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DETECTION OF FLOODED AREAS BY THE TOHOKU EARTHQUAKE/TSUNAMI USING ASTER THERMAL INFRARED IMAGES

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Abstract: Heavy casualties and severe property losses occurred by the tsunami in the Tohoku Off-Pacific-Coast Earthquake on March 11, 2011. Satellite visible images are easy to grasp damages caused by disasters, but they cannot be obtained in nighttime. Hence a blank time of information may occur if a disaster happens in nighttime. On the other hand, satellite thermal infrared images can be taken in nighttime while it has an inferior spatial resolution. Thermal infrared images are also expected to grasp flooded areas by tsunami using the temperature distribution. This study extracts the flooded areas by ASTER thermal infrared images by calculating the difference in temperature before and after the earthquake. Applications of the extraction methods are demonstrated for Soma and Ishinomaki cities, where significant tsunami damages are observed. The results are compared with ASTER false color images and the inundated area map created by Geospatial Information Authority of Japan to evaluate the extraction accuracy. These comparisons show a reasonable agreement in flooded areas with daytime and nighttime images. The extraction results are also compared with NDVI images and high correlation between them is observed.

1. INTRODUCTION

Heavy casualties and severe property losses occurred by the Tohoku, Japan Earthquake on March 11, 2011 (The Headquarters for Earthquake Research Promotion 2011). In particular, the tsunami damage was significant causing transportation and information networks' suspension, by which it became difficult to grasp the overview of damage distributions. Early damage detection is very important to engage in the rapid response to disasters. Recently, a remote sensing is widely used especially at the sites where the access from the ground is limited and the damage distributes over a wide range (Kouchi and Yamazaki 2007, Rathje and Adams 2008). However, it generally takes time for visual interpretation of satellite images to recognize the damage distribution. In addition, many of satellite images such as visible and near infrared images cannot be used during nighttime, and thus "blank time" may occur. On the other hand, thermal infrared images can be used during daytime and nighttime without depending on sunlight (Hanada and Yamazaki, 2011). Yamazaki et al. (2009) extracted the edges of buildings, roads, and greens clearly by aerial thermal infrared images in urban regions. Although a spatial resolution of satellite thermal infrared images is inferior to aerial thermal infrared images, it can grasp large scale disasters like massive inundation by tsunami.

This study uses ASTER thermal infrared bands images taken before and after the Tohoku earthquake. The flooded areas are extracted by taking the difference in temperature between those images. Applications sites are selected in Soma and Ishinomaki cities, where significant tsunami damages are observed. The accuracy of the extraction method is evaluated by the comparison with ASTER false color images and the inundated area map created by Geospatial Information Authority of Japan alias GSI (2011a). Comparing the thermal infrared images and NDVI images, the effectiveness of thermal infrared images in detecting inundated areas is discussed. A further improvement of flooded area extraction is expected in a future, which may lead to a rapid response by quickly recognizing tsunami effects distribution.

2. METHODOLOGY

2.1 Analysis Data

During the Tohoku earthquake on March 11, 2011, many regions experienced tsunami damages along the Pacific coastline. As a study area, Soma City in Fukushima Prefecture and Ishinomaki City in Miyagi Prefecture were selected, where serious damages were observed by the tsunami (Figures 1 and 2). Thermal infrared images were selected before and after the earthquake to detect flooded areas. To eliminate the seasonal variations in temperature as much as possible, pre- and post-event images taken in the same season in different years were used. Table 1 shows property of Figures 1, 2 and ASTER visible images for comparison at the same period. Table 2 lists maximum and minimum air temperature of each date. Figures 1a and 1b are the pre- and post-event ASTER thermal infrared images, which are mosaicked around Soma City in nighttime. The upper image of Figure 1a was taken on February 21, 2010 and the lower image was taken on January 15, 2008. The upper and lower images of Figure 1b were taken on March 12, 2011. Each image was taken at approximately 21:30 in Japan Standard Time (JST). Figures 2a and 2b show pre- and post-event ASTER thermal infrared images of Ishinomaki City in daytime. The both images were taken on April 7, 2009 and April 6, 2011 at approximately 10:30 (JST), respectively. These images are level B1 products, using a temperature value converted by digital number.

2.2 Estimation of the flooded areas by thermal infrared images

ASTER thermal infrared sensor has 5 bands ranging from band 10 to band 14. Each band can observe various wavelengths. The band 10 images were used in the analyses because there was no significant difference between these bands for the study purpose. The minimum size of recognition is in the order of 100 m because a spatial resolution of the thermal infrared band is 90 m.

The difference of the pre- and post-event thermal infrared images was calculated to grasp the temperature change visually. In the nighttime images, the areas where the temperature increased after the earthquake were considered as flooded. On the other hand, in the daytime images, the area where the temperature decreased was considered as flooded. The accuracy of these assumptions is discussed in the following section by comparing with ASTER false color images in daytime, taken in the similar condition.

2.3 Comparison between thermal infrared images and NDVI images

The thermal infrared images are compared with ASTER NDVI images for tsunami damaged areas taken in the similar season. First, the difference of NDVI between the pre- and post-event images was calculated. Then, the upper and lower NDVI values were inverted if the thermal infrared images for comparison were taken in nighttime since water had higher temperature compared with other land-covers. The difference of the pre- and post-event thermal infrared images was also calculated. Then, the inverted difference of NDVI images was adjusted to produce the same maximum and minimum values with those of the thermal infrared images by histogram matching. Finally, calculate the difference of thermal infrared and NDVI images after adjusting resolution of thermal infrared image to NDVI image. Through these processes, the comparison between the thermal infrared and NDVI images could be visually carried out.

3. RESULTS

3.1 Detection of flooded area in Soma City at nighttime

Flooded areas were detected using the nighttime thermal infrared images. In the nighttime images, the flooded areas show an increase in temperature because water

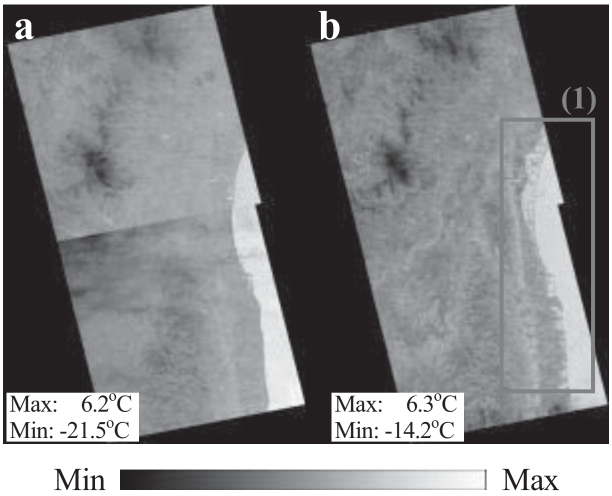

Figure 1 ASTER thermal infrared images, clipped for Soma City. **a**: Pre-event, **b**: Post-event.

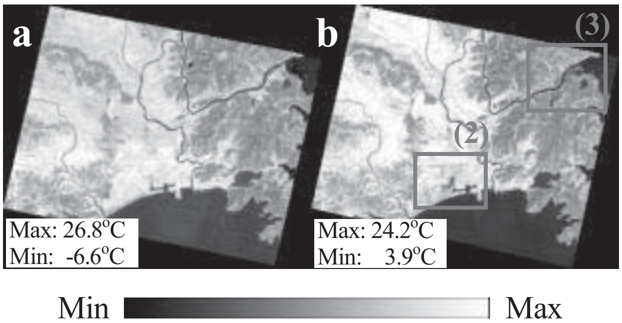

Figure 2 ASTER thermal infrared images, clipped for Ishinomaki City. **a**: Pre-event, **b**: Post-event.

Table 1 Property of the images used in this study

	ASTER TIR image (resolution: 90m)	
	Pre-event	Post-event
Soma (Nighttime)	Upper: Feb. 21, 2010 Lower: Jan. 15, 2008	March 12, 2011
Ishinomaki (Daytime)	April 7,2009	April 6, 2011

	ASTER False Color and NDVI image (resolution: 15m)	
	Pre-event	Post-event
Soma (Daytime)	April 7, 2009	March 19, 2011
Ishinomaki (Daytime)	April 7, 2009	April 6, 2011

Table 2 Max and min air temperature of each date

Date (Sort by Month)	Air Temperature (°C)	
	Max	Min
January 15, 2008	5.3	-1.5
February 21, 2010	6.4	-1.6
March 12, 2011	8.8	-1.1
March 19, 2011	14.2	-0.8
April 6, 2011	18.6	2.7
April 7, 2009	19.6	6.2

has large heat capacity.

Figures 3a-c show the images in Soma City whose location is shown in Figure 1b (1). Figure 3a shows the difference in temperature before and after the earthquake displayed -1.8 to 6.0 ^{o}C. It shows that coastal areas experienced the increase in temperature after the earthquake. Some inland areas also show an increase of temperature, which was caused by clouds existing in the pre-event image.

Figure 3b shows the estimated flooded area obtained from Figure 3a with the temperature difference greater than 5^{o}C. The threshold value of 5 ^{o}C was selected based on visual comparison with the post-event false color image in Figure 3c. These areas are approximately overlapping with regions where lots of paddy field exist, and thus seawater was sustained after the tsunami inundations. The center of the image shows a lagoon whose shapes were significantly change by tsunami. These changes can be observed in Figure 3b. The change of paddy field shapes by the intrusion of sea water were also observed in Figure 3b. These tsunami damages were confirmed well by comparing with the post-event false color image in Figure 3c. These results indicate that the use of ASTER thermal infrared images is effective, especially at nighttime. However, the specific care is required to apply them for different conditions since thermal infrared images are affected by seasons and weather.

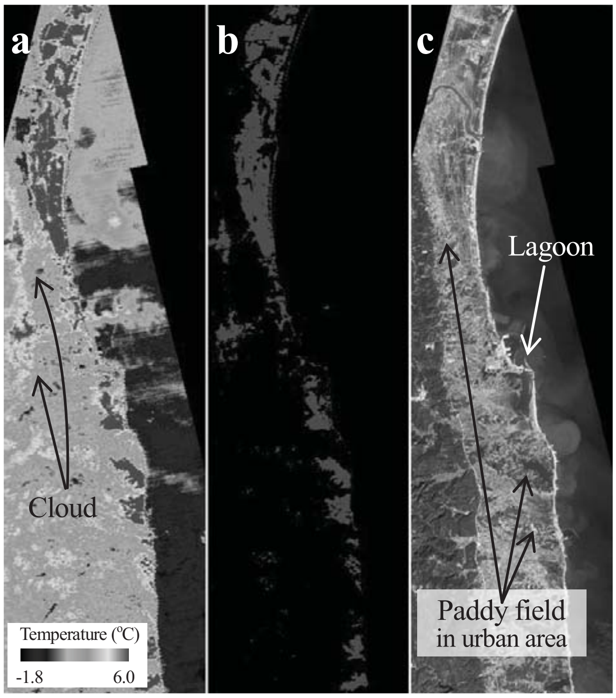

Figure 3 **a**: Difference of pre- and post-event thermal infrared images for the enlarged place of Figure 1b (1), **b**: Estimated flooded area extracted only 5^{o}C to maximum in Figure 3a, **c**: Post-event ASTER false color image.

3.2 Detection of flooded area in Ishinomaki City at daytime

Flooded areas were detected using the daytime thermal infrared images. In the daytime images, the flooded areas show a decrease in temperature because water has large heat capacity. This difference is generally larger than that from nighttime images.

Figures 4a-c show the area in Ishinomaki City whose locations are shown in Figure 2b (2). Many paddy fields exist in this site. Tsunami ran up along Sada River and caused extensive damage to these areas. Figure 4a shows the differences between the pre- and post-event ASTER thermal infrared images, displayed -6.0 to 10.0^{o}C. Paddy fields were inundated by tsunami and show lower temperature even in the image taken one month after the earthquake. This is because that flooded seawater was sustained by the paddy fields and land subsidence due to crustal movements (GSI, 2011b). Figure 4b shows the estimated flooded areas where the temperature difference is less than -1 ^{o}C in Figure 4a. The results show a good agreement with visually observed flooded areas in the post-event false color image in Figure 4c.

Figure 4d-f shows estuary of Kitakami River in Ishinomaki City whose location is shown in Figure 2b (3). Tsunami ran up along the river and caused extensive damages at this site. The land near the estuary was washed away by tsunami and filled with seawater. Figure 4d shows the differences between the pre- and post-event ASTER thermal infrared images from -6.0 to 10.0^{o}C. Many paddy fields show lower temperature in the post-event image. Figure 4e shows the estimated flooded areas, which is in a good agreement with visually observed flooded areas in the

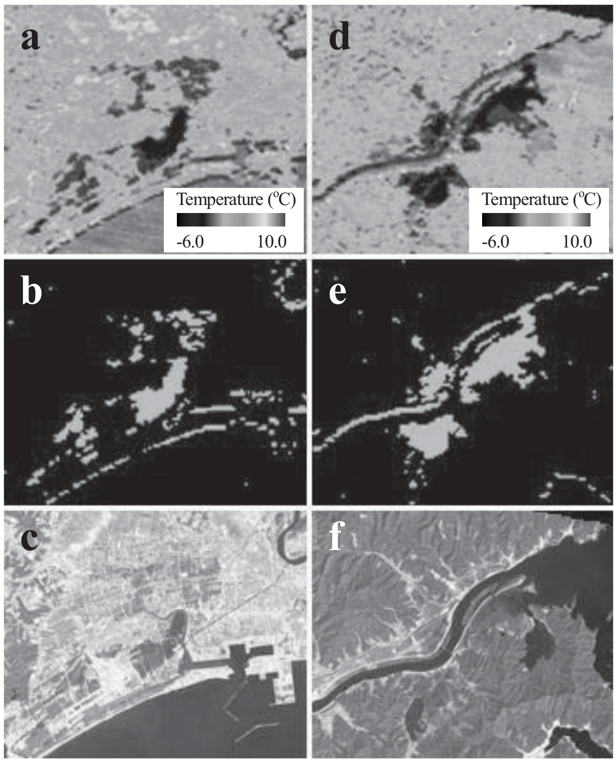

Figure 4 **a, d**: Difference of pre- and post-event thermal infrared images for the enlarged place of Figure 2b (2) and (3), **b**: Estimated flooded area extracted only minimum to -1^{o}C in Figure 3a and 3b, **c**: Post-event ASTER false color image.

post-event false color image in Figure 4f.

These analyses indicate that ASTER thermal infrared images are very effective to detect flooded areas also at daytime although it requires a specific care to apply to the different sites since thermal infrared images are affected by season and weather conditions.

3.3 Comparison with Inundated Area Map by GSI

Figures 5a and 5b shows expected flooded areas from the thermal infrared images compared with an inundated area map created by GSI for Soma and Ishinomaki cities. The inundated areas by GSI are displayed in purple color whereas the other parts are displayed in gray scale. The areas displayed in red color show the estimated flooded areas by this study in Soma City shown in Figure 3b. The areas displayed in cyan show the estimated flooded areas by this study in Ishinomaki City shown in Figures 4b and 4e. In each image, the estimated flooded areas are located inside of the inundated areas by GSI, showing a good agreement between those. The difference between our estimation and GSI map is reasonably explained by the fact that the flooded areas decreased over the time.

3.4 Comparison of thermal infrared images with NDVI images

Figure 6a shows the difference of the pre- and post-event thermal infrared image at nighttime. Figure 6b shows the difference of the pre- and post-event NDVI image at daytime that has inverted upper and lower values and adjusted to -12.0 and 18.0 using the histogram. Figure 6c shows the difference between Figure 6a and 6b. Figure 6a-c are displayed for the same interval, -5.0 to 5.0. Figure 6d is the ASTER false color image in Soma City, the same to Figure 3c. It is observed that the most areas have small differences in Figure 6c, indicating a high correlation between thermal infrared and NDVI images in nighttime.

Figure 7a is the difference of the pre- and post-event thermal infrared images in Ishinomaki area at daytime. Figure 7b is the difference of the pre- and post-event NDVI images. Figure 7c is the difference between Figure 7a and 7b after adjusting upper and lower values in Figure 7b to -13.0 and 16.0, respectively. Figure 7a-c are displayed for the same interval, -10.0 to 10.0. Figure 7d is the ASTER false color image at the same place. Similar to the previous site in Soma City, Figure 7c shows small values for the most of lower elevation areas, which are urban and flooded areas. It is sufficient to grasp the tsunami disaster in urban areas although plains located far from the coastal line and vegetation in higher elevation areas are slightly different. Therefore, ASTER thermal infrared images have relatively high correlation with NDVI images in daytime also.

On the basis of these analyses, ASTER thermal infrared images were demonstrated to have high correlation with NDVI images for both at daytime and at nighttime in the season investigated in this study. Since a spatial resolution of thermal infrared images is inferior to that of visible and near-infrared images, the NDVI may be more suitable to observe the detail of flooded areas. However,

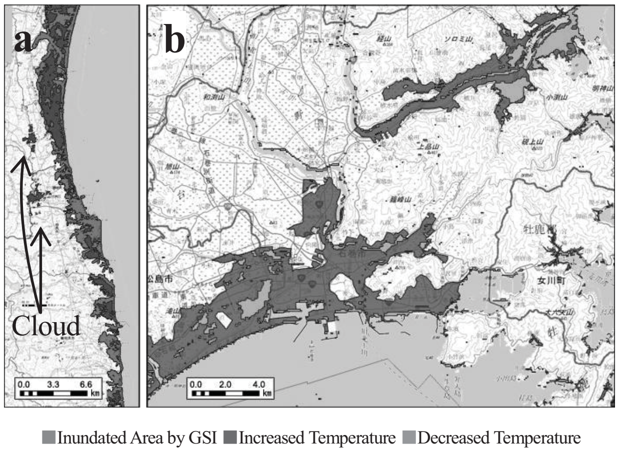

Figure 5 Superposition of large temperature difference areas on the inundated area map created by GSI. **a**: Soma City (Nighttime), **b**: Ishinomaki City (Daytime).

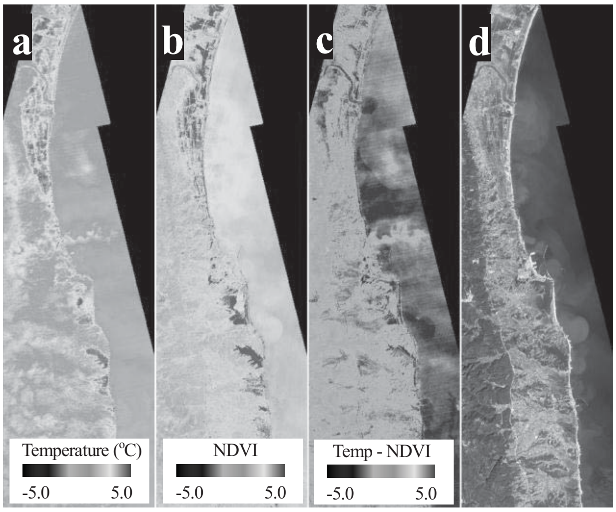

Figure 6 Soma City. **a**: Difference of pre- and post-event TIR image, **b**: Inverted and adjusted difference of pre- and post-event ASTER NDVI image, **c**: Difference of Figure 6b and 6c, **d**: Post-event ASTER false color image.

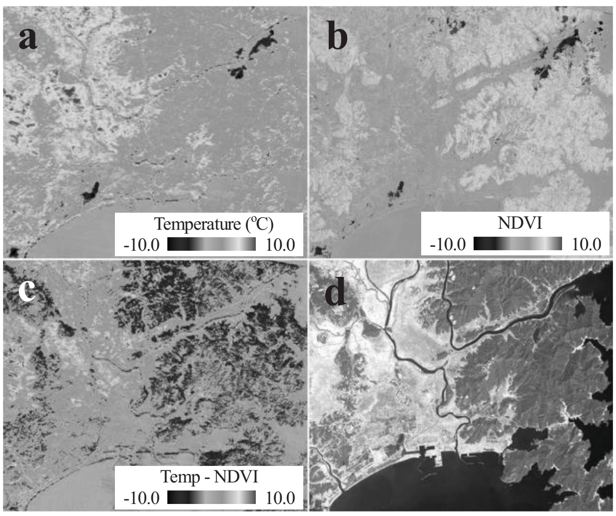

Figure 7 Ishinomaki City. **a**: Difference of pre- and post-event TIR image, **b**: Difference of pre- and post-event ASTER NDVI image, **c**: Difference of Figure 7a and 7b, **d**: Post-event ASTER false color image.

ASTER thermal infrared images can be obtained both at nighttime and daytime, and hence they may be especially useful to grasp a large scale disaster occurred at nighttime, like massive inundation by tsunami. Further exploration is required for the application of thermal infrared and NDVI images since both images are affected by the difference of land-covers, seasons and weather conditions.

4. CONCLUSION

This study uses ASTER thermal infrared images to detect flooded areas caused by the Tohoku earthquake /tsunami occurred on March 11, 2011. By taking the difference of temperatures between the pre- and post-event images, the flooded areas were extracted as those where temperature increased at nighttime, or decreased at daytime. The estimated flooded areas were relatively in good agreement with the post-event ASTER false color images. The estimated flooded areas were further compared with the inundated area map by GSI. The comparison shows that most of the estimated flooded areas are within the inundated areas, which is reasonably expected since the flooded areas decrease over the time.

The thermal infrared images and NDVI images were compared to discuss those similarities. The differences of temperature and NVDI values between the pre- and post-event times were calculated, respectively and their values were adjusted to have the same upper and lower values by histogram matching. As the result, high correlation between the changes in thermal infrared and NDVI images was confirmed. Since a spatial resolution of thermal infrared images is inferior to that of NDVI images, thermal infrared images may be useful for a large scale disaster like massive inundation by tsunami, especially at nighttime.

A further discuss is required about the threshold values to develop an easy and quantitative extraction method. Since thermal infrared images are affected by the differences of season and weather conditions, the application method needs to be verified under various situations. In addition, it is difficult to prepare a pair of pre- and post-event images with the same condition because thermal infrared images are affected by clouds significantly. On the basis of these restrictions, the further study will be considered to use GIS data as pre-event optical daytime images. It is important to build an early detection method for future tsunami disasters considering the temperature properties of inundated areas.

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