Spatial and Temporal Analysis of Probabilities for Acquiring Cloud-free Optical Sensor Images Using MODIS Cloud Mask Products 2000-2008 in Southeast Asia

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ABSTRACT

Accessibility to cloud-free optical sensor images is essential for large-area monitoring of land and forest cover changes. In this study, the acquisition probabilities of cloud-free images were analyzed using MODIS cloud mask products from 2000 to 2008 in Southeast Asia. The daily cloud masks were summarized into monthly acquisition probabilities for cloud-free images over the period at a spatial resolution of 1km. The mean annual acquisition probability profiles were extracted averaging nine years’ observation. Unsupervised clustering was conducted for zoning of the acquisition probabilities using the mean annual profiles. Annual variations in the acquisition probabilities were examined by the standard deviations calculated for each month and comparisons of the mean annual profiles of the whole period and individual years. The distributions of annual acquisition probabilities in forested areas were different in each country. These results suggested that selection of suitable methods and data allowing for the spatial and temporal differences in the acquisition probabilities is necessary for periodic large-area monitoring.

Keywords: cloud-free image acquisition, large-area monitoring, MODIS cloud mask, Southeast Asia

INTRODUCTION

The IPCC Fourth Assessment Report (AR4) pointed out the possibility that emissions caused by land use change may account for 20% of total emissions of greenhouse gases that cause global warming (Denman et al., 2007). To reduce emissions caused by land and forest cover changes, the REDD-plus (Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks) scheme is now under discussion. REDD-plus is a political framework that aims at stopping deforestation by giving incentives to developing countries that achieve conservation of carbon levels (Angelsen, 2008). Therefore, it is essential to monitor land and forest cover at the national level.

Remote sensing techniques are expected to be an adequate tool for enabling this large-area monitoring in a transparent and cost effective way (Achard et al., 2010). Land and forest cover change monitoring has been conducted using remote sensing in many cases and a national inventory of forest cover is conducted in some countries (GOFC-GOLD, 2012). For example, some Southeast Asian countries has been reporting land and forest cover using medium spatial resolution data such as Landsat TM / ETM+ and SPOT (e.g., Department of Forestry, 2005; Forestry Administration, 2008; Royal Forest Department, 2008). The monitoring is usually conducted based on the manual delineation and interpretation of land cover and forest types by skillful technicians. Optical medium spatial resolution satellite imagery has been utilized because of its data accessibility, coverage, long historical observation and easy data handling. It still has some advantages in terms of cost-effectiveness, spatial resolution and multi-spectral observations (Hansen and Loveland, 2012; Wulder et al., 2012). However, the appearance of clouds is one of the main problems that prevent constant observation using optical sensors from space (Hansen and Loveland, 2012). The image acquisition date or season also have a large effect on the accuracy of change detection and multi-temporal land cover classification (Lanetta and Elvidge, 1999; Franklin and Wulder, 2002). Therefore, it is important to study the probabilities for acquiring cloud-free optical sensor images when considering the utility of optical remote sensing for large-area monitoring.

Cloud-free image acquisition has been studied all over
Such studies calculated spatial patterns and seasonality of acquisition probabilities using time-series Landsat images and summarized them at the scene level. Therefore, these studies cannot analyze spatial patterns within a scene or annual variations. On the other hand, the Moderate Resolution Imaging Spectrometer (MODIS), onboard the Terra and Aqua satellites, performs daily observations consistently with a wide coverage and a fairly high spatial resolution (Savtchenko et al., 2004). Therefore, it is possible to clarify the spatial patterns and annual variations in probabilities of cloud-free acquisition using the MODIS historical dataset.

In the present study, the targets were in Southeast Asia, where the climate is strongly affected by the Asian monsoon (Lau and Yang, 1997). There is a long dry season, especially in the inland Indochina Peninsular (Lau et al., 1988). This leads to high acquisition probabilities of cloud-free images during the dry season. On the other hand, it is said that the acquisition probabilities are low in the equatorial region and coastal or island areas such as Kalimantan, Indonesia. These facts are empirically known, but there is little quantitative analysis. Therefore, the objective of the present study was to clarify the spatial and seasonal patterns and the annual variations in acquisition probabilities of cloud-free optical images using nine years of MODIS cloud mask data in the Southeast Asian region.

MATERIALS AND METHODS

Study Area

The study area was the Southeast Asian region (Fig. 1). The study area was separated into two parts: 1. Continental Southeast Asian region (N 5° -29°, E 92° -110°) and 2. Insular Southeast Asian region (S 10° -N 8°, E 95° -120°). This study area covered the Southeastern Asian countries such as Cambodia, Lao PDR, Malaysia, Myanmar, Thailand, Vietnam and West Indonesia (hereinafter, referred as Indonesia). As Indonesia and Myanmar are listed in the Global Forest Resources Assessment 2005 (FAO, 2006) as two of ten countries with the largest annual net loss of forested areas from 2000 to 2005, land and forest cover monitoring are very important in this region. Tropical evergreen forests have expanded in equatorial regions such as Kalimantan in Indonesia. The vegetation gradually changes from evergreen forests to seasonal forests caused by strong Asian monsoons at higher latitude and altitude, especially in the inland area of the Indochina Peninsular (Kira, 1991; Blasco et al., 1996).

Fig. 1 Study area (1. Continental region (N5-29, E92-110) and 2. Insular islands (S10-N8, E95-120))
Materials

MODIS Level 2 Cloud Mask Product (MOD35_L2, Version Collection 5) (Frey et al., 2008) with spatial resolution of 1 km downloaded from NASA-LAADS (the Level 1 and Atmosphere Archive and Distribution System) were utilized for this study. The geo-projection was conducted using the MODIS Reprojection Tool Swath (MRTSwath) program with additional Geolocation files. The coordinates were set to Lat / Lon WGS 1984. The geo-projection was conducted using the nearest neighbor method to preserve the original discrete data value. Some gaps caused in the projection process were dealt with as deficit pixels at each observation date. MODIS onboard Terra passes the equator at 10:30 am (Savchenko et al., 2004). The data acquisition time corresponds to those of typical satellites with sun-synchronous orbits. Therefore, only the products of the MODIS onboard Terra satellite were analyzed in the present study. Terra MODIS started observations from the end of February in the year 2000. The analysis period was almost nine years from March 2000 to December 2008. The MODIS sensor has been collecting data constantly, though a lack of data was observed for some short periods over these nine years (NASA-LAADS, 2013).

Calculation of Monthly Acquisition Probability of Cloud-free Images Using MODIS Cloud Mask (MOD35) Products

MODIS cloud mask is created by integrating the results of multiple tests using multiple bands with grouping according to the cloud type (Ackerman et al., 1998). The results are given by four ranks of confidential flags such as 1. Clear, 2. Probably clear, 3. Uncertain / Probably Cloudy, and 4. Cloudy (Frey et al., 2008). Therefore, the end users can inspect the products according to their own interests (Ackerman et al., 1998). This algorithm is conservative in terms of clear sky detection. It means that only very high confidence pixels are designated as clear (Ackerman et al., 1998). In this study, the days with the flag “Clear” were counted as clear days in a monthly summary. “Probably clear” appeared at the edge between clouds and clear sky, but the occurrence frequency was not high. Monthly observation days were summarized by accumulating actually observed days within a month and excluding the days with deficit data. Following this procedure, the monthly cloud-free image acquisition probability was calculated as below.

\[
\text{Monthly acquisition probability (\%)} = \frac{\text{Total days with clear sky}}{\text{Total observation days}} \times 100
\]

where Monthly acquisition probability is a percentage of clear sky occurring each month. Total days with clear sky are the number of days observed as “clear” sky in the cloud mask each month. Total observation days are the number of days observed by Terra MODIS each month. As a result, 12 scenes of monthly acquisition probabilities for cloud-free image acquisition, corresponding to 12 months, were created. Standard deviation for each month was calculated using nine years of data. This standard deviation value was expected to be a good indicator for showing the intensity in annual variations. The null area mask of GTOPO30 global Digital Elevation Model in the TNT Global Geodata, prepared for user groups of GIS and Image processing software TNTmips (MicroImages, Inc.), was adapted to analyze the land area. All the geospatial analysis and image processing were conducted using TNTmips (MicroImages, Inc.).

Clustering Based on the Differences in Acquisition Probabilities of Cloud-free Images

An averaged monthly acquisition probability profile was created by averaging 9 years of data to minimize the annual variations. To clarify the spatial pattern of the acquisition probability profiles, clustering was conducted. Unsupervised Fuzzy c-means clustering was conducted using 12 averaged monthly acquisition probabilities with setting of initial class numbers of 12. Those classes were integrated into 8 classes in the final product by checking the class separability and co-occurrence.

Summary of Probabilities in Forested Area at National Levels

In the REDD-plus scheme, changes in forested areas at the national or sub-national level were the main concerns of monitoring. Therefore, annual acquisition probabilities in forested areas were summarized for each country and compared. The annual acquisition probability was calculated by averaging the nine years’ mean monthly probabilities in a 1-km Grid generated within the whole study area. Grid points in forested areas were defined using Global Land Cover 2000 (GLC2000) database (Joint Research Centre, 2003). Changes such as deforestation that occurred during 2000 to 2008 were not considered in this study because our main concern here was to clarify the differences in probabilities among countries. Country attributes were added to the Grid points by using the country boundary vector data in the Global Geodata (MicroImages, Inc.). Frequency distribution of annual acquisition probabilities of cloud-free images was compared by country.

RESULTS

Spatiality and Seasonality of Acquisition Probabilities

The average monthly acquisition probabilities of cloud-free images are shown in Fig. 2. The bright color shows high acquisition probabilities and the dark color shows low acquisition probabilities. This result showed the obvious seasonality in some regions.

Clustering

Fig. 3 shows the results of unsupervised Fuzzy c-means clustering using 12 averaged monthly acquisition probabilities. The example of the 9-years’ mean probability profile and annual variation at a point in each cluster are shown in Fig. 4. There were areas where the probability was constantly high in the dry season in the inland Indochina Peninsula (e.g. C7). On the other hand, there were areas where the probability was
low all year round, such as the equatorial Indonesian islands, Malay Peninsula and coastal Vietnam (e.g. C3).

Annual Variations

Standard deviation was calculated using 9 years of data for each month (Fig. 5). Standard deviation was rather high in the dry season with high monthly acquisition probability, especially at the beginning and end of the dry season. This was caused by annual variations in the timing of seasonal changes. Fig. 4 also gives a visual description of the annual variations in the acquisition probability profile at some typical points belonging to each cluster. The difference between the 9-years average profile and the profile of each year in Fig. 4 shows the annual variations.

Summary of Annual Acquisition Probabilities in Forested Area at the National Level

Fig. 6 shows the frequency distribution of annual acquisition probabilities of cloud-free images in the forested areas of each country. Myanmar showed a peak in the high probability zone. Thailand and Lao PDR gave a similar frequency distribution. On the other hand, Indonesia and Malaysia had a peak in the low probability zone. Cambodia and Vietnam distributed in the middle range.

DISCUSSION

Spatiality, Seasonality and Annual Variation

This study quantitatively clarified the spatial and seasonal patterns of cloud-free image acquisition in Southeast Asia. The acquisition probability in the Indochina Peninsula, especially in inland Indochina, was rather high compared with other regions. On the other hand, the probability was rather low in coastal Vietnam, although it is also located in the Indochina Peninsula. The low acquisition probability in equatorial regions such as Kalimantan, Indonesia, supported the empirical facts quantitatively. As shown by our results, the achievable observation period should also be varied according to the difficulty of cloud-free image acquisition with optical sensors. Our clustering results can help to understand in
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detail the overall variety of difficulty in data accessibility. Long term observation of MODIS also helped to reveal the annual variations in each region.

Appropriate selection of the imagery acquisition date is crucial for change detection, and then the anniversary dates or anniversary windows are often used for analysis (Coppin and Bauer, 1996). Actual opportunities for monitoring are limited to the availability of data. In addition, although the probabilities are high in the dry season, for example, deciduous trees shed their leaves and it causes confusion due to the different types of land cover such as tropical dry forest, savanna, shrubland and grassland (Bautista et al., 2011). Especially, the influence becomes large at the end of the dry season. In such a case, more detailed setting of the time interval should be considered. On the other hand, in areas where there is no strong seasonality with evergreen vegetation types, the probabilities tend to be low all year round, for example, at the equator. However, the annual acquisition probability may directly show the probabilities of monitoring because monitoring can be done at any time period due to its stability in areas such as evergreen forests, although there may be minor seasonality factors such as leaf change. Therefore, in the application of optical sensors, the probabilities of cloud-free image acquisition during the targeted period when the acquired images can be suitably applied for the intended purpose of change detection or monitoring according to the applied method will be important.

The monitoring period may have to be set longer in regions where the acquisition probabilities are low.

Now, there are many types of sensors and satellites observing land cover from space. Each sensor has advantages and disadvantages. For example, operational optical satellite sensors, such as onboard Spot, Landsat and IRS satellite series, have a moderately high spatial resolution, but a narrow observation width (Hirata et al., 2012). Frequent observation sensors such as MODIS and Spot Vegetation have a limited spatial resolution. The SAR sensor can conduct all-weather observation but has a disadvantage in terms of terrain area monitoring (GOFC-GOLD, 2012). Therefore, the selection of remote sensing data is an important issue. In the REDD-plus scheme, monitoring carbon levels is assumed to be conducted at the national or sub-national level to avoid leakage (Angelsen, 2008). It will be essential to consider the proper combination of methodology and remotely sensed imagery for large-area monitoring such as the REDD-plus scheme (Kiyono et al., 2011). Our results revealed the large difference in the acquisition probability of cloud-free images among countries and even within a country in some regions (e.g., Vietnam). Accessibility of the images can affect and limit the applicable remotely sensed data and methodology (GOFC-GOLD, 2012). It also influences the cost. Our clustering results can contribute to this discussion. More detailed clustering can be conducted by adding other sources such as terrain information that can be extracted using the Digital Elevation Model (DEM).

Fig. 3  Result of Clustering using averaged monthly acquisition probability profile. 8 classes (C1 to C8) are shown with different colors (C1: pink, C2: light blue, C3: blue, C4: light green, C5: orange, C6: yellow, C7: red and C8: purple).
Other types of clustering or analysis that have been applied to the time-series Normalized Difference Vegetation Index (NDVI) can also be applied to utilize a seasonal pattern of amplitude and phase (e.g., Jakubauskas et al., 2001; Bradley et al., 2007).

Application of MOD35 MODIS Cloud Mask Products

In this study, MODIS cloud mask with a spatial resolution of 1km was utilized. Therefore, the spatial pattern could be analyzed in more detail than previous studies that were based on the Landsat scene level analysis (e.g., Kontoes and Stakenborg, 1990; Fuller et al., 1994; Asner, 2001; Akiyama and Kawamura, 2003; Sano et al., 2007; Ju and Roy, 2008). This study clearly revealed the spatial pattern of acquisition probabilities as explained above. In addition, using high frequency observation with long-term constant observation enables us to summarize acquisition probabilities of cloud-free images at monthly time intervals and to analyze any annual variations. These are the novel points of our analysis using MODIS cloud mask products. On the other hand, it should be taken into account that the concept of probability is slightly different between Landsat scene-based and MODIS pixel-based analysis. In this study, even small gaps in clouds

![Fig. 4 Comparison of 9-years' average acquisition probability profile and original probability profile at a sample point for each cluster. The location of each point is shown in Fig. 3.](image-url)
Fig. 5  Standard deviations of monthly acquisition probabilities at each pixel. The bright color shows high values of standard deviations and the dark color shows low values.

Fig. 6  Distributions of annual acquisition probability summarized in a 1-km Grid located in the forest type in each country.
could be counted as clear pixels, but when using Landsat images, especially for full or semi-automatic analysis, a wide extent of clear coverage is essential, for example, to collect Ground Control Points (GCPs) for geo-correction or to collect sufficient training data for supervised classification. In such cases, the probability based on the extent of a scene is more suitable.

MODIS cloud mask is one of the most reliable and efficient products at present because the algorithm is based on multiple tests using the advantages of multiple spectral observations of MODIS. However, there some errors remain (Ackerman et al., 1998). For example, while clouds are detected as a high reflectance in the visible band and low temperature in the Infrared wavelength, the results can be biased by the background land cover when setting a fuzzy threshold (Ackerman et al., 1998). In this study, the probability tended to be low in regions where the land was covered by dark cover objects. The accuracy of cloud detection could be improved through refinement of the algorithm and development of sensors and techniques in the future (Ackerman et al., 1998). Our procedure can be applied to other cloud mask products created using other sensors or methodologies. Climate changes and local land cover changes can cause changes in seasonal patterns and differences in timing. Such cases should be considered by changing or updating the averaging period and zoning.

CONCLUSION

MODIS cloud mask analysis clarified the spatial and seasonal patterns of acquisition probabilities of cloud-free images in Southeast Asia. Nine years of data analysis also clarified the annual variations. Some regions showed a high probability in the dry season influenced by the Asian monsoon, such as Inland Indochina. Some other regions showed a low probability all year round such as the equatorial Indonesian islands, Malay Peninsula and coastal Vietnam. These results should be considered when selecting suitable remotely sensed data and methods for periodic large-area monitoring.

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