DEVELOPMENTS IN
EARTH SURFACE PROCESSES 13

NATURAL HAZARDS AND HUMAN-EXACERBATED DISASTERS IN LATIN AMERICA

SPECIAL VOLUMES OF GEOMORPHOLOGY

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Developments in Earth Surface Processes, 13

NATURAL HAZARDS AND HUMAN-EXACERBATED DISASTERS IN LATIN AMERICA

Special Volumes of Geomorphology

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Editorial Foreword

This new book edited by Edgardo Latrubesse concerns natural hazards and their associated processes and disasters in many parts of Latin America. Most people can recall reading or hearing about a catastrophe in that part of the world, but are usually vague about where it or how it occurred, or about what caused the problem in the first place. This thirteenth volume in our book series on Developments in Earth-Surface Processes sets the stage for a new look at these phenomena in this part of the world, where mainly scientists skilled in Iberian languages have much information.

The natural hazards of earthquakes and volcanic eruptions are, of course, directly related to plate-tectonic translocations and collisions in the lithosphere. In the uppermost portions of this lithosphere, different kinds of slope-failure hazards reflect the many actions, interactions, and reactions between rock materials and climatic variations, particularly precipitation, although seismic or volcanic accelerations can also play major roles. In addition, the interactions and translocations of the hydrosphere and the atmosphere with the lithosphere and its processes generate tsunamis, hurricanes, and floods. These complex or even chaotic processes cause great hardship, the study of which can enable better scientific understandings of the many processes, about which we need far greater information to deal with more effectively.

In these times of accelerating global change, as climates shift worldwide and human populations increase exponentially without much constraint, it is clearly incumbent on us to pay close attention to these natural hazards. To know the problems is to move closer to solutions to them. Many countries of Latin America, with their limited infrastructure and weak economies, are highly vulnerable to environmental and political problems brought on by these natural hazards, especially as they are exacerbated by the actions of humankind.

Another serious world issue is that some forms of attempted predictive geomorphology, such as flood-hazard mapping and recurrent landslides require long-term monitoring, good record keeping, and analysis of old writings to find comparable events and to translate them into modern equivalents. Such data can be used to produce statistical probabilities of the future occurrence of similar events in the same areas. But as global change shifts climatic thresholds, such statistical treatments will perhaps not be so feasible and so unpredicted hazards will lead to greater damage to infrastructure and to greater loss of life. Thus this book is a useful beginning in the assessment of hazards and catastrophes on one of the most vital continents of the Southern Hemisphere. Because the people of this area are vulnerable to the vagaries of forces from plate-tectonic, atmospheric, hydrospheric, and cryospheric motions, regional assessments provide an important analytic tool.

In the first millennium CE in South America, the Tiwanaku population on the Altiplano around Lake Titicaca grew beyond the carrying capacity of their land, as a result of which they were unable to cope when a catastrophic 400-year drought arrived. Ultimately, it meant the end of their empire (Thompson, et al., 1988; Kolata, 2001). Similarly, the El Niño–Southen Oscillation (ENSO) affected irrigation capabilities so profoundly in coastal Peru that it apparently brought the Moche civilization to an end there as well (Fagen, 1999; Bowen, 2005). The fate of many of these prehistoric civilizations in Latin America therefore has strong implications for the modern world, illustrating the potentially devastating effects of similar natural hazards. This book, therefore, can serve as a useful warning for the future about possible environmental cataclysms and other Earth-surface problems in Latin America. In producing this volume in the English language, which ensures greater distribution of knowledge about natural hazards and human-exacerbated disasters in Latin America, Edgardo Latrubesse has done a significant service.

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Editor-in-Chief

FOREWORD

The International Association of Geomorphologists (IAG) welcomes this book on the Geomorphology of Natural Hazards and Human-Exacerbated Disasters in Latin America, for it is a truly international compilation that deals with a very important and timely issue. I congratulate its editor, Professor Edgardo Latrubesse, on bringing it to fruition. The IAG has recognized the significance of geomorphology for understanding, predicting and mitigating hazards and disasters by establishing a working party on Geomorphological Hazards, and hazards will be the theme of the Regional Meeting we are holding at Brasov in Romania in September 2008.

As a recent report by the Centre for Research on the Epidemiology of Disasters (CRED) has shown (CRED, 2007), natural disasters have devastating impacts. In 2006, for example, there were 427 reported natural disasters that globally killed more than 23,000 people, affected almost 143 million others, and were the cause of more than US$ 34.5 billion in economic damages. Floods and various types of windstorms were the two major causes of economic damage. Not all natural disasters are essentially geomorphological, but many of them are, including avalanches, landslides and other types of mass movements, desertification and soil erosion, floods, coastal storm surges, earthquakes, tsunamis, and volcanic eruptions (Alćantara-Ayala, 2002).

Hydrometeorological disasters appear to be increasing in occurrence and tend to be more frequent than geological disasters. The occurrence and consequences of disasters may be changing because of increasing human impacts on the environment, because of changes in climate (especially a tendency to more intense storm activity in many parts of the world), and because more people and economic activities are being located in hazardous places. Whether one is talking about new housing estates located on flood-prone areas in the United Kingdom, or favelas constructed on very steep slopes in Brazil, or the position of New Orleans, it is clear that much economic activity is located in illogical sites.

Geomorphologists cancontribute to the study of natural disasters and hazards in many different ways (Rosenfeld, 2004). Identifying potentially susceptible locations is important and can involve locating those places where disasters have occurred in the past, and at the same time assessing their past frequency and magnitude. A huge number of techniques are available, including sequential photography, archival material, and dendrochronology. Geographical Information Systems (GIS) and analysis of geotechnical properties of materials can be used to determine where disasters such as landslides might occur in the future. Geomorphological maps can show areas that may be at risk and may form the basis for land zonation and planning decisions. It is also crucial to understand the causation and mechanics of geomorphological change if appropriate mitigation procedures are to be undertaken successfully. It is equally crucial to understand some of the geomorphological and environmental consequences of engineering solutions that have been proposed for natural disaster mitigation and to evaluate the relative merits of "hard" and "soft" solutions. Geomorphologists also need to be involved in debates about the future significance and impacts of global climate changes and to identify those ?hot spots? where systems may be tipped beyond some crucial threshold. For example, sea-level rise and increased storm surge activity may both combine to make coastal lowlands highly vulnerable to flooding; glacier retreat may remove buttressing from slopes and make them more prone to mass movements; permafrost decay may cause shorelines and riverbanks to become more prone to catastrophic retreat; and lower soil moisture levels in drylands may stimulate dune reactivation and dust storm generation.

The chapters in this volume indicate the wide range of geomorphological disasters that afflict the different parts of Latin America, the role of climate change and anthropogenic factors, and the methods employed by geomorphologists in their attempts to understand and mitigate their worst effects, not least in developing countries.

Andrew Goudie
University of Oxford and President of the IAG

Preface

Disasters have been a main concern at the global scale, and many of them are essentially geomorphologic. Developing countries are among the countries most profoundly affected by these disasters, and Latin American countries are not the exception. In addition to the typical disasters that affect people in a direct way and produce economic loss, Latin America is also suffering environmental disasters, notably, massive rates of deforestation, desertification, or glacier recession in which geomorphologic processes have a main role. Large disasters have happened in every decade: for example, the eruption of Nevado de El Ruiz (1985), Hurricane Mitch (1998), the killer floods and landslides in Vargas-Venezuela (1999), and the Pisco earthquake (2007). These disasters shocked society and reminded us that, with minor exceptions, our region has advanced little in disaster mitigation and prevention because of the general failure of public policies during these last decades.

In spite of this not very hopeful perspective, some links between Latin American researchers have started to appear through some broad scientific programs such as CYTED (Science and Technology Program among Ibero-American Countries) and between South American researchers through the pioneer PROSUL program implemented by the National Council of Research of Brazil (CNPq), which offers some hope of obtaining a broad scientific interaction among South American researchers in the future. In each South American country, geomorphologists have been trying to provide results and interactions with political and social actors, with varying success. Often geomorphologists have been relegated to a secondary role because of politicians' preference for "hard" engineering solutions after disasters rather than "soft" prevention and mitigation policies. On the other hand, the International Association of Geomorphologists (IAG) has been trying to increase the participation of geomorphology in society as well as to create mechanisms for strengthening the links between Latin American researchers. During the International Conference on Geomorphology, in Tokyo, Japan, 2001, I was elected to participate on the Executive Committee of the International Association of Geomorphologists. Between 2001 and 2005, with the support of the past IAG president, Mario Panizza, my main tasks related to promoting Latin American research, increasing the participation of young scientists from developing countries, fostering the creation of new national associations/groups in geomorphology, and improving the participation of scientists in developing countries in geomorphologic research. Because of these novel initiatives of IAG, three national groups of geomorphology have been created in Venezuela, Colombia and Bolivia. In addition, the participation of the Argentinean Group of Geomorphology in the IAG has become regularized. All this was possible because of our effort and work in collaboration with Latin American colleagues. A very good start in reactivating interest in geomorphology and disasters in Latin American countries was the Regional Conference on Geomorphology Geomorphic Hazards: Towards the Prevention of

Disasters, which was organized by Mexican colleagues from the Universidad Autónoma de México in 2003, such as Irasema Alcántara Ayala (one of the contributors to this book).

During the last few years, the IAG under the current president, Andrew Goudie (2005–2009), has maintained that our specialists should have a more active role in society, implementing the appropriate means to increase the awareness of other scientists, decision makers, stakeholders, planners, authorities, and the general public about the role of geomorphology in the understanding of hazards and disaster prevention. To reach these goals, several specific meetings and activities have been organized, and a new working group was created.

In September 2006, together with my colleague Selma Simões de Castro (one of the contributors to this book), we organized the IAG Regional Conference on Geomorphology and the VI SINAGEO (Brazilian Symposium of Geomorphology, official activity of the Brazilian Union of Geomorphology). Our main objective was to strengthen the links between South American researchers and to enable our students and young researchers to access results from researchers with particular experience in tropical areas across the world. The Symposium involved more than 700 participants from 21 countries and proved successful. The meeting was the largest conference specifically devoted to geomorphology ever organized in South America, in terms of both the number of national and international participants. Geomorphologic hazards in tropical countries were an important concern of the meeting. A new successful Latin American Symposium on Geomorphology was organized in 2008 in Belo Horizonte, Brazil by the Brazilian Union of Geomorphologists in association with the VII Symposium of Geomorphology. This exemplifies the increasing academic interest in geomorphology. The quantity of results on applied geomorphology presented at the meetings is an indicator that geomorphology's contribution to society has been growing substantially during the last years in several Latin American countries, especially Brazil. This book combines both policies of the IAG in a single product: the participation of Latin America researchers in a "hot" topic such as hazards and disasters.

Natural hazards and human-exacerbated disasters occur particularly in developing countries, and geomorphologic processes are one of the main agents. In this book the geomorphology of natural hazards and human-exacerbated disasters in Latin America is addressed by experts with a long history of research on the continent and includes results from Mexico, Central America, Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina, and Brazil. The book contains 21 chapters written by 39 researchers from over 28 academic or research institutions from 11 countries.

The main objective of the book is to offer a vision of the geomorphologic dynamics of the main disasters, describing their mechanisms and consequences for South American societies. Major disasters produced by volcanoes, earthquakes, floods, landslides, and tsunami hazards are a main focus as well as the description of the main hydrometeorological and geological drivers. Human-induced environmental disasters are also included, such as desertification in Patagonia and soil erosion in Brazil. The recession of South American glaciers as a response to recent climatic trends and sea-level scenarios is also discussed.

The approach is broad, analyzing causes and consequences and including social and economic costs, discussing environmental and planning problems, but always describing the geomorphologic/geologic-involved processes. This particular approach differentiates this book from others which are devoted to assessing the more "social" aspects of disasters, thus emphasizing mainly economic and social effects.

I believe that this book can be a main reference for a variety of graduate and undergraduate students and professionals interested in geomorphology, physical geography, environmental sciences, environmental geology, and ecology, as well as for planners, environmental engineers, and environmental consultants. I am hopeful and expectant that mitigation and prevention policies in Latin America encouraged by the active participation of geomorphologists in society and as a consequence of better interaction among the different social and politic actors can help to decrease the impact of disasters in the future.

My sincere thanks are due to Andrew Goudie, president of the International Association of Geomorphologists, for contributing the Foreword. I would also like to acknowledge the colleagues who acted as referees, helping us to obtain a better result. I also especially thank John (Jack) Shroder, Editor-in-Chief of the Developments in Earth Surface Processes Series, for his fundamental help in the editorial process and to the staff of Elsevier that helped me through the edition of this book.

Finally, I am totally grateful to the authors for participating in this book, thereby transmitting their research results and their social understanding of the countries where many of them have been living their entire lives or where they have acquired much of the scientific experiences that have shaped their professional careers.

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CHAPTER 1

Climate and Geomorphologic-related Disasters in Latin America

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1. Introduction

Latin America extends from the northern border of Mexico at 32°N to Cape Horn at 56°S in the southernmost tip of Chile, and from Cape Branco at 35° 30′W to Cape Fariñas at 81° 20′W. With a landmass that extends over 20,340,000 km^2, mostly in the Southern Hemisphere, Latin America represents 16% of the Earth's landmass and is much more extensive in the tropics than in the higher latitudes. The Andes Mountains run along the entire western coast of South America (Fig. 1.1) forming an effective meteorological barrier between the Pacific Ocean and the continent. Similarly, along Mexico and Central America the Sierra Madre Mountains act as a barrier to the trade wind easterlies. In Latin America the topography, geographic position, and contrasting surrounding oceanic conditions create great climatic diversity. Section 2 of this chapter offers an overview of Latin America's

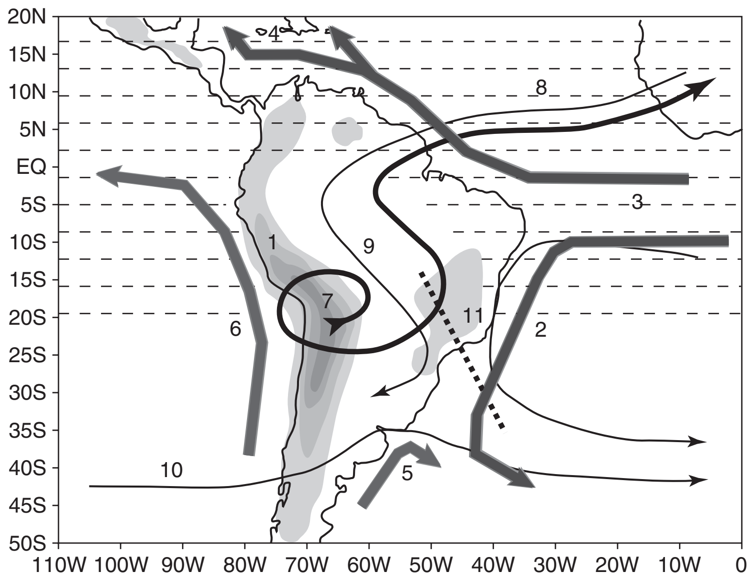

Figure 1.1 Schematic of the summertime circulation in Latin America (adapted from Zhou and Lau, 1998).

1. Andes Mountains
2. Warm Brazil Current
3. Equatorial Current
4. Caribbean Current
5. Malvinas Current
6. Humboldt Current
7. Bolivian Anticyclone
8. Trade wind easterlies
9. South American Low-Level Jet
10. Midlatitude Westerlies
11. South American Convergence Zone

complex climate variability from the monsoon cycle to the effects of the El Niño–Southern Oscillation (ENSO) phenomenon, as well as from the effects of tropical storms and hurricanes in the tropical regions of Latin America, to the effects of extratropical cyclones in the midlatitudes. Section 3 ties the climate and weather features to their geomorphological effects over many regions of Latin America.

2. Latin American Climate

The combination of the wide range of latitudes covered by Latin America, the existence of major orographic features, and significant oceanic influences has produced extremely diverse, complex climate patterns. This section discusses the main climate patterns in Latin America.

2.1. Ocean Currents

Ocean currents play an important role in modulating local and global climate patterns. Latin American climate is strongly influenced by oceanic currents in both the Atlantic and Pacific oceans. The main oceanic currents that influence Latin America are as follows.

The Antarctic circumpolar current influencing the southern continental extreme is situated between 50° and 60° south latitude. The present narrowness of the water connection between South America and Antarctica, however, causes this great oceanic current to suffer perturbations and modifies its sweep. The main discharge passes through Drake Strait, and a smaller discharge is deflected north up the south Chilean coast. The northern deflection, called the Humboldt Current (Fig. 1.1), travels along the western coast of South America to the vicinity of the equator, giving unique characteristics to the coastal climates.

The Humboldt Current transports cold waters northward along the Chilean coast. The shape of the coast, the depth of the sea, and the Coriolis force, together with the southeast trade winds, cause a deflection in its northerly reaches, and thus the current separates from the Peruvian coast. This causes upwelling of colder deep waters that rise to the surface, conditioning the principal climatic features in the coastal zone between the equator and 20°S.

On the other hand, the eastern coast of South America has notably different characteristics, showing a seasonal behavior that is not observed with the same intensity along the Pacific coast. On the eastern coast, the Atlantic equatorial current is of vital importance and meets the South American continent near Cape Branco. As it flows from east to west, the Atlantic equatorial current (Fig. 1.1) bifurcates into two warm currents that travel along the South American coast, the northward-flowing Northern Brazil and Caribbean Currents, and the southward-flowing Brazil Current.

The Brazil Current (Fig. 1.1) travels southwesterly, reaching Cape Corrientes on the Argentine coast. At the end of the summer months in the Cape Corrientes zone, the warm Brazil Current converges with the Malvinas Current that flows past the Patagonian coast, carrying cold waters toward the north. At the end of winter, the Malvinas Current (Fig. 1.1) displaces the Brazil Current away from the coast and extends northward to Cape Frio (7°S) along the Brazilian Atlantic coast. The warm waters, thus separated from the continental margin, then bathe the Brazilian coast only between Cape Branco (7°S) and Cape Frio (20°S, García, 1994). This direct effect of the shifting oceanic conditions can be clearly observed by comparing the monthly mean temperatures in the warmest and coldest months of both continental coasts (Table 1.1 and Fig. 1.2).

Another indication of the effect of the adjacent seas on the occidental and oriental coasts of South America is the thermal contrast between the shores (Fig. 1.2). During the austral summer, the oriental coast of South America is everywhere warmer than the occidental coast. This characteristic, however, does not prevail throughout the year because during the winter the cool Malvinas Current influences the oriental coast and the monthly temperatures are practically the same along both coasts from the southern extremity to 30°S.

The Northern Brazil Current bathes the northern coast of Brazil and becomes the Caribbean Current as it flows northwestward between the northern coast of South America and the Caribbean Islands. The Caribbean Current ultimately flows into the Gulf of Mexico through the narrow strait that separates the Yucatan Peninsula and the Island of Cuba. The seasonal variability of these currents causes a marked seasonal variability of sea-surface temperatures (SSTs) in the Caribbean Sea and Gulf of Mexico, with the warmest SSTs occurring during the boreal summer in the Caribbean Sea. The seasonal changes in SSTs in the Caribbean

Table 1.1 Warmest and Coldest Monthly Mean Temperatures on the Oriental and Occidental South American Coasts (in °C)

Latitude	Locality	Temp. Warmest Month (°C)	Temp. Coldest Month (°C)	Annual Amplitude (°C)
8° S	**Lambayeque (west)**	24.2	17.5	6.7
	Recife (east)	26.3	22.9	3.4
23° S	**Antofagasta (west)**	20.3	13.4	6.9
	Rio de Janeiro (east)	26.1	20.8	5.3
33° S	**Valparaiso (west)**	19.7	11.7	6.2
	Curitiba (east)	20.1	12.6	7.5
40° S	**Valdivia (west)**	16.5	7.6	8.9
	Bahía Blanca (east)	22.8	7.6	15.2
50° S	**Punta Arenas (west)**	10.7	2.3	8.4
	Río Gallegos (east)	13.1	1.9	11.2

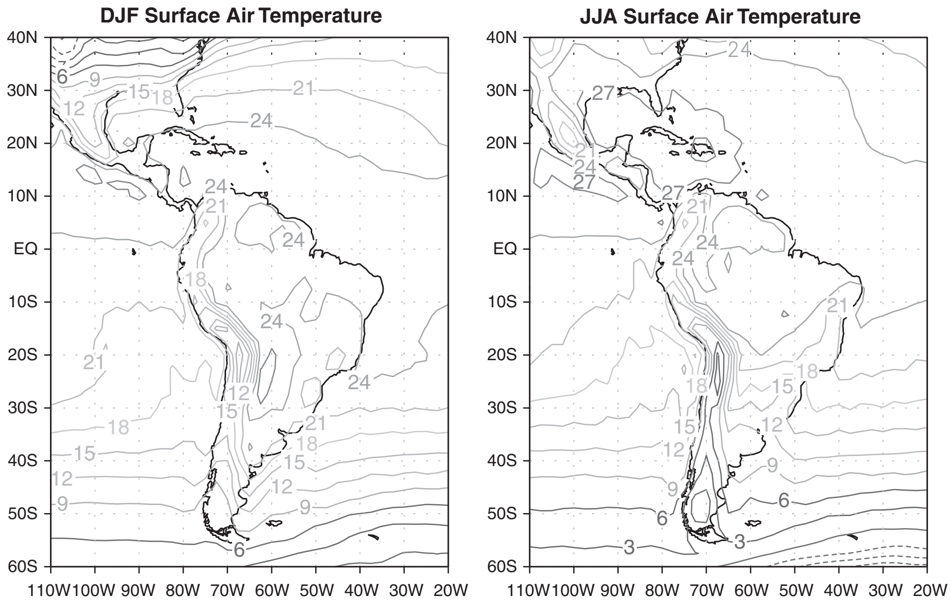

Figure 1.2 Average (1979–2006) surface air temperature (°C) from the National Centers for Environmental Prediction (NCEP). Reanalysis dataset during (a) December–January–February, and (b) June–July–August.

Sea and Gulf of Mexico are reflected in the seasonal changes of surface air temperature shown in Figure 1.2. During the boreal summer, the presence of warm ocean SSTs in the Caribbean Sea and Gulf of Mexico contribute to the maintenance, intensification, and formation of hurricanes that affect Central America and the Caribbean.

2.2. Air Temperature Patterns

The surface air temperature patterns in Latin America show well-established seasonal characteristics, with the land quickly responding to the Sun's apparent movement with respect to the equatorial plane, so that the maximum temperature occurs in South America on the summer of southern hemisphere. During the austral summer (December, January, and February—DJF), the continent's warmest area is situated in southcentral Brazil, Bolivia, and northern Argentina (Fig. 1.2). In addition, over the occidental coastal zones the effect of the cold Humboldt Current is notable. To a lesser extent, the effect of the cold Malvinas Current is also felt in the temperatures of the Argentine coast as far north as the mouth of the Rio de la Plata.

During the austral winter (June, July and August—JJA), the highest temperatures are present in Central America, Mexico, and the Caribbean. During the austral winter, cooler temperatures occur in southern South America, lessening the temperature differences between land and sea. The effect of the Humboldt