REVIEW

# Global trends in satellite-based emergency mapping

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**Over the past 15 years, scientists and disaster responders have increasingly used satellite-based Earth observations for global rapid assessment of disaster situations. We review global trends in satellite rapid response and emergency mapping from 2000 to 2014, analyzing more than 1000 incidents in which satellite monitoring was used for assessing major disaster situations. We provide a synthesis of spatial patterns and temporal trends in global satellite emergency mapping efforts and show that satellite-based emergency mapping is most intensively deployed in Asia and Europe and follows well the geographic, physical, and temporal distributions of global natural disasters. We present an outlook on the future use of Earth observation technology for disaster response and mitigation by putting past and current developments into context and perspective.**

Disaster responders and the humanitarian community increasingly use Earth Observation (EO) satellite systems to assess the impact of and to plan and coordinate emergency response activities after major natural disasters around the world. EO systems provide response and relief workers with tools to lift the "fog off disaster." EO satellites help overcome operational uncertainties after major disasters that impede emergency response because of limited, incomplete, and often contradictory ground information. Furthermore, EO satellites provide emergency responders with a situational overview otherwise difficult to obtain during an ongoing disaster event. For example, synthetic aperture radar (SAR) sensors can see through storm clouds to remotely assess in near real time the exact extent or severity of flood disasters as they unfold. Local, national, and international agencies also use satellite-based emergency mapping (SEM) as part of larger resilience strategies (*1*) to help design, implement, and evaluate disaster risk reduction and recovery programs (*2*–*4*). The ultimate goal of SEM is to improve disaster relief effectiveness and thus to help reduce suffering and fatalities before, during, and after a disaster event occurs. We focus our Review on the response phase immediately after a disaster, which typically lasts from several days to a few weeks. This phase is technically challenging because of the strict time constraints and demands special skill sets and coordination among disaster responders, the SEM community, satellite operators, and international organizations. The global SEM response capabilities have been developing over the past 15 years and can today be considered to be at the forefront of the use of satellite technology and geoinformation in the broader field of disaster risk management (Box 1) (*5*).

> ***"The availability of … EO satellite systems has increased during the past 15 years."***

Partly in response to growing demand, larger satellite constellations with more advanced sensors are being built, with the potential to provide unprecedented capacity for monitoring the Earth more rapidly and in more detail than ever before. This development has not been limited to the traditional space agencies in Europe, Japan, and the United States. Over the past 15 years, countries throughout Latin America, Africa, and Asia have started their own space programs. Dozens of new satellites have been launched, transforming availability and access to EO technology and data, further expanding the EO constellations and the ease of use of satellite data. The provision of vast quantities of raw satellite data to the disaster response community has no operational value per se. Being time sensitive in its relevance to immediate disaster mitigation, the data need to be rapidly processed, analyzed, and transformed by remote sensing professionals (*6*) into intuitive and understandable information products such as maps or reports; these can then directly be used in emergency management operations (*7*, *8*).

In reviewing global SEM responses of the past 15 years, five major events stand out, given their influence on the development of the international SEM community: (i) After the Indian Ocean Tsunami in 2004 (*7*), widespread international SEM cooperation and response coordination were necessary owing to the scale of the event, size of the impacted region, and the number of countries affected. During the disaster, satellite mapping played an important role by providing an overview of the situation on the ground and helping people to understand the magnitude of devastation caused by the tsunami. (ii) The Wenchuan Earthquake in 2008 (*9*) mobilized an at that time unprecedented number of programmed satellites and acquired satellite imagery for a single disaster event. Analysis and mapping of the data was mainly organized by the National Disaster Reduction Centre of China (NDRCC) and resulted in the generation of numerous satellite products. During this event, it became clear that satellite imagery alone could not suffice to assess more subtle structural earthquake damage to buildings and infrastructure. In response to this, the emergency-mapping community realized the need for airborne sensors and imagery from unmanned airborne vehicles (UAVs) in order to complement satellite-derived products. (iii) The Haiti Earthquake in 2010 (*10*) marked a turning point in the accessibility of openly licensed post-event satellite imagery to a broader internet and crisis-mapping community. Many satellite-based emergency maps were produced by many different organizations, which led to an overflow of SEM products and some criticism by the international disaster relief community (*11*). As a result, the International Working Group on Satellite-based Emergency Mapping (IWG-SEM) (*12*) was established to improve mutual information sharing, harmonization, and cooperation across the international SEM community. (iv) The Pakistan flood in 2010 (*13*, *14*) affected ~5% of the Indus River basin and 20 million people. Many varying SEM products were produced by different initiatives. The emergency response community was again overwhelmed with information, making it challenging to prioritize and ingest all the information into their operational workflows. The main concern was the thematic accuracy of the post-event information because of map products showing different extents of affected areas, such as the extent of flooding. This was another catalyst that led to the creation of the IWG-SEM (19, 20). (v) After The Great East Japan Earthquake in 2011 (Tohoku-Oki) (*15*), the Japan Aerospace Exploration Agency (JAXA) enlisted the help of international SEM

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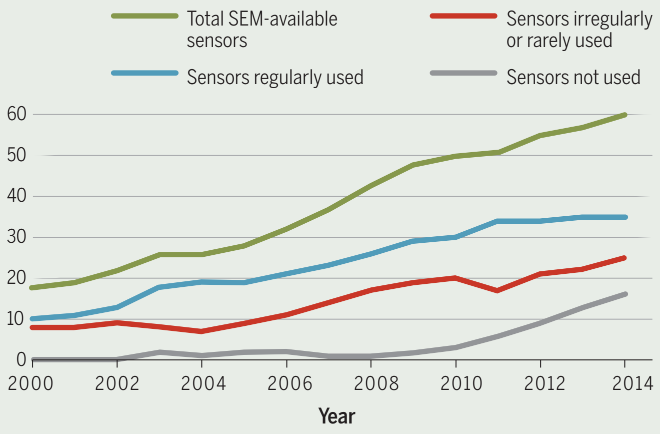
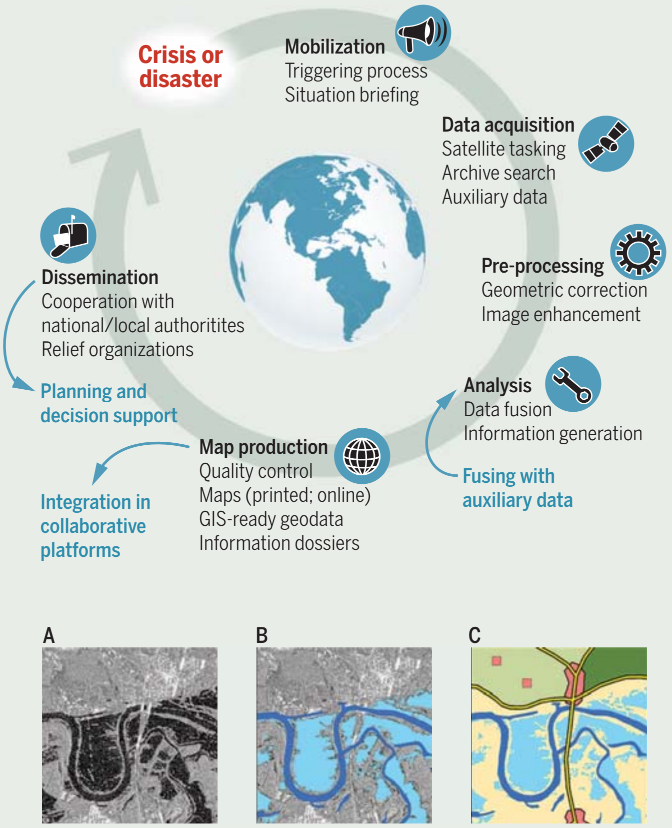
**Box 1. Earth Observation satellites and principles in emergency mapping.**

The availability of scientific and commercial polar orbiting EO satellite systems has increased during the past 15 years (*41–44*). These satellites are equipped with imaging sensors in the visible and near- to mid-infrared part of the electromagnetic spectrum or in the radar frequencies. Systems useful for disaster extent and impact mapping have a ground sampling distance (GSD) in the range of 0.3 m to more than 300 m. A team of experienced image analysts can take from 6 to 16 hours to extract the relevant information from new satellite imagery and turn it into geo-information products, such as maps, for situation centers or decision-makers. Reprogramming the satellite systems and collecting imagery over the disaster site typically takes 1 or 2 days and is considered one of the more time-consuming parts of the overall process (*6*). Many elements of the SEM production chain are becoming automated.

**Number of optical and radar satellite sensors (<300 MGSD)**





(**Above**) **The main steps involved in SEM product generation.** (**A**) Satellite image acquisition and preprocessing. (**B**) Image analysis and information extraction. (**C**) Visualization in dedicated geo-information products.

organizations immediately, contributing to efforts by national and local government bodies to collect information and support relief activities. By teaming up with different partners, more than 5000 satellite images were collected for assessment after the earthquake. These images were used to determine the overall extent of the damage and assess local conditions such as the availability of key facilities, allowing for the prioritization of the disaster response activities (*15*).

In the light of these experiences and the developments described above, the following questions may be raised: What are the temporal trends in overall SEM response rate and time? Are the SEM resources being deployed in the areas of greatest need? What is the individual reach of the different SEM mechanisms? Can we ascertain the fitness for purpose of the SEM? In order to address these questions, we systematically reviewed and assessed more than 1000 satellite emergency-mapping activations for natural and partially manmade disasters occurring globally between 2000 and 2014. The team captured SEM activation parameters of five relevant SEM mechanisms: the International CHARTER Space and Major Disasters (*16–18*), the European COPERNICUS program (including the phase when it was still called GMES) (*19*), United Nations (UNOSAT-UNITAR and ReliefWeb), SENTINEL ASIA (*20*), and the NDRCC (table S1). We linked the data with statistical ground-based information on the associated disaster events from the International Disaster Database EM-DAT (*21*) and data from the World Bank (*22*, *23*).

## Temporal trends in satellite response

To approach the first question, we investigated the temporal trends in SEM response. Globally, we observed a steady increase of SEM activities, growing from seven activations in 2000 to 123 activations in 2014 (Fig. 1A). This trend in international efforts in SEM is an encouraging sign of the readiness of this technology to support disaster management. It is likely that technological innovations—such as internal mechanism enhancements and the launch of virtual globes on the internet—has raised awareness and acceptance of geospatial data, leading to an increase in the number of disasters covered by SEM in the 2006 timeframe (Fig. 1B, dashed line). The COPERNICUS program seems to be the only SEM mechanism still increasing the number of disaster events analyzed per year, whereas other SEM mechanisms seem to have maximized in activation numbers from around 2010 on. The COPERNICUS program is strongly supported by the European Commission policy and funding, with operational integration into the European Union member state administration and disaster management procedures just beginning. Thus, this program is also expected to grow in the years to come. Furthermore, the average number of mapping products has increased from two to five products per SEM activation between 2000 and 2014 (Fig. 1C). This suggests that the SEM community has substantially expanded the capacity to turn satellite imagery into geo-information and mapping products for disaster response purposes. This also implies a greater need for well-organized cooperation, harmonization, and product standardization at a global scale in order to make more coherent use of the international space and ground-based capacities.

Similarly, we assessed delay times from mobilization to image availability so as to understand SEM responsiveness. We controlled for shared activations between SEM mechanisms and excluded nonrapid SEM responses [time ($T$) > 1 week]. The time series analysis on responsiveness only started in 2001 because consistent and reliable records became available at that time. In 2006, the average overall response time from mobilization to first product was ~4.5 days;

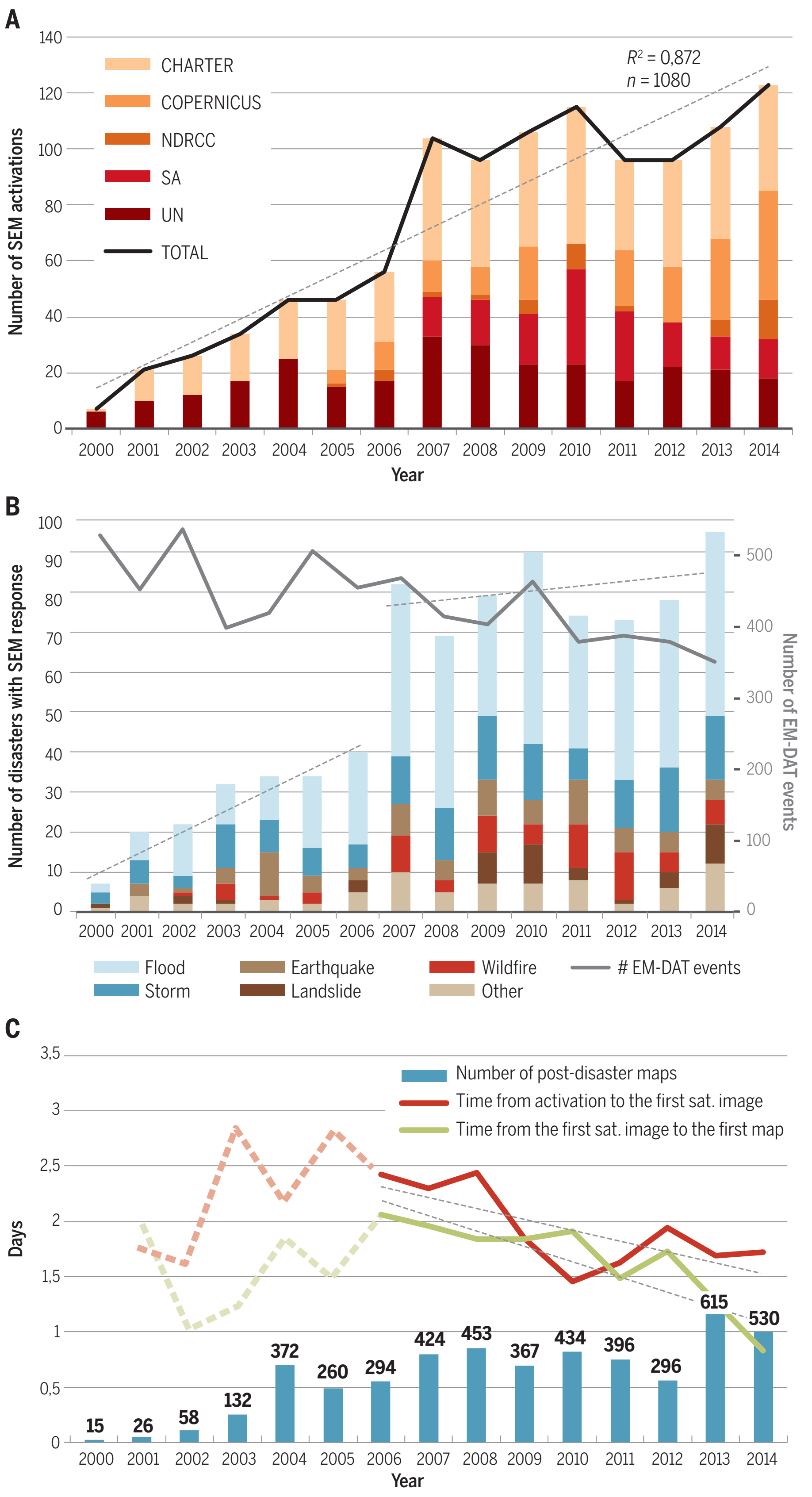


**Fig. 1. SEM temporal trends during the study period 2000–2014.** (**A**) Number of activations and distribution among the different SEM mechanism. (**B**) The differentiation by disaster types over time. (**C**) The overall map production volumes and response times.

this was reduced to ~2.5 days on average by 2014 (Fig. 1C).

## Global spatial pattern in SEM

To determine whether the SEM resources were deployed in areas of greatest need, we visualized the global spatial patterns of SEM responses ($n$ = 804 geocoded SEM responses), controlling for shared activations and synoptically displaying a global population density data set (Fig. 2) (*24*, *25*). The analysis indicates that a large majority (~75%) (fig. S1) of SEM activations are related to hydrometeorological disasters (similar to the EM-DAT percentages for the same period), which cluster in distinct parts of the Americas, Africa, eastern/southeastern Asia, and Europe. However, the SEM activations related to geophysical disasters are clustered along the borders between the Nazca and South American plates as well as the Eurasian and Indo-Australian plates. The main mixed clusters of hydrometeorological and geophysical SEM activities are located in the European and Himalayan regions as well as in parts of the Northern Andes, Central America, and the Caribbean. Generally, the locations of SEM activations resemble the large global natural hazards patterns, with the seismic active zones and the major storm systems. In Europe, the distribution of SEM activations for geophysical events is situated along the border between the African and the Eurasian plates (Fig. 2B). We identified a spatial correlation between the location of the SEM activities and the densely populated areas of the world. This suggests that human exposure drives the decision to request international satellite emergency mapping. We observed that for main parts of India, international SEM activities are not being called on, which is likely to be explained by a preference for domestic SEM capacities in this region (Fig. 2C).

The north-south distribution of the SEM activations matches well with the relative distribution of global population (Fig. 3A). Deviations occur at 15°N and 20°S, with frequent cyclonic flood and storm events hitting at these latitudes. Another deviation occurs around 25°N; we attribute this to the high population density and relatively few international SEM activations over the Indian subcontinent. As for the relative distribution of the land masses, the low populated Nordic landmasses (Canada/Russia/Alaska) and southern sparsely populated regions in the Amazonas, southern Africa, and Australia (mainly between 5°N and 35° S) are not subject to substantial numbers of SEM activities.

Generally, of all studied SEM activations, 25% cover six countries (EM-DAT 25%, six countries), 50% cover 21 countries (EM-DAT 50%, 25 countries), and 75% cover 50 countries (EM-DAT 75%, 62 countries), whereas the overall SEM activations have reached 163 countries.

We observed variations in the use of the SEM mechanisms as well as the distribution of disasters covered by means of SEM. Among the 12 countries with the largest disaster occurrences (according to EM-DAT), Pakistan and Vietnam managed 26 and 19% of their domestic disasters, respectively,

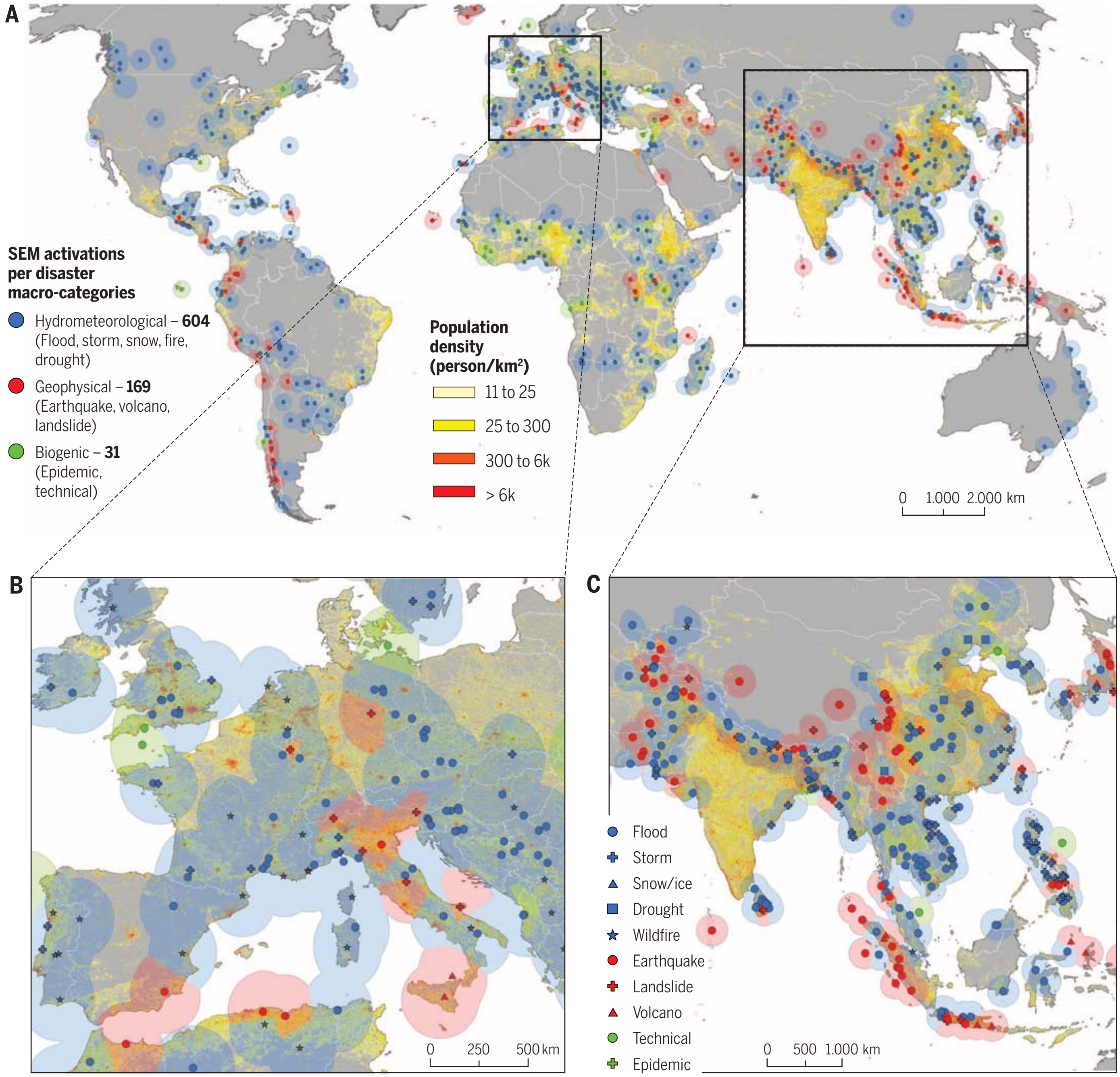


**Fig. 2. Spatial distribution of SEM activations by disaster type.** (**A**) At the global level. The distribution of SEM activations are grouped according to three disaster macrocategories: (i) hydrometeorological, blue symbols (including flood, storm, snow, wildfire, and drought events); (ii) geophysical, red symbols (earthquake, volcano, and landslide events); and (iii) biogenic, green symbols (epidemic outbreaks and technical accidents). (**B** and **C**) At regional level. (B) Western and southern Europe. (C) Southern, eastern, and southeastern Asia. The detailed disaster types can be read from the individual symbols. Polygons highlight the clustering of activations aggregated at disaster macrocategory level. All three sections show population density in the background (*24*).

with SEM support. Countries such as China, India, Philippines, Indonesia, Bangladesh, and Japan managed between 10 and 15% of their domestic disasters with SEM. The United States, Afghanistan, Mexico, and Russia range between 5 and 8%. We also found that Asia is the main global focus of international SEM activities, which is in line with the fact that according to EM-DAT, more disasters occur in this region as compared with others. The CHARTER was activated by the United States more than by any other country, and COPERNICUS was activated mainly for disaster situations in southern and southeastern Europe (table S2). In almost all regions of the world, SEM activities have risen in number substantially during the past 5 years. Only for the Americas and the Caribbean has the SEM frequency remained stable or slightly decreased during the past 5 years. Eastern and Western Africa have also remained stable, with a relatively high level of SEM activities over the past 10 years, whereas Australia, Polynesia, and Melanesia are covered by only a few SEM activations during the study period (Fig. 3B).

## The reach of individual SEM mechanisms

The CHARTER, because of its global scope and as supported by its recent universal access efforts, is the most widely active and fully international SEM

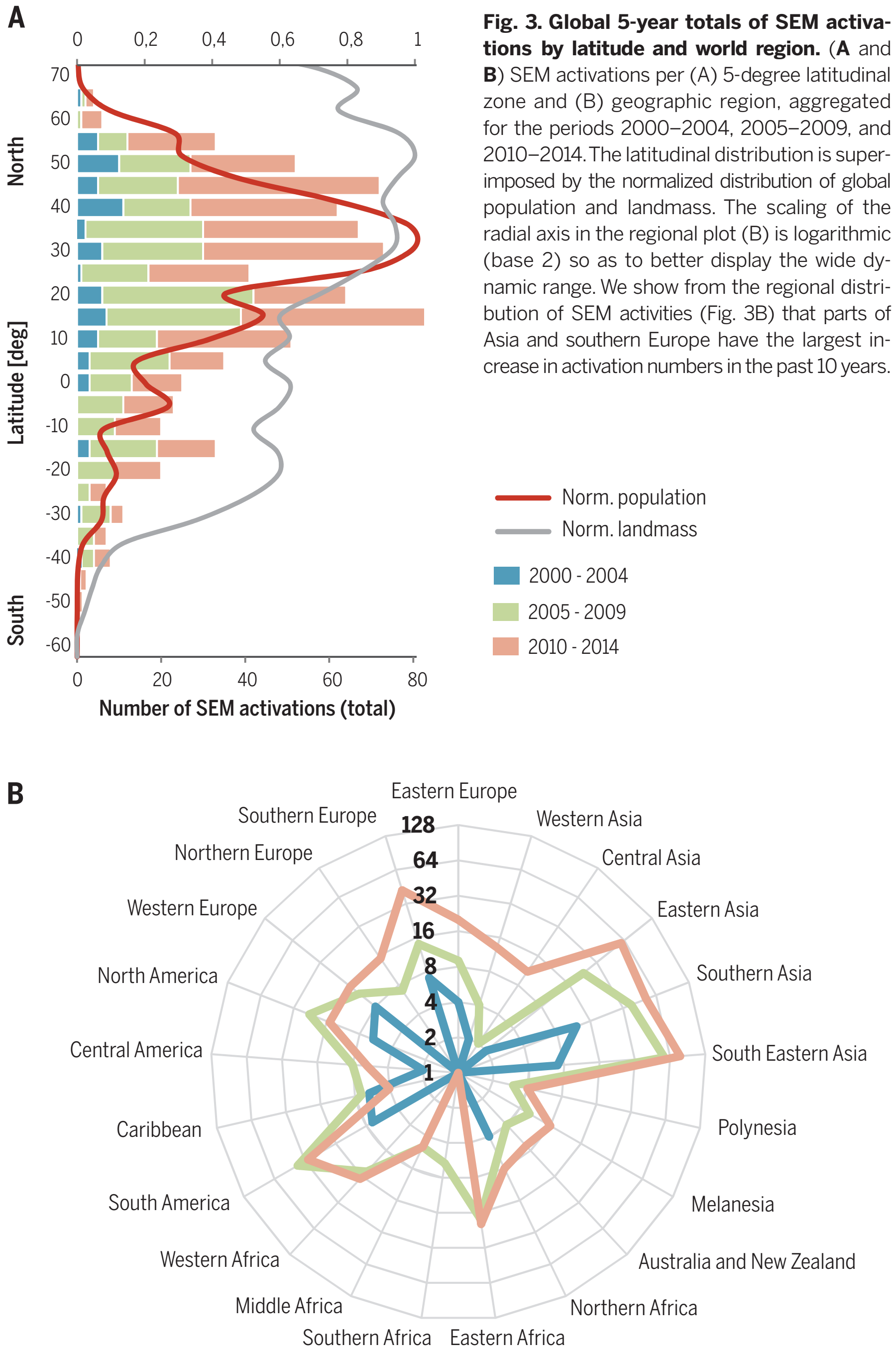


**Fig. 3. Global 5-year totals of SEM activations by latitude and world region.** (**A** and **B**) SEM activations per (A) 5-degree latitudinal zone and (B) geographic region, aggregated for the periods 2000–2004, 2005–2009, and 2010–2014. The latitudinal distribution is superimposed by the normalized distribution of global population and landmass. The scaling of the radial axis in the regional plot (B) is logarithmic (base 2) so as to better display the wide dynamic range. We show from the regional distribution of SEM activities (Fig. 3B) that parts of Asia and southern Europe have the largest increase in activation numbers in the past 10 years.

mechanism. In North America, the CHARTER is the only SEM mechanism used to complement domestic capacities. In South America, Africa, Europe, and Asia, the SEM activities of the CHARTER are increasingly complemented by other mechanisms. For Europe, the COPERNICUS Emergency Management Service (EMS) plays an increasingly important role, resulting in a substantial decrease of CHARTER activations over Europe in the past 5 years. In Asia, the SENTINEL ASIA activities have a strong prevalence, accompanied by CHARTER and United Nations (UN) mapping efforts. The latter also plays a major role in Africa, the Near East, Central America, the Caribbean, and South America. For China, the NDRCC plays the most important role, with the CHARTER complementing NDRCC capacities. The top five ranking countries for which each SEM mechanism was activated is provided in table S2.

## Is global SEM fit for the purpose?

This question is challenging and will require further research to provide a quantitative answer. There have been attempts to assess the value of space- and geo-information for disaster and risk management, including economic and operational value (*26*, *27*). At this time, these assessments remain qualitative. To find a quantitative answer or trends in the usefulness of SEM over time, many complex technological trends (such as impact of information and communication technology, awareness, and preparedness-raising) would have to be eliminated or controlled for. Generally, the demand for and quality of services of global SEM activities has risen over the past decade. In many countries, strong efforts are being made to build SEM capacities within the emergency management services (*8*, *15*), suggesting that they are useful, although the benefits cannot yet be quantified in absolute numbers.

As SEM products increase in quantity, timeliness, and complexity, there are other kinds of emergencies and disaster phases that may benefit. It has already been demonstrated that satellite analyses can be highly relevant to slow on-set events with a vast geographical impact, such as water scarcity or drought (*28*–*30*). Even geodetic satellite signals combined with solid Earth load modeling can be used for drought pattern and severity estimation (*31*). Also, the monitoring of associated large mass population movements, which are difficult to track on the ground, could benefit from existing SEM capabilities (*32*). There are global communities that monitor crop yield and drought by means of satellites (*33*, *34*); however, they are not yet well integrated into the SEM community. The 2011 Horn of Africa drought is an example of a missed opportunity for better integration and consolidation of SEM into global mechanisms aimed at boosting targeted response (*35*). In 2015, SEM was enlisted in response to the Ebola crisis, demonstrating its potential for supporting global health crises (*36*). Of course, SEM can only be used to monitor health-related parameters and indirect physical consequences of epidemic or pandemic situations on the Earth's surface. However, during the Ebola crisis, SEM was used intensively for mapping and planning of health posts as well as mapping of oil palm trees because fruit bats are considered the main natural host of the virus (*37*). After the magnitude 7.8 Gorkha earthquake in Nepal in 2015, extensive use of ad hoc satellite image collections was made, going beyond the regular rapid SEM response, for surveying geohazards such as landslides and destabilized glacier lakes in the mountainous and remote regions that are difficult to assess otherwise (*38*).

## Conclusion

The comparison between EM-DAT and SEM distributions indicates that global SEM activities are progressively evolving. However, rapid response, accuracy, and increased frequency of SEM mappings are necessary considering the growing vulnerability of global societies, technological dependencies, and projected climate change scenarios. Therefore, the scope of global SEM activities should be broadened to better include drought, extreme temperature events, global pandemics, and other slow on-set events. Nonetheless, a major challenge for EO disaster response is still the satellite tasking, reprogramming, and image collection; these require ~2 days on average to complete, as compared with the ~6 to 8 hours required for mapping after the availability of satellite imagery.

Generally speaking, 30 years after the UN General Assembly resolution on remote-sensing principles and the pledge that "Remote sensing shall promote the protection of mankind from natural disasters" (*39*), the initial organizational and procedural hurdles for making satellite analysis available for operational disaster management have been mostly overcome. Recognizing the diversification and intense utilization of SEM at a global scale, we suggest the establishment of international guidelines on emergency mapping, quality assurance, and harmonization, tailored to specific disaster types. In addition, operational global partnerships among agencies and organizations are essential for strengthening space-based disaster relief efforts. Cooperation among the operational SEM mechanisms must be intensified, within the IWG-SEM (*40*), and UN-SPIDER (*1*), as well as through other regional and global initiatives. Improved real-time information exchange on SEM activities, mapping requirements, and locations of available SEM-derived products at any given time is a key step in this process.

In the coming years, government, public, and commercial sectors will have greater capacity for imaging through satellite constellations, such as the European Copernicus Sentinel constellation and the many commercial systems with very-high-resolution optical imaging capability that are in operation or coming up. With the higher throughput of large quantities of imagery and increasingly higher spatial resolution of satellite data, automation and image data mining as well as mass-data processing techniques will play a key role in the global SEM landscape. Single images for disaster mapping will hand over to multiscale, multitemporal nested monitoring approaches, which are relevant to identify disaster hotspots. Coarser and more frequent satellite imagery will be used to identify areas of concern and to then dynamically "zoom in" on the critical regions by using high-spatial-resolution image data. Near real-time observations and direct monitoring of dynamic natural disaster processes such as lava flows, landslides, or floods will be possible from space. In the next 5 to 10 years, substantial scientific, technological, and operational development will handle mass data from different satellite constellations and innovative space sensors. In addition, data relay satellites will be used for boosting reprogramming as well as data downlink. Moreover, automated pattern and object recognition from oblique observations of disaster scenarios is likely to come into wider use. The use of video sequences from space for disaster situation assessment and real-time processing and analysis of satellite imagery for visual analytics and fusion with crowd-sourced and social media information is also likely to play a bigger role, along with high-resolution geostationary EO systems for disaster situational awareness. Online imagery access services and geospatial big data platforms will further shape and advance the global SEM efforts in the near future. These technologies will not all develop at the same pace; nevertheless, there are substantial procedural changes and technological innovations in progress that should be used diligently in order to further advance the global SEM capacities in the years to come.

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## ACKNOWLEDGMENTS

Data sources for this work include International Charter Space and Major Disasters (disasterscharter.org), the European Copernicus EMS (emergency.copernicus.eu), Sentinel Asia (sentinel.tksc.jaxa.jp), UNITAR/UNOSAT (unitar.org/unosat), UNOCHA/ReliefWeb (reliefweb.int), National Disaster Reduction Center of China (jianzai.gov.cn), CRED-EMDAT (emdat.be) Deutsches Zentrum für Luft- und Raumfahrt (DLR) Center for Satellite Based Crisis Information (zki.dlr.de), Sertit (sertit.u-strasbg.fr), and the World Bank (data.worldbank.org/news/new-country-classifications-2015). The support of the International Charter, Copernicus, Sentinel Asia, and NDRCC in granting access to additional SEM statistics and metadata for this Review is kindly acknowledged. We thank A. Thiele, V. Hertel, M. Juessi (DLR), T. Nakao (Asian Disaster Reduction Center), and G. Chaohui (United States Geological Survey) for their enthusiastic efforts in researching the data sources and in database compilation. Many thanks also to R. Kiefl (DLR), A. Vanderveken and A. Beirekdar (UCL), without whom database and geospatial processing would have been difficult. INVAP's support to facilitate the contribution of Gulich Institute to the Review is kindly acknowledged. Last, we thank E. Schoepfer and A. Mager (DLR) for support with graphics and G. Strunz (DLR) for carefully reviewing the manuscript.

## SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/353/6296/247/suppl/DC1
Materials and Methods
Fig. S1
Tables S1 and S2

10.1126/science.aad8728

**Global trends in satellite-based emergency mapping**
Stefan Voigt, Fabio Giulio-Tonolo, Josh Lyons, Jan Kucera, Brenda Jones, Tobias Schneiderhan, Gabriel Platzeck, Kazuya Kaku, Manzul Kumar Hazarika, Lorant Czaran, Suju Li, Wendi Pedersen, Godstime Kadiri James, Catherine Proy, Denis Macharia Muthike, Jerome Bequignon and Debarati Guha-Sapir (July 14, 2016)
*Science* **353** (6296), 247-252. [doi: 10.1126/science.aad8728]

*Science* (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.