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Developing cloudiness climatologies from satellite imagery to map cloud forests and other vegetation features over the tropical Americas

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Abstract

The environment with the greatest biodiversity from a global standpoint is that known as the tropical Andes "hotspot", which is a broad region along the eastern slopes of the Andes in South America. Within this region, one of the subregions with the highest diversity is the cloud forest, a region of very high cloudiness and high annual precipitation. Mapping this cloud forest and surrounding environments has been of high priority because resources for conservation are limited and conservation organizations and governmental agencies need to know what areas should receive highest priority for protection efforts.

Work associated with the South American Low-level Jet Experiment (SALLJEX) carried out in 2002-3 led to the use of GOES imagery to develop composites for describing the mean cloudiness along the eastern slopes of the Andes. More recently MODIS imagery has been used to describe cloudiness at even higher spatial resolution. Together, these imagery sources can be related to cloud forest distribution. In addition, dry canyon environments, the locus of many geographically-restricted species, can likewise be readily described from the cloudiness composites.

Although the results shown here may not be quantitatively useful for estimating some quantities such as rainfall, their qualitative use should help a broad array of individuals interested in mapping relative cloudiness gradients and identifying suitable areas for ground-based studies. The results should also increase awareness of the importance of mesoclimatological features that are closely tied to topography.

1. Motivation

Mapping the distribution of vegetation types can be a complicated task, especially in remote locations. One example of this is determining the distribution of so-called tropical "cloud forests". These regions, as their name implies, are forests that are immersed within clouds for a large fraction of the time. Because these environments have relatively high relative humidity, are usually very rainy, and are generally well above freezing, there is luxuriant plant growth. These regions also show very high diversity of plants and animals, and so they are important to map accurately to aid in conservation planning.

It is very difficult to map the distribution of cloud forest from the ground. Most cloud forests occur on the sides of steep slopes, a consequence of the interaction of the topography, clouds, and wind. Steep, wet slopes make for difficult road construction, which can sometimes minimize the human impact but also makes access difficult for botanists, zoologists and others seeking to describe this environment. In addition, the high frequency of cloudiness, together with the terrain being close to cloud base, makes aerial surveys difficult and potentially dangerous. And although cloud forests and wet forests at lower elevations (well below cloud base) may look superficially similar from satellite imagery they can have very different flora and fauna. Thus, there is a real need to map these regions.

The current report summarizes activities that are an outgrowth of rainfall studies of the eastern Andean slopes and altiplano regions of Bolivia and Peru. These rainfall studies have been carried out under the umbrella of the South American Low-Level Jet EXperiment (SALLJEX), which is a study focused on the variations of the strong low-level winds found over central South America east of the Andes. It partners with research that has been carried out for years by members of the Museo Noel Kempff in Santa Cruz, Bolivia and by members of Conservation International.

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2. Methodology and Data

To determine probable locations of cloud forest it is necessary to map the distribution of clouds and topography. In fact, the intersection of clouds with the topography is actually required, since in-cloud environments (humidity near 100%) and overcast conditions (clouds above the surface) could produce much different vegetation environments. This summary discusses only the observed distribution of cloudiness. We do not attempt to infer the cloud bases, nor exactly where the clouds intersect the terrain. This is being left to later studies. Here we are evaluating some of the routinely available satellite products that can be used to map rainfall and cloudiness at varying spatial scales.

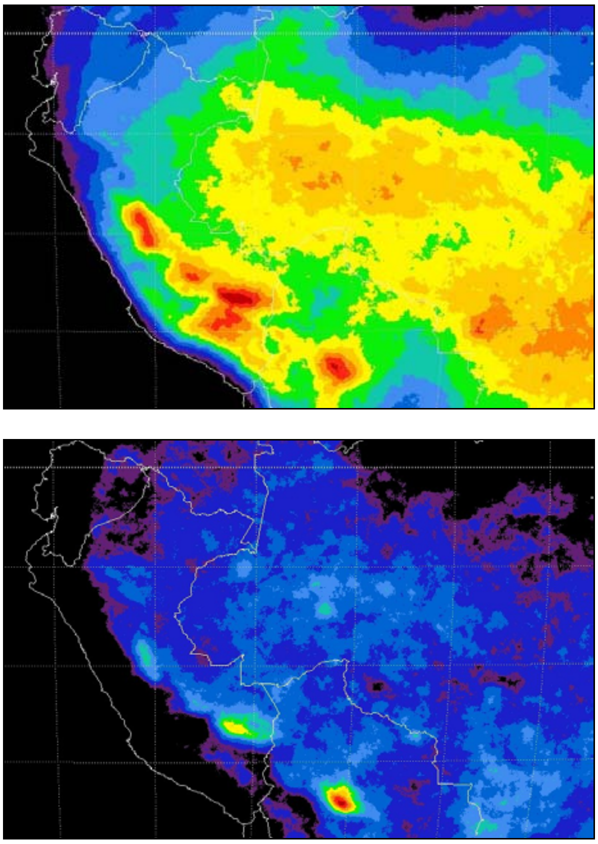

Fig. 1. Frequency of clouds colder than -38˚C (above) and -65˚C(below), averaged over the six months of December-February for the years 2004-5 (Southern Hemisphere summer). Red is highest frequency, black (zero) lowest. Note the small geographical extent of the maxima.

We have used GOES visible and IR imagery at 1 km and 4 km pixel (nadir) scales to generate composites of cloudiness over different regions. This imagery has been downloaded from the GOES Project Science website (http://goes.gsfc.nasa.gov/). In addition, we have used the MODIS imagery that is available from the MODIS Rapid Response Website (http://rapidfire.sci.gsfc.nasa.gov/subsets/). The latter site provides navigated imagery for selected sectors around the globe with a focus on fire detection. However, the website provides a convenient source for quickly accessing some MODIS products that we have used to evaluate the utility of this imagery for cloud mapping.

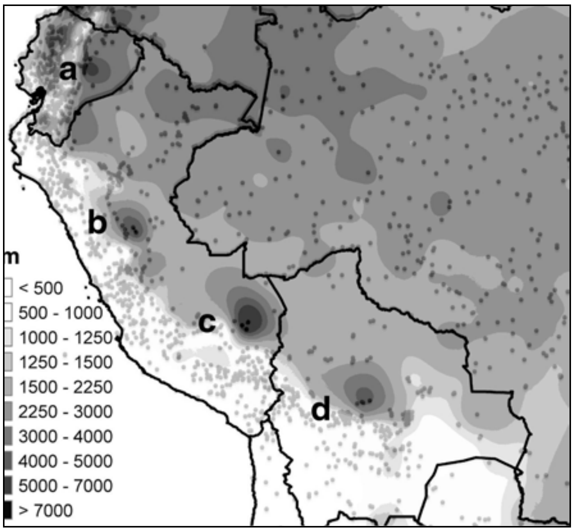

Fig. 2. Annual rainfall from WorldClim data base. Locations of raingauges entering the analysis are shown. The maxima in rainfall on the Andean east slopes is not well-defined because of a lack of raingages.

GOES imagery composites

Both visible and IR GOES imagery have been used to develop cloudiness climatologies for many different studies. Following procedures used in previous studies, we have produced cloud frequency climatologies for different temperature thresholds (Fig. 1). Heavy rainfall rates, associated with deep convective storms, are frequent only in relatively small areas. During the Dec-Feb period the most frequent deep convection occurs over the piedmont region of the Chapare in Bolivia. The IR-based estimates of cold cloud frequencies provide realistic patterns that approximately correspond to the observed rainfall climatology based on in-situ raingauge data (Fig. 2). However, quantitative agreement is not expected in the region along the eastern slopes of the Andes, since rain falls from both shallow and deep convection. Also note that in Figure 2 the rainfall analysis is strongly affected by the distribution of reporting sites; these sites are clearly insufficient to define the spatial structure of the maxima observed along the eastern side of the Andes.

GOES infrared imagery, with 30 min temporal resolution, has the advantage of describing the diurnal cycle of cloudiness. However, it has somewhat limited spatial resolution. Visible imagery pixels, at 1 km, are better than IR imagery (4 km) for identifying the relationship between cloudiness and topography. For example, an average of all GOES visible imagery at 1745 UTC (~ mid-day), for a three-month period (Dec-Feb 2004-5) shows that the cloudiness is strongly modulated by the canyons along the eastern slopes of the Andes in Bolivia (Fig. 3). The canyons are clearly a minimum of cloudiness at this time of day.

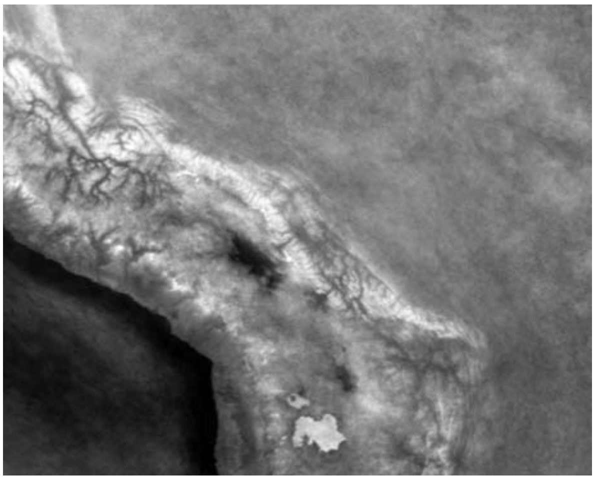

Fig. 3. Average of December-February GOES visible images at 1745 UTC for the year 2004-5. Note that Lake Titicaca is dark (minimum cloudiness), most canyons are dark (little cloudiness). Other features include the large and highly reflective Salar de Uyuni (dry lake) near the bottom, and the region of less stratocumulus along and off the coast of Peru and Chile.

MODIS imagery composites

MODIS imagery, using both TERRA and AQUA satellites, provides only twice-daily daytime coverage, but has the advantage of up to 250 m pixel size at nadir. For highest resolution mapping of potential cloud forest environments we have used the MODIS imagery, despite its poor sampling frequency. One can argue that daytime cloudiness is the most important for defining cloud forest distribution, since evapotranspiration is low at night, and cloudiness at night is not critical to maintaining a moist environment. However, mid-day cloudiness is necessary for keeping solar radiation (and thus evaporation) to a minimum. The Aqua satellite overpass time is near 1340 LT, so that maximum cloudiness at this time ensures low mid-day solar radiation. We have averaged the Terra (~ 1040 LT) with the Aqua imagery (~ 1340 LT) to obtain cloudiness images that represent daytime cloudiness to a fair degree. With the appropriate comparisons with GOES imagery it should be possible to quantitatively improve this estimate of visible cloudiness; we have not done this.

Figure 4 shows composites of 60 Terra and 60 Aqua images from both the ~ 1440 and ~ 1740 UTC overpasses of Bolivia for the year 2004-5. While most major features are evident in both of

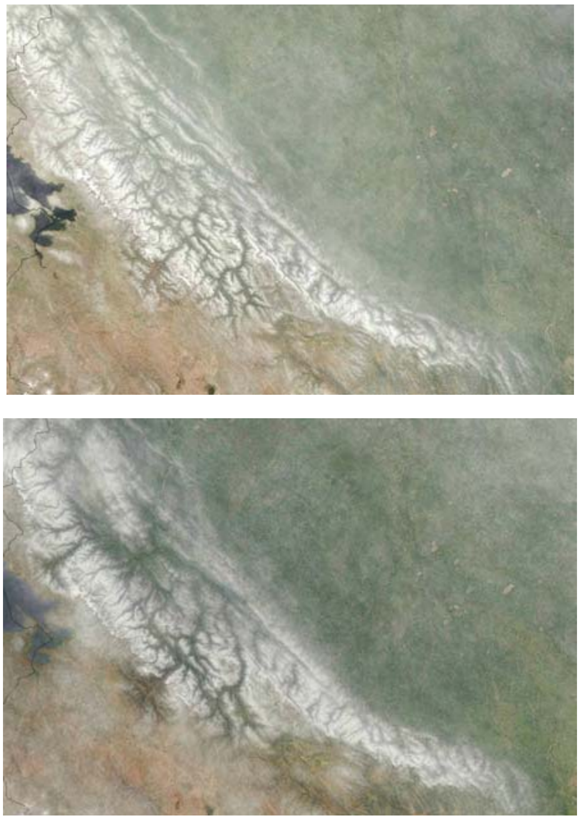

Fig. 4. Terra composite (above) (~1440 UTC) and Aqua composite (below) (~1740 UTC). Each composite used 60 images. Note the more diffuse nature of cloudiness in Aqua composite.

the composites the Terra composite shows “sharper” cloudiness features, in that the cloudiness is more closely associated with the topography. This is likely associated with the deeper boundary layer at ~ 1740 UTC (and thus less closely tied to topographic features) and the more advanced evolution of the slope circulations at this time of day. The major canyon features are actually more evident at ~ 1740 UTC, with subsidence over the canyons resulting in more cloud-free conditions as the day progresses.

The Aqua composite in Figure 4 agrees very well with the GOES composite at nearly the same time (Fig. 3). There is more detail evident in the MODIS composite, due to both the smaller pixel size and the better navigation of the pixels, which may not be evident on the images presented here but is impressive on the original 250m resolution MODIS images.

Averaging the Terra and Aqua composites shown in Figure 4 results in a slightly smoother, and more representative, daytime cloudiness image (Figure 5). This image can be used to compare with digital terrain elevation heights to estimate the likelihood that cloud forest would be present in any given region. However, this actually is not a simple task, since it is actually the cloud base height that is needed rather than the visible reflectivity, which is what is apparent from Figs 4-5. The highly reflective regions could be due to high cirrus, ground-hugging fog, or even a land surface feature like a salt flat. Also, a difference in cloud base height of 500 meters could change some cloud forest distributions significantly. Thus, we stress that Figures 4-5 are very suggestive of the distribution of potential cloud forest, but considerably more work would be needed to improve the product. Having said this, we think that many ecologists, botanists, land use planners, and others needing to know *now* something better about the distribution of cloud forests will find such simple images useful.

We should mention that for the region shown in Figs 4-5, the averaging interval was not critical to showing the detailed patterns of cloudiness. Even an average of as few as 5 images would begin to show the main cloudiness features associated with the major canyons and ridges along the eastern Andean slopes. The differences between averages of 30 images selected randomly is almost undetectable. Of course, seasonal and interannual variability of the cloud amount could vary, but the relative variability of cloudiness on the scale of the topography appears steady. This might not be true for other regions of the world.

Fig. 5. The average of the two images shown in Figure 4. Some enhancements have been made (contrast and saturation changes). Snow (bright white) on higher peaks is evident north, east, and southeast of Lake Titicaca, and on a few volcanic peaks near Chilean-Bolivian border. Everywhere else the white areas reflect cloudiness.

Other uses of interest

We have begun to evaluate the MODIS imagery for describing vegetation gradients elsewhere in the tropics, where an existing explanation based on conventional climatological information seems inadequate. The same imagery shown in Fig 4-5 has been useful for depicting the dry valleys of eastern Bolivia, which are host to many endemic species that are restricted by the unique microclimates produced by these valleys. Imagery at relatively coarse resolution (for example 30 km spatial averages from ISCCP) are not sufficient to describe these topographically-induced gradients in cloudiness. Conventional climatological data is even more limited.

We have generated composites for many of the sectors routinely available on the MODIS rapid response website noted in Section 2, and these are providing composites that can be of considerable interest to both non-meteorologists and to climate researchers. Figures 6-8 show what can be done with even short data records. Although these composites are made from less than 2 years of imagery (actually just selected months within a 2-year window), they appear to reflect longer-term average conditions, in that the vegetation patterns reflect the cloudiness distribution to a high degree.

Fig. 6. The region of far southern Venezuela and extreme northern Brazil (centered around 3˚N, 63˚W). The cloudiness is a maximum over higher peaks and the edges of the Tepui's – elevated sandstone plateaus Cloudiness is clearly a maximum at the edges of these plateaus (rather than on top), contrasting with normal peaks, where cloudiness is more closely centered about the peak. Distinctly less cloudiness (darker green areas) is evident between the higher terrain features. Rivers are darker – less cumulus development over the cooler surface.

Fig. 7. Costa Rica and part of southern Nicaragua and western Panama. This composite is based on images from the dry season, Jan-March, 2004-5. During this period the trade winds are relatively strong from the east and the Pacific side of Central America is relatively cloud-free. The very sharp boundary of the clouds over northern Costa Rica is apparent, as is the effect of canyons (valleys have less cloudiness) on the cloud cover over southeastern Costa Rica. High cloud amounts on the isolated volcanic peaks in Lake Nicaragua are also evident.

Fig. 8. MODIS composite (both Terra and Aqua images) over central Mexico during the June-September wet season. Note the higher cloud frequencies over the high terrain, with the dissected topography apparent. Major valleys are relatively cloud-free.

Concluding remarks

We have used satellite imagery to aid in the identification and mapping of vegetation types, focusing on the cloud forests and dry valleys of eastern Bolivia. The MODIS imagery provides high spatial resolution imagery that can be used to describe where the cloudiness is a maximum, which can in turn be used as an aid in mapping cloud forests. While our procedures are in some ways simplistic and have limitations, such as the inability to determine the cloud base height, the images themselves should stimulate interest in the atmospheric processes that produce such cloud distributions. Our composites clearly show the very strong role of topography in modulating the cloudiness, and we hope they will serve to stimulate our intended audience (botanists, zoologists, ecologists, biogeographers, etc.) to use these sources of data for their work. *To this end we note that often there is a disjunction between atmospheric scientists, struggling to further quantify a type of product (here a high spatial resolution cloud-base climatology) to the satisfaction of other atmospheric scientists, and a large pool of potentially interested researchers in other disciplines who would often gain much from access to even tentative work, which could be lacking to them.*

Aspects of the SALLJEX-related (and other) cloud climatologies can be found at our base web site: http://www.nssl.noaa.gov/projects/pacs

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