Macrophysical and optical properties of midlatitude high-altitude clouds from 4 ground-based lidars and collocated CALIOP observations

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ABSTRACT

In the present work, we applied the cloud structure analysis algorithm STRAT to long time series of lidar backscatter profiles from multiple locations around the world. Our goal was to establish a Mid-Latitude climatology of cirrus clouds macrophysical properties based on active remote sensing: ground-based lidars at four mid-latitude observatories and the spaceborne instrument CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization). Lidar sampling, macrophysical (cloud base height, cloud top height, cloud thickness) and optical (cloud optical thickness) properties statistics are then evaluated and compared between the four observatories ground-based lidar measurements and quasi-simultaneously CALIOP overpasses. We note an overall good consistency in the macrophysical properties statistics derived from ground- based Lidar and CALIOP. For high altitude clouds, using consistent transmission-based retrieval methods, discrepancies are found in COT retrievals between ground Lidars and CALIOP. Ground-based Lidar retrievals contain less thick cirrus clouds than CALIOP. Overall, the results show that cirrus clouds with COD<0.1 (not included in historical cloud climatologies) represent 30-50% of the non-opaque cirrus class (COD<3, Pressure<440mb from ISCCP). Finally, we analyze the statistic consistencies between each dataset and investigate the possible bias due to lidar sampling and instrument/algorithm differences between ground-based lidar and CALIOP.

1. INTRODUCTION

Several cirrus cloud climatologies have been established over time using the different satellite datasets available. References [1] establish, from the ISCCP dataset, that cirrus clouds of optical depth less than 3 cover on average 13% and 19% of the globe, respectively. Reference [2] reveals, based on the TOVS dataset, that these clouds actually cover more than 30% of the globe. Reference [3] shows, using the LITE dataset, that as much as 46% of the globe is covered by cirrus optically thin clouds. Reference [4] find that cirrus cloud extends over 35% of the globe on average, using one year of CALIOP data. The studies using the more sensitive instruments reveal that extensive cloud cover, semi-transparent or subvisible (optical depth less than 0.3 and 0.03, respectively) can be overlooked with the less sensitive instruments. Reference [5] shows that the MODIS cloud mask has problem for optical depth less than 0.4 whereas reference [6] shows that the Atmospheric Infrared Sounder (AIRS) optical depth retrievals is problematic below 0.1 (strong uncertainties in the thermodynamic structure of the atmosphere).

Lidars designed to monitor cirrus clouds have been deployed at several observatories around the globe for nearly a decade. Several authors present regional climatologies from both mid-latitude ([7], [8] and [9]) and tropical observatories ([10]). These studies reveal very high occurrence of cirrus semi-transparent and subvisible clouds, as these lidar systems are very sensitive to scattering by ice particles.

In an attempt to reconcile the various sources of cirrus cloud data, reference [11] presents a comprehensive comparison of ground-based lidar measurements, and spaceborne lidar and sounder datasets. The authors conclude that while they find some consistency between the different climatologies, the sources of discrepancies are numerous and their effects are not quantified because the datasets are not coincident, and analysis methods are not consistent. Hence, to evaluate the consistency between existing lidar based cirrus cloud datasets, we perform a detailed comparison of regional cloud climatologies between 4 mid-latitude ground-based observatories and spatially and temporally collocated CALIOP observations.

2. OBSERVATIONAL DATA SETS

Data used to compare macrophysical and optical properties of high altitude clouds are obtained by four ground-based lidars and CALIOP. Ground lidars are located at middle latitudes in France and in United States. The two American sites are, a continental site, the Southern Great Plains (SGP) Central Facility (SCF; 37°N, 98°W) operated by the Atmospheric Radiation Measurement (ARM) program and a coastal site, the COVE platform (37°N, 76°W), operated by the Cloud and the Earth's Radiant Energy System program. ARM SGP Lidar data are available from 1998-2004 and 2006-2008. COVE lidar data are available in 2005-2008. These lidars are operated in automatic mode 24h per day, 7 days per week. The two French sites are the Observatoire de Haute Provence (OHP; 44°N, 6°E) on the border of the Alps mountain chain and the Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA; 47°N, 2°E) in a large plain 20 km southwest of Paris. Measurements are conducted in semi-automatic mode during several hours during the day (SIRTA) or at night (OHP) depending on weather conditions (the lidars do not operate when rain is present). OHP and SIRTA lidar data are available for 2006-2007 and 2002-2007 respectively.

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The Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) is carried on-board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) spacecraft in a sun-synchronous orbit crossing the equator southward at 0150 and northward at 1350 local standard time ([12]). The CALIPSO satellite was launched in April of 2006 and passes in the same track every 16 days ([13]). Official CALIOP Level 2 (version 2) data products are used in this study.

Table 1. *Number of profiles for each site according to CALIOP and ground-based lidar. We consider 2-years CALIOP dataset, ground-based dataset for the data coincident with CALIOP overpasses and ground-based dataset in all over the cases.*

Number of profiles	***SIRTA***	***OHP***	***SGP***	***COVE***
CALIOP data	14530	14056	14401	14226
Extended regional statistics	78076	36583	263600	123635
Coincident data	21437	10668	64600	30825

3. CIRRUS CLOUD STATISTICS

3.1 Macrophysical properties

Figure 1 shows the vertical distribution of CBH when clouds are present in the troposphere above 7km.

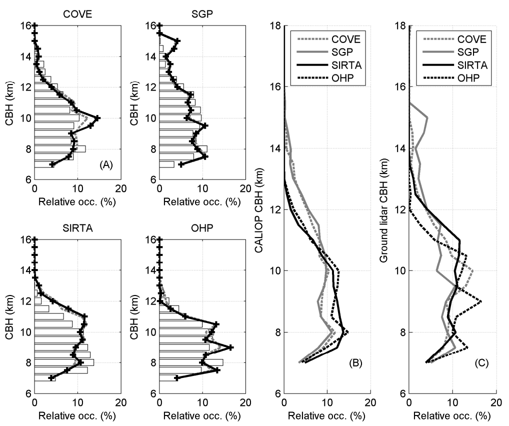

Figure 1. *Vertical distributions of cloud base height (a) CALIOP-ground comparisons at each site. Histograms correspond to CALIOP data for 2006/07-2008/06 period, and black and dash-grey lines correspond to ground-based data for extended and coincident periods (defined in Table 1), respectively; (b) distributions derived from CALIOP data and (c) distributions derived from ground-based lidar data.*

CBH ranges 7-13 km over the two European sites and 7-15 km for the US coastal and continental sites, as a result of a thicker summer troposphere. At SGP the distribution derived from CALIOP is multi-modal with peaks at 8 and 10 km. At COVE both distributions range from 7-15 km. At SIRTA the distributions differ in several aspects: CBH distribution from CALIOP ranges about 2km less than that from the ground site, and peaks at 8 km, versus 8-11 km. At OHP the CALIOP and ground based lidar are similar, however somewhat noised for ground-based lidar due to less frequent sampling.

3.2 Geometrical thickness

Results show that the cloud thickness derived from ground-based lidars (CALIOP) over French and US sites range 0.5-5 km (0.5-4.5 km). For CALIOP data, distributions at all sites are nearly identical and suggest a unique mode exhibiting one maximum centred at 0.6 km with 35% of relative occurrence. On the contrary, cloud geometrical thicknesses derived from ground-based lidars are not consistent from one site to another: SIRTA (SGP) site peaks at 0.5 km (0.7 km) with 15% of relative occurrence (12%), OHP peaks at 1.2 km (12%), and COVE at 1.5 km (9%).

Table 2. *Average and pseudo-standard deviation of cloud thickness derived from ground-based lidar and CALIOP (in parentheses).*

Sites	Average (km)	Pstd. dev.(km)
COVE	1.85 (1.39)	0.97 (0.92)
SGP	1,57 (1.40)	0.99 (0.93)
SIRTA	1.17 (1.32)	0.95 (0.82)
OHP	1.85 (1.29)	1.03 (0.80)

3.3 Optical thickness

Figure 2 reveals that 7-25% of the cloud distribution falls in the sub-visible category (COD<0.03), as defined by Sassen et al. (2001). 48-66% falls in the semi-transparent category (0.03<COD<0.3), while 9-42% falls in the moderate cirrus category (0.3<COD<3). Additionally, we find that 33-64% of the observed cirrus clouds have an optical thickness less than 0.1, which is the lower detection limit typically attributed to satellite passive sounders ([2]).

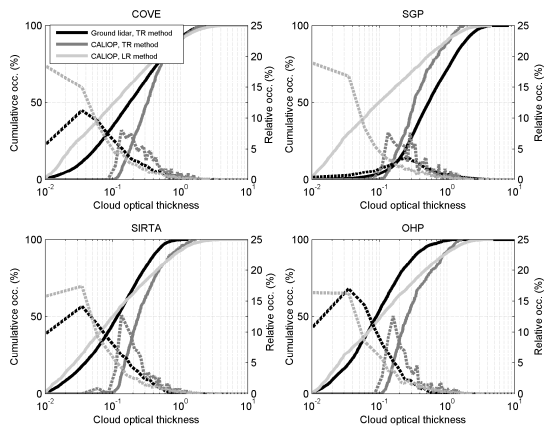

Figure 2. *Cumulative and relative distributions of cirrus cloud optical thickness derived from ground-based lidar (transmission method: TR method) and CALIOP data (transmission method: TR method, and Lidar Ratio method: LR method) at each site. The continuous line corresponds to cumulative occurrence and the dashed line to relative occurrence. The black line corresponds to ground-based lidar COT and the gray lines to CALIOP COT.*

4. DISCUSSIONS ON POSSIBLE SOURCES OF BIAS

4.1 Seasonal variations

Table 3 shows the seasonal variations of cloud base height, cloud top height and cloud geometrical thickness above each site derived from CALIOP data. Above COVE and SGP, mean cloud base and top heights are about 1.5 km higher in summer than in winter. At OHP and SIRTA, the seasonal range of average cloud base and top heights is less than 0.5 km, Cloud geometrical thickness distributions, however, do not reveal seasonal dependences. The seasonal dependence of cirrus cloud altitudes over US continental and coastal sites could be due to the deepening of the moist layer during summer as a result of vertical convective fluxes induced by solar heating of the surface.

Table 3. *Average cloud base height, cloud top height and cloud thickness separating seasonal CALIOP overpasses for the four observatories.*

		Average (km) Winter / Spring / Summer / Autumn				All cases
COVE	***CBH***	**9.20**	**9.58**	**10.58**	**9.53**	9.76
	CTH	**10.67**	**10.93**	**11.91**	**10.99**	11.16
	CT	**1.46**	**1.34**	**1.33**	**1.47**	1.39
SGP	***CBH***	**9.18**	**9.49**	**10.89**	**9.79**	9.93
	CTH	**10.62**	**10.88**	**12.32**	**11.07**	11.32
	CT	**1.44**	**1.39**	**1.43**	**1.28**	1.39
SIRTA	***CBH***	**9.26**	**8.83**	**9.20**	**9.14**	9.11
	CTH	**10.54**	**10.49**	**10.12**	**10.57**	10.44
	CT	**1.31**	**1.29**	**1.30**	**1.40**	1.32
OHP	***CBH***	**9.16**	**8.91**	**9.40**	**9.60**	9.26
	CTH	**10.39**	**10.21**	**10.58**	**10.97**	10.55
	CT	**1.23**	**1.30**	**1.18**	**1.37**	1.29

4.2 Diurnal cycle

We show the average cloud base and top altitudes and the average geometrical thickness for each site separating CALIOP daytime and nighttime overpasses. The average cloud base height is found to be nearly identical above all but one site (COVE) where average daytime CBH is 0.2 km higher than that of nighttime. The average cloud top altitude is 0.1-0.5 km higher at night than during the day (0.1 km at COVE, 0.5km at SGP, 0.4 at SIRTA and 0.3 at OHP). Better signal-to-noise ratio at night allows optically thinner cloud to be detected. The greater cloud geometrical thickness derived at night can thus be due to a better detection of the base and the top of the cirrus clouds (low scattering ratio) resulting in thicker clouds.

4.3 Effect of low-level clouds

We show the mean base and top altitude and the mean geometrical thickness above each site derived from CALIOP overpasses when low-altitude clouds are (with) and are not (without) present. Cirrus clouds are 0.1-0.3 km thicker, geometrically, in the absence of low-level clouds. Cirrus cloud average base (top) altitudes are 0.1-0.4 km (0.3-0.6 km) higher in the absence of low-level clouds. Above SGP and COVE, we find that in summer (winter) the average geometrical thickness of cirrus clouds is greater by 0.5 km (0.1 km) when low-levels clouds are absent compared to when they are present (not shown). This difference during summer and winter period argues that dynamic feedbacks are likely to impact cirrus properties (thickness, altitude): low-level clouds are able to decrease deep convection responsible for vertical humidity transport. No seasonal dependence is observed above SIRTA and OHP.

4.4 Effect of multiple layers

Over all sites, CALIOP data reveal a single cirrus cloud layer in 65% of cloudy situations, a second cirrus cloud layer in 25% of the cases a third cirrus cloud layer in 7% of the cases, and more than 3 cirrus cloud layers 3% of the cases (Figure3). Ground-based data exhibit large differences between sites: SIRTA data are consistent with CALIOP; SGP data show 15 % multiple layer cirrus clouds, whereas COVE/OHP data reveal about 11% multiple cirrus cloud layers. This low percentage is related to the vertical resolution of the lidars operated at each site: 75 m (COVE and OHP) against 15 m for SIRTA and 30 m or 60 m for CALIOP below and above 8 km, respectively. Cloud detection algorithms (e.g. STRAT by the reference [14]) require a minimum of few consecutive cloud pixels in the backscattered lidar profile to detect and classify a cloudy or a clear atmosphere. Hence, cirrus clouds are statistically thicker for low lidar vertical resolution (COVE/OHP) than for SIRTA and CALIOP.

4.5 Impact of cloud optical thickness retrieval algorithms

Figure 2 shows cirrus cloud optical thickness distributions derived from ground-based and CALIOP over US and French sites. The TR method is applied to CALIOP data for clouds ranging about 0.1-3 in optical thickness. Because the TR method requires high signal-to-noise ratio in the molecular region above and below the cloud layer, it can only applied to about 10% of CALIOP data. The TR method is applied to ground-based lidar data for clouds ranging about 0.001-3 in optical thickness. It is successfully applied to about 50% of ground-based lidar profiles. The LR method is applied to about 95% of CALIOP profiles where cirrus layers are identified. Note that the LR method is not applied to the ground-based lidar datasets. Relative occurrences are derived using a constant cloud optical thickness interval of 0.025 and displayed with logarithm scale for x-axis. Significant discrepancies appear for subvisible cirrus cloud (i.e. 0.01<COT<0.03). CALIOP LR data reveal that subvisible clouds represent about 25% of the distribution, while 20% is found in SIRTA and OHP data, but only 10% and 5% in COVE and SGP data, respectively. The semi-transparent class (0.03<COT<0.3) is found to represent 50% of the distribution in the CALIOP LR data, about 60% of the distribution in both SIRTA and OHP data, and about 50% in both COVE and SGP data. The thickest class (0.3<COT<3) represents about 25% of the distribution in CALIOP LR data, 20% in SIRTA and OHP data and more than 40% of COVE and SGP data.

5. CONCLUSIONS

Ground-based lidar and CALIOP datasets gathered over four mid-latitude sites, two US and two French sites, are used to evaluate the consistency of cloud macrophysical and optical property climatologies that can be derived by such datasets. The datasets cover two years of quasi-simultaneous measurements by the spaceborne instrument CALIOP and four ground-based lidars. Cloud base height, cloud top height, cloud geometrical thickness and cloud optical thickness of high altitude clouds distributions are analyzed.

We note that the consistency in average cloud height (both base and top height) between the CALIOP and ground datasets ranges from -0.4km to +0.5km. The consistency in pseudo standard deviations of the cloud height distributions between the two datasets range 0-0.5 km. We find that cloud geometrical thickness distributions vary significantly between the different datasets, due in part to the original vertical resolutions of the lidar profiles. Average cloud geometrical thicknesses vary from 1.2 to 1.9km, i.e. by more than 50%. Cloud optical thickness distributions in subvisible, semi-transparent and moderate intervals differ by more than 50% between ground and space-based datasets. However all lidar datasets agree that the fraction of cirrus clouds with optical thickness below 0.1 (not included in historical cloud climatologies) represent 30-50% of the non-opaque cirrus class. So while the radiative effects of a 0.1 optical thickness cloud maybe considered tenuous, the cumulative effect on the radiative balance due to the high abundance is likely to be significant.

Discrepancies between the ground and CALIOP datasets are attributed in part to sampling. Our study shows that differences in average cloud base altitude (*cloud top altitude*) between ground and CALIOP datasets can be attributed (i) to irregular sampling of seasonal variations in the ground-based data (0.0-0.1 km, *0.0-0.1 km*), (ii) to day-night differences in detection capabilities by CALIOP (0.0-0.2 km, *0.0-0.2 km*) and (iii) to the restriction to situations without low-level clouds in ground-based data (0.0-0.2 km*, 0.1-0.3 km*). Finally, cloud geometrical thicknesses are not affected by irregular sampling of seasonal variations in the ground-based data, while up to 0.0-0.2 km and 0.1-0.3 km differences can be attributed to day-night differences in detection capabilities by CALIOP, and to the restriction to situations without low-level clouds in ground-based data, respectively. We find that the Lidar vertical resolution can have an effect on the number of single versus multiple layer situations detected. This effect does not affect the average cloud base height, but may affect both cloud top height and cloud geometrical thickness by 0.1 km.

For high altitude clouds, using consistent transmission-based retrieval methods, COT distributions from ground and CALIOP data are found to be consistent within about 10%. This comparison is limited to COT greater than 0.1 and to about 10% of the CALIOP retrievals. We find that the CALIOP LR data is biased towards lower optical depth when compared to the ground-based datasets. These comparisons reveal the high sensitivity to the retrieval algorithm. Hence this exercise will have to be conducted again for the next release of CALIOP data. Overall, the results show that cirrus clouds with COD<0.1 and COD<0.3 (detection limits for infrared sounders and visible imagers) represent 25-50% and 50-75% of the non-opaque cirrus class. The occurrence of cirrus clouds at the global scale is thus likely to be significantly underestimated in historical cloud climatologies.

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