# Global patterns of loss of life from landslides

David Petley
International Landslide Centre, Durham University, Durham DH1 3LE, UK

## ABSTRACT

**Global loss of life from landslides is poorly quantified. A global data set of fatalities from nonseismically triggered landslides that resulted in loss of life between A.D. 2004 and 2010 permits for the first time proper quantification of impacts and spatial distributions. In total, 2620 fatal landslides were recorded worldwide during the 7 yr period of the study, causing a total of 32,322 recorded fatalities. These total numbers of landslides and victims are an order of magnitude greater than other data sets have indicated, but analysis of the data suggests that it may still slightly underestimate the true human costs. The majority of human losses occur in Asia, especially along the Himalayan Arc and in China. This geographical concentration dominates the annual landslide cycle, which peaks in the Northern Hemisphere summer months. Finally, numbers of fatalities per event show a fat-tailed power law distribution, with the density of landslides being moderately correlated with the population density on a national basis.**

## INTRODUCTION

Landslides, used here as a term to represent mass movements on the land surface that consist primarily of rock and/or soil, and thus including rockfalls and debris flows (Cruden, 1991), are an important landscape-forming process, providing the main mechanism for sediment release from slopes to permit transportation through the fluvial system (Petley, 2010a). Thus, in advecting mountain chains, landslides play a key role in allowing the development of a long-term dynamic equilibrium between uplift and erosion, and in reducing slopes to their threshold angle (Parker et al., 2011). In so doing, landslides can directly impact humans (Alexander, 2004). Because the ability of the unprotected human body to withstand burial and/or impact by debris is limited, fatalities frequently result (Sanchez et al., 2009; Petley, 2010a), compounded by the roles that humans play in increasing landslide occurrence.

In this context, it is perhaps surprising that the magnitude of human losses from landslides is poorly quantified. There are two major reasons for this: (1) There has been a lack of systematic data collection (Petley, 2010b) in the manner that has been seen for other hazards (Wysession et al., 1991), primarily due to the challenges posed by collecting data for a widely distributed process that mainly occurs in inaccessible terrain; and (2) multihazard databases usually classify by trigger rather than cause of death. Thus, many landslide fatalities are classed as being the result of their earthquake or tropical cyclone trigger. Consequently, previous estimates of human losses associated with landslides underestimate the magnitude of their impact (Kjekstad and Highland, 2008). Furthermore, no quantitative spatiotemporal global analysis has been undertaken of the patterns of fatal landslides, and their associated risks, although Kirschbaum et al. (2010) demonstrated that the compilation of such a database for landslides is both viable and informative. The upshot is a lack of quantification and thus appreciation of the true impacts of landslides, resulting in poor prioritization of global-scale landslide research and mitigation.

This paper provides, for the first time, a spatiotemporal analysis of a multiyear global landslide fatality database, allowing appropriate assessment of their impacts. Previous studies have used data sets that are not comprehensive in spatiotemporal coverage. As such this study represents the first detailed analysis of spatial and temporal fatal landslide occurrence. The data evaluated here cover a 7 yr period from 1 January 2004 through 31 December 2010 inclusive, but explicitly exclude coseismic landslides due to the high levels of uncertainty associated with landslide data for these events. In particular, the chaotic aftermath of a large earthquake means that data are not collected on the cause of death, such that data on the human impact of landslides have very high levels of uncertainty. In addition, the low rate of triggering events renders a 7 yr data set statistically invalid. On the other hand, data on landslides associated with tropical cyclones are usually readily available and are included here.

Prior to this study, studies of global landslide fatalities have mostly relied upon the EM-DAT (International Disaster Database; http://www.emdat.be/database) data set, collated by the University of Leuven (Sapir and Misson, 1992). This database records a total of 130 landslides that have caused loss of life for the period covered by this study, inducing 7431 fatalities (i.e., an average of 1062 fatalities per year). However, note that for fatal events, the EM-DAT database uses a criterion of a minimum of ten fatalities for an event to be included, and that in many cases, it classifies by primary trigger rather than process type, resulting in underestimation of landslide impacts. Other natural hazard databases, such as the NatCatSERVICE (natural catastrophe loss database; http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx) of Munich Re (Munich, Germany), similarly underrepresent landslide occurrence and impacts.

## METHODS

From September 2002, the Durham Fatal Landslide Database (DFLD; http://www.landslidecentre.org/database.htm) has been compiled using systematic metadata search tools, corroborated with analysis from government statistics, aid agency reports, and research papers. The approach mirrors that of Kirschbaum et al. (2010), but covers a longer time period and explicitly includes only landslides that cause loss of life. Exhaustive efforts are made to cross-validate the data, with updating as new information becomes available. The strengths and weaknesses of the methodology and underlying data set are discussed in Petley et al. (2005) and Petley (2010b), which found that the data set slightly underestimates the true impacts because a small proportion of events are missed and because it is difficult to record the deaths of people who die of their injuries long after an event. Comparison has been made with independently collected national data sets where available; this suggests that typical errors are about +5% to –20%, for both numbers of fatalities and numbers of fatal landslides.

The data set analyzed here covers seven full years of data. Although the DFLD also covers the period from 1 September 2002 to 31 December 2003, this period is excluded because it was a phase of technique development, resulting in lower overall data quality. Note that the DFLD records only fatal landslides, and thus does not seek to represent landslide occurrence more generally.

## TEMPORAL OCCURRENCE OF FATAL LANDSLIDES

In total, 2620 nonseismic, fatal landslides were recorded worldwide during the 7 yr period, causing a total of 32,322 recorded deaths. In terms of fatal landslide events, this is ~20 times greater than that indicated by the EM-DAT database (n = 130 for EM-DAT), while the number of fatalities is 4.3 times greater (n = 7431 for EM-DAT).

The time sequence data for the number of recorded landslides, graphed by pentads (five-day blocks), demonstrate a seasonal pattern (Fig. 1), although there is considerable variation in the interannual distribution. Although the number of landslides recorded per year (Fig. 2) has increased during the study, no such trend is seen in the number of recorded fatalities (Fig. 2), probably reflecting lower "noise levels" in the landslide data set (per pentad mean = 5.13, $\sigma$ = 2.54) than in the data for


doi:10.1130/G33217.1

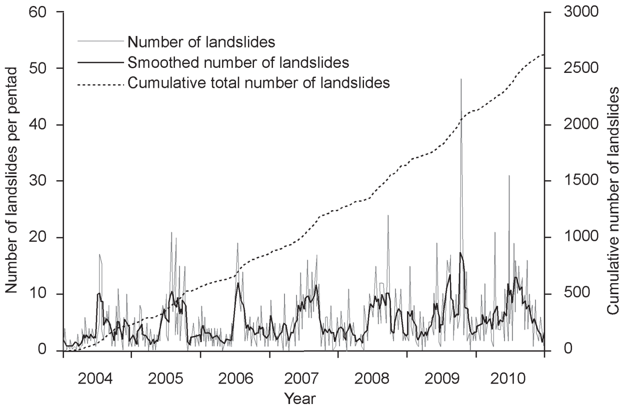


**Figure 1. The occurrence of nonseismically triggered landslides from A.D. 2004 to 2010, and the cumulative total of recorded events. Note that the data are arranged by pentads (five-day bins). Smoothing is with a simple 25-day running mean.**

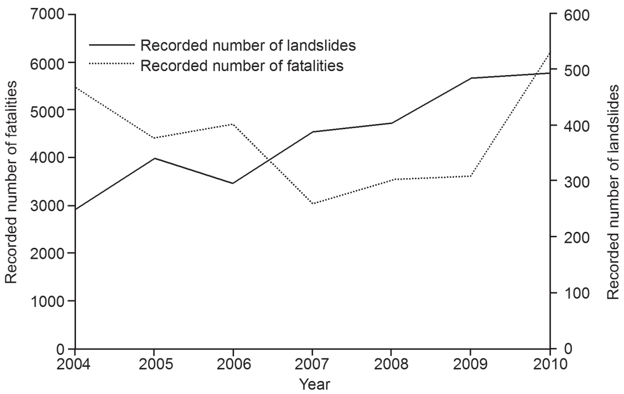


**Figure 2. Annual totals for the landslide data set, showing number of recorded landslides and number of associated fatalities.**

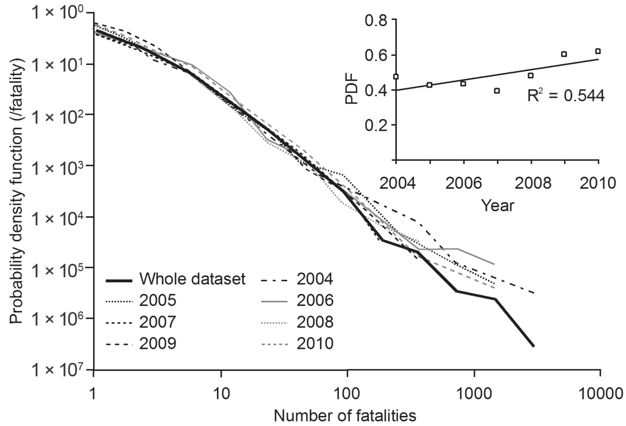


**Figure 3. Power law distributions for each individual year and for the whole data set, based upon probability density function (PDF, a measure of the likelihood of the variable, for which the integral over the full data set is unity). The inset graph plots the PDF for events of a single fatality, which shows a rising trend with time and suggests that the skill in recording smaller landslide events has improved with time.**

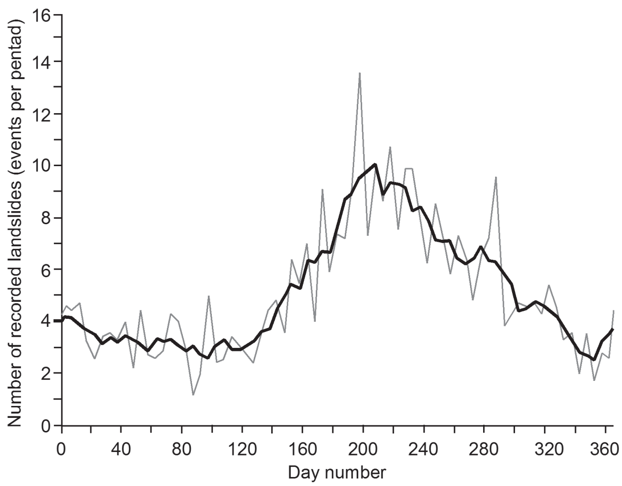


**Figure 4. Average number of landslides per pentad through the annual cycle, showing the strong seasonal trend. Gray line shows the raw data; black line is smoothed with a 25-day running mean.**

fatalities (per pentad mean = 62.71, $\sigma$ = 81.83). Care is needed in interpreting this temporal trend, as the length of the data set is comparatively short in comparison with the time period over which meteorological trigger events vary. The increasing trend in landslide numbers might reflect a true increase in occurrence and/or an improvement in the quality of the data set (i.e., the skill in collating landslide data improved with time). It can be hypothesized that improved skill would be reflected in an increase in the recorded number of landslides with small numbers of fatalities, on the basis that events with larger numbers of fatalities are more likely to be reported widely. The magnitude-frequency distribution for the whole data set and for each individual year is displayed in Figure 3. The complete data set shows a power law distribution with a reduction in gradient (probably representing undersampling) for events with small numbers of deaths, but no rollover as displayed in landslide area and volume data sets (Malamud et al., 2004). There is a high level of interannual consistency, but the probability density for the smallest size (i.e., landslides with a single fatality) shows an increasing trend (Fig. 3, inset graph). This suggests that (1) part of the apparent increase in numbers of recorded landslides is the result of improvements in data quality, and (2) thus the data set underestimates the true impact of landslides in the early part of the study period.

The occurrence of recorded landslides through the year is unevenly distributed, with more events in the Northern Hemisphere summer and fall (i.e., days 150–300) (Fig. 4). During the period between mid-December (day ~350) and mid-April (day ~120), recorded landslide occurrence is low. This pattern reflects the dominant global trigger of fatal landslides, the occurrence of precipitation associated with the Northern Hemisphere summer monsoon (Petley, 2010a), primarily in Asia. The East Asian and the South Asian southwest monsoons occur simultaneously in the Northern Hemisphere summer (Webster et al., 1998), dominating the precipitation pattern across these two regions (Petley, 2010b). This is enhanced by landfalling tropical cyclones (typhoons) in the northwest Pacific Ocean, and to a lesser degree in the Indian Ocean, and by landfalling hurricanes in the Caribbean and Central America, which also occur in the Northern Hemisphere summer/fall. Landfalling tropical cyclones often generate extreme rainfall events (peak intensities >100 mm $h^{-1}$) that trigger landslides. The landslide occurrence peak is asymmetric over the year (the rising limb occurs over ~95 days and the falling limb over ~145 days), reflecting the asymmetry in the onset and withdrawal of the Asian monsoons (e.g., Xie et al., 2003). Thus, the

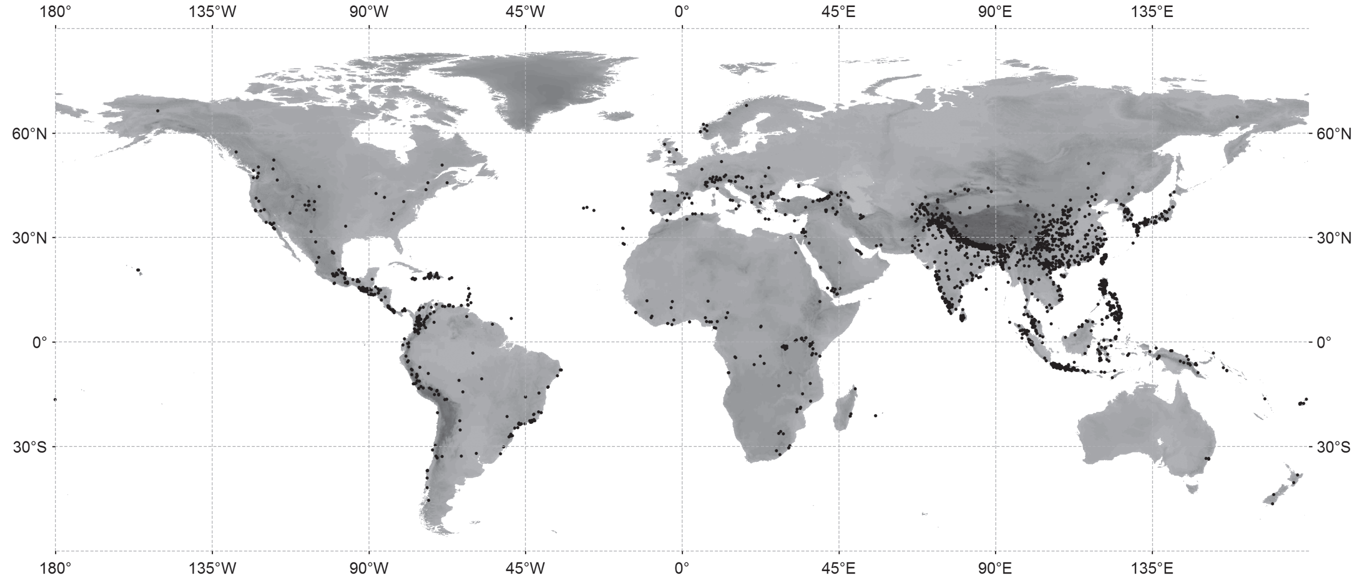


**Figure 5. Spatial distribution of fatal landslides. Each dot represents a single landslide.**

global fatal landslide pattern reflects continental-scale weather patterns that control precipitation.

## THE SPATIAL DISTRIBUTION OF FATAL LANDSLIDES

The global distribution of fatal landslides shows a strongly heterogeneous pattern (Fig. 5). Clusters of fatal landslides are evident in the following locations:

- Along the southern edge of the Himalayan Arc
- Along the coast of southwest India and in Sri Lanka
- Along the southern and eastern coastal regions of China, extending inland ~100 km
- In central China, most notably in the mountains surrounding the Sichuan Basin
- In the mountain chains along the western edge of the Philippine Sea plate
- In the central Caribbean islands
- In a chain that follows the mountains of Central America and South America from Mexico in the north to northern Chile in the south
- In Indonesia, most notably in and around the island of Java.

A number of smaller clusters are also present (e.g., the Alps), while many areas show a low spatial density of recorded landslide events. This clustering is likely to be driven by three key factors:

1. The availability of relief upon which a landslide can occur. The distribution suggests that this relief factor may be strongly dependent upon tectonic uplift rates.

2. The availability of precipitation to trigger landslides. Thus, the arid portions of the central Andes have a low recorded incidence of landslides in this data set.

3. The presence of potential victims (i.e., of humans). Thus, the recorded Himalayan landslides are clustered along the southern margins of the mountain chain. To the north, population densities are low such that landslide-induced fatalities are rare. Humans may also trigger landslides.

Thus, areas with a combination of high relief, intense rainfall, and a high population density are most likely to experience high numbers of fatal landslides. However, the distribution also appears to favor areas of high rates of tectonic processes. Areas of high relief, high rainfall, and large populations that are not currently associated with active tectonic activity or seismicity, such as the Alps, tend to have a much lower number of recorded landslides. This reflects the role that seismic activity plays in creating landscapes in which landslides are predisposed, and in weakening slopes through seismic excitation, allowing mobilization by subsequent rainfall events (e.g., Parker et al., 2012).

There may also be a control on the data set imposed by the economic and social ability of a country or area to invest in landslide mitigation (e.g., Wieczorek and Leahy, 2008). Thus, Italy, which has a long history of significant fatal landslides, does not show a particularly high occurrence of events over this period, probably because of successful landslide mitigation programs (e.g., Guzzetti, 2000), although this may reflect the comparatively short time series for what is a "noisy" data set at the individual country level.

The importance of human factors in the occurrence of fatal landslides is shown in Figure 6, which regresses the landslide density against the population density for those countries with ten or more recorded landslides. A key control on landslides that cause loss of life is the density of the population.

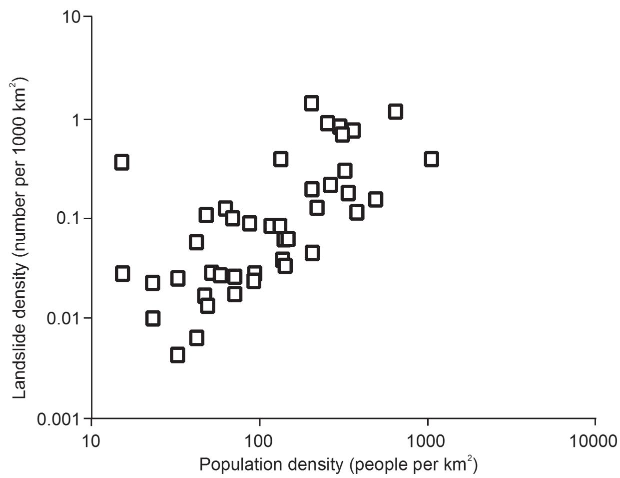


**Figure 6. Regression of recorded fatal-landslide density with population density in A.D. 2010 (as calculated from data in United Nations, 2011).**

## DISCUSSION AND CONCLUSIONS

This data set provides a first detailed attempt to analyze in time and space the global occurrence of fatal landslides. Although the data still probably underestimate the human cost of landslides, the data demonstrate that their impact is much greater than has been hitherto represented in, for example, the EM-DAT database. It is likely that in a number of key locations, the occurrence of landslides is still underestimated in these data (e.g., in North Korea and Ethiopia, where the presence of causative factors indicates a high incidence of landslides, but few have been recorded). These data can now be used to improve models and analyses of global landslide mortality risk (e.g., ISDR, 2009), which currently underestimate the likely level of loss. The distribution of landslide deaths presented here differs substantively from the distribution of landslide mortality risk presented by Nadim et al. (2006). This suggests that a reassessment of the global landslide mortality risk model is needed.

The temporal occurrence of fatal landslides in this data set appears to indicate a rising trend. Although such a trend might result from increases in population, precipitation intensity, and environmental degradation, the length of the data set reported here is insufficient to determine whether such an increase is indeed occurring; most of the trend is probably associated with improving skill in data collection. A further key aspect is that the study period does not include a strong El Niño event such as that in A.D. 1996–1997. Strong El Niño events increase landslide occurrence in Central and South America (e.g., Sepúlveda et al., 2006).

The spatial distribution displayed within the data set is perhaps the most interesting, with the occurrence of landslides being strongly concentrated in Asia, which drives the temporal occurrence through the annual cycle. There are two key disaster management implications of this. First, there is a need for increased research effort on landslides, most notably on trigger processes/thresholds, mechanisms, and mitigation, to be focused on Asia, particularly along the Himalayan Arc and in China, the Philippines, and Indonesia. Second, the quantification of future trends in landslide losses as a result of potential climate change should focus on likely changes to Asian climatic patterns. Unfortunately, at present, climate models handle poorly the likely patterns of monsoon rainfall (Petley, 2010b) and tropical cyclones (Chang, 2011), rendering forecasts problematic.

On a global basis the occurrence of fatalities in landslides follows a fat-tailed power law distribution, in common with other natural hazards (Newman, 2005). While further work is needed to assess variations in the exponents describing this distribution, this observation is important in the context of the assessment of landslide risk.

The approach taken in this study to determine the impact of landslides leads to a particular spatial and temporal pattern, while other measures, such as direct economic costs, would produce a different spatial pattern, with comparatively high losses in Europe, North America, and Japan, and comparatively low economic losses in less-developed countries. In more-developed countries, substantive mitigation efforts have reduced both landslide hazard and human vulnerability. However, the larger amounts of economic assets means that vulnerability to large financial losses is likely to be higher. Thus, the data presented here do not indicate a low level of landslide risk in such places.

## REFERENCES CITED

Alexander, E.D., 2004, Vulnerability to landslides, *in* Glade, T., et al., eds., Landslide risk assessment: New York, John Wiley, p. 175–198.

Chang, C.H., 2011, Preparedness and storm hazards in a global warming world: Lessons from Southeast Asia: Natural Hazards, v. 56, p. 667–679, doi:10.1007/s11069-010-9581-y.

Cruden, D.M., 1991, A simple definition of a landslide: Bulletin of the International Association for Engineering Geology, v. 43, p. 27–29, doi:10.1007/BF02590167.

Guzzetti, F., 2000, Landslide fatalities and the evaluation of landslide risk in Italy: Engineering Geology, v. 58, p. 89–107, doi:10.1016/S0013-7952(00)00047-8.

ISDR (International Strategy for Disaster Reduction), 2009, Global assessment report on disaster risk reduction: Geneva, Switzerland, United Nations, 207 p.

Kirschbaum, D.B., Adler, R., Hong, Y., Hill, S., and Lerner-Lam, A.L., 2010, A global landslide catalog for hazard applications—Method, results, and limitations: Natural Hazards, v. 52, p. 561–575, doi:10.1007/s11069-009-9401-4.

Kjekstad, O., and Highland, L.M., 2008, Economic and social impacts of landslides, *in* Sassa, D., and Canuti, P., eds., Landslides—Disaster risk reduction: Berlin, Springer-Verlag, p. 573–587.

Malamud, B.D., Turcotte, D.L., Guzzetti, F., and Reichenbach, P., 2004, Landslide inventories and their statistical properties: Earth Surface Processes and Landforms, v. 29, p. 687–711, doi:10.1002/esp.1064.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., and Jaedicke, C., 2006, Global landslide and avalanche hotspots: Landslides, v. 3, p. 159–173, doi:10.1007/s10346-006-0036-1.

Newman, M.E.J., 2005, Power laws, Pareto distributions and Zipf's law: Contemporary Physics, v. 46, p. 323–351, doi:10.1080/00107510500052444.

Parker, R.N., Densmore, A.L., Rosser, N.J., de Michele, M., Li, Y., Huang, R.Q., Whadcoat, S., and Petley, D.N., 2011, Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth: Nature Geoscience, v. 4, p. 449–452, doi:10.1038/ngeo1154.

Petley, D.N., 2010a, Landslide hazards, *in* Alcantara-Ayala, I., and Goudie, A., eds., Geomorphological hazards and disaster prevention: Cambridge, UK, Cambridge University Press, p. 63–74.

Petley, D.N., 2010b, On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia: Quarterly Journal of Engineering Geology and Hydrogeology, v. 43, p. 487–496, doi:10.1144/1470-9236/09-001.

Petley, D.N., Dunning, S.A., and Rosser, N.J., 2005, The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities, *in* Hungr, O., et al., eds., Landslide risk management: Amsterdam, A.A. Balkema, p. 367–374.

Sanchez, C., Lee, T.-S., Young, S., Batts, D., Benjamin, J., and Malilay, J., 2009, Risk factors for mortality during the 2002 landslides in Chuuk, Federated States of Micronesia: Disasters, v. 33, p. 705–720, doi:10.1111/j.1467-7717.2009.01105.x.

Sapir, D.G., and Misson, C., 1992, The development of a database on disasters: Disasters, v. 16, p. 74–80, doi:10.1111/j.1467-7717.1992.tb00378.x.

Sepúlveda, S.A., Rebolledo, S., and Vargas, G., 2006, Recent catastrophic debris flows in Chile: Geological hazard, climatic relationships and human response: Quaternary International, v. 158, p. 83–95, doi:10.1016/j.quaint.2006.05.031.

United Nations, 2011, World population prospects—The 2010 revision: http://esa.un.org/unpd/wpp/unpp/panel_population.htm (April 2012).

Webster, P.J., Magana, V.O., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M., and Yasunari, T., 1998, Monsoons: Processes, predictability, and the prospects for prediction: Journal of Geophysical Research (Oceans), v. 103, p. 14,451–14,510, doi:10.1029/97JC02719.

Wieczorek, G.F., and Leahy, P.P., 2008, Landslide hazard mitigation in North America: Environmental & Engineering Geoscience, v. 14, p. 133–144, doi:10.2113/gseegeosci.14.2.133.

Wysession, M.E., Okal, E.A., and Miller, K.L., 1991, Intraplate seismicity of the Pacific Basin, 1913–1988: Pure and Applied Geophysics, v. 135, p. 261–359, doi:10.1007/BF00880241.

Xie, P.P., Janowiak, J.E., Arkin, P.A., Adler, R., Gruber, A., Ferraro, R., Huffman, G.J., and Curtis, S., 2003, GPCP pentad precipitation analyses: An experimental dataset based on gauge observations and satellite estimates: Journal of Climate, v. 16, p. 2197–2214, doi:10.1175/2769.1.

Manuscript received 18 January 2012
Revised manuscript received 15 April 2012
Manuscript accepted 23 April 2012

Printed in USA