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Thomas Gillespie
Jasmine Chu
Elizabeth Frankenberg
Duncan Thomas

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Assessment and prediction of natural hazards from satellite imagery

Thomas W. Gillespie,[1]* Jasmine Chu,[2] Elizabeth Frankenberg[3] and Duncan Thomas[4]

[1]Department of Geography, University of California, Los Angeles 90095, USA
[2]Department of Geography, University of California, Los Angeles 90095, USA
[3]Department of Sociology, University of California, Los Angeles 90095, USA
[4]Department of Economics, University of California, Los Angeles 90095, USA

Abstract: Since 2000, there have been a number of spaceborne satellites that have changed the way we assess and predict natural hazards. These satellites are able to quantify physical geographic phenomena associated with the movements of the earth's surface (earthquakes, mass movements), water (floods, tsunamis, storms), and fire (wildfires). Most of these satellites contain active or passive sensors that can be utilized by the scientific community for the remote sensing of natural hazards over a number of spatial and temporal scales. The most useful satellite imagery for the assessment of earthquake damage comes from high-resolution (0.6 m to 1 m pixel size) passive sensors and moderate resolution active sensors that can quantify the vertical and horizontal movement of the earth's surface. High-resolution passive sensors have been used successfully to assess flood damage while predictive maps of flood vulnerability areas are possible based on physical variables collected from passive and active sensors. Recent moderate resolution sensors are able to provide near real-time data on fires and provide quantitative data used in fire behavior models. Limitations currently exist due to atmospheric interference, pixel resolution, and revisit times. However, a number of new microsatellites and constellations of satellites will be launched in the next five years that contain increased resolution (0.5 m to 1 m pixel resolution for active sensors) and revisit times (daily < 2.5 m resolution images from passive sensors) that will significantly improve our ability to assess and predict natural hazards from space.

Key words: active sensors, earthquakes, fire, floods, natural hazards, passive sensors

I Introduction

Since 2000, there have been a number of spaceborne satellites and sensors that have changed the way we assess and predict natural disasters. These sensors are able to quantify geophyscial phenomena associated with the movements of the earth surface (earthquakes, mass movements), water (floods, tsunamis, storms), and fire (wildfires). Significant improvements in the near

* Author for correspondence. Email: tg@geog.ucla.edu

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real-time assessments of natural hazards have been made due to increases in data acquisition rates, sensor resolution, improvement of change detection algorithms, and integration of remote sensing systems. Concurrently, there has been an increase in the ability to predict certain natural hazards using satellite imagery that can be incorporated into early warning systems (Committee on Energy and Commerce, 2005). Thus it has become increasingly important to examine the accuracy, applications, limitations, and future prospects of remote sensing technology as they relate to natural hazards research (National Research Council, 2007).

This review of spaceborne satellites and their applications for natural hazards research has three primary objectives. First, we review successfully launched satellites and advances in sensors that have become operational since 2000. Second, we review remote sensing and natural hazards case studies undertaken between 2000 and 2006. In particular, we identify significant advances in the assessment and prediction of natural hazards related to the movements of earth, water, and fire. Third, we examine the current limitation of remote sensing technologies and identify future directions of natural hazards research.

II Recent satellites and sensors

There have been over 73 successful launches of earth observing satellites between 2000 and 2006 (ITC, 2007). Most of these satellites contain passive or active sensors that can be utilized by the scientific community for the remote sensing of natural hazards. Passive sensors record reflected (visible and infrared wavelengths) and emitted energy (thermal wavelengths). Since the year 2000, a number of new high-resolution passive sensors that provide panchromatic, visible, near infrared, and thermal imagery have become operational (Table 1). Panchromatic imagery contains the entire wavelength of visible light and provides a black and white image similar to a black and white photograph. Currently, spaceborne satellites such as IKONOS 2, EROS, QuickBird 2, SPOT 5, and OrbView 3 can provide panchromatic imagery with 0.6 m to 2.5 m pixel size and have repeat times of 3 to 14 days. These satellites can also provide multi-spectral imagery using individual bands in the visible (blue, green, red) and near infrared wavelengths to provide true color and infrared imagery. The resolution of this multi-spectral imagery ranges from 2.5 m to 10 m pixel size and have repeat times of 3 to 16 days. Shortwave infrared and thermal imagery provide information on temperature and sensors such as ASTER and MODIS have a number of bands that collect this information. Most shortwave infrared and thermal imagery have relatively large pixel sizes of 30 m to 1 km but higher temporal resolution with repeat times of one day. Finally, the Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) and MODIS can provide daily panchromatic nighttime light imagery (500 m) and thermal imagery (1000 m) at a global spatial scale.

Active sensors send and receive an energy pulse to create an image. Radar (Radio Detection And Ranging) is the most commonly used active remote sensing technique and can provide moderate resolution imagery and digital elevation models of the earth's surface. Unlike passive sensors, radar can penetrate cloud cover, providing imagery over a target area both day and night regardless of weather conditions. There are a number of satellites equipped with radar sensors that have been used in the remote sensing of natural hazards (Table 2). The pixel size from radar sensors (10 m to 30 m) is significantly larger than data provided by passive sensors. Radar sensors measure microwave backscatter within discrete wavelengths or bands such as the X, C, and L bands. The shortest X (3 cm) and C (5.6 cm) bands reflect off the top of objects on the earth while longer wavelengths, such as the L band (24 cm), are able to penetrate into the vegetation and substrate. Recent satellite missions such as ERS-2, SRTM, and Envisat have provided

Table 1 Recent satellites with passive sensors that provide panchromatic (Pan.), visible and near infrared (VNIR), short wave infrared (SWIR), and thermal data that can be used in remote sensing of natural hazards.

Satellite (sensor)	Launch	Pan. (m)	VNIR (m)	SWIR & thermal (m)	Spectral bands	Swath size(Km)	Repeat Time (days)
IKONOS 2	1999	1	4		4	11	3–5
Terra (ASTER)	1999		15	30, 90	14	60	16
Terra (MODIS)	1999		250	500,1000	36	2300	1–2
EROS A	2000	1.9			0	13.5	3–7
QuickBird 2	2001	0.6	2.5		4	16.5	3
Spot 5	2002	2.5	10	20	5	60	5–26
Aqua (MODIS)	2002		250	500,1000	36	2300	1–2
OrbView 3	2003	1	4		4	8	3
FORMOSAT 2	2004	2	8		4	24	14
ALOS	2006	2.5	10		4	35	2–46
KOMPSAT 2	2006	1	4		4	15	28
DMSP (OLS)	2006	560		560	2	2,960	1
EROS B	2006	0.7	2.8		1	7	2

Table 2 Recent satellites with active sensors can be used in remote sensing research of natural hazards.

Satellite (sensor) time(days)	Launch(year)	Pixel(m)	Bands	Polarization	Swath size(Km)	Repeat
ERS-2	1995	26	C	VV	100	3–35
Radarsat-1	1995	10	C	HH	45-500	24
SRTM	2000	30, 90	C, X	VV	225	0
Envisat (ASAR)	2002	30	C	All	500	35
ALOS (Palsar)	2006	7–100	L	All	40-350	2–46

high-resolution topography imagery using interferometric synthetic aperture radar (SAR) techniques. Interferometric synthetic aperture radar sends out a microwave pulse and records the reflected pulse at two points separated by a baseline distance. The resulting parallax can be used to measure elevation with a high degree of accuracy (Metternicht *et al*., 2005). These active systems are able to survey large areas due to their larger pixel and swath size but have long repeat times between 24 to 46 days.

III Earth

Several million earthquakes occur annually worldwide with an average of 18 earthquakes over 7.0 magnitude (USGS, 2007). Since 2000, an estimated 437,060 deaths have occurred as a result of earthquakes and many more have occurred from mass movements such as landslides (USGS, 2007). Satellite imagery has played an important role in pre- and post-disaster assessment and has shown recent potential in predicting earth movements and landslides.

1. Assessment

The most useful real-time data available for the identification of earthquake damaged areas come from very high-resolution commercial satellites such as IKONOS (1 m) and QuickBird (0.6 m). Al-Khudhairy *et al*. (2005) used IKONOS imagery (1 m and 2 m) to create an object oriented segmentation and classification system for Jenin, Palestine and Brest, Netherlands. They demonstrated that object oriented classification techniques enhance quantitative analysis of traditional pixel based techniques for change detection of urban features. This provides a potential new method to automatically extract data from damaged zones in near real time from very high-resolution satellite imagery in the aftermath of disasters (Rejaie and Shinozuka, 2004). Li and Tao (2005) used SPOT imagery to undertake pre- and post-earthquake damage of the 2003 Xinjiang Bachu-Jiashi earthquake in China and developed a probabilistic model for earthquake intensity. Fu *et al*. (2004) utilized three-dimensional pre- and post-earthquake ASTER imagery to identify the fault in the 26 December 2003 Bam earthquake in Iran that caused over 40,000 deaths. They determined that the fault extended 65 km and potential damage from this earthquake could have been identified in advance. Fu and Lin (2001) examined surface rupture zones after an 8.1 magnitude earthquake in northern Tibet using Landsat, SPOT, and ASTER imagery before and after the earthquake to detect the spatial distribution of the surface rupture zone. These sensors identified a surface rupture zone of at least 400 km long, the longest surface rupture zone ever reported worldwide. Their remote sensing analysis was consistent with ground data and provided a rapid assessment for the detection of seismic surface ruptures.

Radar sensors are able to provide high-resolution data on the horizontal (1 m) and vertical (10 cm) movement of the earth's surface (Tronin, 2006). Eguchi *et al*. (2003) used synthetic aperture radar to determine the extent of the 1999 Marmara earthquake in Turkey that could be utilized in response efforts and resource allocation. Using SAR they were able to determine the difference in elevation between pre-and post-earthquake imagery and rapidly provide post-classification of damaged areas. SAR has also been used to detect building damage in Kobe, Japan (Matsuoka and Yamazaki, 2004). Using pre- and post-ERS imagery, they developed an algorithm that identified hard hit areas. The improvement of these change detection algorithms can be used for near real-time disaster management.

2. Prediction

Generally, prediction capabilities of spaceborne satellites remain poor given the unpredictable nature of earthquakes. However, vulnerability of landscapes to earthquake hazards can be quantified with fault and demographic data. Mueller *et al*. (2006)

explored the potential utility of satellite images to determine the vulnerability of buildings to earthquakes using IKONOS and QuickBird imagery. They examined features such as building characteristics (material, height, shape), geologic and edaphic conditions, and context (the position of a house in relation to its surroundings). Ouzounov and Freund (2004) demonstrated the potential capabilities of remote sensing technologies to predict an earthquake up to a week before its occurrence based on mid-infrared emissions from the earth's surface. MODIS imagery provides per-pixel temperature and emissivity values that enable researchers to detect land and sea surface temperature anomalies ranging up to 5 C° from mean values. Before the Bhuj earthquake in Gujarat, India, 2001, MODIS imagery was able to detect a land surface temperature anomaly of 4 C° five to six days before the earthquake hit (Figure 1). This thermal anomaly was hypothesized to occur due to high levels of rock stress prior to the earthquake. The prediction of mass movements such as landslides, avalanches, and debris flows are significantly easier to predict than earthquakes. Metternicht *et al.* (2005) provide an excellent review of satellite imagery and landslides. They show how satellite data on topography and slope collected from active sensors and high-resolution data on vegetation cover and geologic substrate from passive sensors can be used in models to predict slope failures.

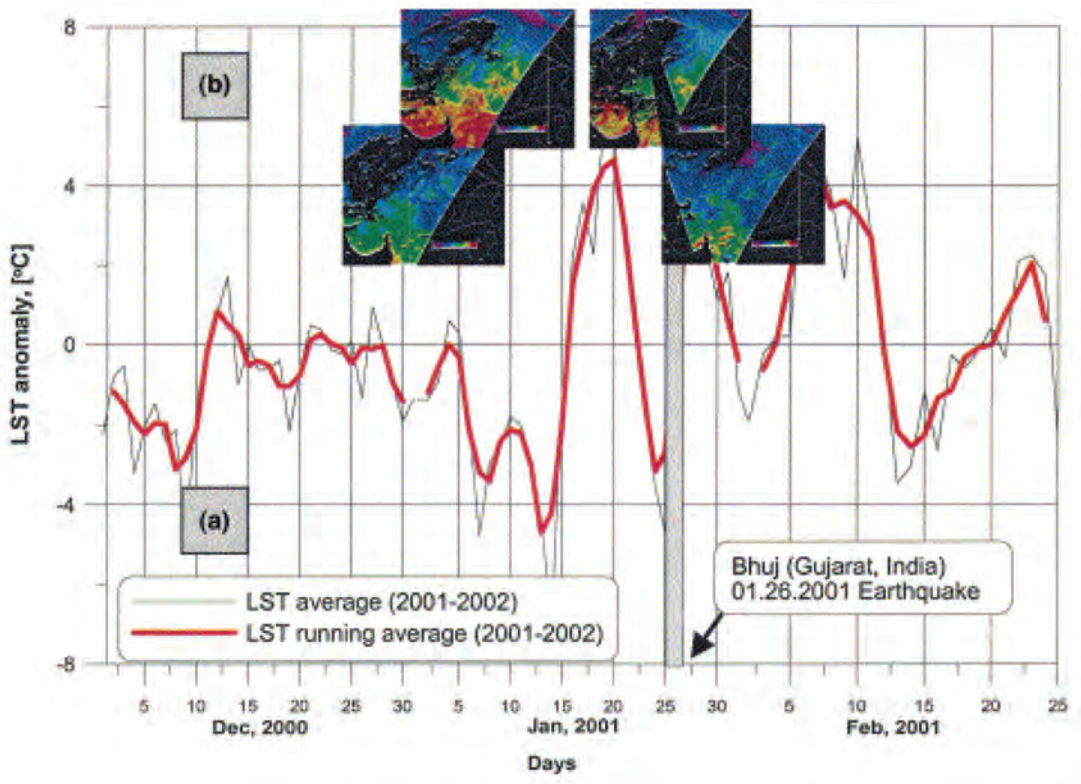

Figure 1 MODIS detection of a land surface temperature anomaly of 4 C° 5–6 days before the Bhuj earthquake hit in Gujarat, India 2001 from Ouzounov and Freud (2004).

IV Water

Floods are the most extensive and devastating of all natural hazards (Sanyal and Lu, 2004). Past studies have employed Landsat and SPOT imagery in conjunction with radar imagery to determine flood extent and damage (Profeiti and MacIntosh, 1997; Sado and Islam, 1997; Sanyal and Lu, 2005). Currently, satellite imagery can play an important role in both the post-disaster assessment and high-resolution predictive maps of flood vulnerability areas.

1. Assessment

High-resolution satellite imagery was widely employed in assessing damage caused by the 2004 Indian Ocean tsunami (Borrero, 2005; Chen *et al.*, 2005; Ghosh *et al.*, 2005; Miura *et al.*, 2006). SPOT images were used in conjunction with IKONOS images for ground-truthing and change/damage detection to allow for rapid disaster response and assessment through measurements of tsunami inundation depth, run-up height, and area of affected land (Chen *et al.*, 2005). Borrero (2005) combined QuickBird imagery and digital elevation models to assess the run-up height (elevation above sea level), inundation distance, shoreline erosion, and co-seismic subsidence of the tsunami in Banda Aceh, Sumatra. Run-up heights were estimated during the initial survey in excess of 25 m. This value was later confirmed by comparing the inundation line inferred in satellite images to digital elevation data on the coastal topography. This suggests satellites could be directed to image affected regions in the future and guide emergency response, allowing for more focused damage assessment and field measurements (Borrero, 2005). Indeed, IKONOS imagery of Sri Lanka was able to successfully quantify damage levels of individual buildings after the 2004 Indian Ocean tsunami (Figure 2). Washed away and completely collapsed buildings showed good agreement with actual damage; however, it was difficult to distinguish partially collapsed buildings from slightly damaged buildings (Miura *et al.*, 2006).

Sanyal and Lu (2004) reviewed the effectiveness of various sensors and their applications in regards to remote sensing of floods in monsoon Asia and demonstrated that radar imagery can also be a cost-effective and efficient means of managing flood disasters. The combination of Landsat and SAR imagery greatly improve the ability to

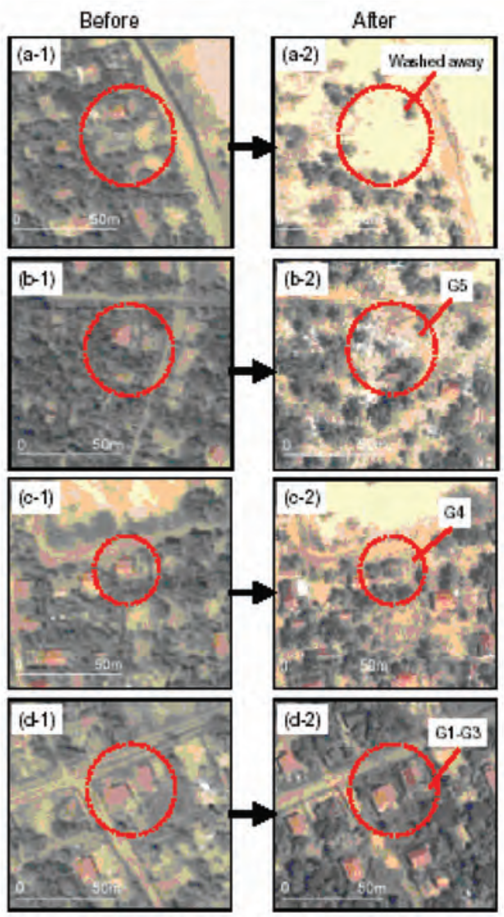

Figure 2 Evaluation of building damage (washed away a-2, totally collapsed b-2, partial collapsed c-2, slightly damaged d-2) after tsunami damage in the eastern part of Sri Lanka using remote sensing technique from Miura et al. (2006).

correctly identify flood areas (Sanyal and Lu, 2004). Radar imagery has been used in flood damage assessment to discriminate between flooded and non-flooded areas (Townshend and Walsh, 1998; Brivio *et al*., 2002). Change detection from comparisons of pre- and post-disaster radar images can be used to illustrate the extent of affected land. Kiage *et al*. (2005) used Radarsat-1 SAR imagery and found significant differences between pre- and post-Hurricane Lili impacted areas in the coastal lowlands of Louisiana. However, SAR imagery was unable to map water levels in urban areas after Hurricane Katrina due to a large amount of backscatter from buildings (Kiage *et al*., 2005).

2. Prediction

The prediction of natural hazards such as storms and hurricanes has long been a central theme in satellite remote sensing. The first earth observation satellites were launched specifically to monitor weather phenomena in the 1960s. Today, weather satellites like GOES provide imagery of storm and hurricane tracks in North America every 15 minutes. Recently developed high-resolution satellites are becoming near real-time and can quantify wind speed, sea level height, and liquid water within and below the clouds (Kastaros *et al*., 2002). SAR images of the ocean can identify areas of high surface winds that may indicate formation of tropical storms and SAR-derived wind data on ocean surface can also provide information regarding storm intensity and asymmetry (Kastaros *et al*., 2002).

In addition to storm monitoring technology, there have been great advances in prediction of flood damage via flood hazard maps of vulnerable gradients. Although hurricanes or high rainfall flood events are not always predictable, the movement of water over the landscape is easy to quantify and predict based on features such as slope, topography, and roughness (Sanyal and Lu, 2005). Flood severity is determined by the height of inundation, which can be extracted from digital elevation models. The accuracy of digital elevation models required for such analyses were often not available for rural regions within developing countries that are prone to monsoon-induced flooding (Profeiti and MacIntosh, 1997; Sado and Islam, 1997). However, the 2001 Shuttle Radar Topography Missions provides 90 m resolution data on elevation at a global spatial scale. Currently, the delineation of flood zones and vulnerability maps has been undertaken on a large scale (Sanyal and Lu, 2004, 2005). High-resolution imagery of topography and land use classifications has also been used to predict flood risk. Van Der Sande *et al*. (2003) combined high-resolution land cover data from IKONOS, digital elevation models, and flood simulation models to provide flood damage assessments in the Netherlands. IKONOS imagery was used in combination with object segmentation software to increase the accuracy of the image classification and create simulations of flood flow velocity. Ultimately, the flood maps derived from the IKONOS imagery were more accurate in comparison to maps created from other sources such as the EU CORINE dataset (Van Der Sande *et al*., 2003). Technologies with the capacity to predict tsunamis are of great significance following the 2004 Indian Ocean tsunami. Lipa *et al*. (2006) demonstrated that radar systems have the capability to detect offshore tsunamis well before the tsunami wave hits the coastline. These radar systems are able to monitor ocean surface currents and waves up to 200 km from the location of the radar.

V Fire

In the year 2005, there were 66,552 wildfires in the United States that cost $875,713,000 to control (NIFC, 2005). Satellites such as NOAA, SPOT, and Landsat have been used in the past to map fire location and extent of fire damage using the visible wavelengths (Li *et al*., 1997; Fuller, 2000). However, recent spaceborne sensors are able to provide near real-time data on global fires and physical geographic variables used in predictive fire behavior models.

1 Assessment

A major objective in the remote sensing of fire from spaceborne sensors has been to obtain accurate measurements of the spatial and temporal distribution of burn areas and active burning on a global scale (Fuller, 2000). For the near real-time assessment of fire, thermal bands from the MODIS sensors have proven relatively successful (Justice *et al*., 2002). MODIS offers fire products that give the locations of active burning fires and identify the extent of burns over different time periods (Justice *et al*., 2002) (Figure 3).

MODIS also provides eight-day binary fire detection products that can map fires within a 2 km by 1 km area (Giglio *et al*., 2003; Quayle *et al.,* 2004). In Zhan *et al.* (2002), the applicability of MODIS Level 1B 250m resolution images were used to assess areas burned by the Idaho-Montana wildfires in 2000. The Vegetative Cover Conversion product, which was designed to serve as an alarm to indicate regions where vegetative cover conversion may have occurred, was applied to MODIS imagery of the fire regions. This study demonstrated that remote sensing can identify burned areas at a higher spatial resolution than the traditional methods employed by the United States Forest Service. However, these fire products still need to be validated at a global spatial scale (San-Miguel-Ayanz *et al*., 2005). Csizar *et al.* (2006) compared coincident ASTER and MODIS imagery for fires in both Siberia and the Amazon. They demonstrated that ASTER could identify and delineate fire three to five times more accurately than MODIS imagery. However, ASTER is an on-demand sensor, so global real-time data are not yet available. The Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) provides nighttime fire data at 560 m pixel resolution. For forest fires in India, DMSP-OLS has been shown to be 98% accurate when validated against ground observations (Kiran Chand *et al*., 2006). This nighttime sensor combined with MODIS daytime sensors can greatly increase accuracy of fire detection (Justice *et al*., 2002). However, Stolle *et al.* (2004) compared eight fire dataset, including DMSP-OLS and MODIS, at 10 km by 10 km pixel resolution every 10 days in Indonesia. They showed that these dataset still have high omission errors and more than two-thirds of the fires detected by one dataset were not detected by any other dataset. Oertel *et al.* (2004) used a Bi-spectral InfraRed Detection (BIRD) microsatellite over Benin, West Africa, and detected fires with active burning areas less than a 100 m^2. They were also able to quantify important characteristics of these fires such as radiative fire energy release and the effective fire temperature.

Figure 3 Global cumulative active fire detections (23 April 2001 to 25 February 2002) from the MODIS Land Rapid Response System. Each red dot represents a single 1-km MODIS active fire pixel detected during the time period from Justice et al. (2002)

Radar has also been very effective in near real-time mapping of fire because radar sensors can penetrate clouds, haze, and thick smoke (Huang and Siegert, 2006). An analysis on ERS SAR images of fire burn scars in Alaskan forest conducted by Huang and Siegert (2006) demonstrated that non-burnt forests have lower backscatter signals than burnt forests and can be useful in detecting burned areas. In East Kalimantan, multi-temporal SAR images from ERS-2 were used to map burn scars (Siegert and Hoffman, 2000). They found SAR imagery could complement current fire monitoring systems and provide data at a resolution 900 times higher than NOAA/AVHRR satellites.

2. Prediction

In Europe, only 5% of forest fires are started by natural causes and most are detected by ground-based systems such as towers and mobile observers (San-Miguel-Ayanz *et al.*, 2005). Although satellite remote sensing cannot be used to predict fire ignition from arson and negligence, fire prediction has progressed in the form of wildfire behavior models. There are a number of fire prediction models such as FARSITE that can model fire patterns within a landscape (Finney, 1998). These models require high-resolution data on physical geographic variables such as weather (moisture indices, wind speeds), vegetation characteristics (live and dead fuel loads in grasslands, shrublands, and forests) and land use to predict fire behavior and intensity (Anderson *et al.*, 2005). Satellite imagery can be used to quantify a number of these variables (Fuller, 2000; Boyd and Danson, 2005). Radar imagery from ERS-1 and RADARSAT have been used to predict the potential for fires based on fuel loads and fuel moisture; however, there is still significant noise in quantifying these variables from radar sensors and further tests are needed (Leblon, 2005).

VI Limitations

Although the use of satellite imagery in natural hazards damage assessment and prediction can be very cost and time effective, some limitations still exist. Atmospheric interferences in the form of clouds, haze, and smoke present a significant problem in passive optical imagery analysis because they block parts of the image and can cause distortions (Zhan *et al.*, 2002). Often, these clouded and shadowed areas must be excluded from damage assessment analyses, resulting in gaps in the data. Active sensors can avoid this problem but there are still significant limitations due to large pixel sizes, classification accuracy, and revisit times (Sanyal and Lu, 2004). The temporal resolution of active and passive sensors can also pose a problem for the damage assessment of natural hazards in near real-time. Although sensors such as MODIS have a daily revisit time, other sensors on satellites such as QuickBird and IKONOS have longer revisit times. Earthquakes, landslides, and floods can occur very rapidly and the peak of the disaster may only persist for a few hours, so the most severe point of a disaster may not be captured (Sanyal and Lu, 2004). Although open access satellite images are significantly changing our response to natural hazards, the resolution on these images can be high enough to be a national security risk (Butler, 2005; Nourbakhsh *et al.*, 2006). In an effort to help disaster relief after the 8 October 2005 earthquake in Kashmir, Pakistan, numerous international aid agencies posted high-resolution satellite images on the web. However, the Pakistan government forced the removal of these images because they feared the security of the Kashmir region might be compromised. Finally, there is still a need to increase the ability of disseminating data that can be integrated with demographic and socioeconomic data for risk mitigation planning and disaster response (Duda and Abrams, 2005; Tralli *et al.*, 2005; National Research Council, 2007).

VII Future directions

A satellite that contained 1 m resolution passive sensors (visible, infrared, and thermal bands), active sensors that recorded elevation to within 1 cm, and a repeat time of one hour would significantly improve our ability to assess and predict natural hazards. Such a satellite is not likely in the near future, but remote sensing of natural hazards appears to be headed towards an increase in micro-satellites, increased pixel resolutions, increased repeat times, and an increase in the integration of satellites. New satellites and constellations of satellites will be launched in the next five years (Table 3). The Disaster Monitoring Constellation (DMC) will consist of five satellites, operated by the Chinese, British, Algerian, Nigerian, and Turkish governments, and will provide emergency imagery comparable in resolution to the Landsat series (Wooster, 2007). Rapid Eyes, a constellation of five satellites with five multi-spectral bands at 6.5 m pixel resolution, will have a repeat time of one day. By the year 2010, if these satellites are successfully launched and current sensors are operational, we estimate that five panchromatic images of 2.5 m or less and eight multi-spectral images of 10 m or less will be available daily (ITC, 2007).

There are also a number of active sensors that will significantly improve damage assessment (Table 3). Cosmo/SkyMed is a constellation of four satellites that will be launched in 2007 and provide high-resolution radar data at 1 m and a repeat time of five days. This can be used to create global benchmarks on the topography of the earth's surface and populated regions. After a natural hazard, these benchmarks can rapidly be compared to post-natural disaster imagery to assess damage in near real-time. A number of regional disaster centers have been developed that provide local, state, federal, and regional emergency managers with remote sensing data and tools to aid in response and recovery (Laben, 2002; National Research Council, 2007). These advances in satellites, sensors, and data distribution should significantly improve our ability to assess and predict natural hazards over the next five years.

Table 3 Spaceborne satellites with passive and active sensors that will be launched in the next five years.

	Satellites (*n*)	Launch date	Sensor attributes			Swath size (Km)	Repeat time (days)
Passive			Pan. (m)		VNIR (m)		
DMC	5	2005–9	4–12		32	600	4
CartoSat-2	2	2007	1			10	4
Rapid Eye	5	2007	6.5		6.5	78	1
Pleiades	2	2008–10	0.7		2.8	520	1
EROS C	2	2009	0.7		2.8	11	na
Active			Pixel (m)	Band	Polarization		
SAR-Lupe	5	2007–09	0.5	X	All	70	1
COSMO- SkyMed	4	2007–09	1	X	All	520	5
TerraSAR-X	1	2007	1	X	All	5	11

References

Al-Khudhairy, D.H.A., Caravaggi, I. and **Glada, S.** 2005: Structural damage assessments from Ikonos data using change detection, object-oriented segmentation, and classification techniques. *Photogrammetric Engineering and Remote Sensing* 71, 825–37.

Anderson, H.E., McGaughey, R.J. and **Reutebuch, S.E.** 2005: Estimating forest canopy fuel parameters using LIDAR data. *Remote Sensing of Environment* 94, 441–9.

Borrero, J.C. 2005: Field data and satellite imagery of tsunami effects in Banda Aceh. *Science* 308, 1596.

Boyd, B.S. and **Danson, F.M.** 2005: Satellite remote sensing of forest resources: three decades of research development. *Progress in Physical Geography* 29, 1–26.

Brivio, P.A., Colombo, R., Maggi, M. and **Tomasoni, R.** 2002: Integration of remote sensing data and GIS for accurate mapping of flooded areas. *International Journal of Remote Sensing* 23(3), 429–41.

Butler, D. 2005: Quake aid hampered by ban on web shots. *Nature* 437, 1072–3.

Chen, P. Liew, S.C. and **Kwoh, L.K.** 2005: Tsunami damage assessment using high resolution satellite imagery: a case study of Aceh, Indonesia. *Geoscience and Remote Sensing Symposium, 2005. Proceedings 2005 IEEE International* 2, 1405–8.

Committee on Energy and Commerce. 2005: *The implementation of GEOSS: a review of the all-hazards warning system and its benefits to public health, energy, and the environment*. Washington, DC: US Government Printing Office.

Csizar, I.A., Morisette, J.T. and **Giglio, L.** 2006: Validation of active fire detection from moderate-resolution satellite sensors: the MODIS example in northern Eurasia. *IEEE Transactions on Geoscience and Remote Sensing* 44, 1757–64.

Duda, K.A. and **Abrams, M.** 2005: ASTER and USGS EROS disaster response: emergency imaging after hurricane Katrina. *Photogrammetric Engineering and Remote Sensing* 71, 1346–50.

Eguchi, R.T., Huyck, C.K., Adams, B.J.; Mansouri, B., Houshmand, B. and **Shinozuka, M.** 2003: Resilient disaster response: using remote sensing technologies for post-earthquake damage detection. *MCEER Research Progress and Accomplishments, 2001–2003*.

Finney, M.A. 1998: *FARSITE: Fire area simulator-model development and evaluation*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station Research Paper RMRS-RP-4.

Fu, B. and **Lin, A.** 2001: Spatial distribution of the surface rupture zone associated with the 2001 Ms 8.1 Central Kunlun earthquake, northern Tibet, revealed by satellite remote sensing data. *International Journal of Remote Sensing* 24, 2191–8.

Fu, B., Ninomiya, Y., Lei, X., Toda, S. and **Awata, Y.** 2004: Mapping active fault associated with the 2003 mw 6.6 Bam (SE Iran) earthquake with ASTER 3D images. *Remote Sensing of Environment* 92, 153–7.

Fuller, D.O. 2000: Satellite remote sensing of biomass burning with optical and thermal sensors. *Progress in Physical Geography* 24, 543–61.

Giglio, L., Descloitres, J., Justice, C.O. and **Kaufman, Y.J.** 2003: An enhanced contextual fire detection algorithm for MODIS. *Remote Sensing of Environment* 87, 272–82.

Ghosh, S., Adams, B.J., Huyck, C.K., Mio, M., Eguchi, R.T., Yamazaki, F. and **Matsuoka, M.** 2005: Preliminary field report: post-tsunami urban damage survey in Thailand using the VIEWS reconnaissance system. *MCEER Quick Response Report Series*.

Huang, S. and **Siegert, F.** 2006: Backscatter change on fire scars in Siberian Boreal forests in ENVISAT ASAR wide-swath images. *Geoscience and Remote Sensing Letters IEEE* 3, 154–8.

ITC. 2007: International Institute for Geo-Information Science and Earth Observation Launch schedule. http://www.itc.nl/research/products/sensordb/Launch_Schedule.aspx.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, D., Petitcolin, F. and **Kaufman, Y.** 2002: The MODIS fire products. *Remote Sensing of Environment* 83, 244–62.

Kastaros, K.B., Vachon, P.W., Liu, T.W. and **Black, P.G.** 2002: Microwave remote sensing of tropical cyclones from space. *Journal of Oceanography* 58, 137–51.

Kiage, L.M., Walker, N.D., Balasubramanian, S., Babin, A. and **Barras, J.** 2005: Applications of radarsat-1 synthetic aperture radar imagery to assess hurricane-related flooding of coastal Louisiana. *International Journal of Remote Sensing* 26, 5359–80.

Kiran Chand, T.R., Badarinath, K.V.S., Prasad, V.K., Murthy, M.S.R., Elvidge, C.D. and **Tuttle, B.T.** 2006: Monitoring forest fires over the Indian region using Defense Meteorological Program-Operational Linescan System nighttime satellite data.*Remote Sensing of Environment* 103, 165–78.

Laben, C. 2002: Integration of remote sensing data and geographic information system technology for emergency managers and their applications at the pacific disaster center. *Optical Engineering* 41, 2129–36.

Leblon, B. 2005: Monitoring forest fire danger with remote sensing. *Natural Hazards* 35, 343–59.

Li, P. and **Tao, X.** 2005: Quantitative earthquake damage detection from changes in remote sensing images: a case study. *IEEE Transaction on Geoscience and Remote Sensing* 2, 1026–9.

Li, Z., Cihlar, J., Moreau, L., Huang, F. and **Lee, B.** 1997: Monitoring fire activities in the boreal ecosystems. *Journal of Geophysical Research* 102(D24), 29611–24.

Lipa, B.J., Barrick, D.E., Bourg, J. and **Nyden, B.B.** 2006: HF radar detection of tsunamis. *Journal of Oceanography* 62, 705–16.

Matsuoka, M. and **Yamazaki, F.** 2004: Use of satellite SAR intensity imagery for detecting building areas damaged due to earthquakes. *Earthquake Spectra* 20, 975–94.

Metternicht, G., Hurni, L. and **Gogu, R.** 2005: Remote sensing of landslides: an analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. *Remote Sensing of Environment* 98, 284–303

Miura, H., Wijeyewickrema, A.C. and **Inoue, S.** 2006: Evaluation of tsunami damage in the eastern part of Sri Lanka due to the 2004 Sumatra earthquake using remote sensing techniques. *Proceedings of the Eighth US National Conference on Earthquake Engineering*, 18–22 April, San Francisco, CA. Paper No. 8NCEE-856.

Mueller, M., Segl, K., Heiden, U. and **Kaufmann, H.** 2006: Potential of high-resolution satellite data in the context of vulnerability of buildings. *Natural Hazards* 38, 247–58.

National Research Council. 2007: *Tools and methods for estimating populations at risk from natural hazards and complex humanitarian crises*. Washington, DC: The National Academies Press.

NIFC. 2005: Wildland fire statistics: http://www.nifc.gov/stats/index.html (accessed 20 January 2007).

Nourbakhsh, I., Sargent, R., Wright, A., Cramer, K., McClendon, B. and **Jones, M.** 2006: Mapping disaster zones. *Nature* 439, 787–8.

Oertel D., Zhukov, B., Thamm, H.P. Roehrig, J. and **Orthmann, B.** 2004: Space-borne high-resolution fire remote sensing in Benin, West Africa. *International Journal of Remote Sensing* 25, 2209–16.

Ouzounov, D. and **Freund, F.** 2004: Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data. *Advances in Space Research* 33, 268–73.

Profeiti, G. and **MacIntosh, H.** 1997: Flood management through Landsat TM and ERS SAR data: a case study. *Hydrological Processes* 11, 1397–1408.

Quayle, B., Sohlberg, R. and **Descloitres, J.** 2004: Operational remote sensing technologies for wildfire assessment. *Geoscience and Remote Sensing Symposium, 2004. Proceedings IEEE International* 3, 2245–7.

Rejaie, A. and **Shinozuka, M.** 2004: Reconnaissance of Golcuk 1999 earthquake damage using satellite images. *Journal of Aerospace Engineering* 17, 120–5.

Sado, K. and **Islam, M.M.** 1997: Satellite remote sensing data analysis for flooded area and weather study: case study of Dhaka city, Bangladesh. *Journal of Hydraulic Engineering* 41, 945–50.

San-Miguel-Ayanz, J., Ravail, N., Kelha, V. and **Ollero, A.** 2005: Active fire detection for fire emergency management: potential and limitations for operational use of remote sensing. *Natural Hazards* 35, 361–76.

Sanyal, J. and Lu, X.X. 2004: Application of remote sensing in flood management with special reference to monsoon Asia: a review. *Natural Hazards* 33, 283–301.

Sanyal, J. and **Lu, X.X.** 2005: Remote sensing and GIS-based flood vulnerability assessment of human settlements: a case study of Gangetic West Bengal, India. *Hydrological Processes* 19, 3699–3716.

Siegert, F. and **Hoffman, A.A.** 2000: The 1998 forest fires in East Kalimantan (Indonesia): a quantitative evaluation using high-resolution, multitemporal ERS-2 images and NOAA-AVHRR hotspot data. *Remote Sensing of the Environment* 72, 64–77.

Stolle, F., Dennis, R.A., Kurniwan, I. and **Lambin, E.F.** 2004: Evaluation of remote sensing-based active fire datasets in Indonesia. *International Journal of Remote Sensing* 25, 471–9.

Townshend, P.A. and **Walsh, S.J.** 1998: Modelling flood plain inundation using integrated GIS with radar and optical remote sensing. *Geomorphology* 21(98): 295–312.

Tralli, D.M., Blom, R.G., Zlotnicki, V., Donnellan, A. and **Evans, D.L.** 2005: Satellite remote sensing of earthquake, volcano, flood, landslide, and coastal inundation hazards. *ISPRS Journal of Photogrammetry and Remote Sensing* 59, 185–98.

Tronin, A.A. 2006: Remote sensing and earthquakes: a review. *Physics and Chemistry of the Earth* 31, 138–42.

USGS. 2007: Earthquake hazards program: earthquake facts and statistics. http://neic.usgs.gov/neis/eqlists/eqstats.html (accessed 20 January 2007).

Van Der Sande, C.J., de Jong, S.M. and **de Roo, A.P.J.** 2003: A segmentation and classification approach of IKONOS-2 imagery for land cover mapping to assist flood risk and flood damage assessment. *International Journal of Applied Earth Observation* 4, 217–29.

Wooster, M. 2007: Remote sensing: sensors and systems. *Progress in Physical Geography* 31, 95–100.

Zhan, X., Sohlberg, R.A., Townshend, J.R.G., DiMiceli, C., Carroll, M.L., Eastman, J.C., Hansen, M.C. and **DeFries, R.S.** 2002: Detection of land cover changes using MODIS 250 m data. *Remote Sensing of Environment* 83, 336–50.