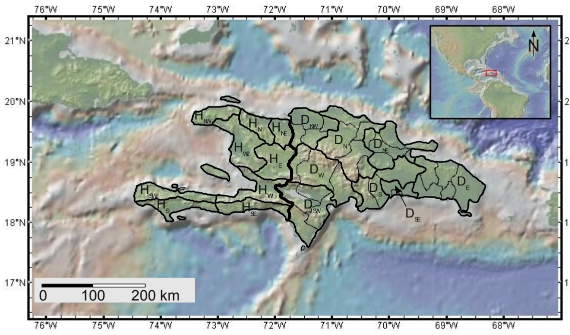

Fig. 2. Spatial distribution of the departments/regions of Haiti and the Dominican Republic. Indices of the departments are explained in section 2.

Departments and labels of the Dominican Republic:

North (D_N):	Monseñor Nouel, La Vega, Santiago, Puerto Plata, Espaillat
North-West (D_NW):	Monte Cristi, Dajabón, Santiago Rodríguez, Valverde
Nort-East (D_NE):	María Trinidad Sánchez, Hermanas Mirabal, Duarte,
West (D_W):	Elías Piña, San Juan, Azua
East (D_E):	San Pedro de Macorís, Hato Mayor, El Seibo, Saona, La Romana, La Altagracia
South (D_S):	Monte Plata, San Cristóbal, San José de Ocoa, Peravia
South-West (D_SW):	Baoruco, Independencia, Pedernales, Barahona Samaná, Sánchez Ramírez
South-East (D_SE):	Santo Domingo, Distrito Nacional

The following two sections introduce and describe the occurrence and intensity of seismic and atmospheric forces which determine the hazard levels that Haiti and the Dominican Republic are exposed to. The third section of this chapter outlines the methods that were utilized for the analysis of the spatio-temporal multi-modality data, followed by a discussion of the results.

2.1 Seismic hazards on Hispaniola island

Several major earthquakes have occurred in Haiti over the last 300 years: 1751, 1770, 1842, 1860, 1887, 1897, 1946 and lastly in 2010 (Table 2).(Manaker et al. , 2008; Shedlock, 1999; Panagiotopoulos , 1995; Pubellier et al., 1991; Scherer , 1912) Figure 3 shows the spatial distribution of earthquakes with seismic moment magnitudes >4.5 whose exact locations or ruptured fault zones are relatively well known, including the Septentrional fault in the North and the Enriquillo fault in the South. As Table 2 outlines, the most severe seismic events have repeatedly damaged Haiti's two major cities, Port-au-Prince in Haiti's South and Cap-Haïtien in the North. The M7 earthquake of January 12, 2010 resulted in more than 230,000 fatalities, affected over 3 Million people, and destroyed most governmental buildings in Port-au-Prince, including the presidential palace. Of similar destruction was the earthquake of May 7, 1842, that caused severe loss of life and damages in the city of Cap-Haïtien (Figure 3).

The Dominican Republic experienced more and stronger earthquakes in the 20th century, while Haiti was more affected by major earthquakes in the period before 1900 as shown in Table 2. It should be noticed that the earthquake hazard shown in Table 2 indicates that the 2010 M7 earthquake occurred in an area where the seismic hazard was not reported as being high (Figure 3), in spite of identified active faults as discussed by Manaker et al. (2008). In addition, peak ground acceleration estimates prior the 2010 M7 event (Figure 1C) refer only to bedrock conditions without taking variations of local effects into account (e.g., bad soil conditions and local topography). Prevalent softer or harder soil conditions may significantly impact the shaking intensities and their probabilities. Moreover, analyses prior the 2010 M7 earthqauake were completed without infrastructure effects (e.g., bad housing etc).

2.2 Atmospheric hazards on Hispaniola island

Tropical storms have also had major impacts on Hispaniola island. Additionally, associated precipitation can cause floods and trigger landslides. In total, 72 storms directly made landfall on the island between 1850-2009 (Table 1). These storms resulted in human fatalities and caused socio-economic damages, in particular in Haiti (Table 2). In 1935, a severe hurricane killed more than 2,000 people. Hurricane George destroyed more than 75% of all the crops in Haiti in 1998. Moreover, tropical storms Gustav and Fay directly affected more than 800,000 people (10%) in Haiti in August and September 2008 (UNDP , 2009a). Although it is disputed whether the number of tropical storms have increased (Webster et al. , 2005a,b), the intensity and, thus, severity of category 4 and 5 hurricanes has been increasing in the Gulf of Mexico since the nineteenth century (Landsea et al. , 2006; Giorgi et al. , 2001). Figure 4 illuminates that total storm frequencies remained relatively constant while intensities of storms increased with time, specifically when comparing storm patterns of the periods 1850-1899, 1900-1949, 1950-2009.

Table 1. Population growth and natural hazard data in Haiti and the Dominican Republic between 1850-2009. The department index (e.g., H_N) is explained in section 2 and illustrated in Figures 1, 2, and 5. Data sources: [a] Der Gotha (1891);[b] Institut Haïtien de Statistique et d'Informatique; [c] PAHO/WHO 2000;[d]U.S. Geological Survey;[e] Oficina Nacional de Estadística, Portal de las Estadistícas Dominicanas; [f]Average over all departments.

Departement index	H_N	H_W1	H_E	H_S	H_W2	H_NW	H_NE	H_SW	H_SE	total
Area \ km^{-2}	2175	4827	3675	2794	4984	2176	1805	3237	2077	27750
Population (1887)[a] \ 10^3	102	214	105	86	134	39	85	100	64	960
Population (2009)[b] \ 10^3	971	3665	679	704	1571	663	358	737	575	9923
Population growth (annual) \	0.017	0.026	0.016	0.014	0.020	0.023	0.013	0.021	0.017	0.019
Population density (1887) \ km^{-2}	47	44	29	31	27	18	47	31	31	35
Population density (2009) \ km^{-2}	451	721	173	300	264	230	177	117	281	326
Number of hospitals, health centers, dispensary[c] \	53	209	44	69	84	61	25	55	35	635
Number of storms (1850-2009) \	14	19	14	9	22	15	10	5	13	13[f]
Storm hit rate (1850-2009) \	0.019	0.026	0.019	0.013	0.031	0.021	0.014	0.007	0.017	0.019[f]
Max. storm intensity \ km h^{-1}	100	100	130	125	100	100	100	130	100	130
Earthquake hazard (ave. pga)[d] \%	1.63	1.45	1.71	1.18	1.55	1.48	2.22	1.1	1.37	1.52[f]

Table 1. Continued.

Departements	D_N	D_W	D_E	D_S	D_NW	D_NE	D_SW	D_SE	total
Area \ km^{-2}	8808	7527	8036	5546	4880	5367	7103	1401	48667
Population (1887)[a] \ 10^3	246	36	40	13	20	14	12	90	471
Population (2009)[e] \ 10^3	3200	593	1129	1091	451	944	301	2204	9914
Population growth (annual) \	0.021	0.023	0.027	0.036	0.026	0.035	0.026	0.026	0.025
Population density (1887) \ km^{-2}	28	5	5	2	4	3	2	64	10
Population density (2009) \ km^{-2}	371	80	143	201	94	179	43	1606	208
Number of storms (1850-2009) \	22	27	19	30	15	17	23	13	21[f]
Storm hit rate (1850-2009) \	0.31	0.38	0.26	0.42	0.21	0.24	0.32	0.18	0.29[f]
Max. storm intensity \ km h^{-1}	130	130	105	150	70	80	110	150	150
Earthquake hazard (ave. pga)[d] \%	2.22	2.49	3.32	2.68	2.91	2.91	2.10	3.12	3.0[f]

2.3 Data Analyses

In order to delineate inter-relationships between natural forces and population growth in space and time, a data set was generated including occurrence and intensity of storms and earthquakes and annual population growth rates for each province in Haiti and the Dominican Republic (Figure 1). These data were analyzed from two different perspectives,

- with a wider focus to illuminate relationships between hazard event frequencies and population growth rates for both countries between the 19th and 21st centuries and
- with a narrower focus to extract statistical annual patterns within the human-nature system.

First, Figures 1E and F visualize an "initial or early" spatial population density in 1871 and a "final or latest" situation in 2009. Moreover, Figure 5 shows the average population growth versus the frequency of storms or maximum peak ground acceleration of earthquakes (with 10% probability of exceedance in 50 years). An ANOVA test was conducted to delineate significant differences between the annual population growth in years that were *affected* by storms and earthquakes and years that were *not affected* by both natural forces. The purpose of this statistical test is to find out, whether the following hypothesis H_0 has to be accepted or rejected:

> *Annual occurrences of storms and earthquakes do have negative impacts on population growth rates in the same or the following year.*

Second, a machine intelligence scheme was employed based on Self-Organizing Mapping to deal with the interpretation of the annual population-hazard data of the human-

Table 2. Major earthquakes and hurricanes in Haiti (H) and the Dominican Republic (DR) since the 18th century, their socio-economic consequences and political context at the time when the geohazard event occurred.

dd.mm.yyyy	hazard type	location	Socio-economic damage/ political instability
18.10.1751	major earthquake	South Haiti	H: destruction of 3/4 of masonry houses in Port Au Prince
21.11.1751	major earthquake	South Haiti	H: destroyed Port-au-Prince
03.06.1770	M7.5 earthquake	South Haiti	H: killed 250 people; destroyed Port-au-Prince
07.06.1842	major earthquake	North Haiti	H: major damages in Cap-Haïtien; 10,000 fatalities; revolts that lead to the foundation of the Dominican Republic two years later
08.04.1860	major earthquake	South Haiti	H: destruction of Port-au-Prince, DR: interregnum period (1861-64)
23.09.1887	earthquake	North Haiti	H: major damage in Moles St Nicholas
29.09.1897	earthquake	North Haiti	No data available.
04.08.1946	M8.0 earthquake,tsunami	North DR	DR: killed 2550 people; year of political transition period 1946-1949 from democratic to autocratic
12.01.2010	M7.0 earthquake	Southwest Haiti	H: killed 230,000 people, 3 Million people affected 300,000 injured, 1 Million homeless; destroyed Port-au-Prince, Léogâne and Petit-Goâve
03.09.1930	not-named storm	Hispaniola	H: Political transition period 1930-1931, from democratic to autocratic
01.09.1958	Cat 2 hurricane Ella	Southwest Haiti	H: 28.06.1958 (before Ella) USA attempted invasion against Duvalier
03.10.1961	Tropical Storm Frances	East DR	H: U.S. administration suspended aid DR: attempt of one year of political transition from autocratic to democratic
27.09.1963	Cat 1 hurricane Edit	Northeast DR	DR: killed 7190 people; interregnum period (1963-1965) with complete collapse of central political authority from democratic to autocratic
03/04.10.1963	Cat 4 hurricane Flora	Southwest Haiti	killed 7190 in H and DR
07.10.1985	Tropical storm Isabel	DR	H: 07.02.1986 president Duvalier flees after disorder; autocratic political transition period (1985/86)
22.09.1998	Cat2/3 hurricane Gorge	Hispaniola	H: Januar 1999 Chamber, Senate, and president Préval ruled; political transition (1999) from democratic to autocratic; 3/4 of crop destroyed
10.10.2003	Tropical storm Mindy	DR	
05.12.2003	Tropical storm Odette	DR	H: The 2004 coup d'état and Aristide's ousting; political transition period (2004/05) from autocratic to democratic

nature system. The annual storm-earthquake data set was explored and sorted trough by the computer aided expert system (Klose , 2006). The main purpose of utilizing such a classification scheme was to:

- support the results of the statistical ANOVA test and
- show the complex inter-correlations between earthquake and storm hazard intensities and population growth rates.

Results will show how storms or earthquakes resulted in positive or negative population growth rates in the same or following year. For the visualization purposes, the machine intelligence algorithm transforms a feature/property vector $\boldsymbol{x}_n$ of arbitrary dimension n of the given feature space (here two dimensions of storm and earthquake hazard intensities) into simplified generally 1-dimensional graphs or 2-dimensional discrete maps. These maps illustrate the features of each input vector in relation to the features of all other vectors. For example, maps show whether feature vectors are similar or dissimilar to each other. This helps experts and non-experts to better understand the complexity of multi-dimensional data in general (Klose , 2006). The functionality of Self-Organized Maps (SOMs) is briefly described in Appendix B. Finally, relationships between population growth and hazard patterns, that can be seen in Figure 6, will be discussed in section 3.

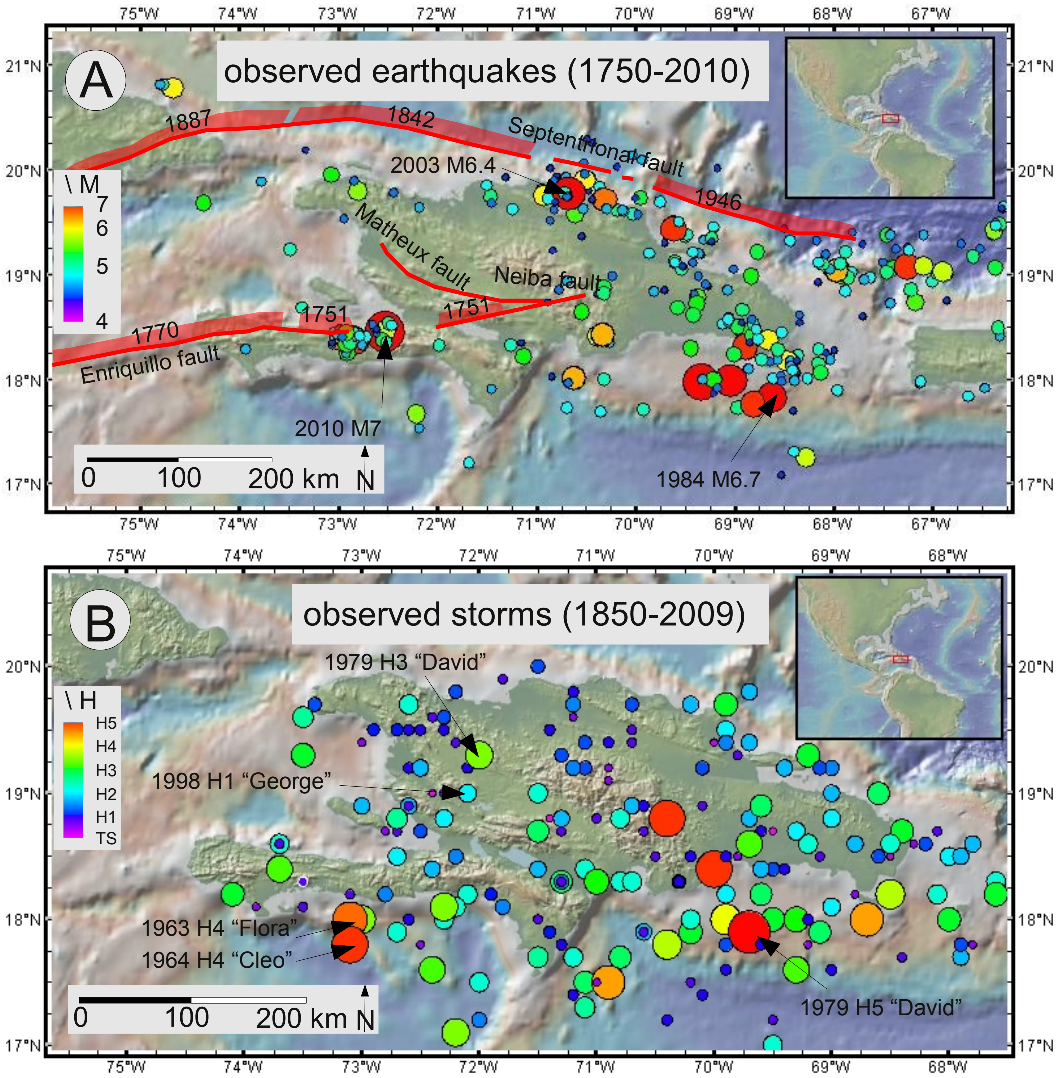

Fig. 3. Spatial distribution of observed earthquakes and storms in Haiti and the Dominican Republic: A) Locations of earthquakes that were in part instrumentally recorded since 1900 and extensions of fault zones that ruptured between 1750-1900. Earthquake catalog data were provided by U.S. Geological Survey (USGS); B) Locations of storms and hurricanes that were observed between 1850-2009. Storm catalog data were provided by the U.S. National Oceanic and Atmospheric Administration (NOAA). The size of the colored cirlces indicate the relative magnitude of the earthquakes or intensity of the storms. Magnitude/intensity increases with size of a circle.

3 Results and Discussion

Overall, Haiti and the Dominican Republic experienced similarly severe storms between 1850 and 2009 (Table 1 and Figure 5), although in average 30% more tropical storms made landfall in the Dominican Republic with a maximum observed hurricane category 4 on the Saffir Simpson Hurricane Scale (Kantha , 2008). The Dominican Republic also experienced a higher earthquake hazard within the 20th century, while Haiti was more affected by major earthquakes in the period before 1900 as shown in Table 2. Revised 2010 earthquake hazard estimates by Frankel et al. (2010), indicate that Haiti’s northern departments and the western department of Port-au-Prince are characterized by a higher earthquake hazard than the rest of the country. More reliable hazard models would need to integrate more region-specific data or

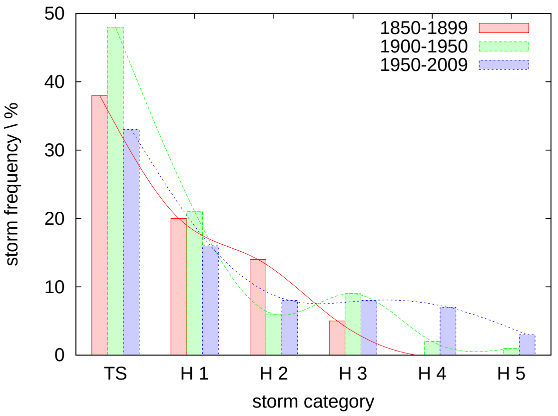

Fig. 4. Frequency of storms and hurricanes that were observed on Hispaniola island between 1850-2009. Frequencies are plotted for each storm or hurricane category observed during the periods 1850-1899, 1900-1949, and 1950-2009.(Source data: U.S. National Oceanic and Atmospheric Administration)

research results from paleoseismic studies, regional ground-motion prediction equations and in-depth historic seismicity catalogue research, once available.

Haiti's frequent occurrence of severe natural forces coupled with economic and political instabilities make the country highly vulnerable. However, it can be only speculated whether extreme seismic and atmospheric events tend to have negative implications on the political stability in both countries, which, in turn, might effect the population growth as well (Klose , 2009). Since 1850, Hispaniola island experienced in total 72 storms and five damaging earthquakes that directly hit the island (Table 2). The 1842 earthquake in northern Haiti, for example, coincides with political turmoils. In the aftermath of the 1842 earthquake, the Dominican Republic declared its independence from Haiti in 1844 (Table 2 and Figure 3). From 72 observed storms, only three storms (4%) occurred in the Dominican Republic simultaneously with a political regime change in the same or the following year: one tropical storm in 1930 and two hurricanes in 1963 (Table 2). In Haiti, five storms (7%) coincided with a change in the political regime characteristics in the same or the following year. All these events occurred after 1950. There might be a causal relation between hurricane Frances on October 3 in 1961 and political instabilities in Haiti. But these instabilities might also be due the aid suspension of the U.S. Administration in the same year. Possible relations that need further investigations are summarized as follows:

- between hurricane Isabel on October 7 in 1985 and the political disorder of the following year which resulted in President Duvalier's escape,
- between hurricane George on September 22 in 1998 and the regime change, when Chamber, Senate, and President Préval ruled in January 1999, and
- major floods due to severe precipitation of several hurricanes that passed Hispaniola island in its North and South and the ouster of Prime Minister Michéle Pierre-Louis in October 2009, which was censured by the Senate.

A negative example that does not show causal relations include hurricane Ella on September 1 in 1958 and the attempted invasion against President Duvalier two months earlier, on July 28 of the same year. Moreover, it can be speculated whether tropical storm Mindy on October 10 in 2003 and storm Odette on December 6 in 2003, which passed the coast of the Dominican Republic, may have triggered violent unrests in Haiti in February 2004 and the ouster of President Jean-Bertrand Aristide who went into exile.

When natural forces, such as hurricanes and earthquakes, became available as threatening events to vulnerable assets of the human system, they affected both countries in different ways. Over time, departments were characterized by different population growth rates and population densities with respect to the experienced earthquakes and storms (Figure 1). Figures 5A and B show that population densities and population growth rates of departments in the Dominican Republic are uncorrelated with the frequency of storms observed between 1850-2009. The Southeast of the Dominican Republic with the city of Santo Domingo, the highest populated city of the country, experienced only 60% of the number of storms in comparison to Port-au-Prince. The Dominican Republic's Southeast developed outstandingly, mainly due to the increase of tourism industry, although a not-named category 3-5 hurricane in 1930 and hurricane David with maximum category 5 in 1979 hit this province and killed overall 2,078 people. Haiti shows a completely different picture. The more frequently storms make landfall in a certain department in Haiti between 1850-2009, the higher is the departments average population growth rate and, ultimately, its population density (Figures 5A and B). This positive correlation between storm frequencies and population growth rates became stronger since 1930 and, in particular, in the departments Ouest and Artibonite, where the population rose, and in Grand'Anse, Nippes, and Nord-Est, where the population remained constant or rose less. In other words, both southern departments Grand'Anse and Nippes and the northern department Nord-Est experienced much smaller population growth rates between 1850 and 2009, in contrast to the other departments (Table 1). The positive correlation between storm frequencies and population growth might be explained by

1. negative effects of storms and associated floods on the hygienic situation in less developed and non-resilient parts of Haiti or
2. an increasing urbanization since the second half of the 20th century.

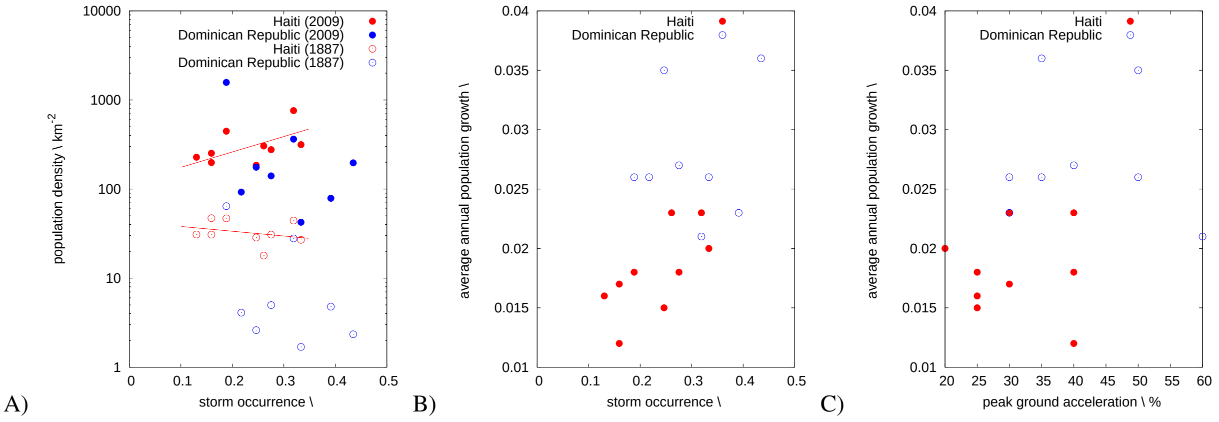

Fig. 5. Cross plots of population data and natural forces data that were sampled from the departments in Haiti and the Dominican Republic: A) Population density in 1887 and 2009 versus storm frequency/occurrence observed between 1850-2009, B) Annual population growth between 1850-2009 versus storm frequency/occurrence observed between 1850-2009, and C) Maximum expected fraction of the peak ground acceleration (PGA) with a 2% probability of exceedance in 50 years. Data sources and actual numbers are summarized in Table 1 and their spatial distributions are visualized in Figure 1.

First, the lack in hygiene might increase infant mortality rates and might bring rise to a delayed fertility in women, when following the demographic transition theory (Knodel , 1978). Fertility rates in Haiti range between 4-5% within the first decade of the 21st century, while its infant mortality rate is almost twice as high as the rate of the Dominican Republic. Although Haiti has still one of the highest birth-to-death-rate ratios, for example, in comparison to Latin-American countries(Brea , 2003), this fertility-mortality relationship, may differ from region to region and can depend on many other factors.(Rutstein and Medica , 1978) The population growth rates among all departments are highly correlated with the hospital density in Haiti (Table 1). This means that hygiene is highest in densely populated departments in which the storm frequency is highest as well (e.g., departments Ouest and Artibonite). Thus, it can not be shown that storms and earthquakes negatively impact women's fertility and, finally, the population growth.

A hazard contemplation shows that most negative annual population growth rates are not related to hurricanes or earthquakes that hit the territory of Haiti in the same or previous year, whereas exceptional cases did exist. For example, the devastating M7 earthquake of 2010 has shown that the greater Port-au-Prince region, in Haiti's South, is exposed to high socio-economic hazard risks, but also the region of Cap-Haïtien, in the country's North. Cap-Haïtien's population, for example, shrunk tremendously during the 1842 earthquake (Table 2). Moreover, Figure 6 reveals that there is no statistical difference between population growth rates in Haiti in years that were *affected* or *not affected* by storms and earthquakes. Here, a data set was analyzed, which is characterized by completeness of the catalog of storms, earthquakes, and population growth rates between 1912 and 2009. Storm and seismic intensities were annually cummulated and analyzed. The scale of magnitudes for earthquakes in Figure 6 does not exceed M6 since no earthquake occured between 1912 and 2009 that was larger than M6. Classes of the self-organized map label different instances of years in which storms or earthquakes were observed. These classes, ranked from 0-30, illuminate that the population growth rates in these years do not have a significant relationship to the storm-earthquake patterns. The average growth in *affected* years is 0.013±0.005 (mean±std. error; N=132) and 0.014±0.002 (N=690) in *not affected* years. One can see that the population growth is smaller in years that were affected by storms or earthquakes than in not-affected years. However, a one-way ANOVA test suggests that there is no significant difference between the *affected* and *not affected* samples. The test reveals a p-value of 0.939, which is far above the necessary 0.05-value need to show significant differences. Thus, the H_0-hypothesis (see Section 2.3) has to be rejected and the following alternative hypothesis is valid:

> *Annual occurrences of storms and earthquakes do not have negative impacts on population growth rates in Haiti in the same or the following year.*

Second and more important is a contemplation of the vulnerability. Haiti's population has rapidly grown from 431,140 inhabitants in 1804 to 10 million in 2009. The average population density in 2009 is 326 people km^{-2} (Table 1). The department Ouest with the city of Port-au-Prince and the department Artibonite with the city of Gonaïves are characterized by a drastically accelerating urbanization since the second half of the 20th century. Half of the residents in the Port-au-Prince are migrants and were not born there. On the other hand, 40% of the population between age of 20-30 mi-

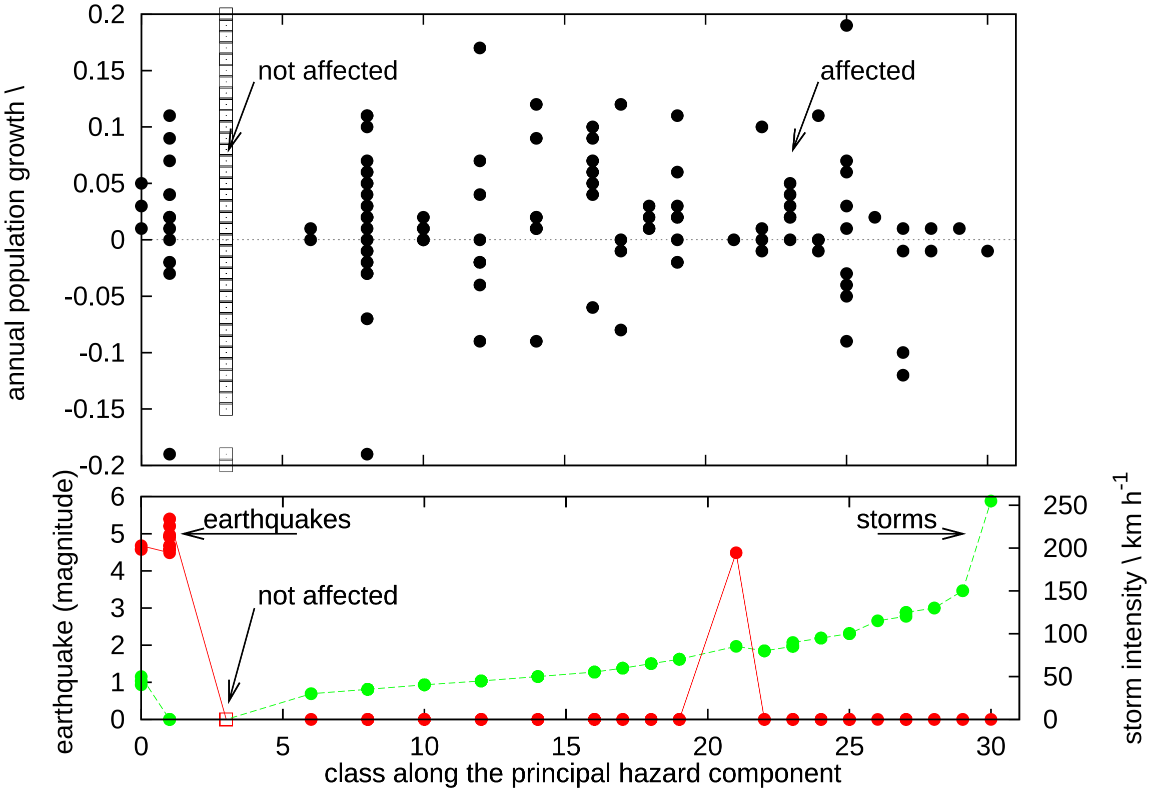

Fig. 6. Classification of annual population growth data in Haiti (upper graph) as a function of the intensity/magnitude of both observed storms and earthquakes in the same and previous year (lower graphs) between 1912-2009. The graphs illustrate that those years that were *not affected* by storms (green line) or earthquakes (red line) are characterized by a population growth ranging between -0.2 and 0.2 and, statistically, do not differ from those years that were *affected* by storms or earthquakes. All data values were classified and visualized by a self-organized map (see Section 2.3). Classes are plotted along the largest principal hazard component with the purpose to illuminate the in/dependence of the annual population growth as a function of the storm and earthquake intensities.

grate from their birth towns in rural areas into urbanized departments, such as, Nord-Est and Nord-Ouest which have the highest poverty rates and one of the lowest hospital densities in the country, including health centers and dispensaries (Table 1). Figure 5A shows in detail that the frequency of storms that were observed between 1850 and 2009 are negatively correlated with the population density of Haiti in 1887 (declining red line). The correlation, however, changed within one century resulting in a positive correlation between the storm frequency and the population density in 2009 (inclining red line). Thus, more people have been exposed to natural hazard events (e.g., tropical storms, M7 earthquake in 2010) in fast growing departments like Ouest and Artibonite. As Haiti's prevalent vulnerability index (PVI) indicates, which is 20-40% lower than the index for the Dominican Republic, governmental policies were not able to increase the country's resilience against hurricanes and earthquakes. Today, Haiti is the poorest nation in the western hemisphere with more than two-thirds of its population living on less than two US dollars per day with no sustainable access to portable water (UNDP , 2009b). Its human development index (HDI) ranks with 149 of 182 (values of 2009) as one the least developed countries in the world (UNDP , 2009b).

On the other hand, the Dominican Republic was able to respond more effectively to natural disasters than Haiti due to its political and economic climate but also due to its environmental policies and practices. For example, governmental policies during the autocratic regimes of Trujillo and Balaguer from 1930 until 1996 strengthened the country's resilience to cope with natural forces, including, for example, measures of infrastructure modernization, industrialization, and response and crisis management in conjunction with environmental protection. As a result, the Dominican Republic with US$8,896 per capita income (2009 GDP-values) tends to be more resilient and more able to cope with natural catastrophes than Haiti. It has a lower per capita income of US\$1,338 (2009 GDP-values) and 30% of its GDP results from contributions of permanently displaced and relocated Haitians, who mainly live in the United States.

4 Conclusions

Historic data (1912 - 2009) show no direct correlations between annual population growth rates and seismic events with magnitudes >4.5. There is also no statistical relationship between the annual population growth rates and tropical storms and hurricanes that directly made landfall in Haiti. Moreover, the data show that Haiti's population has been growing in regions that are more prone to storm hazard events. This is particularly true for the departments Ouest and Artibonite. Both departments have the highest population densities of the country, which have been 20 to 40-fold between 1850 and 2010. However, it can be speculated whether urbanization has been increasing the country's socio-economic risks. The severity of impacts of natural forces on the Haitian society might have been amplified by additional human-influenced factors, such as massive deforestation. Thus, new approaches are needed that respond to local needs by nature protection policies, including educational measures of the public, legal measures to ensure environmental protection and sustainable forest management.

Appendix A

Historical development of Haiti and Dominican Republic (1850-2010)

Domestic politics and the colonial era also played a major role in shaping the development trajectories of Haiti and the Dominican Republic. Both countries had a series of regime changes within the last two centuries. The developmental paths of the two countries diverted already in the 18th century when Hispaniola was divided into a French and Spanish colony. The French colony, which was later to become Haiti, had a much larger population and a greater percentage of slaves (80% compared to 10%). In 1804, France gave up its claims to its colony and in the same year, Haiti gained independence being the first country in the New World. The years following independence were characterized by political coups and instability in both countries. All but one of 22 Haitian presidents from 1843 to 1915 were either assassinated or driven out of office. (Diamond , 2006) Although, slavery was abolished, large-scale plantations were destroyed and the land divided into small holder farms. Moreover, Haitians spoke Creole making it more difficult for European traders to do business. Consequently, agricultural productivity declined and exports dwindled.

The Eastern part of the island, on the other hand, remained more open towards the "Old World." Relations with Europe continued in the Spanish-speaking part of Hispaniola following independence from Spain in 1821. Thus, economically important immigrant groups preferred to settle in the Dominican Republic. The country continued to have a lower population density (Table 1) putting less pressure on environmental resources. It can be speculated whether higher population pressures and colonial exploitation in Haiti had been responsible for stripping of its forests by the mid-nineteenth century. Since its independence from Haiti in 1844, politics was equally tumultuous in the Dominican Republic, which had 50 regime changes between 1844 and 1930. Outside occupations followed. The United States, for example, invaded Haiti in 1915 and stayed until 1934 and in the Dominican Republic from 1916 to 1924. Political instability was then replaced with military dictatorships that lasted for many years.

Starting from 1930, President Rafael Trujillo autocratically ruled the Dominican Republic until 1961 when he was assassinated. Although the country suffered under his dictatorship, it was the beginning of modernization and industrialization. This was also the beginning of environmental protection, when Trujillo began to protect forests to generate hydro-electric power and to protect his personal interest in logging. President Joaquín Balaguer who shaped Dominican politics for the next three decades continued with this path of development and environmental protection until 1996.

While the Dominican Republic was on track to economic growth and prosperity, Haiti continued to experience political instability. In 1957, Haiti came under the control of President

François Papa Doc, an equally ruthless politician as Trujillo but with no interest in developing and modernizing the country. When he died in 1971, Jean-Claude Baby Doc Duvalier who ruled until 1986 succeeded him. The years that followed were characterized by political instability and economic decline. Finally, between 2006-2009, politics during President René Préval's second term increased Haiti's economic development slightly.

Appendix B

Self-Organizing Mapping

SOMs are part of the family of artificial neural networks and are structured in two layers: an input layer and a Kohonen layer. The input layer is a one-to-one representation of a feature vector consisting of two annual features: cumulated storm intensity and released seismic energy (moment magnitude). Therefore one neuron is accepting each feature vector of each year and department. The Kohonen layer, on the other hand, represents a structure with a single feature, for example, 1-dimensional map (lattice) consisting of fixed neurons (labels) arranged in a row. Each neuron of this discrete lattice is fixed and is fully connected with both source neurons in the input layer. For the given task of interpreting the multi-dimensional data, each feature vector, which is presented to neurons of the input layer, typically activates (stimulates) a neuron in the Kohonen layer. Based on the given input data set, learning occurs during a self-organizing procedure as feature vectors and are presented to the input layer of the network. During this optimization process, neurons of the Kohonen layer compete to see which neuron will be activated by an input data vector. The weights between vectors are used to determine only one activated neuron in the Kohonen layer after the winner-takes-all principle. After the learning process, a SOM is considered as trained and its weights $\boldsymbol{w}_m$ store the interrelations of all feature vectors $\boldsymbol{x}_n$. This process can be understood as a principal component analysis with the advantage of visualizing its features along the first and second principal component (i.e., 1- and 2-dimensional maps). A more detailed overview about the learning process of this clustering-interpretation scheme can be found in Klose (2006).

At the end, input vectors with similar features will be assigned to the same label of the winning neuron in the discrete lattice of the Kohonen layer. Thus, a clustering or classification was finally performed. Figure 6 illustrates the result of such a classification. It visualizes the relationships between storm-earthquake hazard patterns along a 1-dimensional Kohonen lattice, which is the maximum principal hazard component. The Kohonen lattice consists of 30 clusters w_m (i.e., axis with the principal component) which illuminate the inter-relationships between storm-earthquake feature vectors x_n for all nine departments in Haiti between 1912 and 2009. The SOM algorithm basically clustered the input feature space into 30 clusters by taking both features simultaneously into account: storm intensity and earthquake intensity. Both features are independent properties of the nature-system which might have an impact on the human-system: here, population growth (dependent property). Again, the SOM visualizes these features along their largest principal hazard component sorted along the 30 clusters. Utilizing such machine learning tool allows one to integrate two or more features simultaneously by maintaining the completeness and overview of the data. Furthermore, this approach shows more robustness when using vague and sometimes incomplete information or data with high statistic/non-systematic sampling errors.

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