W

WARNING SYSTEMS

Graham S. Leonard[1], David M. Johnston[2],
Chris E. Gregg[3]
[1]Massey University, Lower Hutt, New Zealand
[2]GNS Science, Massey University, Lower Hutt,
New Zealand
[3]East Tennessee State University, Johnson City, TN, USA

Synonyms

Alerting system; Early warning systems; End-to-end warning system; Immediate warning system; Short fuse warning

Definition

A *warning system* is a network of interrelated sensors and processes that detect signals of a possible or imminent dangerous event and provide *information* that people can use to make protective action decisions before the moment of impact.

A *natural hazard warning system* is usually technology based, monitors signs of a natural hazard, evaluates the signs against rules and notifies people, triggering a human response.

End-to-end warning systems consider, or are owned by, responding communities.

Early warning systems are often synonymous with warning systems.

Public notification systems are the mechanisms by which the public are notified within a warning system.

Natural warnings are provided by nature. They are often synonymous with *environmental* cues, but are distinguished from them in that some geological or meteorological phenomena, for example, serve as a warning of an event, whereas other phenomena serve only as a cue that an event may occur.

Informal warnings are provided by people not acting in an official warning capacity (e.g., a friend calling another friend to alert them of a dangerous event).

Official warnings are provided by people acting in an official warning capacity.

Social warnings or social cues are provided via observations of other people's behavior.

Introduction

Warnings are a natural part of everyday life for humans. When we detect fear or pain our built-in biological warning system is letting us know something unusual is happening and that it may be detrimental to our health. *Natural hazard warning systems* are usually technological, designed to detect hazardous events and inform us of those events in a time frame that permits us to take protective action, perhaps through evacuation, sheltering, or protecting property (see Lindell and Perry, 2004). The use of a canary to detect gas in a coal mine is one early and well-known warning system. In this case, a miner's canary encapsulates two core components of most warning systems: monitoring (canary biology) and notification (the canary stops singing). Warning system research has increasingly recognized the need for "people centered" warning systems (summarized by Basher, 2006), which are not considered effective unless they trigger appropriate human behavior. This requires that the hazard detection and monitoring aspects of a warning system be integrated with emergency management and the public. Such an integrated warning system focused on reaching at-risk communities, ideally managed and owned by those communities, is often referred to as an "end-to-end" warning system.

A warning system is only as effective as its weakest link. That is, a failure of one component may render the whole system ineffective. An effective warning system requires the integration of several features of warnings in

P.T. Bobrowsky (ed.), *Encyclopedia of Natural Hazards*, DOI 10.1007/978-1-4020-4399-4,

the design of the system. These include (a) Standard Operating Procedures (SOPs) of scientists and emergency managers, (b) channels of message dissemination, and (c) public response (Sorensen, 2000). Redundancy, especially in communication and notification technologies and SOPs, reduces the chance of a broken link. Warning systems that are solely "hardware based" with no focus on community response or participation have proven ineffective.

Warning systems and risk management

Warning systems are one *risk management* option available to reduce the *risk* posed by a *hazard*. It is therefore advisable to complete a *risk assessment* before embarking on developing a warning system. A 100% reliable warning system does not exist for any hazard, which leaves some level of residual risk (Sorensen, 2000). This is especially true in the case of infrequent, difficult to detect, or short lead-time hazards. Development of a warning system may also increase risk by perpetuating the occupation of marginal land (Sorensen, 2000). A flood warning system, for example, may encourage development in the floodplain where it would otherwise not be desirable. *Land use planning* and *structural mitigation* are additional risk reduction options, which for some hazards have the potential to remove the risk entirely. For example, in the case of land use planning, if a hazardous location is not developed or otherwise occupied then risk is reduced or eliminated. In such a situation, no warning system is needed. Some combination of land use planning, structural mitigation, and warning systems is often recommended to maximize risk reduction and use of land. Increasing development and population growth in coastal areas and increasing diversity in global travelers, especially visitors to coastal areas, demands that warnings are issued for multiple languages, a point underscored by the loss of life of visitors from some two dozen countries in the 2004 Indian Ocean tsunami. This requires additional complexity in warnings and other risk communications.

Monitoring, forecasting, and prediction

A warning system is dependent upon reliable *detection and monitoring* of an event or hazardous processes. In order to provide maximum response time, a warning system is designed to detect a change in a monitored parameter and provide a clear indication (forecast or prediction) when a hazardous event is expected to occur. Warning for natural hazards relies on lead-time between detection of a precursory sign(s), or the event or hazards themselves, and the impact of the hazard. Longer lead-times correspond to improved decision making, notification, and human response. The "lead-time" of a hazard varies considerably across hazards. For example, hurricanes have a particularly long lead-time measured in days, whereas earthquakes have little lead-time, often measured in a few seconds at best. Onset of the hazard event must be able to be predicted with a degree of certainty, and within a relatively small time window, to be of use in decision making concerning response. Some hazards, such as earthquakes, can only be predicted to within decades or centuries. Although this is not considered to be a traditional warning system, it can be very useful to inform other risk management strategies with enough time for changes, such as land use planning, to be implemented (Sorensen, 2000).

Hazards with warnings

A given warning system is often proposed and developed for a single natural hazard, despite the fact that most communities are exposed to multiple hazards. Warning systems and other risk management strategies should be considered in an all-hazard context wherever practical to achieve maximum community resilience (Paton, 2003). Only a few hazards regularly have no currently detectable precursors: earthquakes; dry landslides; landslide-induced tsunamis; and mud volcanoes, for example. Other hazards usually have detectable precursors, but in some cases such as small volcanic eruptions, the precursors are below detectable levels. Warnings based upon the onset of the hazard event itself, as opposed to a precursor, are theoretically possible for all hazards. These post-onset warning systems have typically short lead-times with the extreme case being earthquakes. Several countries (e.g., Mexico City, Japan, USA, and Taiwan) have implemented or are testing an earthquake warning system that gives seconds of lead-time once an earthquake is detected by issuing warnings after non-damaging seismic Primary waves are detected but in advance of the damaging Secondary and Surface waves (Cyranoski, 2004). This may provide sufficient time to shut down critical infrastructure such as trains or gas lines, or start alternate generators in hospitals and for people to drop, cover and hold. Such warnings are more likely to be useful with increasing distance from the epicenter, but only up to a distance where the intensity of ground shaking is potentially damaging. It is not very useful for near source areas because the time between the arrival of the Primary waves and subsequent damaging waves is too short.

Decision to warn

For a warning system to notify the public, a specific warning message needs to be generated and a notification disseminated. Issuing a warning notification requires that a criteria or threshold within monitored parameters must usually be reached. Such criteria often include geographic location and magnitude, or the expected intensity. Determination as to whether or not the criteria have been met must be rapid, but some decision time is nearly always needed and this should not be underestimated. The most effective warning system will minimize the frequency of warnings for events that either do not happen or are much smaller in magnitude or intensity than expected. Emergency managers are often overcautious of the potential to "cry wolf." However, research has shown that only repetitive false alarms will begin to reduce human behavioral response rates, as long as the reason for false alarms is disclosed by officials and understood by recipients (Dow and Cutter, 1998).

Interpretation of initial data for the purpose of evaluating whether an event will actually occur may have high uncertainty. As time progresses more data often become available; but the time until the impact of the event is also reduced during this time. There is a minimum time period before an event within which a warning must be given if it is to achieve the expected response actions, such as evacuation of a population. Setting criteria for the decision to warn involves a trade-off over time between decreasing uncertainty or error and decreasing the time remaining to respond once a warning is issued. These criteria influence critical response actions such as evacuation. Emergency managers often find the criteria particularly difficult to set. This can be compounded in cases where a decision is either "yes" (evacuate) or "no" (do not evacuate), because scientists usually often provide information to emergency managers in the form of probabilities. Decision support systems, with preplanned probability thresholds and critical timeframes, reduce the time required to make decisions and issue warnings or evacuations.

Dissemination of warning messages

The process of detecting and monitoring a hazardous event and disseminating a notification requires time, which must be allowed for when planning response times. Notifications are usually technological and sent through telephone, radio, television, etc., but warnings may also be perceived directly from natural processes in one's environment. With the correct prior knowledge, a wide range of natural phenomena can be interpreted by members of the public either as a warning of an imminent event or as a cue to simply be alert. These notifications are termed "natural warnings" or "environmental cues" and include earthquake-generated ground shaking preceding the arrival of a tsunami and heavy rainfall or a high rate of *river stage* rise preceding a flood. If the time between onset of precursor signs and a hazard is too short for official warnings to be issued or if a warning system does not exist or fails to disseminate a warning message, natural warnings or environmental cues may be the only warning (Gregg et al., 2007).

Warnings from one person to another can be classed as either "official" or "informal." Official warnings are those communicated by people acting in an official capacity to do so. They are preplanned and the most likely to be accurate. Informal warnings are warnings communicated by individuals not acting in an official capacity. They may increase the reach of, or occur in place of, official warnings (which may have failed or been too slow to be useful). Informal warnings are often diffused through a population in advance of official warnings (Sorensen and Mileti, 1989; Gregg et al., 2007). Because natural warnings or environmental cues sometimes provide the first and only warning of an event and informal warnings are often received before official warnings, it is significant that those developing official warning systems understand how receipt of different warnings and cues in time and space influences response.

Technological notification systems can be grouped into either "third party" systems that are usually used for a non-warning-related purpose or "dedicated" systems that exist for the specific purpose of warning notification, such as those used in industrial settings where hazardous material is handled. There are wide ranges of warning notification technologies available and new possibilities continuously emerge.

Third party systems include:

- Radio and television station broadcasts
- Break-in broadcast
- Landline telephone
- Mobile telephone/device (Short Message Service (SMS) text message, broadcast, multicast)
- Pagers
- Websites
- Inserted website banners
- E-mail
- Emergency responders and their hardware (e.g., route alert with car/appliance loud-hailers)
- GPS receiver messaging
- Power-line messaging
- Loudspeakers (e.g., those separately used for public address or prayer calls)

Dedicated systems include:

- Tone-activated alert radio
- Private radio
- Sirens
- Flares and explosives.

The advantage of third party systems is that they are often self-maintaining and self-testing through regular use (e.g., telephones). Dedicated notification systems generally have a higher rate of failure, unless very regularly tested in realistic conditions and designed with redundancy (Gruntfest and Huber, 1989). Notifications that catch a person's attention even though they are focused on something else (e.g., telephone or siren) are more effective than those where the target person will only get the message if they are actively using the notification pathway (e.g., watching television, viewing a website). A person's location and activity changes throughout the day, so one notification technology that might reach them at work might not reach them while they are recreating or asleep at home. Warnings at night are also more slowly disseminated and acted upon (Sorensen, 2000). Transient populations, especially tourists, may need notification via different means than local residents. This can be accentuated from season to season as tourists visit coastal areas in summer months or snowy mountains in winter months.

Weather conditions can alter the effectiveness of a system. Loud-hailers are harder to hear in wind, and cold weather may mean more people are inside insulated from outdoor notification systems. Mobile technologies provide an obvious opportunity to reach large numbers of people regardless of their location. SMS text messages have been used to warn of many hazard events in recent years, with mixed success. Generally, delivery time may increase as the number of messages increases, and delivery is not guaranteed (Sillem and Wiersma, 2006). Lists of phone numbers need to be created through either a voluntary preregister, with typically very low uptake, or generated for an area at the time of warning, which introduces a further time lag. Mobile "cell broadcast" and "multicast" protocols can be implemented to send a message to all devices on that network in a geographic area. The advantages over SMS appear to be high speed, low traffic volume, geographic control, and avoidance of requiring phone number lists. These protocols are currently being tested (e.g., Sri Lanka, Samarajiva and Waidyanatha, 2009; Netherlands, Jagtman, 2010). Break-in broadcasting takes precedence over standard radio and television channels via an automated protocol. In the United States this is a cornerstone of the Emergency Alert System and is mandated by legislation. Land-line telephones, when used in warning systems, are usually utilized by auto-dialer equipment, by people enacting prearranged phone trees or as call-in phone lines. Computer control of notification systems has enabled greater speed and geographical control for many of the warning technologies listed, especially mobile and landline-based telephones (Sorensen, 2000).

Warning systems should also consider other populations with special needs including groups based on gender, age, language, and disability. For example, perceptual changes in older adults can impair their ability to notice warnings during the alerting phase, whereas limitations in cognitive abilities, such as text comprehension and memory, might limit their understanding in the decision-making and response phase. These issues also apply to other disabled groups, who may need special assistance to compensate for their physical and/or cognitive disabilities. Special consideration is needed for notification of institutional populations including hospitals, prisons, nursing homes, large worksites, and tourist facilities. Warning systems can specifically utilize community networks (e.g., church, ethnic social groups, volunteer fire fighters), capitalizing on their already-established communication networks and also aiding in reaching those who might otherwise be isolated (e.g., by geography, language).

Warning messages

The format and content of an official warning message is critical to its effectiveness. The most effective messages: are detailed, contain local information, are specific, explain the event, specify location, give instructions, are time-stamped with a time frame for the next message, are verifiable; come from a specific authoritative source, are frequent, and are consistent across notification media (Mileti and Beck, 1975; Lindell and Perry, 1983; Mileti et al., 2004; Sorenson and Mileti, 1989). Templates allow for consistent warning information to be given, reducing the chance that important content is forgotten. Data interoperability is of increasing importance to propagate a warning message through multiple technological systems. The Common Alerting Protocol (CAP; Oasis Open, 2005), for example, provides consistent machine-readable headings and metadata; therefore, a message generated by a CAP-compliant system can be propagated through and notified via all other CAP-compliant systems. Protocol-based interoperability reduces the chance of parts of the message being dropped or changed, increasing consistency of the message, as well as reducing any time required to retype and edit messages.

Education, participation, and response

Social aspects of warning systems are often underemphasized compared to the scientific and emergency management aspects. This focus on the science of detecting and monitoring hazards and the hardware and software linking scientists to emergency managers limits a system's ability to ultimately deliver messages to end-users or motivate the public to comply with warning messages (Sorensen, 2000; OEM and ODGAMI, 2001; Twigg, 2002; Mileti et al., 2004). For example, engaging community members at large in the development of warning systems, and maintaining adequate levels of public education about the dynamics of warning messages including expected human responses, seldom occurs. Passive education through brochures and advertisements has been shown to have only limited effect (Paton 2006). Community-based planning for effective warning responses is needed to help ensure that people understand messages and know what to do. For warning systems to be effective they must ensure that factors beyond knowledge and understanding are incorporated into education. Individuals first need to become motivated to confront hazards they face in their local environment, and then form intentions to actually make preparations. Improved preparedness is likely to result from enhancing community members' beliefs in the feasibility of successfully responding to a warning through personal actions (i.e., to counter beliefs that hazards have totally catastrophic effects) and enhancing beliefs in personal competency to implement these activities (i.e., self-efficacy). Changing these factors requires a mix of public education, social policy, training, and empowerment strategies. Full scale exercises that allow people to experience the breadth of warnings and response, such as that obtained during evacuation or sheltering drills, are rare. However, exercises are one of the most effective means of education and are most important for hazards with long time periods between events (years to decades).

Summary

Warning systems for natural hazards provide notification of potential hazard events through the monitoring of natural processes. Monitoring is usually technological with a wide range of detection and notification hardware available and in use. Warning sources can be natural, informal, or official and if available time to respond is short, natural and informal warnings may be the only source of information before impact of a hazard. In recent years there has been an increasing focus on end-to-end warning systems, which focus heavily on community involvement, preparedness, and warning response actions. Response actions are usually to either evacuate or shelter in place, with the added complexity of sometimes protecting valuables. Decisions to disseminate a warning are often difficult to make, especially if the desired response is to evacuate, because as certainty of the onset or specifics of a hazard such as location, magnitude, and intensity increases over time the time remaining to respond decreases. The delivery and content of a warning message has been heavily studied and there are a range of characteristics of effective warning messages. Warning systems are often not fully effective, so they should be considered along with a range of risk management options, especially land use planning.

Bibliography

Aguirre, B. E., 2004. Homeland security warnings: lessons learned and unlearned. *International Journal of Mass Emergencies and Disasters*, **22**, 103–115.

Basher, R., 2006. Global early warning systems for natural hazards: systematic and people-centred. *Philosophical Transactions of the Royal Society A*, **364**, 2167–2182.

Cyranoski, D., 2004. Earthquake prediction: a seismic shift in thinking. *Nature*, **431**, 1032.

Dengler, L., 2005. The role of education in the National Tsunami Hazard Mitigation Program. *Natural Hazards*, **35**, 141–153.

Dow, K., and Cutter, S., 1998. Crying wolf: repeat responses to hurricane evacuation orders. *Coastal Management*, **26**, 237–252.

Gregg, C. E., Houghton, B. F., Paton, D., Lachman, R., Lachman, J., Johnston, D. M., and Wongbusarakum, S., 2006. Natural warning signs of tsunamis: human sensory experience and response to the 2004 Great Sumatra earthquake and tsunami in Thailand. *Earthquake Spectra*, **22**, 671–691.

Gregg, C. E., Houghton, B. F., Paton, D., Johnston, D. M., Swanson, D. A., and Yanagi, B. S., 2007. Tsunami warnings: understanding in Hawai'i. *Natural Hazards*, **40**, 71–87.

Gruntfest, E. C., and Huber, C., 1989. Status report on flood warning systems in the United States. *Environmental Management*, **13**, 279–286.

Handmer, J., 2000. Are flood warnings futile? Risk communication in emergencies. *The Australasian Journal of Disaster and Trauma Studies*, 2000–2, http://www.massey.ac.nz/~trauma/issues/2000-2/handmer.htm

Jagtman, H. M., 2010. *Cell broadcast trials in The Netherlands: Using mobile phone technology for citizens' alarming Reliability Engineering and System Safety*, **95**, 18–28.

Johnston, D. M., Becker, J., Gregg, C., Houghton, B., Paton, D., Leonard, G., and Garside, R., 2007. Developing warning and disaster response capacity in the tourism sector in coastal Washington, USA. *Disaster Prevention and Management*, **16**, 210–216.

Leonard, G. S., Johnston, D. M., Paton, D., Christianson, A., Becker, J., and Keys, H., 2008. Developing effective warning systems: ongoing research at Ruapehu volcano, New Zealand. *Journal of Volcanology and Geothermal Research*, **172**, 199–215.

Lindell, M. K., and Perry, R. W., 1983. *Nuclear Power Plant Emergency Warnings: How Would the Public Respond?* February: Nuclear News, pp. 49–57.

Lindell, M. K., and Perry, R. W., 2004. *Communicating Risk in Multiethnic Communities*. Thousand Oaks: Sage. 262 pp.

Mileti, D. S., and Beck, E. M., 1975. Communication in crisis: explaining evacuation symbolically. *Communication Research*, **2**, 24–49.

Mileti, D. S., and Sorensen, J. H., 1990. *Communication of emergency public warnings*. Oak Ridge: Oak Ridge National Laboratory.

Mileti, D., Nathe, S., Gori, P., Greene, M., and Lemersal, E., 2004. *Public Hazards Communication and Education: The State of the Art*. Boulder: Natural Hazards Informer. Issue 2.

Oasis Open, 2005. *Common Alerting Protocol, v1.1: OASIS Standard CAP-V1.1*. Billerica: Oasis Open. 35p.

OEM, and ODGAMI, 2001. Tsunami Warning Systems and Procedures guidance for local officials., Oregon Department of Geology and Mineral Industries (ODGAMI) Special Paper 35, Portland.

Partnership for Public Warning (PPW), 2003. *A National Strategy for Integrated Public Warning Policy and Capability*. Report 2003–01. Partnership for Public Warning, McLean

Paton, D., 2003. Disaster Preparedness: A social-cognitive perspective. *Disaster Prevention and Management*, **12**, 210–216.

Paton, D., 2006. Disaster resilience: integrating individual, community, institutional and environmental perspectives. In Paton, D., and Johnston, D. (eds.), *Disaster Resilience: An integrated approach*. Springfield: Charles C. Thomas.

Quarantelli, E. L., 1984. Perceptions and reactions to emergency warnings of sudden hazards. *Ekistics*, **51**, 511–515.

Samarajiva, R., and Waidyanatha, N., 2009. Two complementary mobile technologies for disaster warning. *Info*, **11**, 58–65.

Sillem, S., Wiersma, E., 2006. Comparing cell broadcast and text messaging for citizen warning. In *Proceedings of the 3rd International ISCRAM Conference*, Newark, pp. 147–153.

Sorensen, J. H., 2000. Hazard warning systems: review of 20 years of progress. *Natural Hazards Review*, **1**, 119–125.

Sorensen, J., and Mileti, D., 1989. Warning and evacuation: answering some basic questions. *Industrial Crisis Quarterly*, **2**, 195–210.

Twigg, J., 2002. The human factor in early warnings: risk perception and appropriate communications. In Zschau, J., and Kuppers, A. N. (eds.), *Early Warning Systems for Natural Disaster Reduction*. Berlin: Springer, pp. 19–26. Voight.

UN/ISDR Platform for the Promotion of Early Warning (UN/ISDR-PPEW), 2006. *Developing Early Warning Systems: A Checklist*. Bonn: United Nations International Strategy for Disaster Reduction (UN/ISDR).

Cross-references

Automated Local Evaluation in Real Time (ALERT)
Communicating Emergency Information
Disaster Risk Management
Disaster Risk Reduction (DRR)
Early Warning Systems
Evacuation
Geographic Information Systems (GIS)
Geographical Information Technology
Global Seismograph Network (GSN)
Hyogo framework for action 2005–2015
Inclinometer
International Strategies for Disaster Reduction (IDNDR and ISDR)
Internet, World Wide Web and Natural Hazards
Land-Use Planning
Pacific Tsunami Warning and Mitigation System (PTWS)

Queensland Floods (2010–2011) and "Tweeting"
Resilience
Sociology of Disasters
Structural Mitigation
Susceptibility
Tiltmeters
Uncertainty
Vulnerability
Zoning

WATERSPOUT

Miquel Gayà
Agencia Estatal de Meteorología, Palma, Spain

Synonyms

Whirlwind

Definition

Waterspout is an intense vortex of air, linked to convection, with small horizontal dimension (tens of meters to a few hundred meters), which occurs on a surface of water, usually on the sea. With this definition, waterspouts are no different than tornadoes, except in the area on which they occur.

Discussion

Tornadoes and waterspouts can be formed in association with a supercell cloud (containing mesocyclone) or linked to a "fair" weather. When the vortex is generated by a supercell, its damage, intensity, duration, and path length normally increase. However, waterspouts usually are generated in an environment with weak convection, with low level unstable air, and in conjunction with a convergence zone that had an inherent vorticity. Because these convergent areas are very common close to shores, many waterspouts can be seen from the coast, sometimes reach land and continue inland as a tornado. Often, the land roughness perturbs and destroys one of the ingredients to form the waterspout and this new tornado vanishes quickly. The other essential ingredient to form a waterspout is the instability of the low-level atmosphere. This instability comes from a high lapse rate at low troposphere (difference of temperature between the air closest to the sea and 3,000 m height) and from its high moisture content.

Because warm seas provide the air its high water vapor, and also can produce a large lapse rate of temperature, such warm seas will be the most frequent waterspout generators. Thus, when cold air overrides a warmer sea, waterspouts can appear. For these reasons, the tropical and subtropical seas are those water surfaces with a high incidence of waterspouts. Still, sometimes waterspouts have been observed over cold waters if the unstable air is much colder. On the polar seas, such vortices cannot occur.

Waterspout, Figure 1 A waterspout over the Mediterranean sea, close to the coast of Formentera, Balearic Islands (Spain), on September 20, 2009 (Courtesy of Barbara Klahr).

Converging air intensifies its vertical vorticity when the condensation is produced. A convective cloud (not necessarily a *Cumulonimbus*) grows at the same time as the funnel cloud seems to be pendant: the waterspout is typically developed early in the *Cumulus* life cycle. When the parent cloud produces its first drops, the downflow can destroy the convergence line and the vorticity starts to diminish. Then, the waterspout initiates its last step before termination. If the conditions are similar, the front produced by the precipitation can generate another focus of convergence and the process of another waterspout can start again. Often, over the same convergence boundary or front, it can be possible to see a family of waterspouts.

Although the rough surface of the sea can be observed, the water itself is not lifted to the cloud. The funnel is a cloud of droplets produced by the condensation of the water vapor. The dimensions and the maximum velocity that a waterspout reaches can be dangerous to small boats or to ships. People may be displaced and thrown into the sea. The masts can be broken and the objects that were on the deck can become projectiles with fatal consequences (Figure 1).

Bibliography

Doswell C. A., 2001. Severe convective storms: an overview. In *Severe Convective Storms*. Meteorological Monographs, Vol. 28, No. 50, American Meteorological Society, pp. 1–26.

Golden, J. H., 1974. Scale-interaction implications for the waterspout life cycle II. *Journal of Applied Meteorology*, **13**, 693–709.

Cross-references

Cloud Seeding
Doppler Weather Radar
Dvorak Classification of Hurricanes
Fujita Tornado Scale

Hurricane (Cyclone, Typhoon)
Hydrometeorological Hazards
Monsoon
Saffir–Simpson Hurricane Intensity Scale
Storms
Thunderstorms
Torino Scale
Tornadoes

CASE STUDY

WENCHUAN, CHINA (2008 EARTHQUAKE)

Zhengwen Zeng[1], Chenghu Wang[1,2]
[1]University of North Dakota, Grand Forks, ND, USA
[2]China Earthquake Administration, Beijing, China

Introduction

On May 12, 2008, at 14:28:04 (Beijing Time), an Ms 8.0 earthquake struck Wenchuan, a small county of Sichuan Province in southwest China. The quake lasted for about 18 s. The geographic coordinates of the epicenter were N30°57′ and E103°24′; and the focal depth was estimated at 14–19 km. The Wenchuan Earthquake sequences included one major shock (Ms 8.0) and many fairly large aftershocks (Yuan, 2008). Within 3 months after the major shock, over 20 aftershocks exceeded Ms 5.4. The main shock and the aftershock sequences were scattered along the seismic faults, as indicated in Figure 1 (USGS, 2008; China Earthquake Administration Monitoring and Prediction Division, 2009).

Geologically, the Ms 8.0 Wenchuan Earthquake occurred on the Longmenshan faulting belt, a large, active, partly strike-slipping, partly thrust-faulting belt in the middle of the north-to-south seismogenic zone and on the eastern edge of the Qinghai-Tibet Plateau in China. The instrumental epicenter was in the middle of the Longmenshan faulting belt, below Yinxiu Township at the west of Dujiangyan and the south of Wenchuan County (Figure 1). The northeast trending Longmenshan faulting belt belongs to a fault system that was formed by the Mesozoic orogenesis. It is 500 km long and 40–50 km wide. The fault belt starts at Luding and Tianquan, at its southwest end, passes through Baoxing, Guanxian, Jiangyou, and Guangyuan, all in Sichuan Provinces, and finally enters into Ningqiang and Mianxian in Shaanxi Province at its northeast end.

The Ms 8.0 Wenchuan Earthquake created two new surface fractures inside the Longmenshan faulting belt, that is, the Wenchuan Earthquake fractures. The major surface fracture is over 250 km in total length, extending parallel to the middle and northern sections of the Longmenshan faulting belt. The secondary surface fracture extends along the Guanxian-Jiangyou fault of the Longmenshan faulting belt, with a discontinuous length of 90 km.

The Wenchuan Earthquake was shallow-focused, and thus caused significant damage and loss. The relative location of the earthquake epicenter inside China is shown in Figure 2. This earthquake affected almost all the population within a radius of 200 km around the surface epicenter. Except Heilongjiang, Jilin, and Xinjiang, all provinces in mainland China were shocked by this terrible earthquake, with Sichuan, Shaanxi and Gansu suffering the most. The shock was also felt in several countries in eastern Asia, including Thailand, Vietnam, Philippines, and Japan. Based on the Chinese Seismic Intensity Scale (CSIS), the intensity of the Wenchuan Earthquake is shown in Figure 3 (China Earthquake Administration Monitoring and Prediction Division, 2009).

According to detailed investigations after the earthquake, the disaster area was classified into four categories of damage: (1) extremely severe, (2) severe, (3) heavily affected, and (4) slightly affected (National Disaster Relief Commission, 2008). The distribution of the four categories and the demographical statistics are shown in Table 1.

Casualties

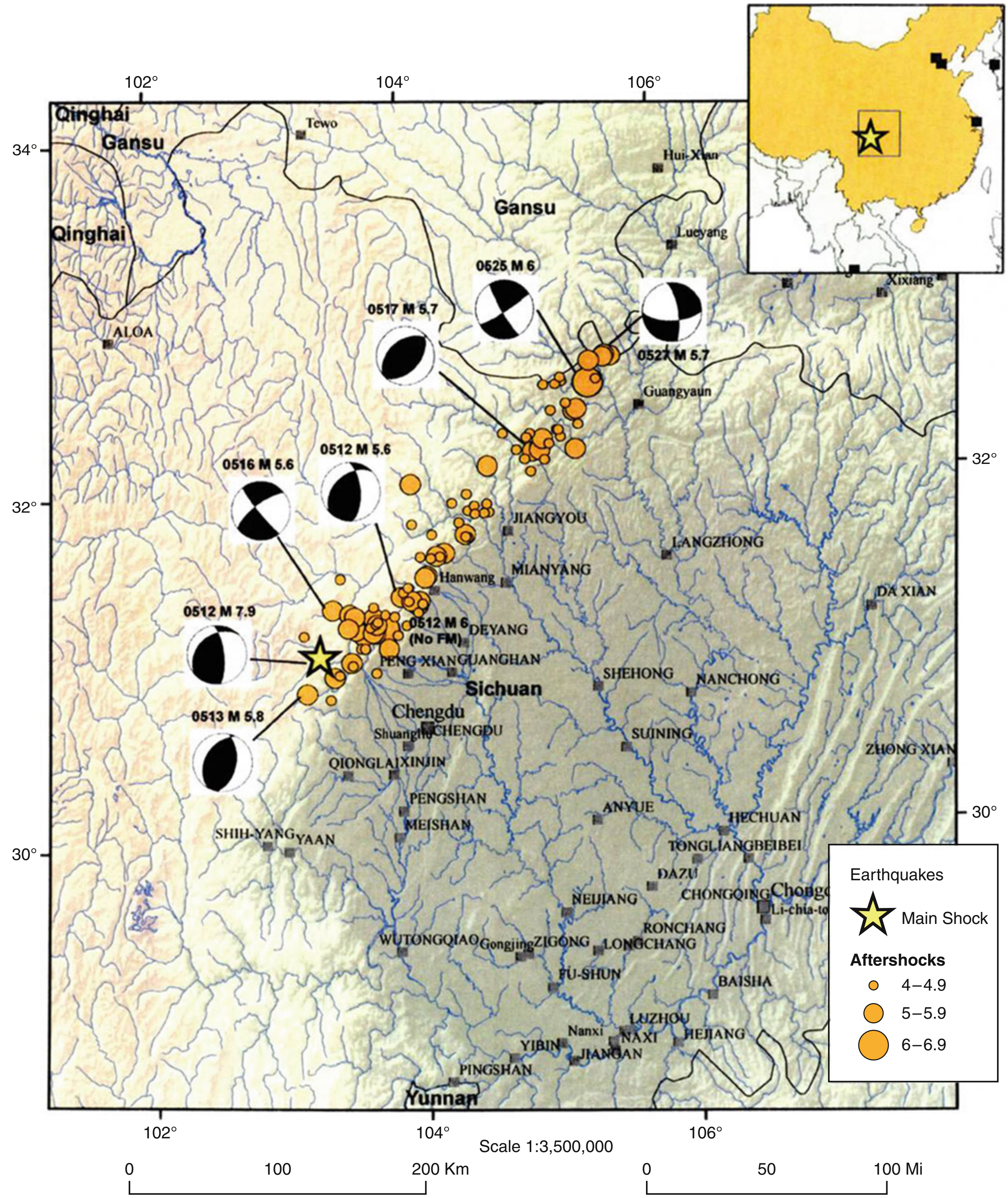
As of May 5, 2009, 69,220 people died, 374,643 people were injured, and 17,923 people were missing as a result of the Wenchuan Earthquake. The casualty statistics of each province are shown in Table 2 (National Disaster Relief Commission, 2008). Table 3 indicates the extent to which the extremely severe areas suffered in the categories of casualties and building collapses (National Disaster Relief Commission, 2008).

Economic losses

The Wenchuan Earthquake caused a direct economic loss of 845.14 billion RMB, approximately US$122.85 billion (2008 dollars) (National Disaster Relief Commission, 2008). Among all the losses, Sichuan Province suffered the most, accounting for 91.3% of the total losses; Gansu Province accounted for 5.8%; and Shaanxi Province accounted for 2.9%. The combined losses of other provinces were about two billion RMB (US$0.29 billion).

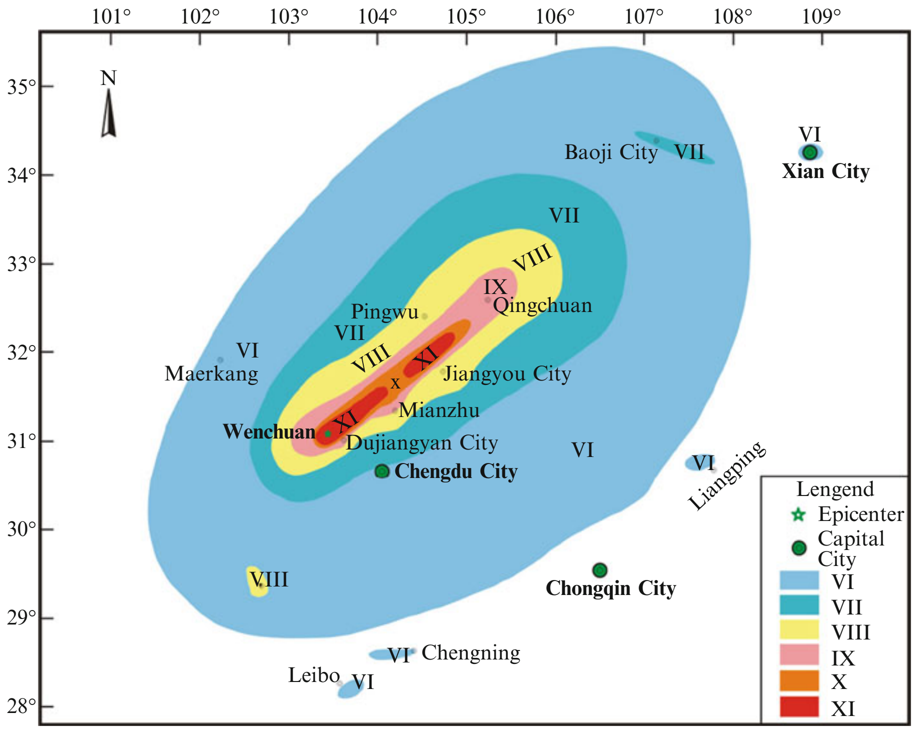
Among all the losses, buildings and infrastructures accounted for the most, up to almost 70% of the total losses. Ranked by the percentage share of the total losses, losses of civil buildings were ranked the first, at 24.7% of the total losses; infrastructure, including roads, bridges, and other municipal facilities, ranked second at 21.9%. Nonresidential buildings, including schools, hospitals, and other public buildings held third at 20.4% of the total losses.

The direct economic losses of the disaster areas comprised 2.81% of China's GDP in 2007. The losses of Sichuan Province alone accounted for 58.80% of the provincial GDP in 2007, and 2.51% of China's total GDP.



Wenchuan, China (2008 Earthquake), Figure 1 Distribution of main shock and aftershocks of the Wenchuan Earthquake, M - moment magnitude, preferably being used for M8+ shocks (After USGS, 2008; China Earthquake Administration Monitoring and Prediction Division, 2009).

Wenchuan, China (2008 Earthquake), Figure 2 Epicenter of the Wenchuan Earthquake in China.



Wenchuan, China (2008 Earthquake), Figure 3 CSIS-based intensity map of the Ms 8.0 Wenchuan Earthquake (China Earthquake Administration Monitoring and Prediction Division, 2009).

Wenchuan, China (2008 Earthquake), Table 1 Demographics of each category of the Wenchuan Earthquake severity (National Disaster Relief Commission, 2008)

Category	Number of districts and counties affected	Area (km^2)	Population ($\times$10,000)
Extremely severe	10 in Sichuan	26,000	365
Severe	26 in Sichuan	61,473	1,332
	7 in Gansu	20,293	190
	3 in Shaanxi	8,480	97
Heavily affected	103 in Sichuan 37 in Shaanxi, 33 in Gansu, 10 in Chongqing, 5 in Ningxia, and 3 in Yunnan	383,615	About 8,600
Slightly affected	180	10,410	About 8,100
Total	417	510,271	About 18,684

The population in the heavily and slightly affected areas was estimated

Wenchuan, China (2008 Earthquake), Table 2 Casualty statistics by provinces (National Disaster Relief Commission, 2008)

Province	Sichuan	Gansu	Shaanxi	Chongqing	Henan	Yunnan	Guizhou	Hubei	Hunan
Dead	68,712	365	121	16	2	1	1	1	1
Missing	17,921	2							
Injured	360,341	10,158	2,948	637	7	51	15	14	

Wenchuan, China (2008 Earthquake), Table 3 Casualties and building collapses in the category of “extremely severe” (National Disaster Relief Commission, 2008)

		Number of dead and missing		Number of collapsed buildings	
County or City	Total population ($\times$10,000)	Number of dead and missing	Number of dead and missing per 10,000 people	Number of building collapses	Number of collapses per 10,000 people
Wenchuan	11	23,871	2,170	608,198	55,291
Beichuan	16	20,047	1,253	347,856	21,741
Mianzhu	51	11,380	223	1,397,925	27,410
Shifang	43	6,132	143	1,006,921	23,417
Qinchuan	25	4,819	193	714,804	28,592
Maoxian	11	4,088	372	300,229	27,294
Anxian	50	3,295	66	774,896	15,498
Dujiangyan	61	3,388	56	655,265	10,742
Pingwu	19	6,565	346	299,557	15,766
Pengzhou	78	1,131	15	622,066	7,975

Earthquake prediction and preparation

Seismic zoning and earthquake preparation

China’s Code for Earthquake Resistant Design of Buildings and the Seismic Zoning Map (State Seismological Bureau, 1992) have been put into force to set standards for the buildings and infrastructures all over the country, but adherence to these codes and regulations were not compulsory in less-developed areas until 2006 because of economic factors. Before this earthquake, these codes and regulations set the maximum seismic intensity at CSIS VI for all the extremely severe disaster areas and at CSIS VII for a few of the more potentially severe disaster areas (Shi and Li, 2001), because there had been no large earthquakes in this area before these codes was established.

According to these earthquake resistant design codes, infrastructure in areas of CSIS VI and below would be built with no earthquake-resistant design. Earthquake-resistant design was only mandatory in areas of CSIS VII and above. Therefore, seismic resistant capabilities of buildings designed by such standards would not have met the required strength to withstand such a shallow focused Ms 8.0 earthquake.

Earthquake prediction

Whether the Wenchuan Earthquake was predicted or not aroused many controversies and rumors in both international and Chinese societies. Unlike the 1976 Tangshan earthquake in China, the middle section of the Longmenshan faulting belt – the meizoseismal area of the Wenchuan Earthquake – had been considered inactive before this earthquake according to analyses of Chinese mainstream earthquake experts. Compared with the middle section of the Longmenshan faulting belt, the Xianshuihe faulting belt, the Anninghe-Zemuhe-Xiaojiang faulting belt, and the Songpan-Ganzi faulting zone in the southwest China had more tectonic activities, and attracted much more research attention; thus, many seismic monitoring measures and research efforts were applied to those areas. However, prior to the Wenchuan Earthquake, a few Chinese specialists and American experts did give a fairly accurate middle-term prediction for the possible earthquake, and some advice for future research. Unfortunately, such predictions and research findings were not accepted by the mainstream earthquake experts in China. Obviously, earthquake prediction is still not an exact science and remains an unsolved world-class challenge. A large gap still exists between the actual problem-solving ability of scientists and the need for community disaster preparation.

Emergency responses and relief measures

After the occurrence of the Wenchuan Earthquake, the Chinese government immediately began an emergency rescue and relief program (China Earthquake Administration, et al., 2010). Headquarters for victim rescue and disaster relief were established all around the affected areas.

According to statistics issued by the Headquarters at the State Council, all relevant ministries and organizations of the Chinese central government had allocated a large amount of resources and exerted many efforts during the disaster relief campaign. As of May 24, 2008, the Headquarters had mobilized 111,278 soldiers, 22,970 armed policemen, 24,401 special policemen, 4,000 specialized earthquake rescue workers, 88,341 medical workers, and 6,013 volunteers to help in the disaster areas. As of June 14, 2008, the central government and the local governments had allocated 1.31 million tents, 4.82 million quilts, 14.09 million articles of clothing, 1.04 million tons of liquid fuel, and 2.23 million tons of coal to the disaster area. As of August 4, 2008, the central government and the local governments had devoted 64.16 billion RMB to the disaster areas, and about 59.41 billion RMB was received from public and private donations for the disaster relief.

After the occurrence of the Wenchuan Earthquake, the international society expressed its sincere sympathy to the Chinese people through the central government, together with various kinds of support. As of July 18, 2008, the Chinese Ministry of Foreign Affairs and other Chinese embassies and diplomatic missions all over the world had received about 1.71 billion RMB in donations, including 0.77 billion RMB from foreign governments, international, and regional organizations; 1.99 million RMB from foreign embassies, diplomatic missions, and individuals in China; and 0.94 billion RMB from foreign civilian organizations, foreign enterprises and individuals, overseas Chinese, Chinese scholars and students living overseas, overseas branches of China-based companies and organizations, and other individuals.

Recovery and reconstruction after the earthquake

One month after the Wenchuan Earthquake, the Chinese central government began to implement recovery and reconstruction work by establishing basic guidelines (Wen, 2008). At the same time, the relevant ministries jointly issued specific instructions to direct the recovery and reconstruction work. In September 2008, the State Overall Planning for Post-Wenchuan Earthquake Restoration and Reconstruction (SOP) was issued (State Planning Group, 2008).

According to the statistics issued by the China Ministry of Finance, by May 4, 2009, the Chinese central government had supplied almost 85 billion RMB to the disaster area for the recovery and reconstruction. By the end of 2009, 160 billion RMB from the central government and 17 billion RMB from the provincial government were allocated to the affected areas in Sichuan province. In addition, a total of 250 billion RMB was available from other provincial governments through the “Twin Assistance” program, social donations, contributions from Hong Kong, Macao, and Taiwan, and rehabilitation funds from the county and city governments of the affected areas.

Following the SOP, 29,704 recovery and reconstruction projects were planned for Sichuan Province, the worst-struck province, including 1,500,000 rural dwelling houses, 259,000 urban dwelling houses, 3,002 schools, 1,362 medical and health institutes (including hospitals), and 38 towns and cities.

As of March 2010, 95% of these projects were being implemented, and 74% were completed; special efforts were made to care for the most vulnerable groups (China Earthquake Administration, et al., 2010).

Parallel to the Chinese central government’s efforts, recovery projects assisted by international loans were also being implemented. The World Bank loaned a total of US $710 million to the Chinese central government for recovery and reconstruction projects in Sichuan and Gansu Provinces for a period of 5 years from March 2009 to March 2014 (World Bank, 2009). As of June 2010, US$116 million had been disbursed for infrastructure, health, and educational projects (World Bank, 2010). One year later, the cumulative disbursement reached 35% of the total loan, and the progress on the project was moderately satisfactory (World Bank, 2011).

In March 2012, the Chinese central government announced that the SOP recovery and reconstruction tasks were completed; the basic working and living conditions and the level of economic and social development in the disaster areas were significantly better than that before the earthquake (NDRC, 2012).

Bibliography

China Earthquake Administration Monitoring and Prediction Division, 2009. *Scientific Research Report of Ms 8.0 Wenchuan Earthquake (in Chinese)*. Beijing: Earthquake Press.

China Earthquake Administration, Department of Civil Affairs of Sichuan Province, International Labor Organization, United Nations International Strategy for Disaster Reduction and the International Recovery Platform, 2010. *Wenchuan Earthquake 2008: Recovery and Reconstruction in Sichuan Province, Recovery Status Report* (*#04*). International Recovery Platform Secretariat, Kobe.

National Disaster Relief Commission, 2008. *Comprehensive Analysis and Evaluation of the Wenchuan Earthquake Disaster (in Chinese)*. Beijing: Science Press.

NDRC, 2012. *Report on China's Economic and Social Development Plan*. National Development and Reform Commission, Beijing.

Shi, Z., and Li, Y., 2001. Seismic Zonation in China. *Engineering Sciences in China*, **3**(6), 65–68.

State Planning Group, 2008. *The State Overall Planning for Post-Wenchuan Earthquake Restoration and Reconstruction*. National Development and Reform Commission, State Council, Beijing.

State Seismological Bureau, 1992. *China Seismic Intensity Map (1:4,000,000) and Instructions (in Chinese)*. Beijing: Earthquake Press.

USGS, 2008. Earthquake Summary-Magnitude 7.9 Eastern Sichuan, China.

Wen, J., 2008. *Decree on Post-Wenchuan Earthquake Recovery and Reconstruction*. State Council, Beijing.

World Bank, 2009. *Loan Agreement (Wenchuan Earthquake Recovery Project) between People's Republic of China and International Bank for Reconstruction and Development*. Washington, DC.

World Bank, 2010. *Implementation Status & Results of China Wenchuan Earthquake Recovery Project (P114107)*. Washington, DC.

World Bank, 2011. *Implementation Status & Results of China Wenchuan Earthquake Recovery Project (P114107)*. Washington, DC.

Yuan, Y., 2008. Loss assessment of Wenchuan earthquake. *Journal of Earthquake Engineering and Engineering Vibration*, **28**(5), 10–19.

Cross-references

Casualties Following Natural Hazards
Earthquake
Earthquake Damage
Earthquake Prediction and Forecasting
Earthquake Resistant Design
Tangshan, China (1976 Earthquake)

WILDFIRE

Brigitte Leblon, Laura Bourgeau-Chavez
University of New Brunswick, Fredericton, NB, Canada

Synonyms

Burn; Bush fire; Fire; Forest fire; Natural fire; Wildland fire

Definition

A wildfire is an unplanned or unwanted natural or person-caused fire occurring in a natural setting or wilderness (Merrill and Alexander 1987: 44). A fire is a simultaneous release of heat, light, and flame generated by the combustion of flammable material (Merrill and Alexander, 1987: 12). It requires the so-called fire triangle elements: fuel, oxygen, and a heat source. Naturally occurring wildfires are less frequent than man-made wildfires, but usually burn large areas.

Types of wildfires

Several types of wildfires can be defined as a function of the fuel layer involved:

Type	Fuel layer	Remark
Ground or *subsurface*	Below the litter layer of the forest floor (duff, roots, buried punky wood, peat)	Difficult to detect
Crawling or *surface*	Low-lying vegetation (leaf and timber litter, debris, herbaceous vegetation, low-lying shrubbery)	Control depends on the type of fuels involved
Ladder	Between low-level vegetation and tree canopies (medium shrubs, tree seedlings, stumps, small trees, downed-dead logs)	Control depends on the type of fuels involved
Crown, canopy, or *aerial*	Suspended combustible material at the canopy level (tree crowns, vines, mosses)	Difficult to control because it depends on wind; Three types can be defined depending on whether it is dependent or independent of a surface fire
Spotting	Firebrands that are thrown ahead of the main fire by the wind	Difficult to control because it depends on wind

Fire regime

Fire regime refers to the general type of fire activity and pattern of burns that characteristically occur in a given region. Some important elements of fire regimes include fire frequency, fire intensity, type of fire, and burn severity (Merrill and Alexander, 1987). Fire regimes can range from low-intensity, high-frequency surface fires to high-intensity, low-frequency stand-replacing fires. The fire regime is determined by fire climate, lightning incidence, physiography, ecosystem type, and a balance between dry matter production and decay.

Fire risk, hazard, and danger

Ignition and spread of wildfires depends on four main types of factors (Leblon, 2005):

1. The state and nature of the fuel: proportion of live and dead vegetation, compactness, morphology, species, density, stratification, fuel arrangement, continuity of fuel, and moisture content;
2. The physical environment: weather conditions and topography
3. Causing factors: human or nature (lightning)
4. Fire prevention and suppression means

The first two factors define *fire hazard*, whereas the last two factors define *fire risk*. *Fire danger* includes both hazard and risk.

Fire danger rating systems

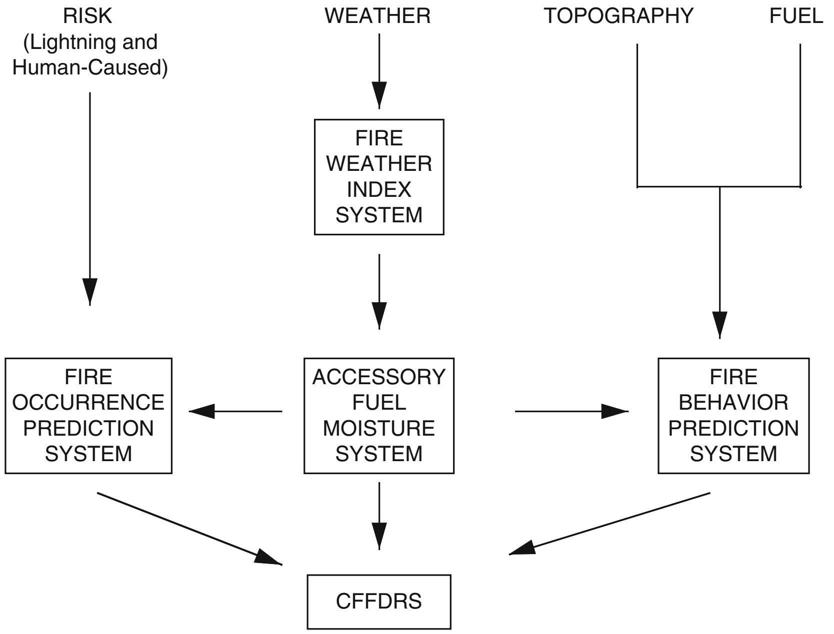
Wildfire is the one of the dominating disturbances in the world's forests and grasslands. Wildfire is part of the natural cycle. For some species, it is necessary to their reproductive cycle. For example, jack, pitch, red, yellow (ponderosa), and lodgepole pines, as well as sequoia and black spruce store for years live seed in their crown cones that are glued by resin. The resin will melt by heat from a fire, allowing the cone opening. Seed germination for red and white pines, white spruce and Douglas fir require ground that has been exposed by fire creating a good seed bed. Exposure to fire smoke promotes seed germination in some plants, like *Eragrostis tef (Zucc.) Trotter*, by inducing production of butenolide (3-methyl-2H-furo[2,3-c]pyran-2-one) (Ghebrehiwot et al., 2008). Despite their ecological benefits, wildfires can also become a threat to property, human life, and economy. For this reason, fire danger predicting systems have been developed for use in fire management, among others for fire suppression. Among others, there are the National Fire Danger Rating System (NFDRS) in USA (see the review of Hardy and Hardy, 2007) and the Canadian Forest Fire Danger Rating System (CFFDRS) in Canada (Van Wagner, 1987; Stocks et al., 1989; Taylor and Alexander, 2006). The CFFDRS is also used in Alaska and in some other parts of the world (see the review of Taylor and Alexander, 2006). It is a semiempirical modular system that has the structure shown in Figure 1.

The relative mid-afternoon fire potential is rated using the Fire Weather Index (FWI). It represents the intensity of a spreading fire. It is computed daily from noon standard time weather records (dry-bulb temperature, relative humidity, 10 m high open wind speed, 24-h precipitation), by one of the *CFFDRS* subsystems, the Fire Weather Index (FWI) system. It considers, as forest type, a generalized pine forest similar to the jack pine and lodgepole pine forest, but three fuel layers (Van Wagner, 1987; Stocks et al., 1989), each of them being characterized by its moisture content represented by a code: (1) *Fuel Moisture Code (FFMC)* for the 1–2 cm depth fine surface litter and other cured fine fuels (mosses, needles, small twigs) having a time lag of 2/3 day (16 h); (2) *Duff Moisture Code (DMC)* for the loosely compact duff of moderate depth (5–10 cm) having a time lag of 15 days; and (3) *Drought Code (DC)* for the deep (15–20 cm) compacted duff layer (organic matter of the soil, large logs) having a time lag of 52 days. *FFMC* determines the potential for fire ignition, *DMC*, the resistance to control of fire and the ability of the fire to spread, and *DC*, the seasonal drought, the smoldering in deep duff or large logs and the resistance to extinguishment and ability to mop-up. These fuel moisture codes are combined into two fire behavior indices: (1) *Initial Spread Index (ISI)* representing the relative fire spread expected immediately after ignition and (2) *Build-Up Index (BUI)* indicating the total amount of fuel available for combustion by a moving flame front. It is used in pre-suppression planning, indicates fire's resistance to control. *ISI* and *BUI* are combined together to produce *FWI* (see Figure 2).

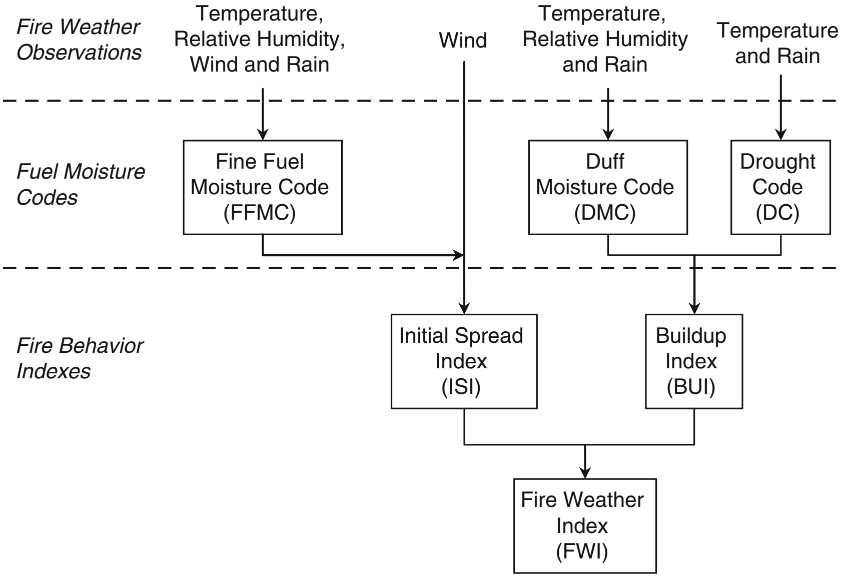
Another *CFFDRS* subsystem, the *Fire Behavior Prediction* (*FBP*) system, predicts the fire behavior in 17 specific fuel types (Stocks et al., 1989; Forestry Canada Fire Danger Group, 1992; Wotton et al., 2009).

Use of remote sensing in wildfire management

The availability of remote sensing technology coupled with the development of geostatistics and spatial analyses using geographic information technology allows moving fire danger rating from point-based estimates based on weather stations to spatially explicit estimates. Indeed, remote sensing has the advantages of larger sampling areas, lack of destruction of the studied resource, gathering data on less accessible areas and is representing, in essence, the integrated response of vegetation to environmental influences. Such a technology can be first used for fire danger monitoring. The first fire danger variable that can be derived from remote sensing is the fuel type, which can be mapped from high spatial resolution optical or radar images, as in classical land use (see the review of Leblon, 2005). Such maps can then be linked within a wildfire threat system, to other fire danger parameters, such as topography, proximity to roads and to urban areas (see the review of Leblon 2005). Fuel moisture is another fire danger parameter, which can be estimated by remote



Wildfire, Figure 1 The Canadian Forest Fire Rating System (CFFDRS) (After Stocks et al., 1989).

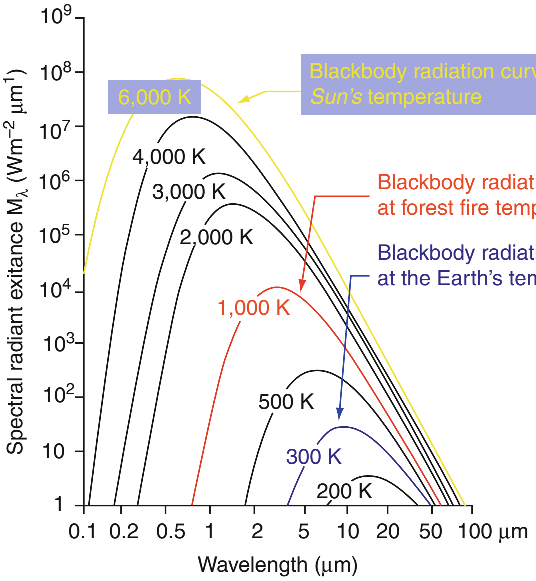


Wildfire, Figure 2 The Fire Weather Index of the CFFDRS (Adapted from Van Wagner, 1987).

sensing. Remote sensing–based fuel moisture monitoring has been done primarily using indices derived from *NOAA-AVHRR* normalized difference vegetation index (NDVI) images, like the *relative greenness* (Burgan et al., 1998) or the *Vegetation Condition Index* (Kogan, 1990). They were also used to estimate the degree of curing, which is an important fuel behavior variable for herbaceous fuel type (e.g., Paltridge and Mitchell, 1990). Thermal infrared data were better correlated than *NDVI* to fire danger codes (see the review of Leblon, 2005; Oldford et al., 2003; Oldford et al., 2006; Leblon et al., 2007) and to foliar moisture content (see the review of Leblon, 2005). There were also studies using indices that combine *NDVI* and thermal infrared *NOAA-AVHRR* images, like the *Vegetation and Temperature Condition Index* of Kogan (2001) and the index of Chuvieco et al. (2001). However, both *NDVI* and thermal infrared images have limited image availability during cloudy days. By contrast, active microwave (or radar or Synthetic Aperture Radar (*SAR*)) images can be acquired in any weather conditions. Good correlations were obtained between *CFFDRS* fuel moisture codes and backscatter images from *ERS-1* (Bourgeau-Chavez et al., 1999; Leblon et al., 2002) or *RADARSAT-1* (Abbott et al., 2007) single-polarized SAR images acquired over boreal forests. The operational use of *SAR* images in fuel moisture monitoring is limited by the influence of interfering factors, including the type, species, structure, and biomass of the vegetation, as well as the topography and surface roughness (see the review of Leblon, 2005). It has been shown that polarimetric *SAR* images are better for estimating the surface roughness independently from the soil moisture and vice versa in the case of agricultural bare soils or crop canopies (Mattia et al., 1997; Hajnsek et al., 2003; Hajnsek et al., 2009). Polarimetric *SAR* images are provided by several existing satellites, for instance, *RADARSAT-2* and *ALOS-PALSAR*. These images are currently being tested for fuel moisture mapping in boreal forests of the interior Alaska (Bourgeau-Chavez et al., 2009). Fuel moisture mapping is not only needed for assessing fire danger probabilities, but also for post-fire regeneration assessment, because vegetation regrowth highly depends on soil moisture availability.

Remote sensing can also be used for detecting active fires. Such detection is based on the detection of either a smoke plume produced by fire emissions, hot surface temperatures above normal environmental temperatures, or hot surface temperatures with respect to the surroundings. Detection of smoke plumes is achieved by optical sensors that are sensitive to atmospheric interferences. The detection of hot surface temperatures due to wildfires is done first using satellite sensors (*NOAA-AVHRR*, *MODIS*) operating in the mid-infrared (3–5 μm) spectral window. Indeed, as shown in Figure 3, wildfires have surface temperatures around 1,000 K leading to a peak of the spectral radiant exitance around 3 μm. By comparison, the Earth has a surface temperature of 300 K (leading to a maximum of exitance around 9.7 μm) and the Sun has a surface temperature of 6,000 K (leading to a maximum of exitance around 0.5 μm). The thermal infrared (8–12 μm) spectral window can also be used, but confusion with the Earth exitance peak can occur. A detailed description of the methods used for detecting active fires on satellite images can be found in the review by San-Miguel-Ayanz et al. (2005).

Finally, remote sensing technology can also be used to map burn scars, either from optical images, such as LANDSAT-TM or SPOT-HRV or from *SAR* images. Burned areas are mapped on the image either as spectrally homogeneous areas that are distinct from the surroundings or by comparison of prefire and postfire satellite imagery. In the optical and mid-infrared spectral bands, burned areas have usually a significant low spectral reflectance. Based on these observations, Fraser et al. (2000) designed the *Hotspot And NDVI Differencing Synergy (HANDS)* algorithm that uses *NOAA-AVHRR NDVI* and mid-infrared images to map burn scars. In their algorithm, the burned area mapping is helped by identifying potential active fires based on satellite-detected hot spots. However, similarly for other remote sensing applications, the use of optical and thermal infrared images is limited, when fire smokes or clouds mask the observed areas. For this reason, the use of single-polarized *SAR* imagery has been successfully tested both in the case of Mediterranean forests (Gimeno and San-Miguel-Ayanz, 2004a, b) and boreal forests (Bourgeau-Chavez et al., 1997). Both the optical and *SAR* images are also used for postfire regeneration assessment.



Wildfire, Figure 3 Spectral distribution of the emitted radiation of black bodies computed by Planck's law.

Summary

A fire is a simultaneous release of heat, light, and flame generated by the combustion of flammable material. The fire is a wildfire, when it corresponds to an unplanned or unwanted natural or person-caused fire, occurring in a natural setting or wilderness. Types of wildfires include ground, surface, ladder, crown, and spotting fires. Although wildfires have an ecological benefit for some species, they can also become a threat to property, human life, and economy. For this reason, fire danger predicting systems, including the National Fire Danger Rating System (NFDRS) in USA and the Canadian Forest Fire Danger Rating System (CFFDRS) in Canada, have been developed for use in fire management, among others in fire suppression. Fire danger is determined as a function of the state and nature of the fuel, of the physical environment, of the causing factors, and of the fire prevention and suppression means. With the availability of remote sensing technology coupled with the development of geostatistics and spatial analyses using geographic information technology, fire danger rating systems have been moved from point-based estimates from weather stations to spatially explicit estimates. Remote sensing can be used to map fuel types and fuel moisture, as well as to detect active fires and to map fire scars and post-fire regeneration.

Bibliography

Abbott, K., Leblon, B., Staples, G., Alexander, M., and MacLean, D., 2007. Fire danger monitoring in a northern boreal forest region using RADARSAT-1 imagery. *International Journal of Remote Sensing*, **28**(5–6), 1317–1338.

Bourgeau-Chavez, L. L., Harrell, P. A., Kasischke, E. S., and French, N. H. F., 1997. The detection and mapping of Alaskan wildfires using a spaceborne imaging radar system. *International Journal of Remote Sensing*, **18**(2), 355–373.

Bourgeau-Chavez, L. L., Kasischke, E. S., and Rutherford, M. D., 1999. Evaluation of ERS SAR data for prediction of fire danger in a boreal region. *International Journal of Wildland Fire*, **9**(3), 183–194.

Bourgeau-Chavez, L. L., Leblon, B., Charbonneau, F., Buckley, J., 2009. *Use of RADARSAT-2 polarimetric SAR images for fuel moisture mapping over boreal forests in interior Alaska*. Interim Report to the Canadian Space Agency, June 2009, 50 p.

Burgan, R. E., Klaver, R. W., and Klaver, J. M., 1998. Fuel models and fire potential from satellite and surface observations. *International Journal of Wildland Fire*, **8**(3), 159–170.

Chuvieco, E., Aguado, I., Cocero, D. Riaño, D., 2001. Design of an empirical index to estimate fuel moisture content from NOAA-AVHRR analysis in forest fire danger studies. In Proceedings 3rd International Workshop of the European Association of Remote Sensing Laboratories (EARSel) on Remote Sensing and GIS applications to Forest Fire Management, Ghent, Belgium, pp. 36–39.

Forestry Canada Fire Danger Group, 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forest Canada, Ottawa, Ont., Inf. Rep. ST-X-3, 63 p.

Fraser, R., Li, Z., and Cihlar, J., 2000. Hotspot and NDVI differencing synergy: a new method for mapping fire scars. *Remote Sensing of Environment*, **74**, 362–375.

Ghebrehiwot, M., Kulkarni, M. G., Kirkman, K. P., and Van Staden, J., 2008. Smoke-water and a smoke-isolated butenolide improve germination and seedling vigour of Eragrostis Tef (Zucc.) Trotter under high temperature and low osmotic potential. *Journal of Agronomy and Crop Science*, **194**(4), 270–277.

Gimeno, M., and San-Miguel-Ayanz, J., 2004a. Evaluation of RADARSAT-1 data for identification of burnt areas in Southern Europe. *Remote Sensing of Environment*, **92**, 370–375.

Gimeno, M., and San-Miguel-Ayanz, J., 2004b. Identification of burnt areas in Mediterranean forest environments from ERS-2 SAR time series. *International Journal of Remote Sensing*, **25**(22), 4873–4888.

Hajnsek, I., Pottier, E., and Cloude, S. R., 2003. Inversion of surface parameters from polarimetric SAR. *IEEE Transactions on Geoscience and Remote Sensing*, **41**(4), 727–744.

Hajnsek, I., Jaghuber, T., Schon, H., and Papathanassiou, K., 2009. Potential of estimating soil moisture under vegetation cover by means of PolSAR. *IEEE Transactions on Geoscience and Remote Sensing*, **47**(2), 442–454.

Hardy, C. C., and Hardy, C. E., 2007. Fire danger rating in the United States of America: an evolution since 1916. *International Journal of Wildland Fire*, **16**, 217–231.

Kogan, F. N., 1990. Remote sensing of weather impacts on vegetation in non homogeneous areas. *International Journal of Remote Sensing*, **11**, 1405–1419.

Kogan, F. N., 2001. Operational space technology for global vegetation assessment. *Bulletin American Meteorology Society*, **82**(9), 1949–1964.

Leblon, B., Kashike, E. S., Alexander, M. E., Doyle, M, and Abbott M., 2002. Fire danger monitoring using ERS_1SAR images over northern boreal forests. *Natural Hazards*, **27**, 231–255.

Leblon, B., 2005. Using remote sensing for fire danger monitoring. *Natural Hazards*, **35**(3), 343–359.

Leblon, B., Fernandez-Garcia, P. A., Oldford, S., MacLean, D., and Flannigan, M., 2007. Using NOAA-AVHRR cumulative indices for estimating fire danger codes in northern boreal forests. *International Journal of Applied Earth Observations and Geoinformation*, **9**, 335–342.

Mattia, F., Le Toan, T., Souyris, J.-C., De Carolis, C., Floury, N., Posa, F., and Pasquariello, N. G., 1997. The effect of surface roughness on multifrequency polarimetric SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, **35**(4), 954–966.

Merrill, D. F., and Alexander, M. E., 1987. Glossary of forest fire management terms, 4th edition, National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, Ontario, Publication NRCC n°26516, 91 p.

Oldford, S., Leblon, B., Gallant, L., and Alexander, M., 2003. Mapping pre-fire conditions in the Northwest Territories, Canada, using NOAA-AVHRR images. *Geocarto International*, **18**(4), 21–32.

Oldford, S., Leblon, B., MacLean, D., and Flannigan, M., 2006. Predicting slow drying fuel moisture codes using NOAA-AVHRR images. *International Journal of Remote Sensing*, **27**(18), 3881–3902.

Paltridge, G. W., and Mitchell, R. M., 1990. Atmospheric and viewing angle correction of vegetation indices and grassland fuel moisture content derived from NOAA-AVHRR. *Remote Sensing of Environment*, **31**, 121–135.

San-Miguel-Ayanz, J., Ravail, N., Kelha, V., and Ollero, A., 2005. Active fire detection for fire emergency management: potential and limitations for the operational use of remote sensing. *Natural Hazards*, **35**(3), 361–376.

Stocks, B. J., Lawson, B. D., Alexander, M. E., Van Wagner, C. E., McAlpine, R. S., Lynham, T. J., and Dubé, D. E., 1989. The Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle*, **65**(6), 450–457.

Taylor, S. W., and Alexander, M. E., 2006. Science, technology, and human factors in fire danger rating: the Canadian experience. *International Journal of Wildland Fire*, **15**, 121–135.

Van Wagner, C. E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Ottawa, Ont., For. Tech. Rep. 35, 37 p.

Wotton, B. M., Alexander, M. E., and Taylor, S. W., 2009. Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System. Natural Resources Canada, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, Info. Rep. GLC-X-10, 52 p.

Cross-references

Airphoto and Satellite Imagery
Drought
Electromagnetic Radiation (EMR)
Fire and Firestorms
Forest and Range Fires (Wildfires)

Geographic Information Systems (GIS) and Natural Hazards
Geographic Information Technology
Hazard and Risk Mapping
Landsat (Satellite)
Lightning
Monitoring and Prediction of Natural Hazards
Remote Sensing of Natural Hazards and Disasters

WORLD ECONOMY, IMPACT OF DISASTERS

Ilan Noy
University of Hawaii, Manoa, Honolulu, HI, USA
Victoria Business School, Wellington, New Zealand

Definition

Human and economic catastrophes that are associated with natural hazards are by no means new. Recent very larger events, such as the Indian Ocean tsunami of 2004 or the 2005 Kashmir earthquake on the de facto Pakistan-India border, have also been experienced across national boundaries. Most of our current and rapidly evolving understanding regarding their relevance to economic dynamics is focused on the domestic economic and socioeconomic impacts (Cavallo and Noy, 2009, survey this literature). Here, the focus is on the international dimension of such economic and socioeconomic impacts, specifically the channels through which a disaster in one region/country can have an impact elsewhere.

Introduction

Barro (2006) has shown that the occurrence of infrequent economic disasters has a much larger welfare cost than continuous economic fluctuations of lower amplitude. For less developed countries, which suffer from a larger propensity to disasters of all types, and of disasters of larger magnitude than advanced economies, such events have an even greater effect on the welfare of the average citizen. These very large events are also the ones that are bound to have repercussions beyond the national borders of the affected countries.

In analyzing the economics of disasters, one typically distinguishes between direct damages, indirect damages, and secondary effects. Direct damage is the damage to fixed assets and capital, to raw materials and extractable natural resources and, of course, the mortality and morbidity that are a direct consequence of the natural hazards. Indirect impacts may be caused by the direct damage to physical infrastructure and productive capacity, or be a consequence of the fact that reconstruction pulls resources away from normal production. Such indirect damages also include the additional costs that are incurred because of the need to use alternative and less efficient means of production and/or spend dire resources for the provision of basic goods and services. At the household level, indirect costs include the loss of income resulting from the non-provision of goods and services or from the destruction of previously used means of production.

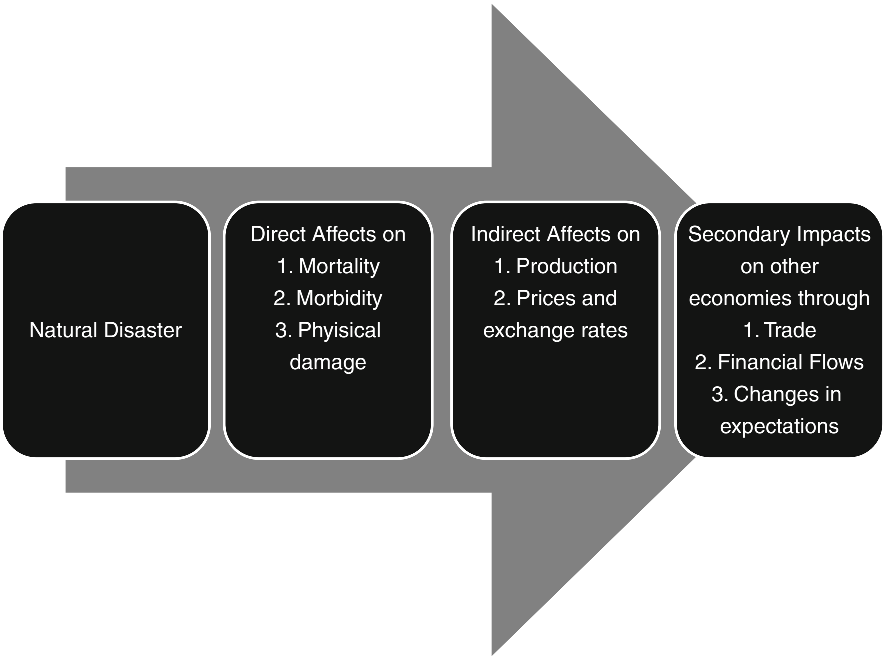
The "secondary effects" are in essence the aggregate measures of the secondary impact of the indirect effects, that is, the effects on other geographical regions, or at a later date, which originate from the indirect impact on the economy. In these secondary effects, one can identify the potential impact of disasters on the world economy, and the latter's effect on the secondary impacts of the disaster. These can, potentially, be even more severe than the initial negative disaster shock.

The secondary consequences of disasters can affect or be affected by other economies through two channels: (1) trade in both goods and services, and (2) flow of capital as aid, debt, or investment. Each of these channels is discussed in turn. An additional potential channel is migration. Disasters, however, have rarely generated large-scale migration; it is likely that only slow climate-related environmental changes, such as extended drought or desertification, will result in future migrations, but rapid-onset disasters most likely will not have such effects. Disasters, however, do frequently lead to internal displacement.

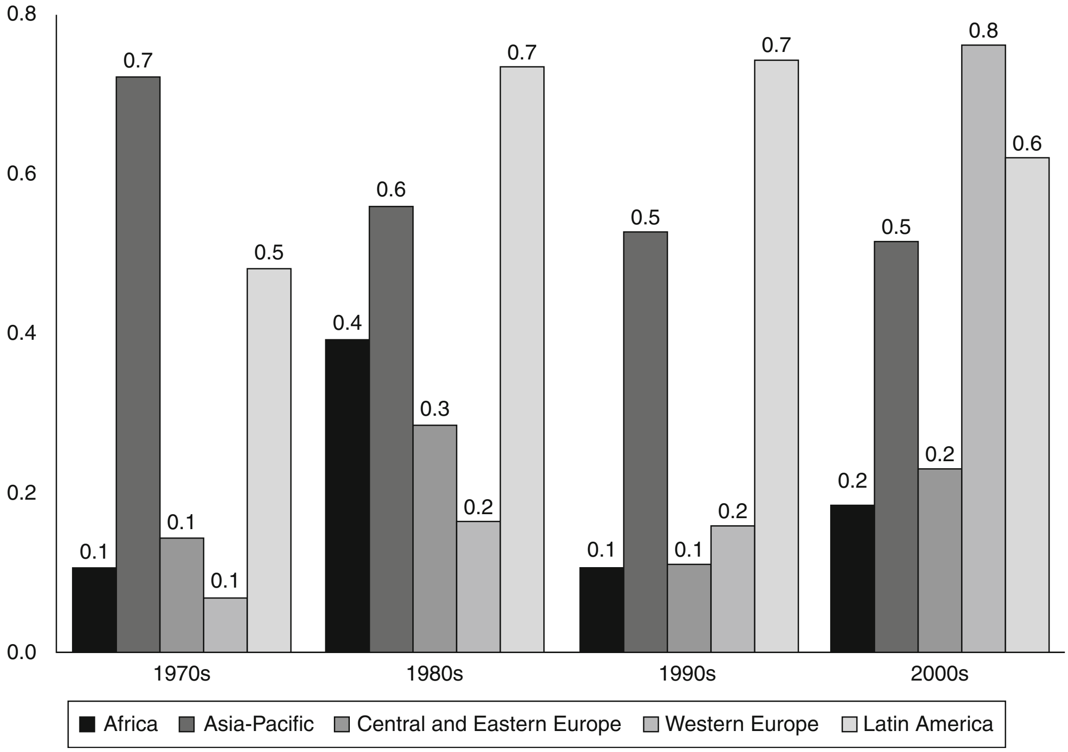
The only publicly available dataset on the economic impact of disasters worldwide is the Emergency Events Database (EM-DAT), maintained by the Center for Research on the Epidemiology of Disasters (http://www.emdat.be). The EM-DAT data reports on the number of people killed, the number of people affected, and the dollar amount of direct damages for each recorded disaster. The amount of damage reported in the database, however, consists only of direct damages (e.g., immediate damage to infrastructure, crops, and housing) and does not include either indirect or secondary damages. Thus, much of the following discussion is speculative, and the few research projects that have attempted to shed a more rigorous light on this issue rely on statistical analysis that is not always robust to permutations and changes in underlying assumptions. Much work remains to be done.

The often-cited data from EM-DAT appears to suggest that the frequency of disasters has been increasing rapidly in the last couple of decades (see, e.g., Figure 1 in Strömberg, 2007). However, much of the apparent increased incidence of disasters is due to an increase in the number of reported "small events." Figure 2 shows the frequency of large events with no apparent trend over time. Whether the reason for the increased frequency in the number of reported disasters is because small events are happening more frequently or because they are reported more often remains an open question.

Disaster fatalities are not distributed evenly across geographical regions, with a large majority occurring in the Asia-Pacific region. The Asia-Pacific region is an important region for the global economy: It includes more than 60% of the world population and more than 60% of world fatalities from disasters; it trades heavily in both goods and services (trade is 64% of the region's GDP, whereas the comparable figure for the United States is 25%); and it is



World Economy, Impact of Disasters, Figure 1 Disasters and their global impacts.



World Economy, Impact of Disasters, Figure 2 Total number of large disasters per country by region. Note for figure: 2000s measures include data up to 2008 and were adjusted for comparability. For more details see Cavallo and Noy (2009) (Data was taken from the EM-DAT database).

the largest recipient of capital flow outside the richest countries, and increasingly also a source of capital outflow to other regions (especially Africa).

Trade

The initial disaster impact leads to mortality, morbidity, and loss of physical infrastructure (housing, roads, telecommunication and electricity networks, and other infrastructure). The main issue here is how these initial direct effects lead to changes in trade patterns. There is some evidence that the trade deficit increases in the aftermath of a disaster. A disaster is unlikely to generate increases in output; it is also likely that a decrease in output will result in decrease in exports. Service exports, especially tourism, are uniquely vulnerable and will likely decrease in a post-disaster period. However, there may be a boost to exports if the disaster causes the local currency to depreciate. Currency depreciation decreases the price of exports and can therefore lead to an increase in their volume. Because of these contradictory effects, empirical work has not yet reached any conclusions regarding the "export channel."

There is some evidence that post-disaster reconstruction leads to an increase in import. Imports, especially of machinery and reconstruction materials, but also potentially of non-aid foodstuffs, are all likely to increase in the post-disaster reconstruction period. In that case, a disaster may have potential benefits for trading partners since demand for their products will increase. This is especially true if there is no discernible impact on the exchange rate that negates some of the increase in demand.

The possibility of major disasters in oil-exporting regions, such as the North Sea or the Arabian Gulf, is another concern that can have a dramatic impact on the world economy. Previous crises that led to a decrease in oil supplies for export have led to dramatic increases in oil prices, and to contractions in economic activity (e.g., 1973 or 1979–1980). A major disaster event in a large oil-exporting region is likely to have a similar detrimental impact on the world economy.

Noy (2009) concludes that countries that are more open to trade (measured by the amount of trade they conduct, relative to the size of their economies), but that have less open capital accounts, are better able to withstand the initial disaster shock and prevent further spillovers. This may be because countries that have been more open to trade historically may find it easier to absorb and finance the additional imports that are normally necessary for reconstruction. The reason why countries that are less open to capital flows may be less vulnerable is less obvious.

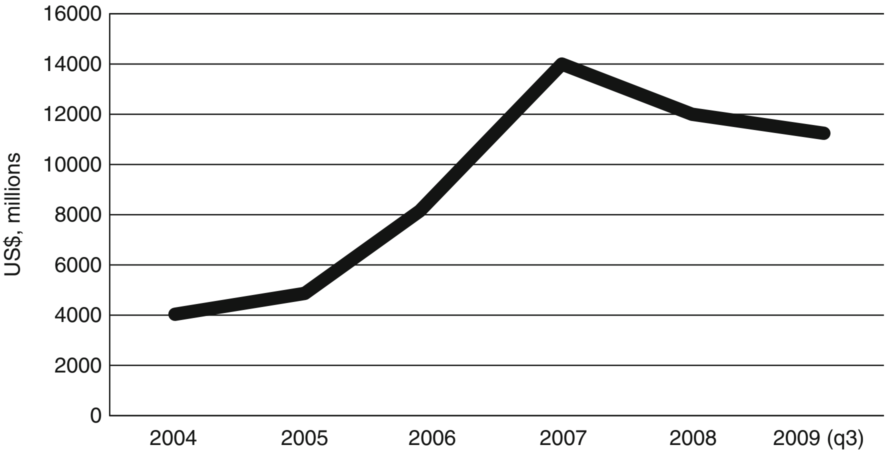
Capital flows

As for trade flows, one can identify several ways in which disasters may have an impact on the flow of financial capital and vice versa. One obvious impact is that a *large* disaster generates inflows of official and private aid. In some cases, these aid flows can be quite sizable, especially if the disaster has been widely reported in the international media (see Eisensee and Strömberg, 2007). For example, the 2004 South-East Asian tsunami led to an initial inflow of $US 6 billion in foreign aid to the affected countries (Economist Intelligence Unit, 2005). There is some evidence that, as happened in this case, aid inflows are useful in reducing the indirect damage to the national economy that may result from a disaster. This is unlike the very mixed evidence as to the effect of aid flows at "normal" times.

Beyond an increase in post-disaster aid, it is less clear what will be the effects of a disaster on other types of capital flows. Official lending may also increase as a form of aid to finance reconstruction; however, private lending may decrease if the disaster has destroyed infrastructure, so that the productive capacity of the country/region decreases. Other types of investment such as direct foreign investment – both in the form of purchases of existing productive assets and in new "green-field" investment creating new production facilities – may increase or decrease, depending on the actual range of damages and their implications for economic opportunities in the affected regions. The same can be expected for capital outflows. Whereas domestic residents may see new opportunities as a result of the destruction, the disaster may also generate capital flight if it changes perceptions regarding the likelihood of future similar events.

Yang (2008) and Bluedorn (2005) have both attempted to investigate the evolution of capital flows following disasters empirically, and both conclude that disasters generate some inflow. Bluedorn finds that, in the case of Caribbean hurricanes, the post-disaster inflow is quite large (5% of GDP). Yang, using a broader dataset, argues that the magnitude of these inflows is relatively small. He observes that international aid and remittances to poorer countries increase, whereas other types of flows are rarely affected in empirically observable magnitudes. He also finds that there is some increase in private capital outflows from the affected countries. This reported increase in capital outflows may be the reason why a closed capital account, and specifically limitations on capital outflows, may enhance an economy's resiliency in the face of a natural hazard.

Given the beneficial impact of foreign capital in financing post-disaster reconstruction and assistance, it is not surprising that governments may be interested in insuring against disaster onset, in order to guarantee this flow of funds. The simplest way to guarantee the availability of post-disaster reconstruction funding is with precautionary savings. However, Borensztein et al. (2008) argue that, in the case of less developed countries exposed to large natural disasters, insurance – or debt contracts with insurance-like features – provides an attractive alternative to a fiscal rainy-day funds. To illustrate this, they examine the vulnerability of Belize's public finance to the occurrence of hurricanes and the potential impact of insurance instruments on reducing that vulnerability. Through numerical simulations they show that the provision of catastrophic risk insurance has the potential to significantly improve Belize's debt sustainability.



World Economy, Impact of Disasters, Figure 3 Cat bonds outstanding.

Implementing disaster insurance faces two types of obstacles: paucity of markets and political resistance (Kunreuther and Pauly, 2009). For a number of reasons, certain markets have traditionally been insufficiently developed, whereas elsewhere they are simply nonexistent. Recently, however, advances such as the development of parametric insurance policies, in which payments are based on externally verifiable disaster magnitude indices (such as the Richter measure for earthquakes), have the potential of increasing the availability of insurance. Political reluctance to engage in insurance purchase derives from the fact that there is little benefit for a political leadership with short-term interests from entering into insurance contracts. Insurance involves immediate costs and a possible payoff in an undetermined future when the government may already have changed hands (Healy and Malhotra, 2009). Since disasters are natural phenomena, and politicians cannot be blamed for their occurrence, the incentives to take relatively complex measures, such as insurance, to offset some of the costs are indeed weak. Political incentives to invest in *ex ante* mitigation are even weaker if the perceived likelihood of the disaster is relatively small.

In less developed countries, an additional obstacle to any *ex ante* preparation that includes the provision of insurance is an inadequate institutional framework – this relates to low government policymaking capabilities, opaque and potentially corrupt management practices of public assets, and systems that may be unable to provide efficient post-disaster disbursing of funds.

Catastrophe debt instruments (cat bonds) are another recently introduced means to transfer risks to the international capital markets. The main difference between a cat bond and a plain-vanilla bond is that if a prespecified disaster strikes, the creditor's claim is extinguished and the issuer's debt is essentially erased. The use of cat bonds is increasing rapidly, as can be seen in Figure 3, using data from GC Securities. However, it is not clear whether the increased use of these assets is indeed motivated by a demand for insurance or is merely speculative.

Conclusion

It seems clear that a large disaster, such as the Indian Ocean tsunami of 2004, will also cause people to change their evaluation of the probability of a future disaster occurring. In Hawaii, for example, the fear of a tsunami has increased markedly since 2004, but whether that has led to behavioral changes is still an open question. Disasters, thus, may have an impact on the global economy, not only because of what they do, but also because of the expectations they modify.

Bibliography

Barro, R., 2006. Rare disasters and asset markets in the twentieth century. *Quarterly Journal of Economics*, **121**, 823–866.

Bluedorn, J. C., 2005. Hurricanes: Intertemporal Trade and Capital Shocks. *Nuffield College Economics Paper* 2005–22.

Borensztein, E., Cavallo E., and Valenzuela P., 2008. *Debt Sustainability Under Catastrophic Risk: The Case for Government Budget Insurance.* IMF Working Paper WP/08/44.

Cavallo, E., and Noy, I., 2009. *The Economics of Natural Disasters – A Survey.* Inter-American Development Bank Working Paper.

Economist Intelligence Unit, 2005. *Asia's Tsunami: The Impact.* EIU Special Report.

Eisensee, T., and Strömberg, D., 2007. News floods, news droughts, and U.S. disaster relief. *Quarterly Journal of Economics*, **122**(2), 693–728.

Healy, A., and Malhotra, N., 2009. Myopic voters and natural disaster policy. *American Political Science Review*, **103**, 387–406.

Kunreuther, H., and Pauly, M., 2009. Insuring against catastrophes. In Diebold, F. X., Doherty, N. J., and Herring, R. J. (eds.), *The Known, the Unknown and the Unknowable in Financial Risk Management*. Princeton: Princeton University Press.

Noy, I., 2009. The macroeconomic consequences of disasters. *Journal of Development Economics*, **88**(2), 221–231.

Sen, A., 1981. *Poverty and Famines: An Essay on Entitlement and Deprivation*. New York: Oxford University Press.

Strömberg, D., 2007. Natural disasters, economic development, and humanitarian aid. *Journal of Economic Perspectives*, **21**(3), 199–222.

Yang, D., 2008. Coping with disaster: the impact of hurricanes on international financial flows. *B.E. Journal of Economic Analysis and Policy*, **8**(1), 13.

Cross-references

Economics of Disasters
World-Wide Trends in Natural Disasters

WORLDWIDE TRENDS IN NATURAL DISASTERS

Margreth Keiler
Duke University, Durham, NC, USA

Definition

Multiple definitions of the term “disaster” exist, which is rooted in different conceptualizations (authorities, scientists, journalists) and the context in which these definitions are used (Perry and Quarantelli, 2005; Perry, 2007). In the context of worldwide trends in natural disasters, the United Nations define disaster within the “International Strategy for Disaster Reduction” (UNISDR, 2010a) as “a serious disruption of the functioning of a community or a society involving widespread human, material, economic, or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.” This UNISDR definition provides the base for different worldwide databases on natural disasters, although it does not provide the basis for NatCat and Sigma, whereas the Centre for Research on the Epidemiology of Disasters (CRED) declares more precisely when the local capacity is exceeded by “necessitating a request to a national or international level for external assistance” (CRED, 2010a).

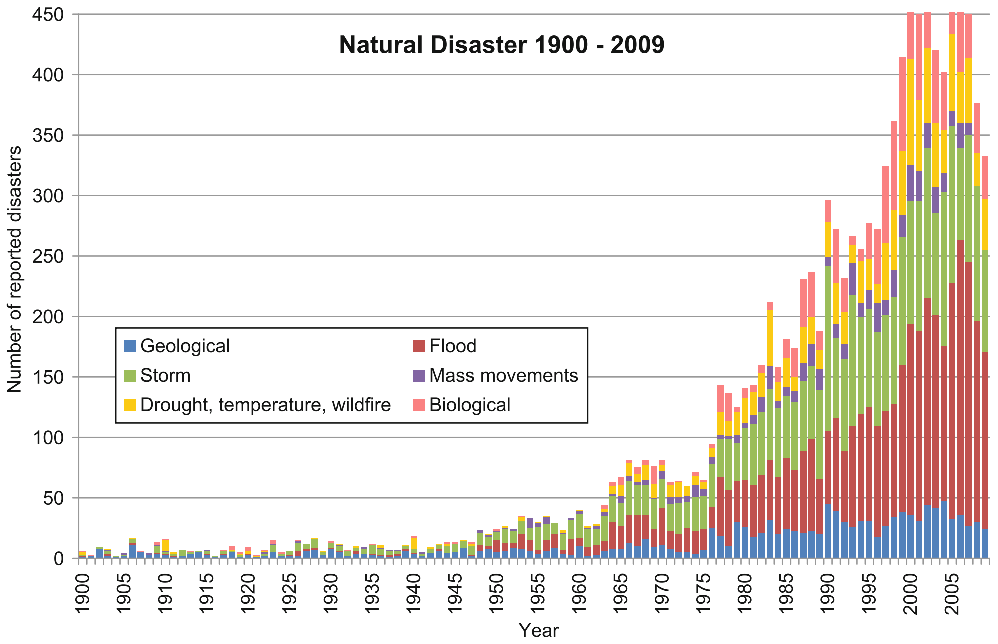
Background: Worldwide database

Worldwide databases of disasters and losses are maintained by, e.g., the Centre of Research on Epidemiology of Disasters in Brussels (CRED) with the sponsorship of the USAID’s Office of Foreign Disaster Assistance (OFDA), the Emergency Events Database (EM-DAT), as well as by reinsurance companies, such as Munich Reinsurance Group (NatCatSERVICE) and Swiss Reinsurance (Sigma). These databases contain essential core data on the occurrence and effects (casualties, people affected, economic losses) of disasters over the globe. While the focus of EM-DAT is to serve the purposes of humanitarian action (disaster preparedness, vulnerability assessment, priority setting) at national and international levels as well as scientific research (CRED, 2010b), the reinsurance companies give more emphasis to economic loss and especially to insured losses. Therefore, due to different foci and, above all, due to a lack of clear internationally accepted standards, definition, and criteria for the disaster data compilation, these global databases are limited by inconsistent reliability and poor interoperability (Below et al., 2009). The following table (Table 1) gives a short overview on the different information contained and criteria applied by taking the EM-DAT and NatCatSERVICE databases as examples.

Recent efforts were undertaken between the provider of global and regional databases by comparing the datasets in the different databases to identify inconsistencies and gaps, to improve data quality, and to allow for a comparison and exchange of data on a detailed level (Guha-Sapir and Below, 2002). The result of a comparative study between data of EM-DAT, NatCatSERVICE, and Sigma, carried out on four countries, showed that the data collected vary significantly (up to 37% difference for casualties, 66% for people affected, and 35% for economic damage according to Guha-Sapir and Below, 2002; Peduzzi et al., 2005). One result to overcome the above-mentioned limitations is an agreement (between CRED and Munich Re) on a common hierarchy and terminology on natural disasters and on a definition of disaster groups. It should be

Worldwide Trends in Natural Disasters, Table 1 Information and criteria applied in worldwide databases EM-DAT (CRED) and NatCatSERVICE (Munich Re), after Guha-Sapir and Below (2002) and Below et al. (2009).

	EM-DAT	NatCatSERVICE
Type of disasters	Natural and technological disasters	Natural disasters
Entry criteria	≥ 10 deaths and/or ≥ 100 affected and/or declaration of a state of emergency/call for international assistance	Entry if any property damage and/or any person sincerely affected (injured, dead) It is distinguished between six categories (two loss events, four catastrophes) Only major events prior to 1970
Methodology	Country entry	Country and event entry, all disasters geo-coded for GIS evaluation
Main sources	UN agencies, US Government agencies, official governmental sources, IFRC, research centers, Lloyd’s, reinsurance sources, press, private	Munich Re branch offices; insurance associations, insurance press, scientific sources, governmental and nongovernmental organizations
Priority source	UN agencies	For monetary losses, priority is given to Munich Re branch offices and insurance associations
Period covered	1900–present	0079–present
Number of entries	17,000	26,000
Access	Public	Partially accessible



Worldwide Trends in Natural Disasters, Figure 1 Number of natural disasters from 1900 to 2009 classified in geological (earthquakes and volcanic eruptions), flood, storm, mass movement, drought (including extreme temperature and wild fire), and biological (epidemics, insect infestations) triggers (Source: CRED, 2010b).

mentioned that a common understanding about the regional scope and the time scale (start and end) of a disaster would also be required to harmonize data. The natural disaster categories are divided into six groups: biological, geophysical, meteorological, hydrological, climatological, and extraterrestrial, and each group includes several disaster main types and subtypes (Below et al., 2009). Still, after redistribution of datasets, differences between the databases exist as a result of the different entry criteria.

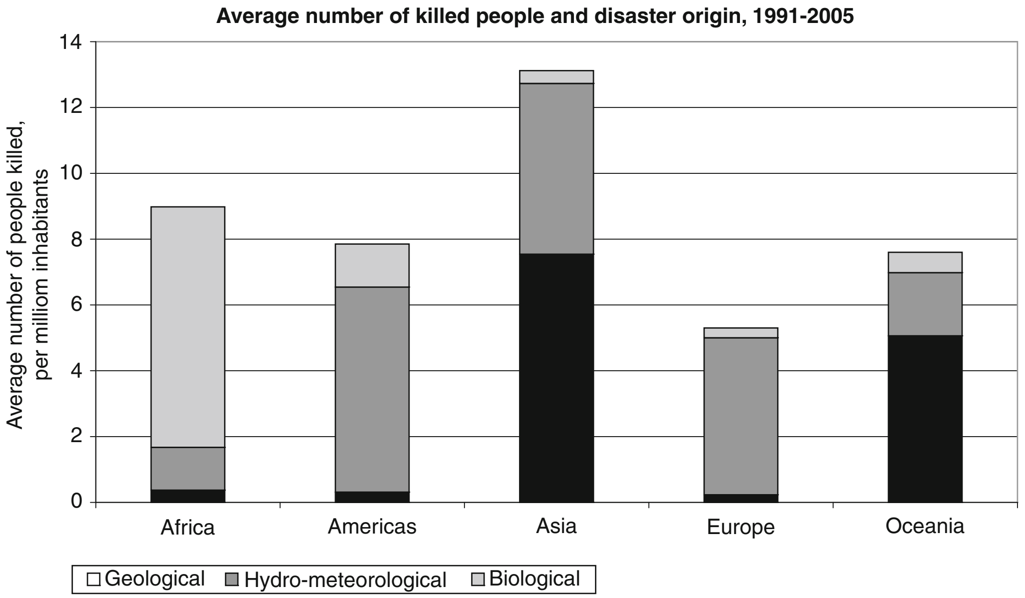
Worldwide trends

Disaster events

The analysis of the data recorded in the EM-DAT database indicates the following worldwide trend (CRED, 2010b). The number of reported disasters has increased, from about 10 per year between 1900 and 1949, 60 per year in the 1960s, 180 per year in the 1980s, almost 300 per year in the 1990s to about 440 per year for the decade 2000–2009. A similar exponentially rising trend is presented by Munich Re (Munich Re, 2009). In the last two decades, 64% of the total disaster numbers were recorded (Figure 1). The high increase in the number of hazardous events reported is probably mainly due to significant improvements in information access and reporting, especially after the establishment of EM-DAT in 1988. The most frequent triggers for disasters are floods (32%) and storms (28%, including hurricanes, typhoons, tornadoes, mid-latitude winter storms); earthquakes and volcanic eruptions (geological) caused about 12% of the disasters.

Disaster mortality and people affected

The related losses due to these natural disasters are concentrated in a small number of infrequently occurring events (UNISDR, 2009). The number of people reported killed by disasters since 1900 has been decreasing since the 1940s, whereas the reported number of people affected, defined as those requiring survival needs such as medical care, food, and shelter during and in the wake of disasters, increased strongly since the 1960s. The average number of people affected rose from about 25 million per year in the 1960s to 300 million in the 2000s due to floods, storms, and droughts (CRED, 2010b; UNISDR, 2010b). Regarding the time period between 1975 and October 2008 (with a more comparable global reporting coverage), 8,866 natural disaster events which were recorded by EM-DAT (excluding epidemics) caused more than two million killed people (UNISDR, 2009). However, only 23 M-disasters (0.26% of the events) accounted for 78.2% of the mortality, mostly in developing countries. Half of the 10 disasters with the highest death tolls since 1975 have occurred between 2003 and 2008 (UNISDR, 2009). For the period between 1975 and 2009, earthquakes (36%) are largest cause of natural disaster mortality, followed by storms (27%), droughts (23%), and floods (9%) (CRED, 2010b). The average number of people reported killed per million inhabitants is presented in Figure 2, indicating the highest number in Asia caused by "geological disasters" (earthquakes and volcanic eruptions) and "hydrometeorological disasters," including floods, storms, droughts and related disasters (extreme temperatures and wild fires), and mass movements



Worldwide Trends in Natural Disasters, Figure 2 Average number of people killed per million inhabitants by continent and disaster origin (Source: UNISDR, 2010b).

(UNISDR, 2010b). Africa shows the highest contribution to biological disasters covering epidemics and insect infestations. The greatest portion of individuals killed in Europe and the Americas are related to hydrometeorological disasters.

Economic losses

Economic losses due to natural disasters highlighted an exponentially rising trend since the mid-1970s regarding the period 1900–2009 (CRED, 2010b). The recorded economic losses in EM-DAT added up more than US$ 1.5 trillion between 1975 and 2008, with high peaks about US$ 160 billion in 1995 (Kobe earthquake), US$ 220 billion in 2005 (hurricane Katrina), and US$ 190 billion in 2008 (Sichuan earthquake and hurricane Ike). Only 25 M-disasters representing 0.28% of the events accounted for 40% of that loss which were located mainly in developed countries (UNISDR, 2009). The annual average of economic damage for the years 2000–2008 was about US$ 94 billion (CRED, 2010b). According to inflation-adjusted data from Munich Re, the average annual losses from the period 1977–1986 to the period 1997–2006 increased at a decadal rate of about 125% (Bouwer et al., 2007). Furthermore, Bouwer et al. (2007) highlighted that global economic losses caused by weather-related disasters have increased from an annual average of US$ 8.9 billion (1977–1986) to US$ 45.1 billion (1997–2006) based on the Munich Re database. The highest economic losses occurred since the 1990s in Asia by hydrometeorological (about 60%) and geological disasters (about 40%), followed by the Americas whose losses were dominated by hydrometeorological disasters (UNISDR, 2010b).

Discussion and conclusion

Trends of the disaster numbers, mortality, and people affected by disaster as well as economic losses show different developments or rate of increase especially if the records are analyzed by different "hazards" and regions. UNDP/BCPR (2004) highlighted the disproportionate impact on developing countries, that while only 11% of those exposed to hazards live in low human development countries, 53% of disaster mortality is concentrated in those countries. Mortality and direct economic losses appear to be highly clustered geographically; these are areas with a major concentration of people and economic assets and associated with a very small number of disaster events (UNISDR, 2009). More frequently occurring lower impact events are often not covered by the global databases, but in contrast, these widespread low-intensity losses are coupled to a large number of affected people and damage to housing and local infrastructure (McBean and Ajibade, 2009; UNISDR, 2009). The following example will illustrate the geographical disparity of disasters due to exposure and vulnerability. A comparable hazard event of a similar severity will generally result in lower mortality and smaller losses in countries with higher income and higher human development levels than in a less developed country when measured against the country's total wealth, despite the higher economic losses in absolute terms (UNISDR, 2009).

Beside the fact that a part of worldwide trends in natural disasters can be explained by improved disaster reporting (UNISDR, 2009), drivers for rising trends of affected people and economic losses are population growth (Strömberg, 2007) and increase in population and housing units in vulnerable areas (Pielke et al., 2008), particularly in urban and coastal areas. The Intergovernmental Panel on Climate Change concluded that the rising number of disasters triggered by hydrometeorological events is likely to have been partly driven by anthropogenic global climate change altering the hazard pattern. Furthermore, it is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent and future tropical cyclones will become more intense (Solomon et al., 2007). Nevertheless, the increasing trend of weather-related disaster losses such as stated by Bouwer et al. (2007) should be carefully considered, as already indicated earlier by Downton and Pielke (2005). Even if flood damages continued to increase despite extensive flood management efforts since 1900, particularly when measured in constant currency units, the trend is not as obvious once normalized. If flood data related to the United States of America are presented in terms of damage per unit wealth, a slight and statistically insignificant downward trend is observed (Loucks and Stedinger, 2007), which suggests that floods might have a lessening or neutral impact on the overall personal wealth of citizens in the United States of America over the course of the past decades. Similarly, no significant loss trends were found for flood and wind storm in Europe (Barredo, 2009; Barredo, 2010), tropical cyclones in India (Raghavan and Rajesh, 2003), and weather-driven disasters in Australia (Crompton and McAneney, 2008) if they were normalized by eliminating the socioeconomic influence of growing exposure in areas affected.

In summary, multiple, interacting drivers and records of disaster that are of poor quality, inhomogeneous, and collected using a wide range of methods for different purposes make the analysis of worldwide trends in natural disasters extremely challenging.

Bibliography

Barredo, J., 2009. Normalised flood losses in Europe: 1970–2006. *Natural Hazards and Earth System Sciences*, **9**, 91–104.

Barredo, J., 2010. No upward trend in normalised windstorm losses in Europe: 1970–2008. *Natural Hazards and Earth System Sciences*, **10**, 97–104.

Below, R., Wirtz, A., and Guha-Sapir, D., 2009. *Disaster Category, Classification and peril – Terminology for Operational Purposes*. Working Paper 264. Brussels/Munich: CRED/ Munich Re.

Bouwer, L. M., Crompton, R. P., Faust, E., Höppe, P., and Pielke, R. A., Jr., 2007. Confronting disaster losses. *Science*, **318**, 753.

CRED 2010a. Glossary. *Emergency Events Database, Centre for Research on the Epidemiology of Disasters*. Université Catholique de Louvain, Belgium. http://www.emdat.be/glossary/9.

CRED 2010b. *EM-DAT - The OFDA/CRED International Disaster Database, Database Advanced Search, Centre for Research on the Epidemiology of Disasters*. Université Catholique de Louvain, Brussels, Belgium. http://www.emdat.be/Database/AdvanceSearch/advsearch.php.

Crompton, R. P., and McAneney, K. J., 2008. Normalised Australian insured losses from meteorological hazards: 1967–2006. *Environmental Science Policy*, **11**, 371–378.

Downton, M., and Pielke, R. A., Jr., 2005. How accurate are disaster loss data? The case of U.S. flood damage. *Natural Hazards*, **35**, 211–228.

Guha-Sapir, D., and Below, R., 2002. Quality and accuracy of disaster data. A comparative analysis of 3 global data sets. *Working Document prepared for the Disaster Management Facility of The World Bank*. Brussels: The World Bank.

Loucks, D., and Stedinger, J., 2007. Thoughts on the economics of floodplain development in the U.S. In Vasiliev, O., van Gelder, P., Plate, E., and Bolgov, M. (eds.), *Extreme Hydrological Events: New Concepts for Security*. Dordrecht: Springer. NATO Science Series IV: Earth and Environmental Sciences, pp. 3–19.

McBean, G., and Ajibade, I., 2009. Climate change, related hazards and human settlements. *Current Opinion in Environmental Sustainability*, **1**, 179–186.

Munich Re, 2009. *Topics Geo, Natural Catastrophes 2008 – Analyses, Assessments, Positions*. Munich: Munich Re.

Peduzzi, P., Dao, H., and Herold, C., 2005. Mapping disastrous natural hazards using global datasets. *Natural Hazards*, **35**, 265–289.

Perry, R. W., 2007. What is a disaster? In Rodríguez, H., Quarantelli, E. L., and Dynes, R. R. (eds.), *Handbook of Disaster Research*. New York: Springer, pp. 1–15.

Perry, R. W., and Quarantelli, E. L., 2005. *What is a Disaster? New Answers to Old Questions*. Philadelphia: Xlibris.

Pielke, R. A., Jr., Gratz, J., Landsea, C. W., Saunders, M. A., and Musulin, R., 2008. Normalized hurricane damage in the United States: 1900–2005. *Natural Hazard Review*, **9**(1), 29–42.

Raghavan, S., and Rajesh, S., 2003. Trends in tropical cyclone impact: a study in Andhra Pradesh, India. *Bulletin of the American Meteorological Society*, **84**, 635–644.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.), 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Strömberg, D., 2007. Natural disaster, economic development, and humanitarian aid. *Journal of Economic Perspectives*, **21**(3), 199–222.

UNDP/BCPR (United Nations Development Programme, Bureau for Crisis Prevention and Recovery), 2004. *Reducing Disaster Risk: A Challenge for Development*. New York: UNDP/BCPR.

UNISDR, 2009. *Global Assessment Report on Disaster Risk Reduction*. Geneva: United Nations.

UNISDR, 2010a. *Terminology on Disaster Risk Reduction, 2009*. Geneva: United Nations. http://www.unisdr.org/eng/terminology/terminology-2009-eng.html.

UNISDR, 2010b. *Disaster Statistics 1991-2005*. Geneva: United Nations. http://www.unisdr.org/.

Cross-references

Classification of Natural Disasters
Cultural Heritage and Natural Hazards
Disaster Diplomacy
Disaster Relief
Disaster Research and Policy, History
Disaster Risk Reduction (DRR)
Global Change and Its Implications for Natural Disaster
Natural Hazard in Developing Countries