JUST HOW FAR DOES CALIPSO'S LIDAR PROFILE INTO CLOUDS?

Stuart A. Young

CSIRO Marine & Atmospheric Research, Private Bag 1, Aspendale VIC 3195, Australia. stuart.young@csiro.au

ABSTRACT

We report on the depth to which CALIPSO's (Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations) lidar can profile into the eight types of clouds it identifies. Penetration depths were determined from an analysis of "expedited" Vertical Feature Mask (VFM) files for the 12-month period from March 2010 to February 2011. The study region was the regional forecast domain of the Numerical Weather Prediction (NWP) module of the Australian Community Climate Earth System Simulator (ACCESS).

Analyses were performed as a function of season, latitudinal band, time of day and whether or not the clouds attenuated the lidar signal completely. We find that mean nighttime penetration depths for clouds determined to be opaque vary from around 800 m for CALIPSO cloud type 3 (broken cumulus) and 970 m for type 2 (stratocumulus) to around 3100 m for cirrus and 3700 m for "deep convective" clouds.

Of interest to a planned study of Southern Ocean clouds, where super-cooled liquid water appears to be relatively abundant, we find that the penetration depths for boundary-layer clouds are comparable to the physical depths measured over the region in aircraft cloud studies during the 1990s.

1. INTRODUCTION

Global data on the vertical profiles of cloud and aerosol location and optical properties have been available from the CALIPSO Mission almost continually since mid-June 2006. Such data have the potential to add significantly to our understanding of the effect of clouds on the Earth's radiation budget, which is currently the largest source of uncertainty in model predictions of future climate change [1]. One quantity of significant interest measured by CALIPSO is the cloud liquid water phase (LWP), which influences the radiative properties of clouds and is also of interest to potential cloud seeding operations. However, a frequent criticism made of lidar profiling of clouds (in particular of water clouds) is that lidar signals are attenuated too rapidly and that the penetration depths are, therefore, too small to be of much use in studying these clouds.

The lidar carried by CALIPSO, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), has a large footprint (~100 m) at cloud top as a result of its great distance (~ 705 km) from the cloud targets. This results in an increased amount of multiple scattering in the signal and less rapid signal attenuation than experienced by comparable ground-based lidars. Consequently, CALIOP can penetrate clouds to a greater distance than can these lidars.

In this work we report the results of an analysis of the penetration depths of the eight types of cloud classified by CALIOP. The penetration depths were obtained from an analysis of "expedited" Vertical Feature Mask files for the 12-month period from March 2010 to February 2011 inclusive. The study area was the regional forecast domain of the ACCESS Numerical Weather Prediction (NWP) model.

2. DATA DESCRIPTION

The data used in the study were "expedited" Vertical Feature Mask (VFM) files obtained from the NASA Langley Atmospheric Science Data Center (ASDC). These data, along with CloudSat data, have been obtained routinely for assessing the performance of the ACCESS NWP module in forecasting cloud amounts and locations [2], and for assessing the accuracy of the Australian Bureau of Meteorology's cloud-drift wind product.

The study area was the mesoscale domain of the ACCESS NWP module (10°N – 60°S latitude and 90°E to 175°E longitude). CALIPSO's ground track passed through this box six to eight times per day, evenly distributed between daytime passes (UTC times less than 12) and nighttime passes (UTC times greater than 12). The analysis window spanned the 12-month period from 1 March 2010 to 28 February 2011, a period during which there were only four days of missing CALIPSO VFM data. This period covered the four austral seasons: autumn (March – May, 2010), winter (June- August, 2010), spring (September – November 2010), and summer (December 2010 – February 2011).

We chose to use expedited, rather than nominal, data because the former were already being obtained routinely for the purposes mentioned above, which required the use of near real time data. The very high data storage and download volumes prohibited the downloading of additional data for the long period studied. For this reason, all the information used in this analysis was obtained from the VFM files, rather than from the files containing cloud profile and layer data, which are also available from the ASDC.

3. ANALYSIS METHODS

Analysis began by extracting the data of interest from the VFM files for all overpasses within the study region for each day. The information included date, time, latitude, longitude, and the feature classification flag at each location. The feature classification flag was decoded to obtain the number of features, feature type, feature subtype, and various quality assurance flags. (The structure of CALIPSO's VFM files is described in the relevant Data Quality Statement: http://eosweb.larc.nasa.gov/PRODOCS/calipso/Quality_Summaries/CALIOP_L2VFMProducts_3.01.html.) Only features that were classified as clouds with a confidence level of at least "medium" were included in this analysis.

The locations of the top and base of any cloud feature were determined by detecting changes in feature type in successive range bins. The minimum altitude at which atmospheric data exist in any column was defined as the altitude bin immediately above the maximum of either the altitude of the surface feature or the altitude where the feature type became either "invalid" (feature type = 0) or "no signal / "totally attenuated" (feature type = 7).

All of the above information was written to a daily file that contained, at each measurement location, the time, latitude, longitude, number of cloud features in the column, minimum valid lidar altitude, and the altitudes of cloud base and top, and cloud subtype. These daily files were also the files that were used with CloudSat data to create a composite file that was then compared with the ACCESS NWP model.

In the present analysis, statistics were gathered on the distribution of depths of penetration into the various cloud subtypes identified by CALIPSO and listed in Table 1. Penetration depth was defined as the difference between the altitudes of cloud top and cloud base. In order that the statistics would not be biased low by thin, transparent clouds, clouds that were determined to be opaque were analyzed separately from transparent clouds. Regardless of the description in Table 1, clouds were deemed to be opaque if the cloud base was at the minimum altitude for atmospheric signals when the latter was above the surface. It was found that some clouds that were nominally opaque according to Table 1, in fact had features below them so were deemed to be transparent. Conversely, some clouds that were nominally transparent had no identified underlying feature (including clear air or surface). There is a caveat here, though, as it is possible for some underlying features to be hidden by noise thereby escaping detection, particularly during the day when the upper feature has high backscatter and high optical depth and thus scatters sunlight strongly.

Cloud penetration depths were accumulated in 220 bins of 60 m depth. Counts were accumulated as a function of cloud subtype, latitude region, season, time of day (day or night), and opacity (opaque or transparent). Three latitude regions were used: Tropical (Equator to Tropic of Capricorn), Sub-Tropical (Tropic of Capricorn to 45°S) and Southern Ocean (here 45°S to 60°S).

The counts array was then normalized by the total number of counts for each particular combination of parameters to create frequency distribution arrays. These were analyzed to determine, the minimum, maximum, mean, and peak frequencies. (Because some frequency distributions were bimodal, we use the term peak rather than mode.)

From the frequency distributions, distributions of cumulative frequency (CFDs) were produced. From these, in turn, median penetration depths were determined as the first bin where the cumulative frequency exceeded 0.5. (Note that some CFDs had high slopes in this region, so the CFD jumped from significantly below 0.5 to significantly above 0.5 in successive bins.)

Table 1. Cloud sub-types identified by CALIPSO

SubType	Description
0	low overcast (transparent)
1	low overcast (opaque)
2	transition stratocumulus
3	low, broken cumulus
4	altocumulus (transparent)
5	altostratus (opaque)
6	cirrus (transparent)
7	deep convective (opaque)

4. RESULTS

Selected results are presented in the following tables. Night-time penetration depths as a function of latitude region and season are presented for opaque Type 1 clouds in Table 2 and for opaque Type 5 clouds in Table 3. The nighttime frequency distributions for selected opaque Type1 clouds are plotted in Figure 1 with corresponding CFDs plotted in Figure 2. The greater penetration in the tropical winter clouds is apparent both in the figures and in the second row of Table 2.

Next we compare the penetration depths as a function of time of day and cloud opacity. Nighttime opaque, daytime opaque, nighttime transparent and daytime transparent statistics are presented in Tables 4 to 8. A significant increase in penetration depth is noted in the nighttime results. However, this may be a result, in part, of the lower daytime SNRs and the consequent, reduced daytime cloud boundary detection capability, which can lead to the detection of apparently shallower clouds.

Table 2. Nighttime penetration depths for CALIPSO Cloud Type 1 (Low Overcast, Opaque). The 2-part code gives: Location (Tropics, Sub-Tropics, Southern Ocean), and Season (Autumn, Winter, Spring and Summer – see text).

Code	Total	Min	Max	Mean	Peak	Median
Tr_Au	16787	60	2580	968	840	900
Tr_Wi	34297	60	2640	1052	900	960
Tr_Sp	25316	60	2520	984	840	900
Tr_Su	11852	60	2640	916	840	840
ST_Au	99107	60	2400	908	840	900
ST_Wi	85092	60	2940	912	840	840
ST_Sp	161840	60	3000	874	840	840
ST_Su	119184	60	2520	896	840	840
SO_Au	121529	60	2820	891	840	840
SO_Wi	154656	60	3000	924	840	840
SO_Sp	192701	60	2880	901	840	840
SO_Su	126216	60	2700	888	840	840
Average	95715	60	2720	926	845	865

Table 3. As for Table 2, but for CALIPSO Cloud Type 5 (Opaque Altostratus)

Code	Total	Min	Max	Mean	Peak	Median
Tr_Au	82931	60	6600	1123	900	960
Tr_Wi	107328	60	5280	1159	900	1020
Tr_Sp	118141	60	5280	1148	900	960
Tr_Su	126692	60	5040	1048	780	900
ST_Au	61056	60	4800	1255	900	1080
ST_Wi	89200	60	5040	1439	960	1260
ST_Sp	86553	60	5040	1228	900	1080
ST_Su	84782	60	5280	1197	900	1080
SO_Au	110384	60	5400	1360	840	1020
SO_Wi	109807	60	5760	1676	840	1440
SO_Sp	147282	60	5760	1543	840	1200
SO_Su	138837	60	5940	1345	840	1020
Average	105249	60	5435	1293	875	1085

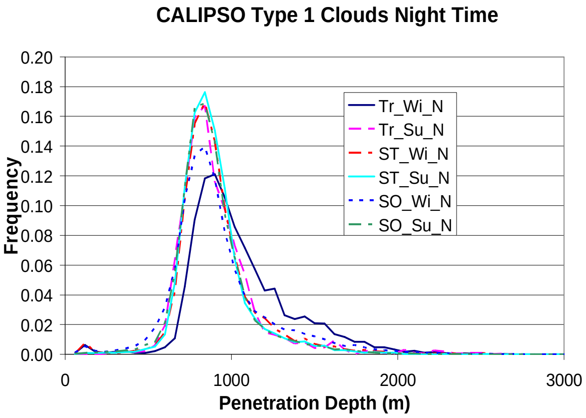

Figure 1. A comparison of Summer and Winter frequency distributions of penetration depths for night-time Type 1 opaque clouds in three latitude bands. Code is as for Table 2.

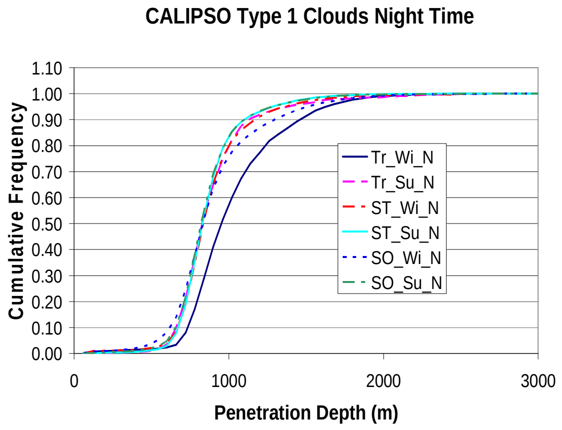

Figure 2. As for Figure 1 but showing cumulative frequency distributions.

Table 4. Nighttime penetration depths for CALIPSO cloud types averaged over season and latitude. Opaque clouds only.

Type	Total	Min	Max	Mean	Peak	Median
0	1922142	60	3075	888	790	820
1	1148577	60	2720	926	845	865
2	3127289	60	3295	973	735	880
3	870803	60	3310	782	140	670
4	814612	60	6625	1532	830	1040
5	1262993	60	5435	1293	875	1085
6	1689063	110	12665	3708	1465	3445
7	1954083	75	9790	3111	1540	2945

Table 5. Daytime penetration depths for CALIPSO cloud types averaged over season and latitude. Opaque clouds only.

Type	Total	Min	Max	Mean	Peak	Median
0	1592039	80	2530	622	515	575
1	971032	60	2260	688	575	635
2	2766627	60	2885	672	520	595
3	745301	60	2735	554	340	460
4	698283	105	4475	864	510	665
5	1293916	60	4255	920	545	760
6	1354988	140	7995	2313	1415	2205
7	2338964	70	6860	2138	1570	2075

Table 6. Nighttime penetration depths for CALIPSO cloud types averaged over season and latitude. Transparent clouds.

Type	Total	Min	Max	Mean	Peak	Median
0	440824	60	2980	731	620	650
1	1318839	60	925	187	105	110
2	2778068	60	3140	668	610	610
3	1318839	60	3135	580	275	510
4	1941598	60	6505	945	620	735
5	20428	60	2375	419	185	275
6	11144238	60	12550	2045	840	1640
7	14503	60	3110	623	240	430

Table 7. Daytime penetration depths for CALIPSO cloud types averaged over season and latitude. Transparent clouds.

Type	Total	Min	Max	Mean	Peak	Median
0	471724	60	2385	476	355	410
1	1728	65	670	205	130	160
2	3041704	60	2685	453	335	400
3	1461270	60	2375	393	255	335
4	1926291	60	4105	622	360	485
5	22935	60	1890	427	170	285
6	9370273	60	7375	1414	610	1130
7	32582	70	2085	420	195	275

5. DISCUSSION

The analyses presented here show that CALIOP can profile to significant depths into clouds. As expected, greatest penetration is found in cirrus and the smallest in cumulus, although mean values approaching 800 m are found for these clouds at nighttime. For both opaque and transparent clouds, increases of around 50% are found in nighttime over daytime values of maximum, mean, peak and median penetration depths. Also, for both daytime and nighttime conditions, mean and median penetration depths for clouds determined to be opaque are found to be almost double the values for transparent clouds which include physically thin clouds.

Finally, we note that the mean penetration depths of the opaque boundary layer water clouds (Type 0 – 3) are 800 – 900 m by night and 600 – 700 m by day. Physical cloud depths from aircraft measurements in the mid 1990s of 470 – 1400 m [3] and 140 – 400 m [4] in winter and 85 – 1600 m [5] in summer indicate that CALIOP can often measure the complete profile of these clouds. This capability will add significant value to a planned frontal cloud study in the Southern Ocean.

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REFERENCES

1. Dufresne J.-L. and S. Bony, 2008: An assessment of the primary sources of spread of global warming estimates from coupled atmosphere-ocean models, *J. Climate*, **21**, pp. 5135–44.

2. Protat A., L. Rikus, S. A. Young, J. Le Marshall, P. May, M. Whimpey, 2010: Evaluation of ACCESS-A Clouds and Convection using Near Real-Time CloudSat-CALIPSO Observations. *CAWCR Research Letters*, **4**, pp.27-33.

3. Boers R. E., J. B. Jensen, P. B. Krummel, H. Gerber, 1996: Microphysical and short-wave radiative structure of wintertime stratocumulus over the Southern Ocean, *Q. J. R. Meteorol. Soc.*, **122**, pp. 1307-1339.

4. Pickett, M. C., 1999: Lidar and infrared studies of stratocumulus clouds. PhD thesis, Victoria University, Melbourne, Australia.

5. Boers R. and P. B. Krummel, 1998: Microphysical properties of boundary layer clouds over the Southern Ocean during ACE 1, *J. Geophys. Res*., **103**, D13, pp. 16651-16663.