A Study of Probability of Clear Line of Sight through Single-Layer Cumulus Cloud Fields in the Tropical Western Pacific

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Introduction

The effective cloud fraction, N_e, has been suggested to account for the three dimensional properties of cumulus cloud fields by many researchers (Ellingson 1982; Harshvardhan and Weinman 1982; Naber and Weinman 1984; Killen and Ellingson 1994; Han and Ellingson 1999). N_e is the flat plate absolute cloud fraction that generates the same flux as a given broken cloud field after accounting for the three dimensional properties of the cloud field. An extension of this concept is the Probability of Clear Line of Sight (PCLoS).

PCLoS is defined as the probability that a line of sight can pass through a cloud field without intersecting a cloud. For a given random cloud field PCLoS is a decreasing function of zenith angle, and the rate of the decrease is dependent upon the size and shape of the clouds. Large clouds with high aspect ratios will cause the PCLoS to decrease quickly with increasing zenith angle. Theoretical attempts have been made to model PCLoS (Kauth and Penquite 1967; Ellingson 1982; Harshvardhan and Weinman 1982). However, few have been able to test these models with experimental data. Lund (1966), Lund and Shanklin (1972; 1973), and Lund and Grantham (1980) have studied PCLoS using sunshine data, and tested results using sky photographs. However, these analyses resulted in climatological averages and do not give information about individual cloud fields. This study will investigate the three dimensional properties and associated PCLoS of individual single-layer cumulus cloud fields.

PCLoS Models

Kauth and Penquite (1967) derive an expression for PCLoS using randomly placed ellipsoids. This approach may be extended to many other shapes: isosceles triangle, right cylinder, and hemisphere. The models tested here apply a Poisson distribution for the cloud spacing, and require a maximum of two input parameters: aspect ratio β and absolute cloud fraction N. All of these models have a similar functional form: $P(\theta)=(1-N)^{f(\theta)}$. The term $f(\theta)$ is dependent upon the assumed shape of the individual clouds. Examples of $f(\theta)$ are given in Table 1. Figure 1 shows example curves of each model for a cloud fraction of $N=0.3$ and a varying aspect ratio.

Table 1. Summary of PCLoS models and input parameters.

Model	f(θ)	Input Parameters
Ellipsoid (Kauth and Penquite 1967)	$\sqrt{1+\beta^2\tan^2\theta}$	N, β
Semi-Ellipse (Kauth and Penquite 1967)	$\frac{1}{2}\left(\sqrt{1+4\beta^2\tan^2\theta}+1\right)$	N, β
Right Cylinder (Ellingson 1982)	$1+\frac{4}{\pi}\beta\tan\theta$	N, β
Isosceles Trapeziod (Ma 2004)	$1+\beta(\tan\theta-\tan\eta)$	N, β,η=0.74
Hemisphere (Ma 2004)	$\frac{1}{2}\left(\sqrt{1+\tan^2\theta}+1\right)$	N, β=0.5

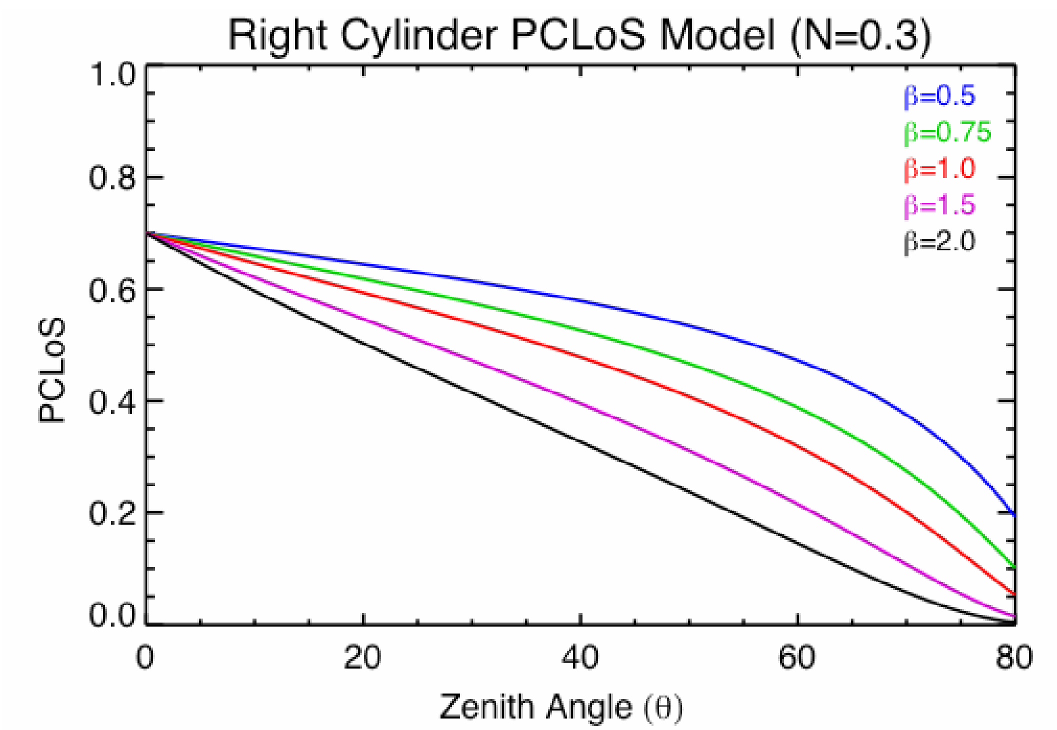

Figure 1. Model PCLoS examples assuming N=0.3 and varying β.

Extraction of Cloud Field Statistics from ARM Data

Each PCLoS model requires β and/or N as input parameters. Atmospheric Radiation Measurement (ARM) Program instruments at the Tropical Western Pacific (TWP) site are used to obtain these quantities following the sampling strategy of Ma (2004). To extract this data, frozen turbulence is assumed. This assumption is critical to the calculation of cloud field statistics. The premise of this assumption considers the statistical properties of a cloud field to remain approximately constant. Considering this assumption, the cloud field properties are measured by allowing the cloud field to be advected over the observation location. Therefore, we consider the time average to be the same as measuring an instantaneous spatial average.

Using frozen turbulence, N is defined as $\frac{1}{M}\sum_{n}^{M} I_n$, where I_n is a binary indicator array (*0=clear and 1=cloud*) and n is a counter stepped from 1 to the total number of observations, M. Ceilometer data are used to create the binary array. The sampling rate of the ceilometer is 15 seconds, which is the highest sampling rate available at TWP sites for this study. This finite sampling time leads to an imposed cloud chord length limit by assuming frozen turbulence: $15*u$, where u is the wind speed in ms^{-1} at cloud base obtained from radiosonde data and *15* refers to the sampling time. The cloud chord length is calculated as $L_{cloud}=u*B$, where B is the number of consecutive cloud observations.

Cloud boundaries are obtained using Active Remotely Sensed Cloud Locations (ARSCL). ARSCL is an algorithm developed by Clothiaux et al. (2000; 2001) to determine cloud boundaries using microwave cloud radar, ceilometer, and micropulse lidar. Here ARSCL is used to determine cloud thickness. ARSCL thickness and ceilometer cloud chord lengths are combined to determine β ($\beta=T/L$, where T is thickness and L is chord length).

Observed PCLoS is calculated using the whole sky imager (WSI) cloud mask. The sampling rate of the WSI is 10 minutes, which provides 13 cloud masks for each case. The PCLoS is calculated by integrating around 3^{o} zenith angle circles from 0^{o} to 90^{o} for a two-hour period.

A case is defined as a two-hour interval of single-layer cumulus. The cases are determined using the instruments identified in Table 2.

Table 2. List of instruments used to extract cloud field parameters.

Instrument	Observation(s)	Parameter(s) Extracted
Ceilometer	Cloud Base Height	Cloud Base Height, Cloud Base Length, N
ARSCL	Cloud Boundaries	Cloud Thickness
Radiosonde	Wind Speed	Cloud Base Length
Whole Sky Imager	Cloud Detection Array	PCLoS, N, N_e
Pyrgeometer	Longwave Downwelling Flux	N_e

Model PCLoS vs. WSI PCLoS

The PCLoS measured from the WSI will be biased based upon the value of *N*. In order to compare all cloud fields independent of *N*, the values are normalized using $f(\theta)=lnP(\theta)/ln(1\text{-}N)$.

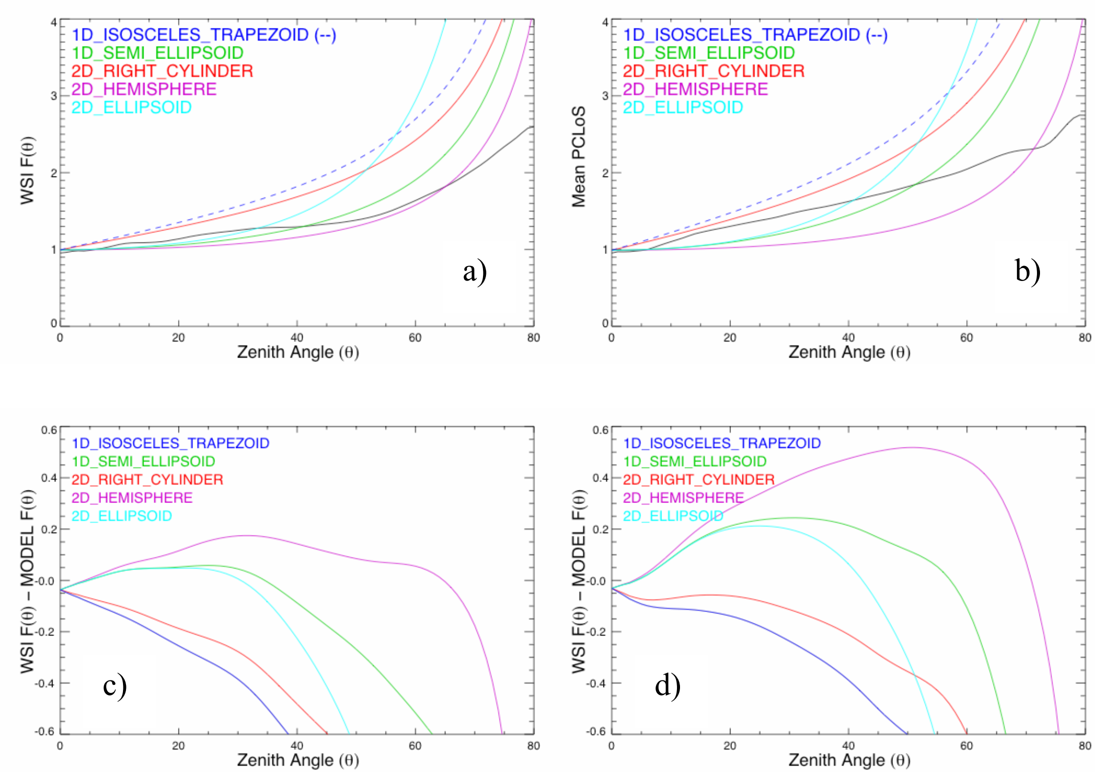

Figure 2. The results are shown for each site examine with the TWP locale: a) Manus *f(θ),* b) Manus differences WSI – Model, c) Nauru *f(θ)*, and d) Nauru WSI – Model.

Summary

The PCLoS through and single-layer cumulus cloud fields is investigated at the ARM Program's TWP locale. Cloud field statistics were retrieved using ARM instruments listed in Table 2 using a sampling strategy developed by Ma (2004). The results suggest that modeling broken cumulus cloud fields at TWP with Poisson distributed semi-ellipses and hemisphere result in the least error. The analysis included a normalization of the data in order to account for the biasing due to different cloud fractions. This allowed a comparison between modeled and observed *f(θ)*. Ma (2004) at the ARM Southern Great Plains locale has done an investigation of PCLoS models. The results at Southern Great Plains suggest that modeling clouds as Poisson distributed hemispheres (constant $\beta=0.5$) yields the least error in the PCLoS, suggesting that clouds at TWP have larger aspect ratios than clouds at Southern Great Plains.

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