Probability of Cloud-Free-Line-of-Sight (PCFLOS) Derived From CloudSat and CALIPSO Cloud Observations

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Abstract

The advent of cloud measurements from the CloudSat Mission's active sensor, the 94 GHz Cloud Profiling Radar (CPR) and the CALIPSO mission's CALIOP Lidar have given us the opportunity to view clouds from a new perspective. This study uses the concept of Cloud-Free Line-of-Sight (CFLOS) and the probability of a CFLOS (PCFLOS) to demonstrate how CloudSat and CALIPSO cloud observations provide an exciting new window into the "off-nadir" analysis of cloud fields.

CFLOS is normally defined as the ability to see from the ground to space, or from the viewers location to the ground. Numerous CFLOS global Climatologies, termed the Probability of CFLOS (PCFLOS) have been derived from satellite observations of cloud. All have inherent limitations due to the fact that they rely on data from passive meteorological sensors which provide a reasonable measurement of the cloud tops, but do not provide information about cloud bases or multi-layered clouds below the highest opaque cloud layer. CloudSat and CALIPSO provide, for the first time from space, a direct measurement of the vertical profile of cloud – including cloud bases and the elusive "hidden layers". More importantly, for this study, they also provide a direct measurement of the slant-range (off-nadir) CFLOS along the direction of flight of each spacecraft.

Four and a half years of CloudSat and CALIPSO data are used to generate Cloud Free Line-of-Sight statistics at 20 vertical levels and 10-degree view angle increments from the satellite perspective.

BACKGROUND - STATEMENT OF THE PROBLEM

Cloud-Free Line of Sight (CFLOS) and the related PCFLOS, (Probability of a Cloud-Free Line of Sight), refer to the ability to obtain a visible line of sight through the atmosphere … unimpeded by Cloud. An application of PCFLOS is for pilots to determine the altitude where they have the highest probability of seeing the ground, without flying too low over rough terrain. The DoD uses PCFLOS to determine the safest altitude to fly while still maintaining a view of ground targets or for choosing the optimum altitude for aerial refueling. PCFLOS can also be used to select the optimum solar energy sites or ground sites for laser communication systems.

Early work by the authors centered on the use of infrared imagery from geostationary weather satellites to augment the limited surface observation based PCFLOS databases. The limitations of surface observations, being well documented, have not diminished – and the subsequent limitations of passive satellite derived CFLOS have also persisted. CFLOS from a passive (visible, infrared, or microwave) satellite sensor's perspective can only be determined based on the highest cloud layer. CFLOS at a level underneath the highest layers cannot be determined directly (fig. 1-3).
CloudSat, for the first time, provides a direct measurement of layered cloud bases and tops that allow us to determine CFLOS from levels below the highest cloud layers, thus, filling the missing gap between surface observations and passive IR satellite measurements. Figures 1-3 illustrate the limitation of calculating CFLOS due to the complication imposed by multilayered clouds beneath an opaque upper level cloud and a solution to the deficiencies of historical CFLOS products.

Figure 3 shows another example where the not only the vertical distribution of cloud is significant, but also the horizontal distribution of underlying clouds. Traditional CFLOS tables refer to a nadir viewing perspective, while this study expands that view to add an off-nadir perspective which can have a wide range of applications for radiative transfer studies as well.

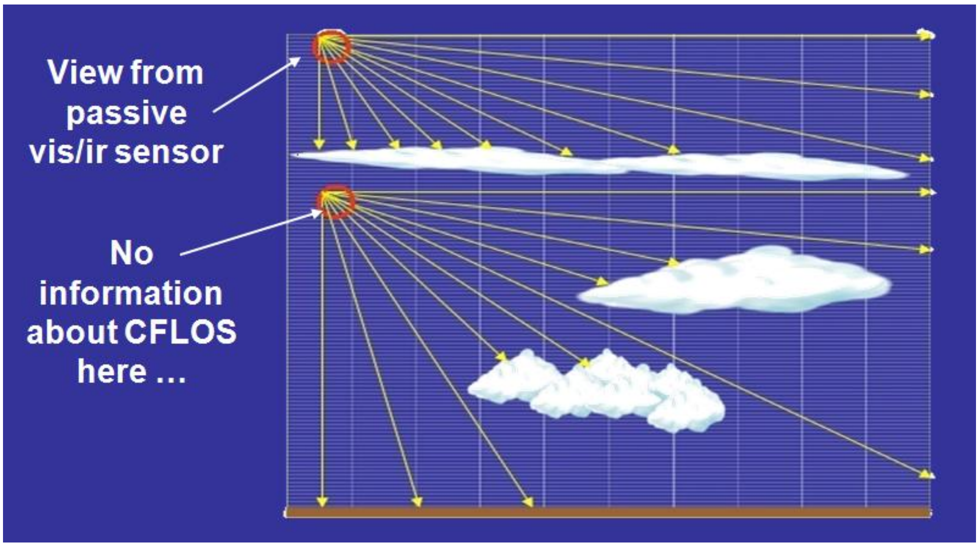

Figure 1. Diagram showing the deficiency of CFLOS calculation from space when an undercast layer of cloud is present.

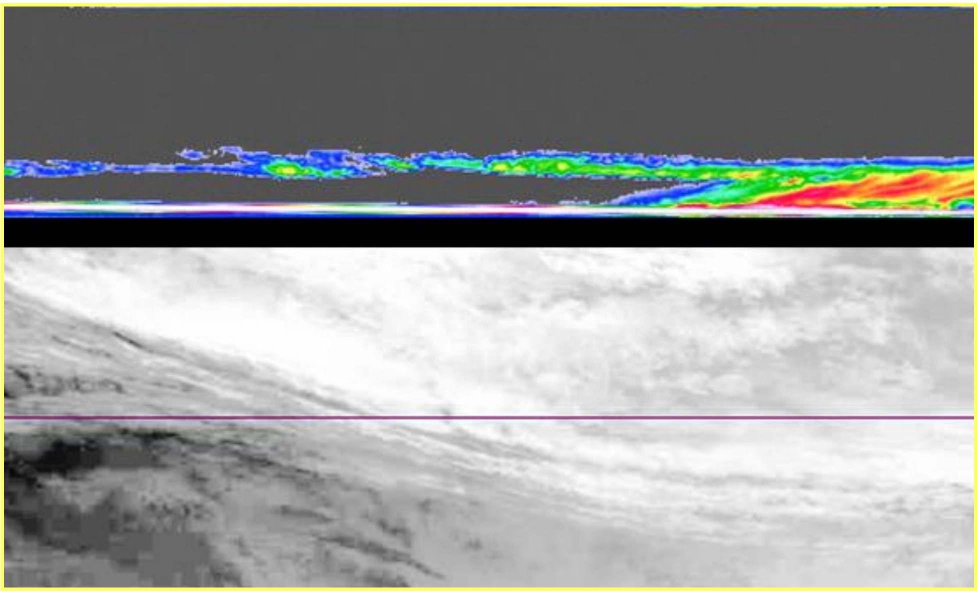

Figure 2. MODIS infrared imagery is shown below the corresponding CloudSat image (purple line shows the CloudSat track). An analysis of the MODIS cloud field cannot determine whether there is a Cloud-Free Line of Sight beneath the cloud mass, while the CloudSat image clearly shows a cloud-free layer (on the left) below the opaque cloud top.

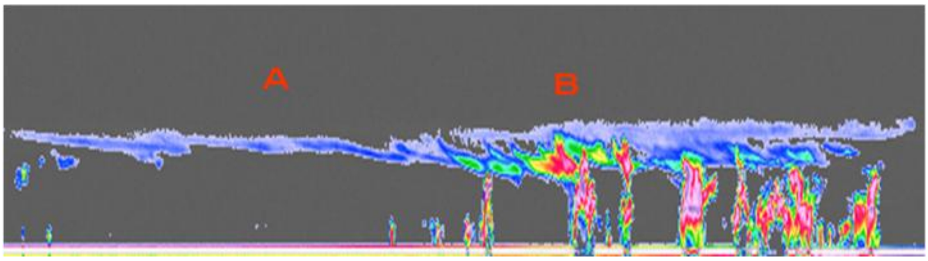

Figure 3. This CloudSat image shows an opaque cloud above a mixture of cloud and cloud-free atmosphere. The cloud at "B" hides the fact that there is no CFLOS at levels below the cloud top, while at "A" it hides a high probability of a CFLOS below the upper cloud layer. Note also the horizontal distribution of cloud in the underlying cloud field.

RESEARCH OBJECTIVE

CloudSat and CALIPSO cloud mask products will be used to generate CFLOS statistics from varying vertical levels and view angles. CFLOS will be calculated at 20 vertical levels, each approximately 1-km deep, and at nine 10-degree view angle increments from nadir. These CFLOS statistics will then be binned on a 1-degree global grid to product PCFLOS plots for each month of the year.

CloudSat offers a unique solution to the determination of CFLOS from space. By directly measuring opaque cloud bases and tops, we are now able to determine the CFLOS from any location within the CloudSat FOV.

DATA

CloudSat CPR

The CloudSat instrument is a 94-GHz (~3mm wavelength), nadir-pointing, Cloud Profiling Radar (CPR). Figure 3 shows the CloudSat footprint and vertical bin structure, and granule size.

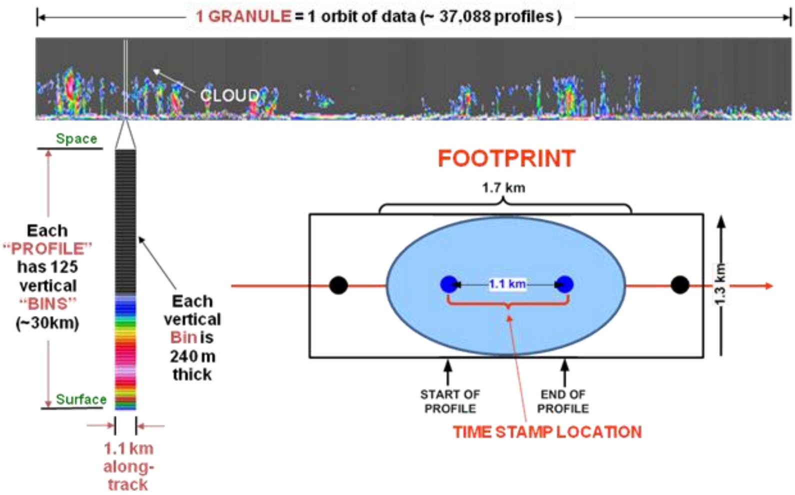

Figure 4. CloudSat footprint, vertical bin structure, and granule size.

CloudSat generates a vertical profile every 160 msec. The vertical resolution of each timing gate is approximatly 500-m. These samples are then binned, by oversampling, to produce 125 240-m bins, to provide a vertical imaging window of 30 km. (Most of the detected clouds will lie in the lower half of this data window, with the upper portion used to calculate the noise floor.) The horizontal footprint of each CloudSat profile is approximately 1.7 km along-track by 1.3 km across-track. In 160-msec, the spacecraft will travel 1.07 km along track – providing the temporal resolution of ~1.1 km between the center of each overlapping profile.

CALIPSO Lidar

The CALIPSO instrument is a dual channel (532 and 1062 nm) near-nadir pointing lidar. It has a vertical resolution of 30 m (< 8 km) and 60 m (< 8 km), with an 80-m instantaneous footprint. The overlap with a CloudSat footprint is shown below.

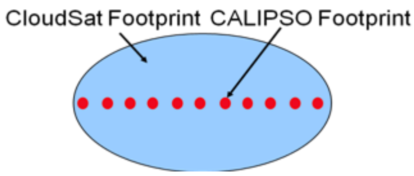

Figure 5. Perspective diagram of CALIPSO footprint overlaying a single CloudSat Footprint.

ADVANTAGES/LIMITATIONS OF BOTH DATA SETS FOR CFLOS CALCULATIONS

CFLOS is generally understood to be based on the attenuation of line-of-sight viewing with the naked eye that is impacted by an intervening opaque cloud. The 3-mm wavelength CloudSat imager will detect the overwhelming majority of opaque clouds that fit within that loose definition, but will miss some thin clouds that may also obscure the ground.

In a similar manner, CALIPSO vertical profiles should provide information about CFLOS … however, the lidar is attenuated rapidly when viewing the atmosphere through optically opaque clouds, so the additional information provided by CALIPSO, in this study, will be to identify the location of thin" cloud above the CloudSat measured cloud top … or the occurance of low level cloud that CloudSat has difficulty with (due to amount of clutter in the layer within 1.5 km of the surface).

Figure 6 shows an example of the CloudSat 2B-GEOPROF-Lidar product which highlights the limitations of both cloud detection instruments.

Combined CloudSat / CALIPSO product (2B-GEOPROF-Lidar)

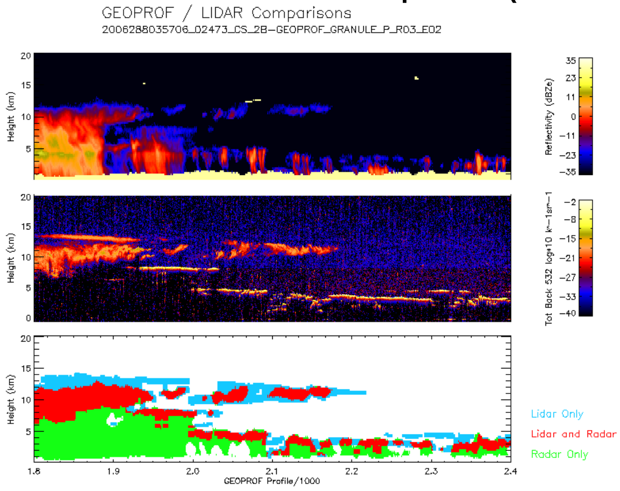

Figure 6. Cloud detection with the CloudSat 2B-GEOPROF-Lidar product which is generated by merging the CloudSat and CALIPSO cloud mask products.

CALCULATING CFLOS AND PCFLOS

CFLOS

CFLOS is determined by looking at 10° intervals from nadir to 90°, at each of 20 vertical levels, to calculate the distance we travel before encountering a cloud. We average 4 CloudSat bins in the vertical (= 4X240m = .96km) for each of our vertical levels. The horizontal distance on our grid is the distance between CloudSat footprints (1.1 km). (For this study we used a distance of 25-km to determine if we have a CFLOS in the off-nadir views)

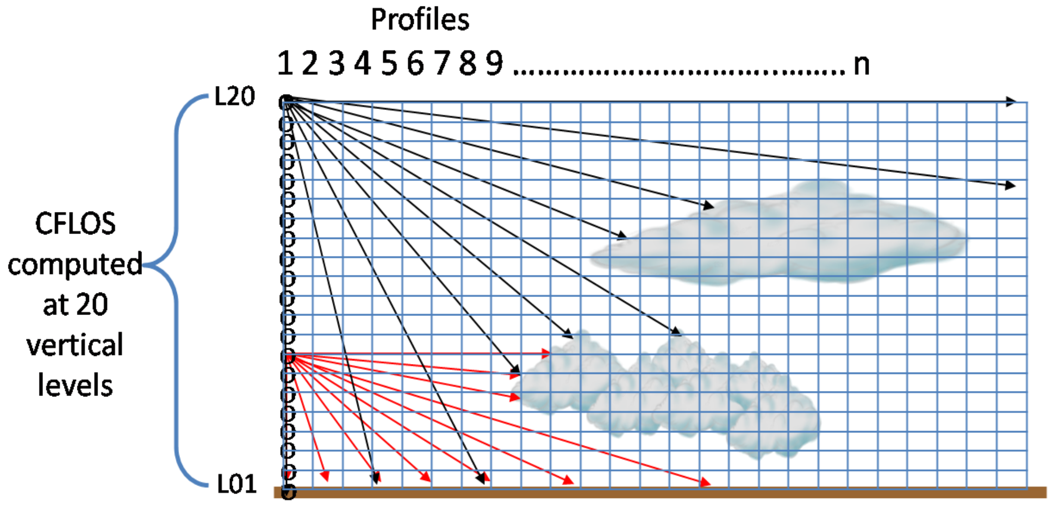

Figure 7. Depiction of the CFLOS view points and viewing angles. Each vertical step is 0.96 km and the horizontal distance is 1.1 km. The vertical step represents the distance of 4 CloudSat vertical bins.

Calculation of "PCFLOS"

CFLOS statistics are gathered over a global 1-degree grid to produce the Probability of a Cloud-Free-Line-of-Sight (PCFLOS). Figure 8 shows an example of a PCFLOS plot from the CloudSat cloud mask product compared with a corresponding MODIS Cloud Fraction plot.

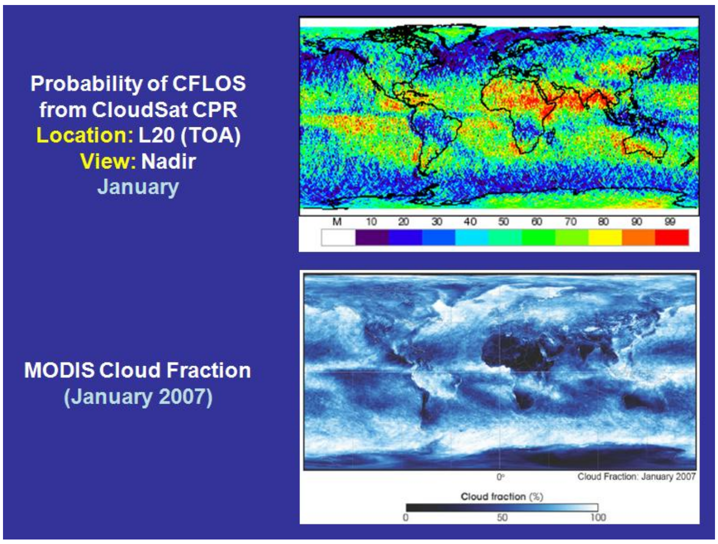

Figure 8. Plot of PCFLOS from CloudSat for January (2007-10) compared with the MODIS Cloud Fraction for January 2007. (Note that 100% cloud fraction is equivalent to 0% PCFLOS)

As noted in the figure 8 caption, these PCFLOS plots are counter intuitive for those who are used to viewing standard "cloud fraction" plots - where a value of 100% represents the highest cloud fraction and 0% represents clear. A value of 100%, in the case of PCFLOS, represents a location with the highest probability of a cloud-free line of sight (a 0% cloud fraction).

Figure 9 shows the impact of adding CALIPSO data to the CFLOS calculation. Now we can see the affect of allowing thin clouds to obscure the cloud-free line-of-sight. The figure on the right represents the cumulative effect of both opaque and thin cloud.

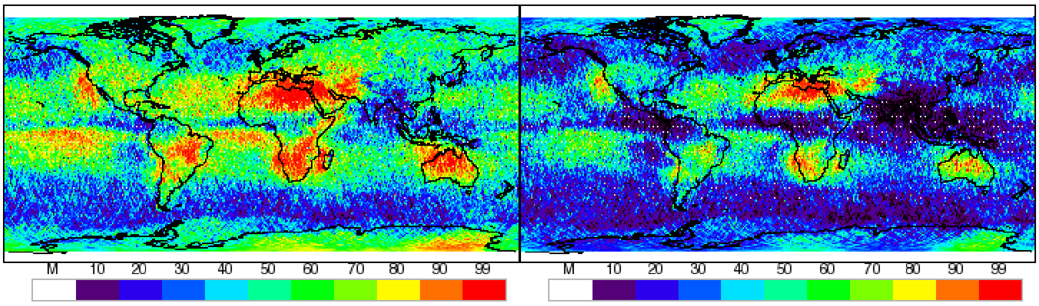

Figure 9. PCFLOS from CloudSat CPR (left) and CALIPSO Lidar (right). Viewing Location is Level 20 (TOA), and Viewing Angle is 0^o (Nadir). Data are for the month of July, 2006-2010.

Additional PCFLOS Examples

Figure 10 shows the predictable effect of holding the view angle constant and varying the height of the view point. Here we see decreasing cloud below the observer as we drop to a lower view point elevation, thus improving the PCFLOS at lower levels. PCFLOS shown is from CloudSat data.

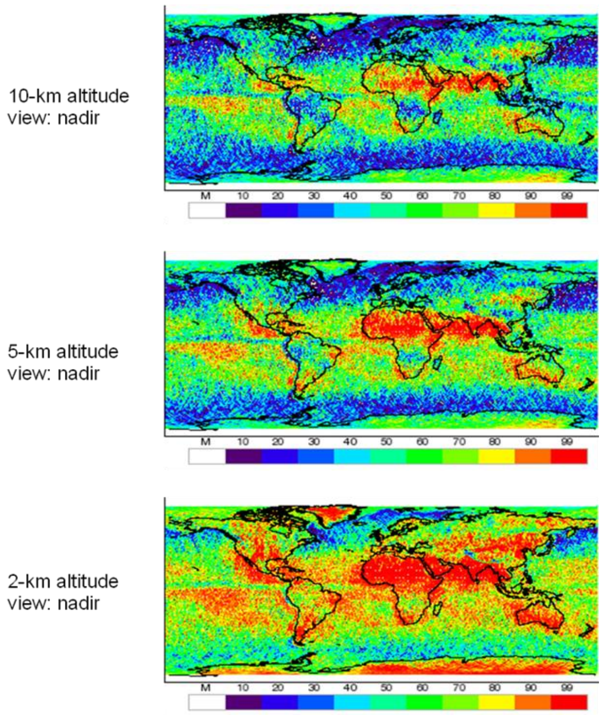

Figure 10. PCFLOS plots with contant view angle (nadir) and varying view height.

Figure 11 shows a new, and more interesting, perspective that is possible from the active sensor data by looking at the change in PCFLOS when we keep the viewing height constant and vary the viewing angle. PCFLOS shown is from CloudSat data.

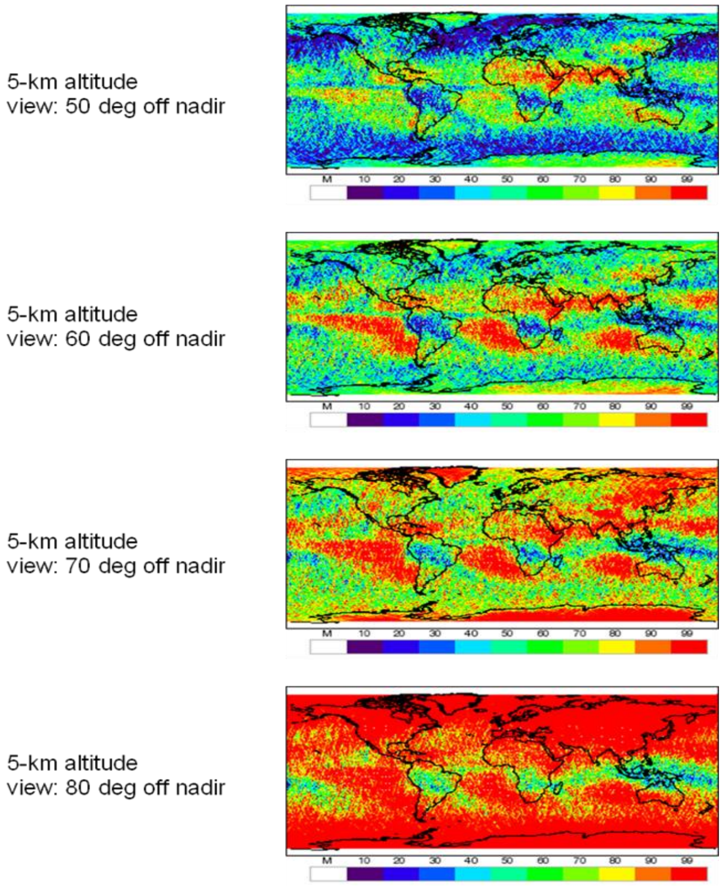

Figure 11. PCFLOS as determined from a fixed elevation of 5-km at varying view angles. As the view angle approaches horizontal, we are seeing the affect of looking between layers of cloud while the view angles approaching nadir are impacted by the clouds beneath our viewing perspective.

COMMENTS - FUTURE WORK

The addition of cloud data from the active CloudSat and CALIPSO instruments has given us the opportunity to take a significant step forward in our attempt to truly identify the 3-dimensional distribution of cloud. To quantify this, our study has shown how the addition of a long-term record of vertical cloud structure from these active sensors should provide a significant improvement to CFLOS calculation from space.

In addition, one can see the potential for using the off-nadir analysis of cloud structure in other research applications. For example, the determination of horizontal liquid or ice water path, or off-nadir radiative fluxes and heating rates. This potential seems especially apparent in regions where cloud-free regions are hidden from view by conventional surface and satellite views. In this light, we are expanding the CFLOS study to look for these “cloud-free vaults” – regions of the atmosphere that are enclosed by cloud – to attempt to quantify the magnitude and frequency of occurrence of these regions.

PCFLOS from these new, active, measurement systems can be used to validate and/or improve existing PCFLOS products from passive space or ground-based observations, or to validate or enhance the generation of cloud or moisture parameters in numerical models.

APPENDIX: Prototype CloudSat/CALIPSO PCFLOS web viewer

Found at: http://www.cloudsat.cira.colostate.edu/pcflos/PCFLOS_prototype.php

This is a prototype product that is generated from CloudSat and CALIPSO cloud mask products (CloudSat 2B-GEOPROF and 2B-GEOPROF-Lidar). CFLOS observations are generated with the following assumptions/background information:

1. View angles are given as the angle displacement from Nadir. For comparison with standard, passive, cloud fraction analyses … one can select the top level and a view angle of 0 (see note 2 below).
2. PCFLOS displays indicate the probability of a cloud-free-line-of-sight. This is the inverse of standard cloud fraction. From the highest level and a view angle of 0 degrees (nadir), a PCFLOS of 30% will be equivalent to a cloud fraction of 70% (0.7).
3. A Cloud-Free-Line-of-Sight is flagged when one can view, along a line of sight of at least 25km, without seeing an intervening cloud. This distance is arbitrary and can easily be modified for specific applications. 25-km was chosen because it is generally considered to be the cloud-free distance that is of interest for aviation applications.
4. In the case where the sight vector intersects the earth surface in less than 25km, a CFLOS is indicated if no clouds are encountered between the view point and the earth surface.
5. CFLOS calculations are done in both the forward and rear directions along the CloudSat orbit track. This is done to both increase the number of observations, and to account for varying direction of cloud advection over the global domain (CloudSat and CALIPSO reach a maximum latitude of +/- 82 degrees). In some domains the cloud advection will have a component in the direction of flight and in others it will be opposed to the direction of flight. The PCFLOS, thus, includes both the forward and backward views.