Abstract: The surface emissivity ratio (SER) between two bands in the thermal infrared (TIR) region varies with snow/ice surface conditions, and is useful for snow/ice monitoring (Tonooka and Watanabe, 2004). In the present study, we demonstrate the applicability of the SER index to lake ice monitoring. The test site is an area around Lakes Kussharo and Mashu (Hokkaido, Japan) which are typically frozen in February and March, and the data used are multi-temporal at-sensor radiance imagery observed by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments over the site in the period of August 2004 to July 2005. For each pixel of each image, surface emissivities in all TIR bands (bands 10 to 14 for ASTER, and bands 29, 31 and 32 for MODIS) are first derived from at-sensor radiances by atmospheric correction and temperature/emissivity separation, and then the SER index is calculated from the surface emissivities in two bands (bands 13 and 14 for ASTER, and bands 31 and 32 for MODIS). The results indicate that, although the SER index is almost 1.00 in liquid water conditions (spring to fall seasons), it increases 1 or 2% in winter, and has particularly larger values during ice forming/deforming processes, or when the lake surface is covered by smooth ice, because the index decreases slightly by snow cover. As an alternative index, the thermal log residuals ratio (TLRR) is also evaluated to show a similar temporal change to the SER index, while the TLRR index is less quantitative than the SER index because the TLRR index depends on statistics in the image used. Thus, we conclude that the SER index and alternatively the TLRR index are effective indices for detecting ice-forming and deforming processes or a smooth ice cover on a lake.

Keywords: frozen lakes, thermal infrared surface emissivity ratio, snow/ice monitoring.

1. Introduction

Snow and ice have high albedo, correspond to more than 80% of fresh water on the earth, and contribute significantly to the radiation balance of the earth [1]. In addition, snow and ice surfaces on the earth will change sensitively with a climate change. Thus, snow and ice surfaces are important as boundary conditions in climate models, and should be monitored in any scales from regional to global. Particularly, high-elevation or high-latitude regions where perpetual ice/snow surfaces are rapidly melting should be elaborately monitored, since these regions will give a signal for assessment of global warming. For such regions, remote sensing will be the most effective monitoring tool, because most of such regions are difficult to access and monitor by in-situ based techniques.

In snow/ice remote sensing, the visible and near-infrared (VNIR), the shortwave infrared (SWIR) and the microwave spectral regions are frequently used. The thermal infrared (TIR) region is also used in assessment of snow/ice surface temperature, but probably it has not been fully used in comparison with the other spectral regions in spite of its nighttime availability with high spatial resolution—the nighttime availability will be valuable particularly for polar regions where the night season continue for two or more months. The surface emissivity in the TIR spectral region is usually an uncertain factor in surface temperature determination [1]–[3], while it is a key parameter in radiation budget analyses. However, laboratory measurements of snow/ice emissivity spectra indicate that these spectra depend on some surface conditions such as a grain size and roughness [4]. Thus, the authors have proposed a new approach to snow/ice condition monitoring [5][6]. These studies demonstrated that the surface emissivity ratio (SER) or the thermal log residuals ratio (TLRR) of two bands located between 10.5 to 12.5 μm would be effective as snow/ice condition indices. In the present paper, the authors will show some investigation results on temporal changes of SER and TLRR on frozen lakes in Japan.
2. Theoretical Basis

Fig. 1 displays emissivity spectra of ice, snow, and frost with the band positions of representative TIR sensors [4][7]. As shown, the inclination of spectral emissivity in the 10.5 to 12.5 µm region increases in order of frost, fine snow, medium snow, coarse snow, and ice. According to this fact, surface emissivity ratio (SER) between two bands located in the 10.5 to 12.5 µm region, defined by the following equation, has been proposed as an index for assessment of snow/ice conditions [5].

\[ SER = \frac{\varepsilon_A}{\varepsilon_B} \]  

where \( \varepsilon_A \) and \( \varepsilon_B \) are the surface emissivities of two bands located in the 10.5 to 12.5 µm region (band A is shorter than band B in wavelength). The SER can be calculated from surface emissivity produced from the at-sensor radiance by atmospheric correction and temperature/emissivity separation. Although the sensitivity of SER to snow/ice conditions is not very large in any sensor (the maximum change in SER between frost and ice is 3.2% for AVHRR, 1.7% for ASTER, and 2.6% for MODIS, see Fig. 2), SER images observed by ASTER and MODIS from the north-east part of Hokkaido Island in Japan indicated that SER was larger on the frozen lakes Kussharo and Mashu (1.013 for ASTER, and 1.020 for MODIS, on average) than on snow-covered land surfaces and floating ices (about 1.00 in both sensors) [5]. In the case of SER images from the Dry Valley in Antarctica, the SER index demonstrated a spatial difference of 1 or 2% on glaciers, indicating differences in surface conditions. Thus, SER can be used for detecting some differences of snow/ice conditions under clear sky conditions in either daytime or nighttime, while their sensitivity to snow/ice conditions is not very large.
On the other hand, the thermal log residuals technique [8] is a method for enhancing spectral emissivity by reducing temperature effects. Although the thermal log residuals are dependent on statistics of the scene, the ratio of the thermal log residuals in two bands can be used for snow/ice condition monitoring instead of SER [5]. In the present study, the thermal log residuals ratio (TLRR) will be also evaluated in the trend analysis for the frozen lakes.

3. Data used

1) Study area

In the present study, Lakes Kussharo and Mashu, Hokkaido, Japan, were selected as the study site (see Fig. 3). These lakes are located in the east part of the Hokkaido Island which is one of four major Japanese islands and is located in the highest latitude among them. Lake Kussharo has the area of 79.5 km$^2$ (the sixth biggest lake in Japan), and the depth of 118 m. Lake Mashu has the area of 19.6 km$^2$, and the depth of 212 m. Lake Kussharo is typically frozen completely from February to March and covered by snow. Lake Mashu is also frozen but ice-forming is typically delayed than Lake Kussharo due to deep water.

2) Satellite data used

In the present study, twenty-one MODIS products observed from August 2004 to July 2005 were used for the trend analysis, and two ASTER products in this period were also used complementarily. All the MODIS products used for this purpose are the MODIS Level-1B (L1B) Calibrated Radiance Products (MOD02). The ASTER products used are the Level-3A (L3A) orthogonal at-sensor radiance products. For each of MODIS L1B and ASTER L3A, surface emissivity images were retrieved and used for SER calculation by the way described in the next section.

In the study, surface emissivity data included in two kinds of the MODIS Land Surface Temperature and Emissivity Products (MOD11A1 and MOD11B1) will be also used for comparison.
Fig. 5: SER images obtained from the MODIS L1B products observed from August 2004 to July 2005.
4. Data processing

1) Retrieval of surface emissivity

Fig. 4 displays the flowchart of surface emissivity retrieval from the MODIS L1B and the ASTER L3A products in the present study.

For each product, the at-sensor radiance in each band was atmospherically corrected by the Water Vapor Scaling (WVS) method [9]–[11]. This method is an atmospheric correction algorithm for TIR multi-spectral data including land surfaces on the basis of a traditional approach using a radiative transfer code, such as MODTRAN [12], combined with external atmospheric profiles, but the errors included in profiles are reduced on a pixel-by-pixel basis using an extended multi-channel approach. Although the WVS method was originally designed for the five TIR spectral bands of ASTER [9], it can be applied to other TIR sensors including MODIS TIR bands [11]. Global analyzed data used in the WVS method were given by products from the Global Data Assimilation System (GDAS) operated by the National Centers for Environmental Prediction (NCEP) [13].

The surface temperature and the surface emissivity in each band were then derived from the atmospherically corrected at-surface radiance by temperature/emissivity separation (TES). As for the ASTER L3A product, the ASTER standard TES algorithm [14] was applied. As for the MODIS L1B product, a similar algorithm modified for MODIS bands 29, 31 and 32 [11] was applied.

Incidentally, all the ASTER L3A radiances were recalibrated because the original radiance includes a calibration error induced by delay in updating of radiometric calibration coefficients [15].
2) Calculation of SER and TLRR

Surface emissivity values of MODIS bands 31 and 32, or ASTER bands 13 and 14 were retrieved by the above processing, and then used for the SER calculation. The TLRR values were derived directly from the at-sensor radiance in each product. First, the thermal log residuals were calculated from the at-sensor radiance, and those in bands 31 and 32 (MODIS), or bands 13 and 14 (ASTER), were used for the TLRR calculation.

In the cases of MOD11A1 and MOD11B1, the emissivity values of MODIS bands 31 and 32 were first derived from each product, and the SER values were calculated by dividing the emissivity of band 31 by that of band 32.

5. Results and discussions

Fig. 5 shows the SER images obtained from the MODIS L1B products observed from August 2004 to July 2005. Each SER image has been geolocated and cropped around Lakes Kussharo and Mashu. In the SER images, 1.000 or less values are shown in white, and 1.030 or grater values are shown in black (see the gray scale bar at the bottom). The figure indicates that Lake Kussharo has large SER values in the late December 2004 (SER=1.023) and the early April 2005 (SER=1.028), and Lake Mashu has large SER values in the early March 2005 (SER=1.027) and the early April 2005 (SER=1.022).
Fig. 6 displays the trend plots of SER at northern and southern sites selected on each lake. In the case of Lake Kussharo, SER has high values from the late December to the late January, then decreases, and has high values again on 5 April. In the case of Lake Mashu, SER has high values from the late February to the early March, then decreases, and has high values again in the early April. Thus, both lakes show two SER peaks in winter, but the first peak appears with some delay in Lake Mashu. Fig. 7 shows the trend plots of TLRR for the same sites with Fig. 6. Although TLRR is not easy to evaluate absolutely because TLRR is dependent on scene statistics, Fig. 7 indicates a similar trend to each case in Fig. 6.

Figs. 8 and 9 show ASTER images around the two lakes observed on 9 February and 4 March 2005, respectively, where the left on each figure is the L3A VNIR image, and the right is the SER image. As of 9 February, Lake Kussharo was in ice-forming, and Lake Mashu was completely water (see the left in Fig. 8). At this time, the SER values were large on Lake Kussharo (about 1.014) and small on Lake Mashu (1.000–1.005) as shown by the right in Fig. 8. As of 4 March, Lake Kussharo was completely frozen and covered by deep snow, and Lake Mashu was completely frozen and covered by smooth ice with partially thin snow, as shown by Fig. 10 which displays a photo of Lake Kussharo on 4 March 2005 and that of Lake Mashu on 1 March 2005. At this time, the SER values were small on Lake Kussharo (about 1.005) and large on Lake Mashu (about 1.018) as shown by the right in Fig. 9.

From these photos and the laboratory measurements of snow/ice emissivity [4], we can state that the first peak appeared by ice-forming, then SER decreased by snow cover, and the second peak appeared by ice-deforming. Since both lakes are filled by water except for winter, they indicate almost constant SER values (about 1.005) from spring to autumn.

Fig. 11 shows the SER images generated from MOD11A1 (left) and MOD11B1 (right) on 4 March. The SER image of MOD11A1 is much different from the results of MODIS L1B and ASTER L3A, because the emissivity data in MOD11A1 are not physically-retrieved values but estimates by a classification-based method [16]. The SER image of MOD11B1 may be similar to the results of MODIS L1B and ASTER L3A because a pixel around Lake Mashu indicates a larger SER than that around Lake Kussharo, but the 5-km spatial resolution of MOD11B1 is too low for such analysis, as shown.

6. Conclusions

In the present paper, the surface emissivity ratio (SER) and the thermal log residuals ratio (TLRR) on Lakes Kussharo and Mashu were obtained from the MODIS L1B products, and the time trends of them were analyzed. The SER values showed two peaks in winter which correspond to ice-forming, a smooth ice cover, or ice-deforming, and almost constant values (about 1.000 to 1.005) except for these peaks. The reason why SER is small in the period between the two peaks is due to snow cover. The SER images obtained from ASTER L3A products on 9 February and 4 March, 2005, showed consistent results with the results from the MODIS L1B products. Although TLRR is dependent on scene statistics, the annual trend of TLRR is similar to that of SER. The SER image of MOD11A1 did not give reasonable results due to errors in spectral emissivity estimated by the classification-based method, and that of MOD11B1 was not suitable for analysis of the two lakes because the spatial resolution is too low for this analysis. From these results, we can conclude that the SER index obtained by the procedure in the present paper, or alternatively the TLRR index, are effective indices for detecting ice-forming and -deforming processes or a smooth ice cover on a lake.
Acknowledgement

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References