A METHOD FOR MAPPING CLOUD FORESTS USING HIGH-RESOLUTION SATELLITE IMAGERY

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ABSTRACT

This paper describes an algorithm to describe the distribution of cloud forests in the tropics using Moderate-Resolution Imaging Spectroradiometer (MODIS) imagery. As an important component to global biodiversity, the conservation of tropical cloud forests is a high priority. Unfortunately, it is difficult to map these forests from space because they tend to look similar to other tropical forests. Our approach uses high-resolution satellite imagery (MODIS) to determine the average cloudiness in a region, and to relate these mean cloudiness patterns to the underlying topography. In addition, we developed techniques to distinguish the cloud forests based not only on the total amount of cloudiness, but its seasonal and diurnal variability. Currently, the Central American region was most closely depicted by averaging monthly mean images into annual mean images for both morning (*Terra* satellite) and afternoon (*Aqua* satellite). The algorithm was created to narrow the favorable conditions for a cloud forest to exist. For this, each corresponding pixel for each month was averaged together to create a mean annual frequency cloudiness image for *Terra* and *Aqua* separately. The difference of maximum and minimum pixel cloud brightness was then calculated in order to locate the lowest variability locations necessary for persistent cloudiness throughout the year. This helps to eliminate any season dependence that may occur with frequent cloudiness locations. Lastly, maintaining the combined overlapped product of *Terra* and *Aqua* provided the lowest amount of diurnal variability essential for an ideal cloud forest to exist. This acts to prevent non-ideal daytime dependence. The results demonstrated the combined product of the thresholds of the Central American MODIS sector, and are placed among topography in order to analyze the detailed locations with the 250 meter spatial resolution. The cloud forest regions are along the northeastern mountain slopes of Central America, which are favorable locations due to the persistent trade winds.

1. INTRODUCTION

Cloud forests are forests found along tropical and subtropical mountain slopes and are submerged within persistent or frequent ground-level clouds throughout the year (Grubb, 1977). The high incidence of low-level cloud cover is due to a variety of atmospheric circulations, but also the convergence of easterly trade winds that are forced up the mountainous slopes. The rising air cools adiabatically and allows for cloud formation at these locations (T. J. Killeen *et al*., 2006). The presence of the cloud cover acts to reduce direct sunlight and evapotranspiration and increase rainfall and horizontal precipitation, creating the opportunity for unique ecosystems to exist. Despite their relatively small geographical coverage, cloud forests are important because they are areas of relatively high biodiversity, with many species adapted to an environment of very little water stress. These areas also play an important role in local and regional hydrological management for down-slope communities that rely on their water source. However, it is explained that cloud forests are frequently cleared for cattle grazing, logged to provide fuel for heating and cooking, paved for transportation and telecommunications networks, and the effects of deforestation and global climate change potentially threaten these dependent areas.

Lowland alterations affect surface albedo, temperature, water storage capacity in the soil, and soil moisture distribution. It also impacts boundary layer air temperature, moisture, and depth (Nair *et al*., 2003). This leads to the change in local rainfall and cloudiness which can directly affect the elevation of cloud base along the upwind mountain slopes, and therefore threatening cloud forest locations. Nair *et al.* focuses on the sensitivity of cloud growth from lowland deforestation and how it appeals to montane cloud forests. The concentration is on deforestation resulting in warmer, drier air upwind of the montane cloud forests. This results in raising cloud base altitude due to the orographic lifting in the Costa Rican region during the dry season. Also, the changes in rainfall affect downstream communities that are dependent on the water production throughout the tropics (Mulligan and Burke, 2005). The need to accurately locate cloud forest locations is essential in the process of conservation planning and future research. Unfortunately, mapping cloud forests is very difficult from the ground, as there are relatively few roads that cross the forests. Also, the mountain slopes are often steep with relatively few specialized biologists available to study these environments in many of the developing countries where these forests are found. Thus, mapping these forests remotely is a high priority and can be recognized by specified methods of using high-resolution satellite imagery.

Clouds reflect a considerable amount of solar energy back into space before it reaches the Earth's surface. This energy is then detected by meteorological satellites and is shown as visible satellite imagery. However, if the energy is absorbed by the clouds, it will emit long-wave radiation that can be viewed through infrared satellite imagery. Both types of imagery may be used to detect cloud cover in the earth's atmosphere, and can be used to generate cloud climatologies. Although the focus here is on trying to identify the so-called "cloud forests" from the satellite-derived cloudiness, the results can be used more widely. As important as detecting the moist cloud forests is, the delimiting of other types of environments is also important such as the cloud-free canyons which are evident in many parts of the mountainous tropics. Since most subtropical and tropical coastal desert areas have small areas of high cloudiness that can be identified by such cloud climatologies, they can be used to explain the distributions of species with very limited distributions.

It is hypothesized that a cloud forest exists in places of persistent cloudiness, low annual variability of cloudiness, and low diurnal variability cloudiness. The algorithm presented in this paper demonstrates a way to geographically locate cloud forests by incorporating averaged monthly visible satellite imagery of Central America. These images were taken from both *Terra* (morning) and *Aqua* (afternoon) missions of the Moderate Resolution Imaging Spectroradiometer (MODIS) using 250 m resolution. Mean monthly images were calculated to provide mean annual cloudiness and annual variability. The National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites-8 and -12 (GOES-8 and -12) 4km resolution infrared imagery was also used to compare diurnal variability of cloudiness because of its 30 minute time interval. Combining these characteristics make it possible to map the distribution and relationship of cloud forests with underlying topography.

Currently, this study is an outgrowth of research activities carried out during the South American Low-Level Jet Experiment in 2002-3, focusing on the study the relationship between rainfall over the Bolivian altiplano and eastern Andean slopes and the variations of the low-level jet east of the Andes. Discussions with collaborating Bolivian and US scientists showed a strong spatial variability in the rainfall over the eastern Andean slopes – without much explanation in the formal literature. This led to the development of some cloud-climatology studies of the region (Killeen *et al*., 2007), and the present paper describes an effort to improve the procedures to map both cloudiness and vegetation variations on very fine spatial scales

2. DATA

MODIS satellites are uniquely designed to have this wide spectral range, along with high spatial resolution and almost daily global coverage. They were created to observe and monitor the climatic changes in the Earth. The products consist of Level 2—Aerosol, Water Vapor, Cloud, and Atmospheric Profile—Products, and also Level 3—Daily, Eight-Day, and Monthly—Global Joint Products. The two Earth Observing System (EOS) MODIS satellites are *Terra* and *Aqua*, which have ±55 degree scanning patterns. *Terra* was launched on 18 December 1999 with its first data received on 24 February 2000. It passes from north to south across the equator at 1030 local solar time. *Aqua* was launched on 4 May 2002 and began transmitting scientific data 12 May 2002. Aqua passes from south to north over the equator at 1330 local crossing time. The satellites consist of 36 spectral bands (0.405 – 14.385 µm) with a swath width of 2,330 km. They provide three spatial resolutions of 250 m, 500 m, and 1 km and assist in surface and lower atmospheric processes (Shutler *et al*., 2005).

The monthly mean 250 m resolution images of Central America (-86.728° to -76.487°W longitude and 13.558° to 3.666°N latitude) were the products of *Terra* and *Aqua*. Each month offered two images, one from *Terra*'s path and one from *Aqua*'s path, and both capture images for designated MODIS subsets (Fig. 1). The images provided 4400 X 4400 pixel dimensions and followed the designated cloud mask algorithm. The data extended from February 2006 to June 2007 with each month containing the averaged pixels of daily cloudiness. Once averaged, the new monthly images illustrated the percentage of cloudiness throughout the month of every individual pixel for two separate times of the day (*Terra* and *Aqua*). This was useful for analyzing monthly annual variability of cloudiness, along with the diurnal differences among *Terra* and *Aqua* images.

Both GOES-8 and GOES-12 are geosynchronous, in which they orbit the equatorial plane of the Earth at a proportional speed of the Earth's rotation. This allows them to maintain one position 35,800 km over the Earth's surface and capture images at frequent intervals of 30 minutes or less. GOES also carries instruments that measure atmospheric temperature and moisture, but they are generally used to watch for severe weather among land and the ocean—especially developing hurricanes. The pixels of each image

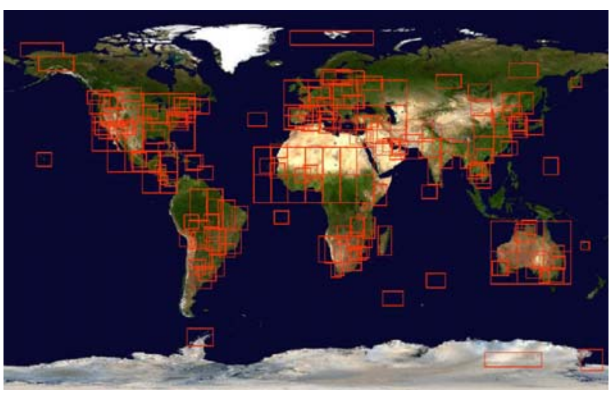

Fig. 1. An example of the MODIS Rapid Response System Subsets. Subsets contain the regions within the red boxes. The current method is focusing on the Central American sector. Online at **http://rapidfire.sci.gsfc.nasa.gov/subsets/**.

taken by the satellites contain an amount of cloudiness within a specified area. Averaging those daily corresponding pixels and combining every hour during 30 April 2002 through 16 April 2004 contributed to understanding the diurnal cycle of the Central American region that also includes southern Mexico and northern South America. The infrared imagery was most useful for the work due to its advantage in viewing full 24-hour patterns but was not included in the final product.

The topography map was obtained from NOAA's National Geophysical Data Center (NGDC) as a 30 arc second elevation data set that spans the entire globe. The data was read in meters, and the oceans were removed through an IDL program. Once a specified domain of latitude and longitude for the Central American sector was in place, the tile of topography was extracted from the program and combined with the collected cloud forest data. The impact of topography on the cloud climatologies can easily be inferred.

3. METHODOLOGY

According to Bubb *et al.* (2004), cloud forests make up 2.5% of the total area of all tropical forests. However, other sources may argue that cloud forests maintain 14.2% of the total tropical forests (Mulligan and Burke, 2005), demonstrating the need for an accurate answer. Some previous methods of locating potential cloud forests are fairly simplistic with limited meteorological input. For example, a designated satellite proclaims potential cloud forests by detecting forests at the altitude of cloud-base level. Presently, an algorithm has been developed to accurately locate the most favorable areas for where cloud forests can exist. The algorithm takes into account the high frequency of annual cloudiness, the low annual variability of cloudiness, and low diurnal variability. All of these aspects of persistent cloudiness illustrate the hypothesized key conditions in a surviving cloud forest.

The monthly visible MODIS images of cloudiness were extracted by an Interactive Data Language (IDL) program. The program analyzes every pixel of every daily image and identifies whether or not the pixel contains clouds. Clouds are placed on a brightness scale from 0-100%, where 0 is black and 100% is white. The program is designed to find pixels of cloudiness that have contamination brightness factors (smoke) that could be mistaken for cloudiness. It then creates monthly *Terra* and *Aqua* images of cloud frequencies in every pixel. Since there was more than one year's worth of images, it was necessary to average each month's images together to create a single image for *Terra* and a single image for *Aqua* of every month. The combined monthly images were then manipulated to calculate the mean frequency (percent) of cloudiness throughout the year at the two times of the day. Figures 2a and 2b illustrate the positions of cloud frequency and help us locate these areas.

To find the variability of cloudiness, it is necessary to view the change of cloudiness, or amplitude, throughout the entire year. Another IDL program was designed to take the difference of the maximum and the minimum of cloudiness in every pixel of the monthly images for both *Terra*

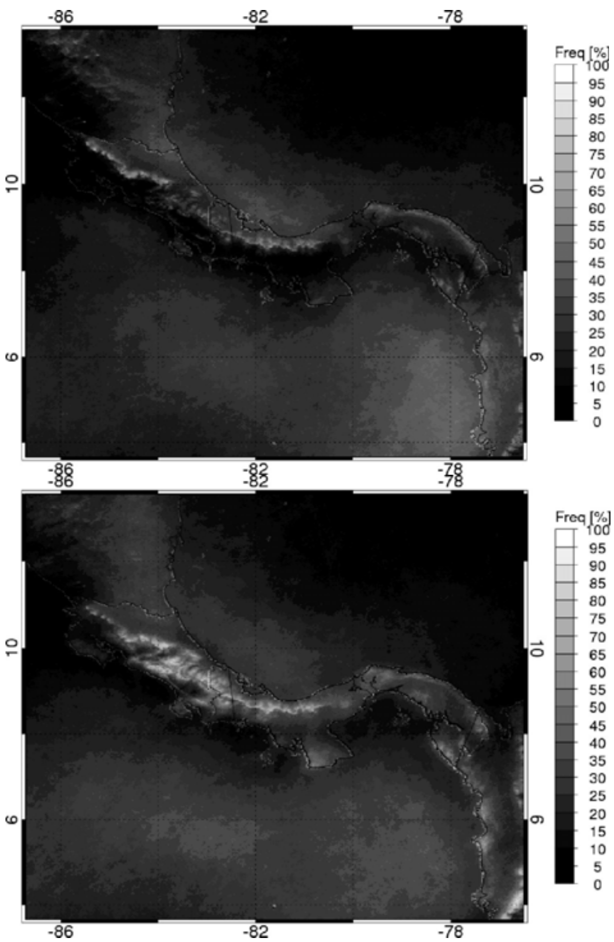

Fig. 2. (a) Mean annual cloud frequencies for *Terra* satellite. The whiter areas are of highest frequencies of cloudiness throughout the year while the blacker areas represent the lowest annual cloud frequencies (%); (b) Same as (a) but for *Aqua*.

and *Aqua*, and then divide by the average frequency of cloudiness. This scales the values so that if the difference between the maximum and minimum is large or small, those separate areas will be magnified. For example, if the amplitude is small and the percentage of cloudiness is also small, it will create a larger value on the coefficient of amplitude scale than if there was a larger percentage of cloudiness. Therefore, if the variability of cloud frequency throughout the year is small, the number on the coefficient of amplitude scale will also be small (Figs. 3a and 3b).

Once the mean annual cloudiness and variability of cloudiness was decided, an IDL

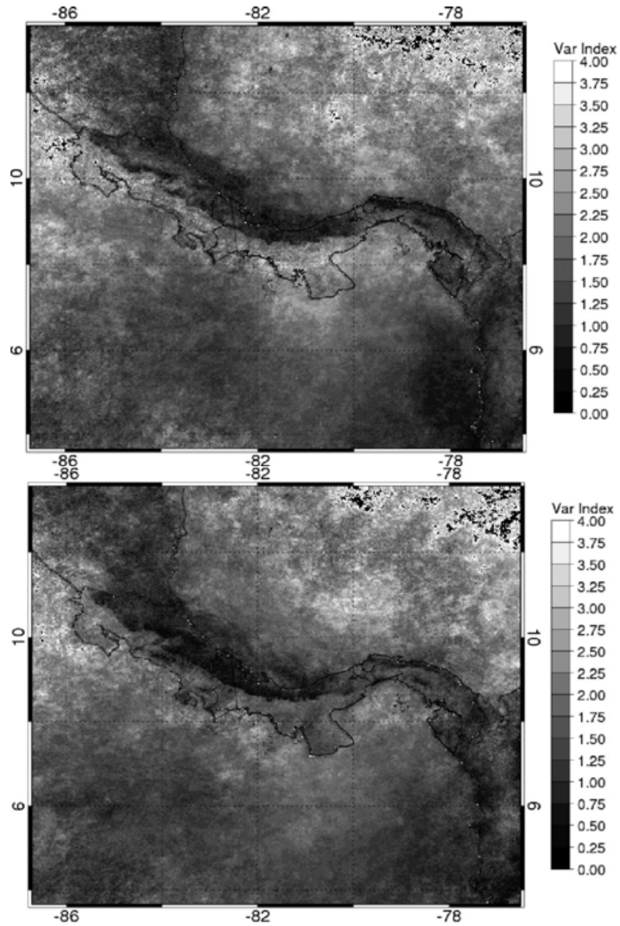

Fig. 3. (a) Mean annual variability using cloud frequencies for *Terra* satellite. The whiter areas are of highest variability of cloudiness throughout the year while the blacker areas represent the lowest annual cloud variability; (b) Same as (a) but for *Aqua*.

program was created to combine the two desired characteristics of a cloud forest such as high cloud frequency and low variability for both *Terra* and *Aqua*. The program looked for high cloud frequency values of greater than 40%, and it also looked for small variability by locating coefficient values of less than 1.0 on the variability index scale. Combined as shown in Figs. 4a and 4b, the designated threshold narrowed the possible locations of cloud forests by maintaining these most desired traits. The darker areas only provide high variability of cloudiness or high and low variability of "clear" areas. However, it is difficult to determine the altitudes of the cloud bases found in these images, and they may not intersect the ground in the areas presumed to do so.

After maintaining an intersection image of both annual frequency and low variability of cloudiness, both *Terra* and *Aqua* displayed areas unique to themselves. However, to presume low diurnal variability using the MODIS data, the represented cloud forest areas of both times of the day must be equivalent for the low variability assumption to exist. Therefore, the differences of *Aqua* and *Terra* were calculated for both mean annual cloudiness, low annual variability, and the intersected combination of both. Overlying the image among topography showed those locations of low diurnal variability, combined with the other two key factors mentioned. GOES satellite data was then examined to verify the persistence of cloudiness throughout the day and to reassure us that the hypothesis was supported.

Because the images we used contained superimposed coastline and political boundaries these showed up as false cloudiness. To remove thiese areas we deleted every cloud forest pixel below 100m altitude. This procedure also is equivalent to assuming that cloud forests exist only above 100 meters above sea level. The remaining pixels are then believed to be cloud forests under our criteria and must be considered in the final product. To accurately locate these areas, it was necessary to relate the cloud forests to topography with the appropriate latitudes and longitudes. Geo-referencing these areas was important in providing better geographical and climatological knowledge of cloud forests.

There are some limitations to our method. It is possible for high cloud frequencies to exist without the presence of forests. Also, since altitude is variable throughout the tropics, the higher cloud frequencies may not be intersecting the ground where it is assumed to do so. The non-uniformity of elevation is a common issue associated with the location of cloud forest areas and is very difficult to detect using satellite imagery.

4. RESULTS

A. Cloud Forest versus Drier Areas

High annual frequency of cloudiness and low annual and diurnal variability were the hypothesized criteria for a cloud forest to exist (not shown). Figures 5a and 5b show the differences between a 51 X 51 "cloudy" pixel area (12.75 x 12.75 km) and a 51 X 51 "clear" pixel area for both *Terra* and *Aqua* for the Central American region. The pixels represent the average monthly percentage of cloudiness for the two chosen areas throughout a controlled year. The cloudy pixel was taken from a location that represented a high annual cloud frequency, with potentially lower variability, of cloudiness. Likewise, a clear pixel was captured from a lower frequency area of cloudiness with potentially higher variability.

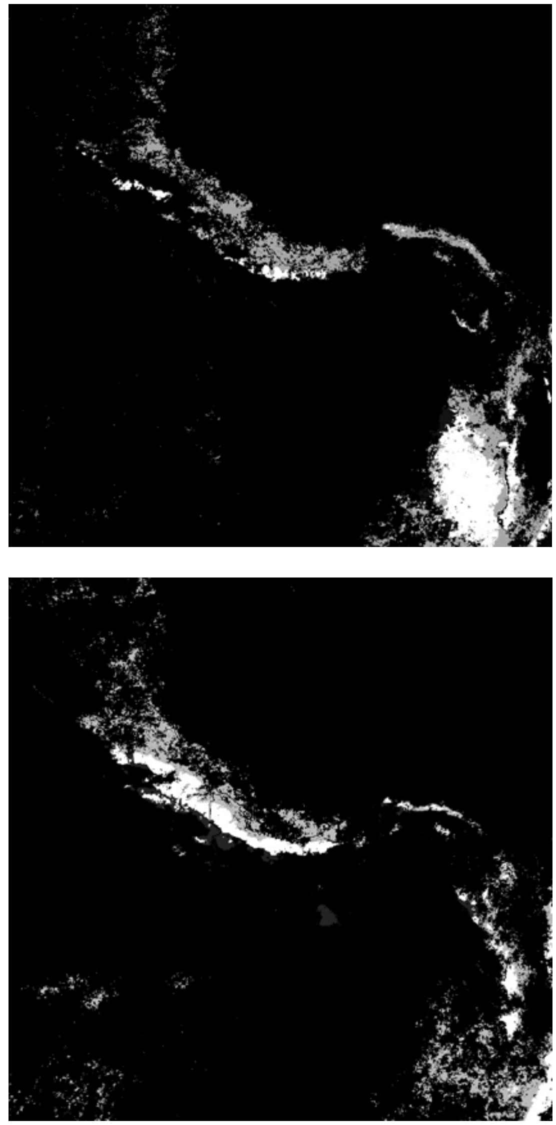

Fig. 4. (a) An annual composite image of the Central American Sector for *Terra*. The white areas are representative of high cloud frequency areas above 40% and low variability cloudiness below 1 on the variability index scale. The gray and black areas are irrelevant; (b) Same as (a) but for *Aqua*.

The annual patterns revealed the amplitudes of variability and also where "drier months" may occur throughout the year. The differences of *Terra* and *Aqua* were quite common: daytime heating allows for instability and cloud growth later in the day than in the morning hours. This led to a higher frequency of cloudiness, and also a slight difference in diurnal variability in potential cloud forest regions. *Aqua* displayed a general enhancement in the percentage of cloudiness from *Terra* on the northern slopes of the Central American Sierra Mountain Range cause by daytime heating and onshore flow. The morning hours revealed a larger variability in reflectivity in the early Northern Hemispheric spring, but also in the fall months, while the afternoon hours showed the most variability in late winter. Since the trade winds are strongest during the winter and early spring months due to larger temperature gradients in the Northern Hemisphere, cloud formation is more favorable along the mountain slopes. Therefore, the higher frequency of cloudiness was more evident for both morning and afternoon for these months.

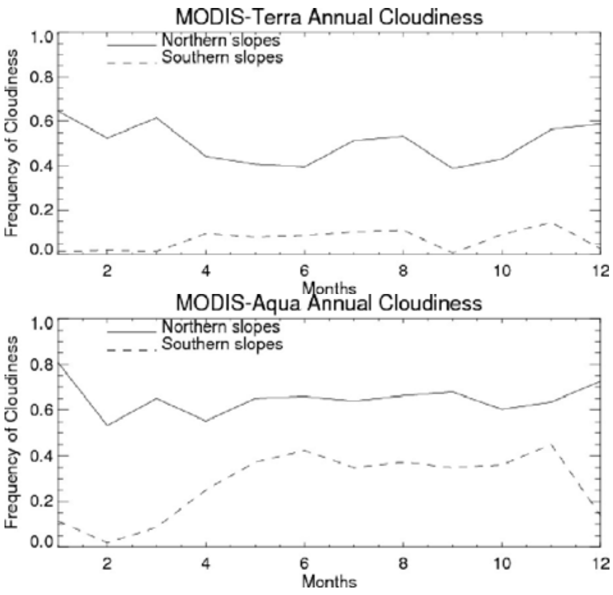

Fig. 5. (a) The cloudy and clear regions are shown because they were chosen regions to be averaged and graphed. The figure shows averaged frequency of cloudiness for each month throughout the year for *Terra*. This also demonstrates the differences in variability when compared to (b); (b) Same as (a) but for *Aqua*.

The “clear” pixel on the southern slope has a large amount of diurnal variability when comparing the three hour span of *Terra* and *Aqua*. In Fig. 5b, cloudiness frequency is generally expected to be greater also due to daytime heating and onshore flow. This was largely noticeable in late spring through early winter months where temperatures are still warmer during the day, leading to a dependency on seasonality. Therefore, the most important aspect was that the southern slope pixel did not maintain the required characteristics of a cloud forest and therefore its annual and diurnal variability eliminated any uncertainty of not declaring it one.

B. Mean Annual Cloud Frequency Combined with Low Annual and Diurnal Variability

Once every corresponding pixel of every month of the year was averaged together, it produced a mean annual cloud frequency image that demonstrated the annual percentage of cloudiness (brightness) for a controlled year for both *Terra* and *Aqua* in Figs. 2a and 2b. Since this is a key step in accurately locating a cloud forest, it is important to note the locations of the highest frequency of cloudiness throughout the controlled year. In this case, the brightest pixels contained the highest percentage of “cloudy” pixel days in a given year. As shown from this sector, the highest frequency was more prominent on the northeastern sides of the Central American Sierra Mountain Range. Once again, this is due to persistent trade winds forcing air particles up the mountain slopes and cooling adiabatically to develop clouds.

The second key step was detecting areas that can maintain cloudiness for a large fraction of the year. Figures 3a and 3b provide the *Terra* and *Aqua* cloudiness variability among the focused region. On the brightness scale 0-100%, the smaller amplitudes sustained a smaller value of variability due to the smaller difference of maximum and minimum. Therefore, the lowest variability of the monthly pixels was arranged by the darker plotted areas. Along the northeastern mountain slopes held the lowest region of variability for cloudiness, but must not be mistaken with the low variability for clear days. The drier areas may also preserve low annual variability, but cloudiness is restricted. *Aqua* held a greater amount of low variability due to dependence on daytime cloud growth, while *Terra*’s low variability was limited due a relatively larger seasonal dependence throughout the year.

The third key step in determining cloud forests was the diurnal variability and how it affects cloud frequency. Since the MODIS data was taken only twice a day, the entire diurnal change (amplitude) could not be measured. However, both *Terra* and *Aqua* were manipulated to produce the intersections of annual frequency and low annual variability of cloudiness in Central America at both times of the day (not shown). It was important to separate the two times of the day in order to observe differences and also meteorological processes that occur throughout the day.

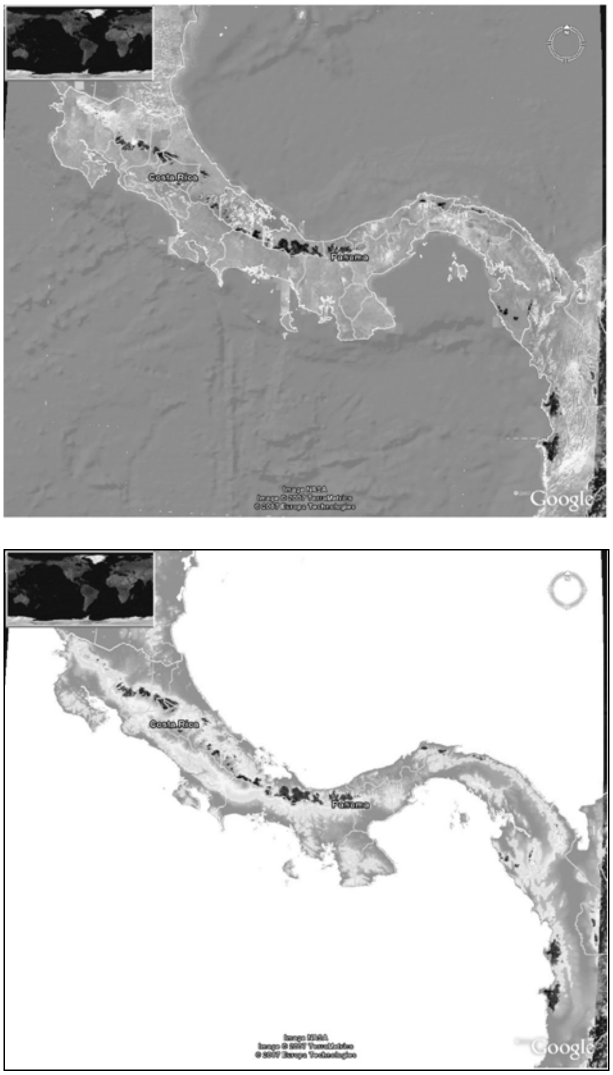

Fig. 6. (a) The final result using the described algorithm and methodology. The black areas are where combined high cloud frequency, low annual variability, and low diurnal variability are located as favorable conditions for cloud forests among the Central American sector; (b) Same as (a) but with underlying topography. It is noticeable that the cloud forests exist on the trade wind (northeastern) slopes of the Central American mountain range located there.

The algorithm used to detect cloud forests required the three key steps to be organized into one main function. Figure 6a displays the final combined product of locating these areas in the Central American sector. The image represents a restricted area of high frequency cloudiness, low annual variability, and only the overlapped areas of both *Terra* and *Aqua.* The area that resides along the northeastern areas of the main Central American mountain slopes are designated cloud forests that maintain the desired characteristics of cloud forests, where the effect of the up-sloping trade winds was evident.

The current threshold to locate these areas was suitable for the Central American sector, but may have to be adjusted for a global map application due to higher terrains or latitude location. However, it is important to maintain the same criteria for each applied sector in order to eliminate bias.

C. Cloud Forest Relationship with Topography

Compared with Mulligan and Burke (2005), the cloud forests found for this current method were underestimated (not shown). However, the thresholds that produce these locations can be manipulated to be less restrictive and provide a greater area of detection. Since this current method is using a 250 m resolution instead of a 1 km resolution, the simulations better identify with the underlying terrain as shown in Fig. 6b. Also, to match the spatial resolution of the cloud forest pixels, it was necessary to downscale the spatial resolution of the topography map to 1 km as well.

It is important to note the cloud forest relationship to the mountainous terrain. The locations have indeed corresponded with mountain slopes affected by the trade winds and atmospheric circulations. The drier valley areas are identified and removed from the final product as a result of the lower frequency of annual cloudiness. Although cloud forests can be found at multiple altitudes, Fig. 7 demonstrates the elevation of the underlying terrain and the percentage of the associated cloud forest pixels. According to the results, majority of the cloud forests reside along ~500 to 1000 meters in elevation. However, this may not be an accurate measurement of cloud intersection with the ground because it is only aimed towards the altitude of terrain where the cloud forest pixels are located.

5. DISCUSSION

Further work will be continued for multiple sectors around the globe using MODIS visible satellite imagery data with 250m spatial resolution. Also, GOES infrared satellite imagery can be used in more depth when analyzing diurnal variability and cloud frequencies throughout the entire 24-hour periods. Since GOES is available for a relatively longer time period than MODIS, it will be useful to determine better cloud climatologies.

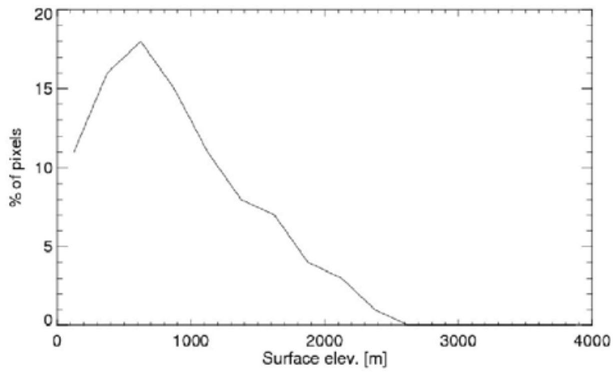

Fig. 7. Histogram of the percentage of pixels associated as cloud forests compared to the altitude of the underlying topography. Most of the pixels occur where the terrain is located at ~300 to 1000 meters in altitude. This only represents the probable height of the cloud forests but may not be where the cloud intersects the ground indefinitely.

Other sectors may need a different threshold for detecting cloud forests and the Central American region will be adjusted to fit the needs of the entire globe. This is due to different ranges of latitude and effects of the trade winds. Also, it is important not to create a bias product to assure that the cloud forest detection algorithm is suitable for all sectors.

Currently, it is difficult to determine whether or not the high frequencies of cloudiness are intercepting the ground (forests) or if they are just merely above it. It will be essential to pinpoint accurate altitudes of the cloud bases and analyze the various terrains of the tropical forests. Further investigation is needed.

This product may be combined with similar products to create an ideal algorithm in conservation of these cloud forests. Since they most likely will be threatened by land use changes and global climate changes, it is important to plan protection for these specialized ecosystems and reassure non-extinction. Future knowledge and research is continuously necessary and useful.

6. CONCLUSIONS

Cloud forests are forests submerged within ground-level clouds among tropical and subtropical mountain slopes and provide very high humidity values and cool temperatures. This allows for unique ecosystems to exist, as well as maintain a hydrological importance for local and regional areas. Deforestation and global climate changes are currently providing a threat towards many cloud forest areas. There is a urgent need to locate these areas to determine their distributions and provide information towards future researchers and others who can benefit from the results.

Previous techniques have been explored using a coarser spatial resolution of satellite data. Also, another disadvantage is the dependency on only altitude, forest distribution, and possibly cloudiness. Not much meteorological input has been involved previously. However, it is difficult to appropriately take into account the detailed features of topography and the undesired over-estimation of these areas. To account for this issue, a cloud detection algorithm was designed and described in this paper to provide favorable conditions for the existence of cloud forests by using the 250 m high spatial resolution of MODIS' *Terra* (AM) and *Aqua* (PM) satellite imageries. The goal was to determine the cloud forest locations and compare it to underlying topography to provide better results for future research.

Our procedure involved distinguishing clouds from contaminations in the imagery such as smoke. Then each corresponding pixel for each averaged month was calculated to present the cloud frequencies of each individual pixel averaged over an entire controlled year. Also, persistence of the cloudiness was calculated using the difference of the maximum of brightness of corresponding pixels and the minimum of brightness of corresponding pixels of each averaged month, divided by the mean frequency of cloudiness. This granted the annual variability of cloudiness for *Terra* and for *Aqua*. The diurnal variability was then extracted from the overlapping areas that both *Terra* and *Aqua* provided. With all three steps combined with a designated threshold, it was possible to narrow locations of potential cloud forest areas for the Central American Sector.

Also, when looking at specific regions of probably "cloudy" and "clear" areas, it is noticeable how much these different locations impact the variability through dependence (or lack thereof) on seasons and daytime heating. It is also important to note that the cloudy region does have some variability and cloud frequency differences throughout the year and day, but is relatively insignificant compared to a region of higher variability of cloudiness.

The final results demonstrated the high spatial resolution of the cloud forests once distributing the algorithm to the designated Central American sector. Not all high mean annual cloud frequency locations are cloud forests, and the drier areas are ideally represented as a non-cloud forest location. Compared with topography, the cloud forest distributions from the algorithm are independent, but are mainly located along the northeastern mountain slopes where the trade winds and other atmospheric circulations are providing the cloud formation for the regions. This is a pleasant result from the current methodology and using high spatial resolution satellite imagery is beneficial. Presently, future research is necessary because the method is needed to be tuned to properly fit a common global threshold and be available to apply to multiple sectors.

Acknowledgements. This material is based upon work supported by the National Science Foundation under Grant No. ATM-0648566. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Bubb, P., I. May, L. Miles, and J. Sayer, 2004: Cloud Forest Agenda. *UNEP-WCMC*, Cambridge, UK. [Available online at http://www.unep-wcmc.org/resources/publications/UNEP_WCMC_bio_series/20htm.]

Grubb, P. J., 1977: Control of Forest Growth and Distribution on wet Tropical Mountains: with Special Reference to Mineral Nutrition. *Annual Review of Ecology and Systematics*, **8,** 83-107.

Killeen, T. J., M. Douglas, T. Consiglio, P. M. Jorgensen, and J. Mejia, 2006: Dry spots and wet spots in the Andean hotspot. *Journal of Biogeography*, 1-17.

Nair, U. S., R. O. Lawton, R. M. Welch, and R. A. Pielke Sr., 2003: Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of cumulus cloud field characteristics to lowland deforestation. *Journal of Geophysical Research*, **108,** 1-13.

Mulligan, M and S. M. Burke, 2005: DFID FRP Project ZF0216 Global cloud forests and environmental change in a hydrological context. *Ambiotek*, 74 pp. [Available online at http://www.ambiotek.com/cloudforests/.]

Shutler, J. D., T. J. Smyth, P. E. Land, and S. B. Groom, 2005: A near-real time automatic MODIS data processing system. *International Journal of Remote Sensing*, **26,** 1049-1055.