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Observations of orographic Cloud Base Heights from satellite and in-situ measurements at the Monteverde Cloud Mist Forest Reserve, Costa Rica

Jian Zeng[1], Qingyuan Han[1], Salvi Asefi[1], Ronald M. Welch[1], Robert O. Lawton[2], Udaysankar S. Nair[1], and Deepak K. Ray3

[1]Department of Atmospheric Science,
National Space Science and Technology Center
University of Alabama in Huntsville,
Huntsville, AL 35806

[2]Department of Biological Sciences
University of Alabama in Huntsville
Huntsville, AL 35899

[3]Department of Forestry and Natural Resources
Purdue University

Abstract

Tropical montane cloud mist forests are among the most biologically rich and diverse ecosystems, providing habitats for many of the world's endangered species. These biodiversity hotspots occupy approximately 0.4% of the Earth's land surface but support 20% and 16% of the Earth's plants and vertebrates, respectively. Survival of these habitats depends strongly on regular and frequent immersion in orographic clouds. However, regional land use change and global climate change has lead to increasing cloud base heights at some of these forest locations. At the Monteverde Cloud Mist Forest Reserve in Costa Rica, the bases of the clouds have shifted upslope, leading to anuran population crashes, an increase in the upper elevation of bird ranges on the Pacific slope, and longer dry season mist-free intervals.

Satellite remote sensing techniques have been developed to determine the orographic cloud base heights; these are tested for the dry season month of March 2003 over the Monteverde cloud forests.
The approach derives MODIS cloud top pressures and then converts them to cloud top heights using geopotential height profiles. The NCAR Land Use and Cloud Interaction Experiment (LUCIE), consisting of paired
mobile radiosonde systems deployed in Costa Rica, provided the means for validating the retrievals. Results show that the four MODIS CO_2 slicing channels do not provide sufficiently accurate cloud top height values, although some of the differences are due to a mismatch in the observational periods. An alternative approach using simulated geopotential height profiles from the CSU Regional Atmospheric Modeling System (RAMS) initialized with the LUCIE soundings provided superior results..

Cloud thicknesses are estimated using three different approaches of: 1) constant liquid water content (CLWC); 2) an empirical relationship; and 3) an adiabatic model. The CLWC approach provided the most

* Corresponding author address: Jian Zeng, Univ. of Alabama in Huntsville, Dept. of Atmospheric Science, 320 Sparkman Dr., Huntsville, AL, 35805;
email: Jian.Zeng@noaa.gov

consistent results. The cloud base heights are computed from subtracting cloud thickness from cloud top height. Orographic cloud base heights derived from the combined MODIS/RAMS approach were then compared with values observed at the study sites. Differences between the observed and remotely sensed values were on the order of 200m. The results suggest that it is possible to monitor global cloud mist forest cloud base heights using the combination of MODIS satellite imagery with model simulations. Further investigations using the Atmospheric Infrared Sounder (AIRS) is now being carried out to develop methods that are wholly dependent on satellite observations.

1. INTRODUCTION

Tropical montane cloud mist forests (TMCMFs) are defined as “forests that are frequently covered in cloud or mist”. They are biologically rich and diverse, providing habitats for many of the world’s endangered species. These biodiversity hotspots occupy approximately 0.4% of the Earth’s land surface but support 20% and 16% of the Earth’s plants and vertebrates, respectively. However, these TMCMFs are among the most threatened ecosystems in the world, in which large stocks of diverse endemic species are rapidly losing their habitats. At the Monteverde Cloud Mist Forest Reserve (MCMFR) in Costa Rica, the cloud base has shifted upslope (Pounds et al. 1999); which has led to anuran population crashes, an increase in the upper elevation of bird ranges on the Pacific slope, and longer dry season mist-free intervals. The reason for the raised cloud base height is attributed to climate feedbacks trigged by the deforestation of the nearby Caribbean lowlands (Lawton et al. 2001; Nair et al. 2003). Monitoring orographic cloud changes using the combination of satellite data and model simulations is the most efficient approach to improve our understanding of the mechanism behind the cloud base height shift that endangers the TMCMFs (Lawton et al. 2001, Nair et al. 2003).

2. DATA

Four of the Moderate Resolution Imaging Spectroradiometer (MODIS) CO_2 absorption bands and the 11 µm window channel have been applied to retrieve cloud top pressure of orographic clouds over the MCMFR. The retrieval of cloud top heights from cloud top pressures requires geopotential height profiles which are obtained on 5 x 5 pixel arrays using the CO_2 slicing technique.

The National Center for Atmospheric Research (NCAR) GPS/Loran Atmospheric Sounding System was used to report temperature, humidity and wind measurements at every 5 hPa interval for the time period of 1-20 March 2003.

Cloud base heights were determined from photographs taken at the Monteverde Cloud Mist Forest Reserve. Cloud photos in Monteverde were taken twice a day at around 0600 and 1200 LT in March 2003. Based upon detailed knowledge of the local region from 25 years of study, cloud base heights were determined from the photographs with an estimated accuracy of 100 m.

Fog liquid water contents were measured by Schmid (2004) in San Gerardo (10.3564ºN, 84.8044ºW, 1550m elevation), Costa Rica from February 20th to May 15th 2003 using the eddy covariance method. Visibility, LWC, and effective droplet size were recorded every 30 seconds. The mean LWC for visibility less than 200m was 255 mg m^{-3} with a standard deviation of 100 mg m^{-3}.

3. METHODOLOGY

Cloud top heights are determined from cloud top pressure and geopotential height profiles. Cloud base height is determined from cloud top height and retrieved geometrical thickness H. Cloud base height Z_b is obtained by subtracting cloud physical thickness H from cloud top height Z_t. If the water cloud layer is assumed vertically homogenous with constant LWC, the cloud geometrical thickness H can the be expressed as

$$H = \frac{LWP}{LWC} = \frac{2}{3}\frac{r_e \tau}{LWC} ,$$

where effective radius (r_e) and cloud optical thickness (τ) are obtained from MODIS retrievals and constant liquid water content (LWC) is obtained from the surface measurements.

Two other methods for estimating cloud thickness also were examined. The Empirical Relationship method is discussed in the Algorithm Theoretical Basis Document (ATBD) of cloud optical property retrievals for the Clouds and the Earth's Radiant Energy System (CERES) by Minnis et al. (1997). The cloud thickness H is computed using empirical formulas. The Adiabatic Model proposed by Brenguier et al. (2000) is based on the assumption of adiabatic evolution in a closed convective cloud system. Ideally, the water vapor mixing ration reaches saturation at cloud base. During convective ascending, the air temperature decreases, and the adiabatic saturation mixing ratio decreases. The adiabatic liquid water content (LWC_{ad}) is defined as the difference between the saturation water vapor mixing ratio at cloud base and the saturation water vapor mixing ratio at cloud level h above cloud base. Therefore, LWC_{ad} increases with altitude and this relationship is nearly linear.

3.1. RAMS SIMULATION

The present study utilizes rawinsonde measurements, in situ soil moisture observations, land use and vegetation characteristics and other physiographical datasets for initializing the Regional Atmospheric Modeling System (RAMS) simulations. Initial atmospheric conditions and lateral boundary conditions for RAMS simulations were analyzed from rawinsonde data obtained during the Land Use Cloud Interaction Experiment (LUCIE) and the National Center for Environmental Prediction (NCEP) reanalysis data. The RAMS simulations provide an alternative approach for determining geopotential height profiles.

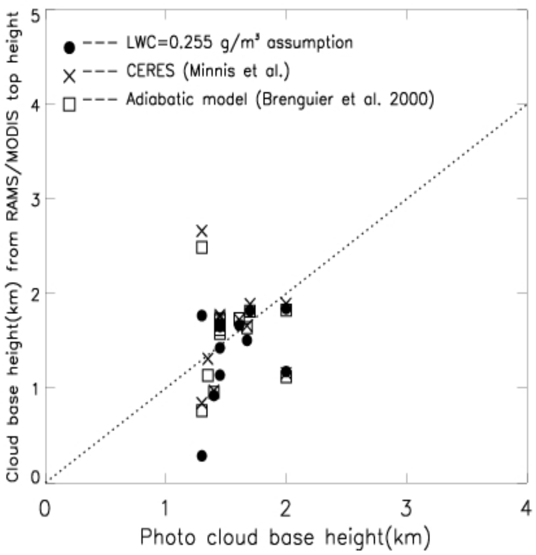
The United States Geological Survey 1 km resolution topography data was used to specify terrain in the RAMS simulations. Global land use categorization at 1 km spatial resolution, developed by the University of Maryland using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, was used to specify the type of vegetation in the RAMS simulations. The Leaf Area Index (LAI), a crucial input characteristic for the vegetation parameterization within RAMS, is also specified using MODIS-derived LAI values. A Food and Agricultural Organization (FAO)-based 1^o x 1^o resolution soils database was utilized for specifying the soil type in the study area.

4. RESULTS

Comparisons of the MODIS-derived cloud top heights with the LUCIE soundings were made. It was found that MODIS-derived cloud top heights were on the order of 1km higher than those found from the LUCIE soundings. Much of the problem seems to be the result of the poor vertical resolution of the MODIS-derived geopotential heights. In addition, the CO_2 slicing technique is very limited for low-level cloud retrievals such as found at Monteverde, since the weighting functions are insensitive to those levels. The RAMS model provides much improved geopotential height profiles over the mountaineous regions. The RMS error of geopotential height between RAMS and MODIS can range from 700m to 1400m.

Cloud base heights estimated from the RAMS/MODIS approach at Monteverde and compared to measured values in photographs are shown in the figure below. Cloud base heights are generated using each of the CLWC, ER and AM cloud thickness computations. The three liquid water content approaches provide similar results in most cases. However, the CLWC approach provides the most consistent retrievals.

Cloud base height differences on the order of 200m result between the photographs and the RAMS/MODIS retrievals. The results suggest that it may be possible to monitor global cloud mist forest cloud base heights using the combination of satellite imagery with model simulations.



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