RAPID FLOODED AREA DETECTION BY APPLYING ROBUST SATELLITE TECHNIQUES ON DIFFERENT GEOSTATIONARY DATA

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Abstract

Facing the impact of floods by remote sensing data requires both satellite systems able to frequently observe soil conditions and robust processing algorithms capable to provide reliable information on surface changes. Only in this way an effective contribution to the management of flood risk can be carried out. In particular, geostationary satellites might give an useful support in timely detecting areas affected by floods. Their very high temporal resolution (presently up to 5 minutes) allows, in fact, to monitor in real time soil conditions and variations. Moreover, such a frequent observing capability maximises the chance of acquiring a cloud-free view of the land surface, the main limit when optical data are used for flood detection and monitoring from space.
An advanced satellite data analysis methodology, named RST (Robust Satellite Techniques), has been recently implemented and successfully applied by using visible and near infrared Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) data for providing reliable and accurate indication about flooded area presence and evolution in daytime.
In this work, the RST technique has been further tested and assessed using two different sensors onboard geostationary satellites. In detail, the Berg river flood occurred in the South Africa's Western Cape province in late July and early August 2007 was analyzed by means of Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI) data. Multi-functional Transport Satellite 1R (MTSAT-1R) data have been instead analyzed to assess their potential in tracking the effects of the huge tsunami which hit eastern coasts of the Honshu Island (Japan) as a consequence of the March 11, 2011 Tohoku earthquake.
The analysis of the results, shown in this paper, highlights the potential of RST in furnishing reliable and updated information on flood presence and evolution also when implemented on satellite data at a coarse spatial resolution like the geostationary ones.

INTRODUCTION

Floods are, among natural disasters, the most frequent and dangerous: between 2002 and 2010 they affected more than one billion people causing more than 100,000 casualties (EM-DAT, 2011). They significantly influence environmental ecological processes as well as the human socio-economic situation. Furthermore, their negative impact is predicted to get worse because climate change may lead to more frequent and more severe events in the future (Kleinen and Petschel-Held, 2007; McGranahan et al., 2007), especially if adequate mitigation activities will not be implemented at global, national and regional scale.
Generally speaking satellite data acquired in different regions of the electromagnetic spectrum (i.e. from visible to microwave) by using different technologies (i.e. active or passive instruments) can provide useful information in all the different phases of the flood risk management cycle (Lacava et al., 2010). Despite this, a few satellite-based techniques exist for the rapid detection and monitoring of flooded land (Proud et al., 2011). Typically such techniques, where they do exist, are based on local

knowledge, news reports and governmental information or require *in situ* monitoring of water conditions (Proud et al., 2011).
Geostationary (GEO) satellites, thanks to their frequent imaging and fixed position relative to the Earth's surface, provide a unique opportunity to examine diurnal trends in soil moisture, land surface temperature and cloud cover, as well as, over long temporal scales, to monitor seasonal vegetation growth and drought events and climatic changes (Proud et al, 2001). In particular, being capable of rapid data acquisition, GEO systems are particularly useful for catching the dynamic and transient nature of flooding events also because the very frequent observing capability which they guarantee maximises the chance of gaining a cloud-free view of the land surface. Thanks to their capability to furnish almost continuous information about surface (i.e. 4 passes per hour for Meteosat Second Generation –MSG), GEO platforms allow for a timely detection of inundated areas and a near real time monitoring of their spatial and temporal evolution. Provided that reliable data analysis algorithms are used, GEO systems might then contribute for an effective support to the management of flood risk emergency (Faruolo et al., 2012a).
The Robust Satellite Techniques (RST) approach (Tramutoli, 2007), a general strategy for multi-temporal data analysis, has already demonstrated its potential in correctly identifying and monitoring flooded areas in daytime conditions by exploiting the peculiar water/soil spectral behaviours in visible and near infrared (VNIR) bands of the Advanced Very High Resolution Radiometer (AVHRR) (Lacava et al., 2010) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (Faruolo et al., 2012a).
In this work, the potential of the RST approach for flooded areas detection and monitoring, when implemented on GEO satellite data, is analyzed and discussed. In detail, data acquired by Spinning Enhanced Visible and InfraRed Imager (SEVIRI) onboard MSG and by Multi-functional Transport Satellite 1R (MTSAT-1R) have been processed to investigate two different study cases occurred in the past, one in South Africa and another in Japan. The preliminary outcomes arising from these analyses are shown and discussed in this paper.

THE RST METHODOLOGY

RST is a general multi-temporal approach of data analysis that has been already successfully applied for investigating different natural and environmental risks. A detailed description of the approach can be found in Tramutoli (2007). Generally speaking, the approach is based on a preliminary characterization of the signal, at pixel level, in terms of expected value and natural variability, by analyzing multi-year homogeneous (e.g. same area, same spectral channel/s, same month and acquisition time) series of satellite records. Then, signal anomalies are identified by means of an unsupervised change detection step, devoted to quantify the statistical significance of observed deviations respect to the above defined background levels. The approach, being based on the signal at hands, can be applied with every kind of satellite data and the "diagnostic" signal can be a single or a multi channel combination. The only fundamental requirement is the availability of long term (higher than 3 years) historical series of satellite data over the investigated region.
In its previous application to flood detection and monitoring, RST has successfully showed the high potential of AVHRR and MODIS VNIR data for such aims (Lacava et al., 2010; Faruolo et al., 2012a). In particular, achieved results have highlighted the capabilities of RST in discriminating permanent water from actually flooded areas with a high level of reliability and a good sensitivity, suggesting the implementation of a multi-sensor flood monitoring system (Faruolo et al., 2012a).
In this paper we implemented this approach to GEO MSG/SEVIRI and MTSAT-1R data and further assessed its potential in investigating different kind of events: a weather-related flooding event in South Africa and an earthquake-induced tsunami inundation in Japan.

RST APPLIED TO MSG/SEVIRI IMAGERY

Among the twelve SEVIRI available channels, the reflectances measured in channel 1 (VISible: 0.56-0.71 μm) and channel 3 (ShortWave InfraRed 1.50-1.78 μm) have been already exploited to discriminate flooded pixels, thanks to the higher contrast between spectral characteristic of soil and water at these wavelengths (Proud et al., 2011). As shown in Faruolo et al. (2012b), the ratio and difference between such bands, when used in the RST context, allowed for discriminating the presence of new water affected areas over SEVIRI scenes with a high level of reliability and accuracy. In detail, two different indices have been used:

$$\otimes_{VIS/SWIR}(x,y,t) = \frac{R_{VIS/SWIR}(x,y,t) - \mu_{VIS/SWIR}(x,y)}{\sigma_{VIS/SWIR}(x,y)} \quad (1)$$

$$\otimes_{VIS-SWIR}(x,y,t) = \frac{R_{VIS-SWIR}(x,y,t) - \mu_{VIS-SWIR}(x,y)}{\sigma_{VIS-SWIR}(x,y)} \quad (2)$$

where $R_{VIS/SWIR}$ ($R_{VIS-SWIR}$) is the ratio (difference) measured for the pixel (x,y) at time t, and $\mu_{VIS/SWIR}$ ($\mu_{VIS-SWIR}$) and $\sigma_{VIS/SWIR}$ ($\sigma_{VIS-SWIR}$) are the temporal mean and the standard deviations (namely the "reference" fields) computed for both the signals analyzing historical series of co-located SEVIRI data. High positive values of such indices are expected in presence of inundated areas.

In detail, each RST index is a standardized variable, characterized by a Gaussian behavior (with $\mu = 0$ and $\sigma = 1$). This means that the probability of occurrence of values higher than 2σ is around 2%, and it becomes lower than 0.2% as far as values higher than 3 are considered. Moreover, it has been demonstrated (Sheng & Xiao, 1994; Sheng et al., 1998) that the "differential" index (Eq. 2) is more sensitive to water presence than the "ratio" one (Eq. 1) which is preferred for a detection "for sure" of anomalies.

The two indices (Eq. 1) and (Eq. 2) were applied in this work for detecting flooded areas along the Berg river which inundated the St. Helena Bay, an area of the South Africa's Western Cape province (Figure 1), in late July and early August 2007, after a week of heavy rains (New Scientist Environment, 2007).

Figure 1. **MODIS image of 31 July 2007 showing the Berg rivers flood in the investigated area highlighted by the gray box. Adapted by NASA, Earth Observatory (2007)**

SEVIRI data from 2004 to 2010 were collected and processed considering in particular a subset of 94 Pixels x 47 Lines, centred over the Berg river (Upper Left 32°07'S 17°41'E, Lower Right 33°15'S 19°06'E) (Figure 1).

To better highlight the reliability of the VIS and SWIR combinations for flooded area detection, a comparison between the two signals measured at different times (from 08:00 to 13:00 GMT) for three days (30 and 31 July, 1 August) for a pixel involved in the flood and for an unperturbed one was carried out (Fig. 2). Specifically, looking at the figure it is evident how for the three selected days, during the flooding event, both ratio (Fig. 2a) and difference (Fig. 2b) signals are significantly higher for flooded pixels than for unperturbed areas, as a consequence of the higher water radiation absorption in the SWIR than in the VIS. The two small peaks in the signal measured on 30 July for the unperturbed pixel are due to the presence of clouds.

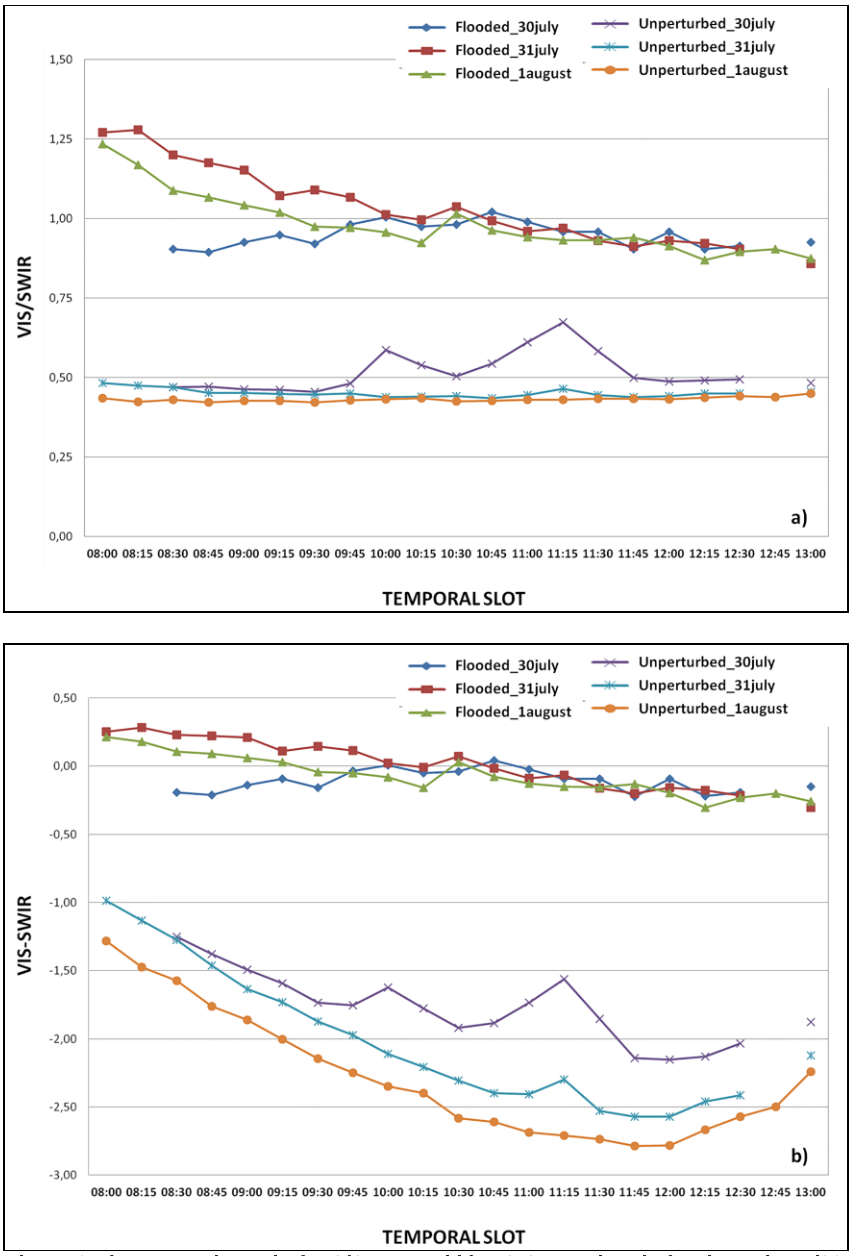


Figure 2. **a) Temporal trend of VIS/SWIR and b) VIS-SWIR signals for three days (30 July, 31 July and 1 August) during the flooding event and two pixels (a flooded and an unperturbed).**

In Figure 3 the achievements obtained using the indices (Eq. 1) and (Eq. 2) are shown for the three days during the flooding event. Flooded pixels were flagged in purple for the ‘ratio’ index and in green when ‘difference’ one was used. It should be stressed that in such a preliminary analysis, among the available daily temporal slots, only three were used (i.e. 08:00, 10:00 and 12:00 GMT). The “anomalous” areas represent the sum of all pixels detected as flooded (at a relative intensity higher than two times the standard deviation) at each of the investigated temporal slot by each index for the passes from 30 July and 1 August 2007.

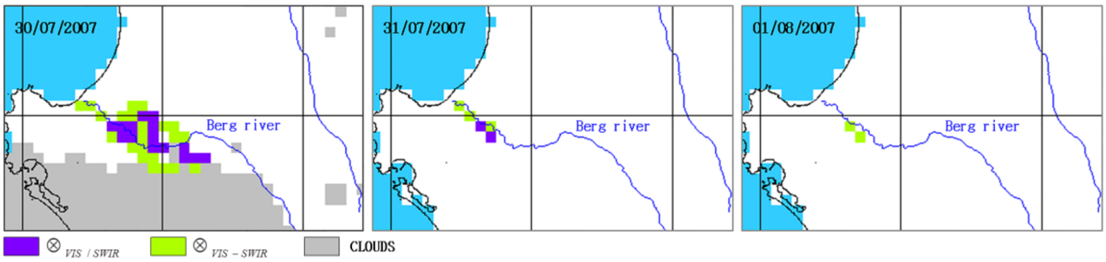


Figure 3. **Temporal evolution of flood extent between 30 July and 1 August 2007 by implementing the two RST SEVIRI based indices. The sea was masked in blue.**

Despite the low spatial resolution of SEVIRI data (not better than 3 km), RST is able to give reliable information about flood presence, extent and space-time evolution, as shown in Figure 3. Due to the heavy rainstorms, on July 30 a large water-covered land is clearly visible around the Berg rivers, while on the days after the flood waters gradually receded and a few anomalies were observed, indicating a restoring of normal conditions. As before explained, note the high number of flooded pixels when the difference index is used, confirming, also for GEO data, the different sensitivity of the two indices already documented by analysing polar satellite data.

RST APPLIED TO MTSAT-1R IMAGERY

MTSAT-1R acquires information in five bands (VIS, MIR and TIR), not providing the opportunity to use the index already implemented with SEVIRI data. Thus, for such kind of data, inundated areas were detected analyzing only the reflectance (R_{VIS}) variation in its VISible band (channel 1: 0.55-0.90 μm) at 1km of spatial resolution. Considering the water spectral behaviour at this wavelength, its presence in a soil should determine a reduction of the investigated signal for the pixels affected by flood. Therefore the RST index used in such an analysis is:

$$\otimes_{VIS}(x,y,t) = \frac{R_{VIS}(x,y,t) - \mu_{VIS}(x,y)}{\sigma_{VIS}(x,y)} \qquad (3)$$

In presence of flooded areas, negative values of such an index are then expected.
The study case is the flood event due to the tsunami which affected the Pacific coast of Tohoku, Japan, on March 11, 2011, following the earthquake of magnitude 9.0 occurred in that region. On the Sendai Plain, the maximum inundation height was 19.5 m and the tsunami wave propagated more than 5 km inland (Mori et al., 2011). In Figure 4 the yellow box represents the spatial subset (201 Pixels x 151 Lines) of the MTSAT imagery of the Japanese coast analyzed by RST (Upper Left 138°17' E 39°12' N, Lower Right 143°09' E 34°34' N).

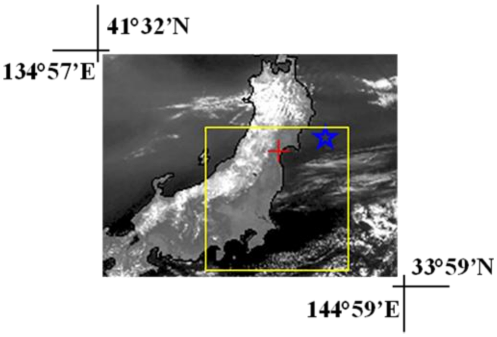


Figure 4. **The yellow box defines the region of interest for RST analyses along the Japanese coasts.**

While implementing RST such a spatial subset was created for each MTSAT-1R image acquired between 09LT and 16LT, with a 1hour time lag, in the period 2005-2011. Coming back to the analyzed signal, i.e. the reflectance measured in the visible channel, also in this case a comparison between the signal measured in a flooded and an unperturbed pixel during the diurnal acquisitions of 12 and 13 of

March was carried out (Fig. 5), finding, as expected, a lower intensity of the signal in correspondence of water covered area (Fig. 5). By Fig. 5, it is interesting to note also the increasing of reflectance from 09-12LT and a gradual decreasing starting from 12LT, as a function of solar illumination. Obviously, being RST a differential approach, which takes into account for the historical behaviour of the investigated signal at pixel level for a specific observational condition (i.e. at same time of the day), this issue is inherently overcome.

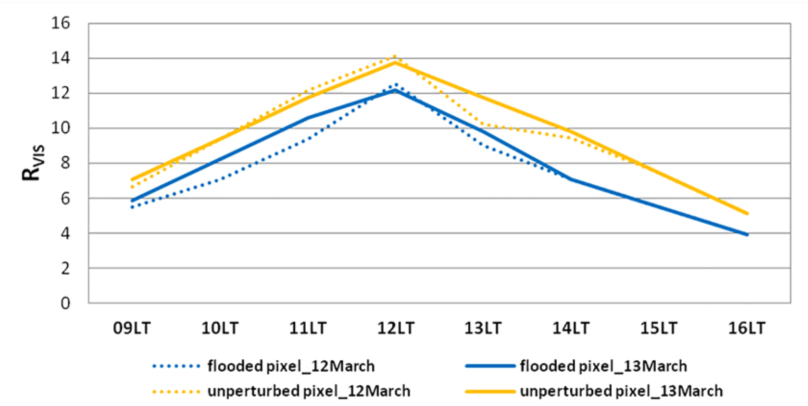
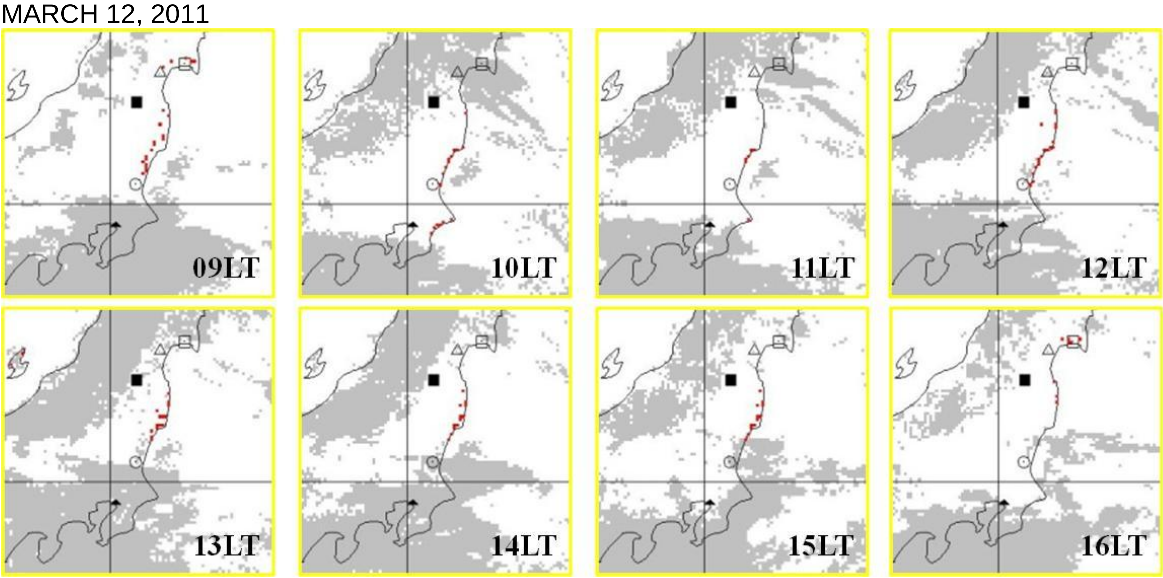


Figure 5. **Reflectance values in the MTSAT-1R visible channel for a flooded and an unperturbed pixel.**

In the following, the maps obtaining applying Eq. 3 on the MTSAT-1R images acquired for March 12 and 13, 2011, the two days just following the tsunami event, are shown. The proposed index was calculated for all diurnal acquisitions from 09LT to 16LT: in the maps the pixels detected as flooded (i.e. those whose reflectance signal is statistically less than 2 times the standard deviation) are masked in red while clouds are depicted in gray (Fig. 6).

MARCH 12, 2011



MARCH 13, 2011

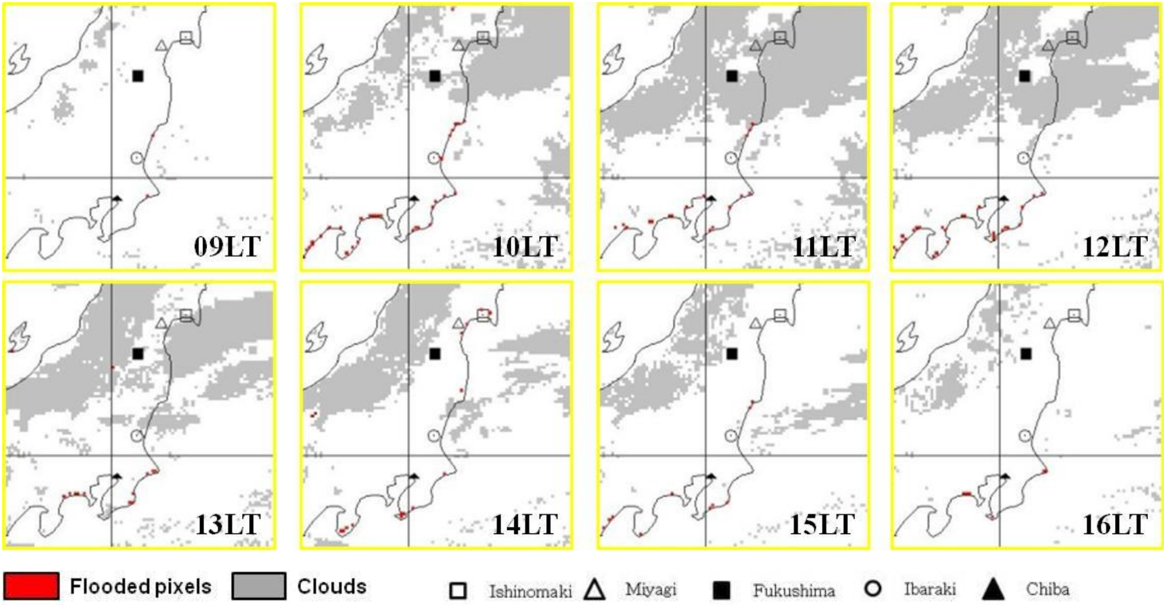


Figure 6. **Detection of flooded pixels (in red) along the Japanese coasts for March 12 (on the top) and 13 (on the bottom) using Eq. 3.**

In the temporal sequence between 09LT and 16LT the RST potential in identifying flooded pixels is clearly evident. All anomalous pixels are located along the Japanese coasts, in correspondence of the higher affected cities; their localization and their persistence both in space and in time, coupled with the independent information about the flood extension (Mori et al., 2011), seem to indicate that they could be undoubtedly related to actual flooded areas.
Moreover, looking at the two sequences, it is possible to observe as on the images of March 12, because of clouds, the anomalous pixels are mostly detected in the central and northern coastal areas while in the images of March 13 flooded areas appear in the southern coasts as well. Finally, looking at the last image (i.e. March 13 at 16LT), it is possible to see as only a few flooded pixels were identified over the area, indicating a gradual restoring to normal conditions.

FINAL REMARKS

In this paper the potential of the RST approach when implemented on geostationary data, like the ones acquired by MSG/SEVIRI and MTSAT-1R sensors, was assessed. For the two analyzed extreme flooding events, one occurred in the South Africa at the end of July 2007 and the other in Japan in March 2011, the implementation of the RST algorithm provided a reliable detection of flood affected areas, despite the coarse spatial resolution of the used data (1 - 3 Km).
Coupling together geostationary satellite data, which in the near future will be able to furnish data with a temporal resolution up to 2.5 minutes and with an improved spatial resolution (e.g. Meteosat Third Generation) and a robust methodology for identifying environmental changes due to natural disasters, like RST, a near real time identification of hazardous phenomena and a near continuous monitoring of their evolution in spatiotemporal domain is definitively possible. Moreover, sampling the territory with a so high frequency will allow to reduce the problem of cloud masking, generally affecting all satellite observations in the optical bands.
Further analyses have to be carry out both to confirm the RST potential in different observational conditions and to assess the potential of such kind of data also in case of smaller local scale floods than the ones investigated in this paper. In such a case, as suggested by other studies (Brakenridge and Anderson, 2006; Hervé et al., 2007), combining multi-platform sensors (e.g. geostationary and polar) could enhance observing capabilities from space, enabling the high temporal resolution of MSG (or MTSAT) to be fused with the high spatial resolution of other sensors, and allowing for a more accurate and effective flood detection and monitoring.

Finally, the possible extension of such a methodology for night-time monitoring, by exploiting the Earth's emitted radiance, will be investigated and assessed to improve observing capabilities of extreme events from space.

REFERENCES

Brakenridge, R., Anderson, E. 2006. MODIS-based flood detection, mapping and measurement: the potential for operational hydrological applications. Transboundary Floods: Reducing Risks Through Flood Management 1, 1.

EM-DAT, 2011 The OFDA/CRED International Disaster Database Universite Catholique de Louvain, Brussels, Belgium. Online. http://www.emdat.be/result-disaster-profiles.

Faruolo, M., Coviello, I., Lacava, T., Pergola, N. and Tramutoli, V. 2012a. A multi-sensor exportable approach for automatic flooded areas detection and monitoring by a composite satellite constellation. IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 51, NO. 4, APRIL 2013, pp. 2136-2149, doi: 10.1109/TGRS.2012.2236336.

Faruolo, M., Coviello, I., Lacava, T., Pergola, N., Tramutoli V. 2012b. Rapid response for flood detection implementing the RST approach on MSG/SEVIRI data. Proceedings of the Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International. 22-27 Luglio 2012, Monaco Germania. DOI: 10.1109/IGARSS.2012.6351412, Page(s): 907 – 910.
http://earthobservatory.nasa.gov/NaturalHazards/view.php?id= 18817

Hervé, Y., Bernard, A., Rémi, A., Stéphanie, B., Claude, B. 2007. Synergy of High SAR and optical data for flood monitoring; the 2005–2006 Central European floods gained experience. In: Proc. 'Envisat Symposium 2007'.

Kleinen T. and Petschel-Held G. 2007. Integrated assessment of changes in flooding probabilities due to climate change. Climatic change, April 2007, Volume 81, Issue 3-4, pp 283-312.

Lacava, T., Pergola, N., Sannazzaro, F., Tramutoli, V. 2010. Improving flood monitoring by the Robust AVHRR Technique (RAT) approach: the case of the April 2000 Hungary flood. International Journal of Remote Sensing, 31(8), 2043-2062.

McGranahan, G., Balk, D. and Anderson B. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and Urbanization, 19 (1) (2007), p. 17-37.

Mori, N., Takahashi, T., Yasuda, T. and Yanagisawa H. 2011. Survey of 2011 Tohoku earthquake tsunami inundation and run-up. Geophys. Res. Lett., 38, L00G14, doi:10.1029/2011GL049210.

New Scientist Environment 2007. http://www.newscientist.com/article/dn12385.

Proud, S. R., Fensholt, R., Rasmussen, L.V. and Sandholt, I. 2011. Rapid response flood detection using the MSG geostationary satellite. International Journal of Applied Earth Observation and Geoinformation, **13**, 4, 536-544.

Sheng, Y., Xiao, Q. 1994. Water identification in cloud-contaminated NOAA/AVHRR Imagery. Remote Sensing of Environment in China, 9:247–255.

Sheng, Y., Su, Y., Xiao, Q. 1998. Challenging the cloud contamination problem in flood monitoring with NOAA/AVHRR imagery. Photogrammetric Engineering and Remote Sensing 64:191–198.

Tramutoli, V. 2007. Robust Satellite Techniques (RST) for Natural and Environmental Hazards Monitoring and Mitigation: Theory and Applications. Fourth International Workshop on the Analysis of Multitemporal Remote Sensing Images. 18-20 July, 2007, Louven, Belgium, doi: 10.1109/MULTITEMP.2007.4293057.