International Journal of Applied Earth Observation and Geoinformation 13 (2011) 220–227

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

A combined spectral and object-based approach to transparent cloud removal in an operational setting for Landsat ETM+

Gary R. Watmough[a,*], Peter M. Atkinson[a], Craig W. Hutton[b]

[a] School of Geography, University of Southampton, Southampton, SO17 2LD, UK
[b] GeoData Institute, University of Southampton, Southampton, SO17 2LD, UK

ARTICLE INFO

Article history:
Received 14 May 2010
Accepted 23 November 2010

Keywords:
Cloud
Landsat ETM+
Remote sensing
Object-based analysis
ACCA

ABSTRACT

The automated cloud cover assessment (ACCA) algorithm has provided automated estimates of cloud cover for the Landsat ETM+ mission since 2001. However, due to the lack of a band around 1.375 μm, cloud edges and transparent clouds such as cirrus cannot be detected. Use of Landsat ETM+ imagery for terrestrial land analysis is further hampered by the relatively long revisit period due to a nadir only viewing sensor. In this study, the ACCA threshold parameters were altered to minimise omission errors in the cloud masks. Object-based analysis was used to reduce the commission errors from the extended cloud filters. The method resulted in the removal of optically thin cirrus cloud and cloud edges which are often missed by other methods in sub-tropical areas. Although not fully automated, the principles of the method developed here provide an opportunity for using otherwise sub-optimal or completely unusable Landsat ETM+ imagery for operational applications. Where specific images are required for particular research goals the method can be used to remove cloud and transparent cloud helping to reduce bias in subsequent land cover classifications.

1. Introduction

Estimates suggest that, at any time, cirrus cloud covers up to 30% of the Earth's surface (Wylie and Menzel, 1999) and more than 50% in tropical and sub-tropical locations (Chepfer et al., 2000) where cirrus cloud can persist for extensive periods (Comstock et al., 2002). Unlike cumulus cloud, cirrus cloud is partially transparent and, thereby, difficult to remove entirely because pixels often contain a mixture of atmospheric cloud and land signals. However, left in place, cirrus cloud can be problematic for studies utilising remotely sensed satellite sensor imagery (Dessler and Yang, 2003) because pixels may be incorrectly assigned to a class with spectral and thermal properties more similar to clouds rather than the underlying land cover.

Landsat satellite sensor imagery provides a suitable choice for operational use where relatively fine spatial resolution is required in conjunction with large areal coverage. However, Foody (2002) highlighted that

> "*. . .regional to global scale mapping is often constrained to use relatively coarse resolution data. . . due to constraints of data cost, volume and the relatively high probability of obtaining a cloud-free view of the land surface with such data*" (p187).

Selected Landsat data are now available free of charge (USGS, 2008), thus, removing one of the constraints highlighted by Foody (2002). The increased levels of information available from the Landsat Enhanced Thematic Mapper Plus (ETM+) sensor's relatively fine spatial resolution is potentially advantageous for regional and global studies. Although, image use is often limited by factors such as cloud coverage, not using images containing cloud reduces the usefulness of satellite data (Wen et al., 2001).

The Landsat ETM+ sensor lacks wavebands that are able to detect cirrus clouds which, by contrast, are available on other satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Gao et al., 2002). The presence of these bands enables more accurate cloud masks to be developed (Platnick et al., 2003). Thus, cirrus cloud cover is a problem when using Landsat ETM+ data. Irish et al. (2006) highlighted that semi-transparent clouds are not easily detected by ETM+ spectral bands. If an image on a specific date is required for subsequent data analysis there may be no option but to select cloud affected imagery and find a method to identify and mask this cloud (El-Araby et al., 2005). Therefore, although the data cost constraint for regional studies has been removed for Landsat data their use may be hampered by a lack of simple cirrus cloud removal procedures.

1.1. Masking cloud in Landsat data

Several cloud identification and masking techniques have been proposed for Landsat data. Helmer and Ruefenacht (2005) created

---

[*] Corresponding author at: School of Geography, University of Southampton, Highfield Campus, Southampton, Hampshire SO17 1BJ, UK.
E-mail address: g.watmough@soton.ac.uk (G.R. Watmough).

0303-2434/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jag.2010.11.006

cloud and cloud shadow masks for Landsat Thematic Mapper (TM) imagery using the Iterative Self-organising data analysis (ISODATA) technique and manual editing. Results were variable with 73–87% overall accuracy for some imagery (acquired 2000), but 18–92% in other imagery (acquired 1991).

To increase discrimination between low altitude cloud and ground features with similar spectral properties such as rooftops, Melesse and Jordan (2002) augmented the data to be used in ISODATA with the Landsat TM thermal band. Data were also augmented using the normalized difference vegetation index (NDVI) to increase discrimination between low altitude cloud and ground features with small amounts of vegetation cover. Masks created using ISODATA with augmented data contributed to a 2.5% increase in accuracy compared to a fuzzy classifier. It was concluded that the additional work required could not be justified for such a small increase in accuracy. However, any increase in the accuracy of a cloud mask will result in increased accuracies if data are required for further analysis. Unsupervised classifiers such as ISODATA are suitable when scenes have several very distinct classes. Optically thin cirrus clouds and cloud edges often allow some form of spectral information from the ground below to be transmitted (Wang et al., 1999). Therefore, particular ground features with similar spectral properties to transparent cloud may have higher numbers of pixels incorrectly assigned to them. Using such classification methods may, therefore, increase inaccuracies when using the images for further analysis.

Several studies have created cloud masks using supervised methods of classification that depend on defining thresholds in specific bands. Song and Civco (2002) used brightness thresholds for Landsat TM band 1 and band 4. Martinuzzi et al. (2007) used Landsat ETM+ band 1 and band 6.1 (low gain thermal band). Wang et al. (1999) used TM band 1 and band 5. Thresholds were used in different ways to identify cloud and cloud shadows. For example, Song and Civco (2002) compared the brightness in a main image (used for further analysis) with a reference image to create a brightness difference image. Band thresholds and brightness differences were then used to create cloud masks. Wang et al. (1999) used multi-image compositing or fusion for cloud masking. Cloud masks were created using absolute brightness differences between the main image and a reference image. The largest differences were said to be more likely to represent cloud. There were omission errors with this method where cloud was present in both the main and reference image.

To identify cloud edges or thinner clouds Song and Civco (2002) and Martinuzzi et al. (2007) extended tolerance thresholds. A Digital Number (DN) tolerance threshold of 10 was employed by Song and Civco (2002) whereas Martinuzzi et al. (2007) used a three pixel buffer around each masked cloud.

Although not designed to be used as a per-pixel cloud mask, the scene averaged automated cloud cover assessment (ACCA) algorithm identifies clouds in Landsat ETM+ imagery (Irish, 2000). The method integrates brightness, temperature and composite thresholds to discriminate cloud from a range of land cover types that can have similar spectral properties to clouds such as bare sand and rock. Such a mask is created as part of the procedure and Irish et al. (2006) recommended that this mask could be made available when users download Landsat ETM+ imagery.

1.2. Limitations of cloud masking methods

The techniques highlighted above all have limitations for creating accurate cloud masks. The main limitation for cloud mask creation using Landsat imagery is the lack of a band designed to identify cirrus clouds. Irish et al. (2006) described the clouds identified by the ACCA method "…as optically thick or nearly opaque…" (1180). The series of thresholds used for the ACCA algorithm enables a hierarchical model to be built that can separate cloud, non-cloud and ambiguous pixels from a range of land covers with similar spectral and thermal responses. However, the ACCA method suffers from omission errors associated with thin cirrus clouds (Irish et al., 2006). The method also suffers from commission errors associated with low solar illumination over snow and ice (Choi and Bindschadler, 2004).

Image compositing methods such as those used in Wang et al. (1999) could require unfeasibly large numbers of images to decrease commission errors and in sub-tropical and tropical locations it may not be possible to acquire imagery with acceptable levels of cloud (<40%) during particular times of the year. DN or pixel buffer tolerance thresholds can help mask transparent cloud. However, DN thresholds will introduce commission errors by using a blanket threshold across the whole image. A pixel buffer tolerance is likely to decrease these commission errors as it adds tolerances only to areas already identified as clouds. However, pixel-buffer tolerances will be affected by omission errors associated with areas of cloud not identified in the original mask.

1.3. Developing an improved method

Aside from those discussed, few cloud masking methods for Landsat imagery have been developed because of the key limitations discussed. From this, it was useful to build upon existing methods to develop an improved technique for cloud removal to ensure that cirrus clouds were captured in a mask. Consequently, this study used the automated cloud cover assessment (ACCA) method to mask cloud from images in a sub-tropical area affected by seasonal cloud. The ACCA method was adapted to increase the accuracy of identification of semi-transparent cloud using a combination of widely available pixel-based and object-based tools.

2. Materials

2.1. Study area

The state of Assam is the largest of 'Seven-sister states' in the North-east of India. It lies between 28°18′ and 24° north Latitude and 89°46′ and 97°4′ east Longitude. It is bounded in the north by the Himalayan range of Bhutan and Arunachal Pradesh and in the east by the Patkai range. The research area mainly covers the Brahmaputra valley, with administrative districts on both north and south banks of the river.

The monsoon climate of the region contributes to perpetual cloud cover from April to September and often longer. The highly braided Brahmaputra River and its tributaries dominate large areas of Assam with the spectral properties of the shifting sand bars and islands easily confused with other ground features containing transparent cloud. Land covers in the region are predominately vegetation (agriculture and forest) and dominated by rain-fed rice cultivation (Government of Assam, 2004).

2.2. Image data

Four Landsat 7 ETM+ L1T images were downloaded from the United States Geological Survey (USGS) Global Visualisation (GloVis) website (http://glovis.usgs.gov/). The scenes are summarised in Table 1.

Images were sub-setted to remove surrounding mountainous areas which were not required for subsequent analysis. Exploratory analysis of the metadata for each image revealed that the region had cloud coverage regularly in excess of 50% during the main growing season (June to September). Thus, compromises had to be made for certain scenes. The October 2001 image for WRS path 135 row 042 could not be used as it had 83% cloud coverage. Scenes immediately