# CALIOP OBSERVATIONS IN COASTAL REGIONS AT SOUTHERN MIDLATITUDES COMPARED TO POLLY$^{XT}$ MEASUREMENTS

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## ABSTRACT

We present a long–term study of the aerosol conditions in Latin America below 50°S, which is based on spaceborne measurements of CALIOP and ground–based Raman lidar measurements of Polly$^{XT}$ at Punta Arenas, Chile (53°S). Punta Arenas is influenced by the Antarctic low–pressure belt and constant westerly winds of marine origin through the whole year. The CALIOP–derived median AOT value of 0.04 confirms the clean aerosol conditions in the surrounding of Punta Arenas. However, we found an unexpectedly high fraction of continental aerosol in the CALIOP typing scheme. A closer view on the CALIOP data analysis showed evidence that this might result from the surface–type–dependent data algorithm. The determination of marine aerosol is prohibited above land which leads to discrepancies in the coastal region of Punta Arenas. Additionally, we found evidence of cloud affected level 2 version 3 data which were unmarked by the CALIOP quality flags. The Raman lidar measurements at Punta Arenas offer the unique opportunity of a ground truthing approach of CALIOP in aerosol conditions close to the detection level in a marine environment.

## 1. INTRODUCTION

The mobile facility of IfT OCEANET takes part in the transatlantic cruises of the research vessel Polarstern to investigate aerosol and cloud effects on radiation which includes the opportunity of lidar measurements in the barely investigated southern hemisphere. To extend the observations in the southern hemisphere the portable Raman and polarization lidar Polly$^{XT}$ was deployed at Punta Arenas, Chile (53°S, 71°W) in between the southwest and northeast cruises to and from Antarctica. These observations can be contrasted with respective observations of aerosols and clouds in the northern hemisphere to quantify anthropogenically caused impacts on climate [1]. Furthermore, they give the unique opportunity of a comparison to spaceborne applications. After the successful launch of the Cloud–Aerosol Lidar Infrared Pathfinder Satellite Observation (CALIPSO) mission in April 2006, the satellite-borne lidar CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization) provides vertically resolved information on aerosol and cloud parameters since June 2006. This unique long–term, global, 4–dimensional data set is used to establish an aerosol climatology in the surrounding of Punta Arenas. We performed a quality test of the level 2 version 3 data and found evidence of misclassified aerosol types by CALIOP's data algorithm in the rugged coastal environment at the most southern tail of Latin America. After a brief introduction to the measurement site and the instruments, the selected data set of CALIOP is introduced. The results are presented in Sec. 5.

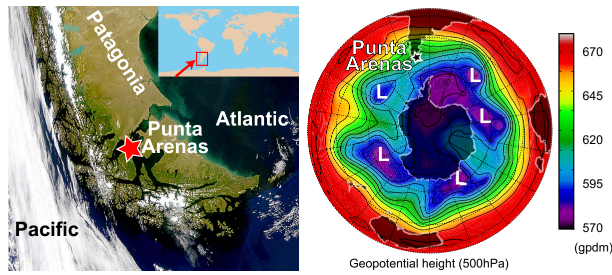


Figure 1. Left: Map of Latin America. Right: Map of the southern hemisphere. Geopotential height at 500 hPa is shown by the color code for 1 January 2010. L denotes low–pressure systems. The location of Punta Arenas is indicated by stars.

## 2. MEASUREMENT AREA

During the **A**erosol **L**idar observations at **P**unta **A**renas in the framework of a **C**hilean Germ**a**n cooperation (**ALPACA**, 4 December 2009 to 4 April 2010) campaign the lidar Polly$^{XT}$ was deployed at the University of Magallanes. Punta Arenas is situated directly at the Strait of the Magellanes (see map in Fig. 1 left). In the west rugged spurs of the Anden Mountains and in the east direction grassy fields dominate the landscape. Constant westerly to north westerly air flows prevail through the whole year with a mean surface speed of 4.6 m s$^{-1}$ which is caused by the Antarctic low–pressure belt. Figure 1 (right) shows a map of the southern hemisphere. The most southern continental area is the peak of Latin America, the place of Punta Arenas. Geopotential height at 500 hPa is denoted by the color code for 1 January 2010 in Fig. 1 (right). Dark colors indicate the low pressure systems around the Antarctic. Air masses are advected along the isobares. As it is clearly shown in Fig. 1 (right), the air masses that are advected to Punta Arenas overpass no other continental areas and are of marine origin.

## 3. INSTRUMENTS

### 3.1. POLLY$^{XT}$

The ground–based measurements were performed with the multiwavelength polarization Raman lidar Polly$^{XT}$

of the Leibniz Institute for Tropospheric Research (IfT), whenever the weather conditions were appropriate. The system emits light at 355, 532, and 1064 nm wavelength, receives the elastically scattered light and furthermore the Raman scattered light at 387 and 607 nm. Thus, profiles of extinction coefficients are determined at 355 and 532 nm. Moreover, cross-polarized light is detected at 355 nm and allows the determination of the linear particle depolarization ratio. Further information about the lidar system is given in Ref. [2].

### 3.2. CALIOP

CALIOP is an elastic–backscatter lidar that orbits the Earth at a height of 705 km with a velocity of 7 km $s^{-1}$. It overpasses the same location each 16th day. CALIOP measures backscattering at 532 and 1064 nm and depolarization at 532 nm. The system itself as well as the provided data algorithm is explained in detail in a special issue [3]. Within this work, we focus on the level 2 version 3 data related to aerosols, especially the particle backscatter coefficient at 532 nm.

## 4. CALIOP DATA SELECTION

A one year dataset of CALIOP has been studied in detail. Within a distance of 200 km CALIPSO passed Punta Arenas 148 times from 1 May 2009 to 31 April 2010 [4]. According to these overpasses HYSPLIT trajetory ensembles [5] were determined to select the meteorologically relevant subsets of the CALIOP measurement. Figure 2 (right) shows a map of the position of Punta Arenas (red star), the flight track of CALIOP (thin white line), and HYSPLIT forward trajetories (colored lines) which were calculated from the position of Punta Arenas for several heights. The CALIOP data subset (thick white line) within the cross section of the HYSPLIT trajetories was extracted and investigated for the presence of determined aerosol (existence of particle backscatter coefficient values). If aerosol was determined, the trajectory heights were adjusted to the aerosol layer heights and the subset was closer defined. Figure 2 (left) shows the frequency distribution of the distance between CALIOP data subsets and Punta Arenas in 25 km–intervals (grey bars). In 31% of all cases profiles of particle backscatter coefficients were available in the data subsets.
A quality assurance of the extracted profiles was performed with the quality flags that are provided by the level 2 version 3 data for each data point. We used the Cloud Aerosol Discrimination (CAD) score and the feature classification flags, which are related to the Scene Classification Algorithm (SCA). According to the Hybrid Extinction Retrieval Algorithm (HERA) the available extinction flags were obtained as well [3].
We found that the best thresholds are CAD score $< -90$ (observed layer consists of aerosol with high probability), feature typing flag $>1$ (confident cloud–aerosol discrimination), feature subtyping flag 1 (confident aerosol typing), and extinction flag $<8$ (only changes in the lidar ratio within HERA are allowed). Finally, in 15 cases the quality assurance refused the data subset completely.

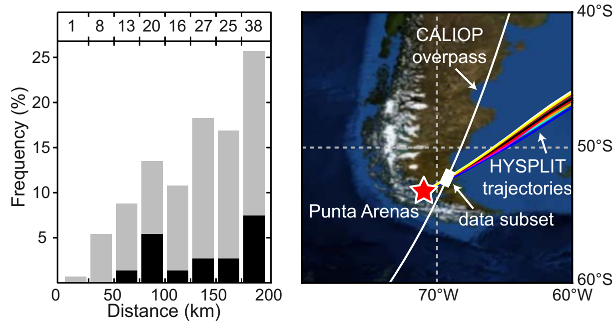


Figure 2. Left: Frequency of the distance between CALIOP measurements and Punta Arenas, Chile. The total number of cases is given at the top. Right: Map of South America. The thin white line shows the CALIOP overpass on 13 January 2010. A star denotes the location of Punta Arenas. Colored lines show forward trajectories determined by HYSPLIT. The thick white line indicates the cross section of trajectories and the CALIOP overpass, and thus the selected data subset of CALIOP.

Thus, 31 cases (21%, black bars in Fig. 2, left) remain in the observed time period of one year.

## 5. RESULTS

The general aerosol conditions in the area of Punta Arenas were investigated with CALIOP observations on the basis of one year from 1 May 2009 to 31 April 2010. Figure 3 (top) presents the aerosol layer top heights and the aerosol optical thickness (AOT) at 532 nm. The top heights range from about 200 to 7000 m and suggest the presence of free–tropospheric aerosol layers. The median AOT value is 0.04 which highlights the supposed clean marine conditions according to the meteorological situation at Punta Arenas. These conditions were confirmed by AOT measurements in the framework of AERONET that show mean values of $0.06 \pm 0.02$ in the Southern Ocean [6]. In contrast, CALIOP's aerosol typing indicates that continental aerosol (including dust and smoke) dominates the aerosol conditions in the area of Punta Arenas (Fig. 3, bottom).
One step of CALIOP's data analysis algorithm (in the SCA) is an aerosol typing under consideration of the integrated backscatter, the depolarization ratio, and the surface type [3]. The obtained surface type is given by the International Geosphere/Biosphere Programme map (IGBP) and the GPS information of CALIOP itself. Marine aerosol can be exclusively determined above the ocean. Thus, if CALIOP overpasses land in a coastal regime, the algorithm prohibits the possibility of the occurrence of marine aerosol. An example is given by the measurement of CALIOP on 13 January 2010. CALIOP passed Punta Arenas in a distance of about 150 km. Figure 4 (left) shows the height–time display of the lidar attenuated backscatter. The red line indicates the surface, which changes between ocean and land. The feature type mask of the white box in Fig. 4 (left) is presented

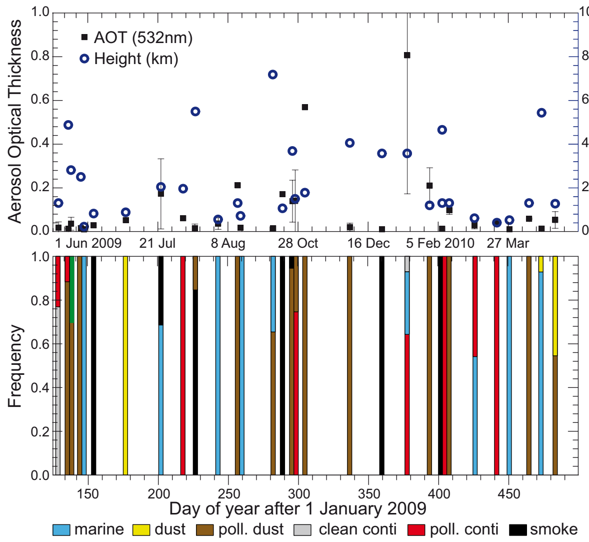


Figure 3. Top: Aerosol optical thickness (black squares) and aerosol layer top height (blue circles) from 1 May 2009 to 31 April 2010 as determined by CALIOP. Bottom: Aerosol types determined by CALIOP's data algorithm.

in Fig. 4 (center) and separates clouds, aerosol, and surface. In the left quarter of Fig. 4 (center) aerosol was determined below clouds up to 1.5 km height and even within the clouds. The elevation of the ground is indicated by mint color. Focussing on the aerosol in more detail, the subtype mask in Fig. 4 (right) shows a change from polluted continental aerosol to marine aerosol from left to right. We added the surface type information of the IGBP map to Fig. 4 (right) at the bottom. Yellow patterns indicate land surfaces and light blue patterns indicate ocean surface. The change in aerosol type from polluted continental aerosol to marine aerosol seems to be directly related to the change in the surface type from land to ocean. This relation can be observed also in the course of the measurement on 13 January 2010 two more times (Fig. 4, right).

We extracted level 2 version 3 particle backscatter profiles from the CALIOP measurement in Fig. 4 (left) to compare them to our measurements with Polly$^{XT}$. The height–time display of the range–corrected signal of the ground–based lidar measurement in Fig. 5 shows comparable patterns of clouds in 10 and 2 km height, and aerosol up to 1.5 km height as the CALIOP observation in Fig. 4 (left). The extracted profiles of the particle backscatter coefficient from CALIOP were selected according to the quality flags explained above. Figure 6 (left) presents the averaged profiles of the particle backscatter coefficient at 532 nm determined with Polly$^{XT}$ (green line) and CALIOP. We distinguished the profiles determined with CALIOP into profiles with overlying clouds (grey line) and cloud–free profiles (red line). While the red curve differs only slightly from the green curve in magnitude, the grey curve is up to one order of magnitude higher. The reason for this difference is not well understood yet, but to avoid cloud effects in the investigations, we define an additional boundary condition and deal only with cloud–free particle backscatter coefficients in the following. Figure 6 (center) shows the averaged profiles of the particle backscatter coefficient as derived with CALIOP measurements in cloud–free conditions. According to Fig. 4 (right) profiles which were determined over water surfaces (blue line) and over land (black line) were distinguished. Both profiles are in agreement. The blue curve shows a strong increase in the backscatter coefficient above 1.5 km which might be related to cloud remnants. However, over the water surface the aerosol layer is determined as marine aerosol and treated with a lidar ratio of 20 sr in the data analysis. Instead, over land the aerosol layer is expected to consist of polluted continental, smoke, and clean continental

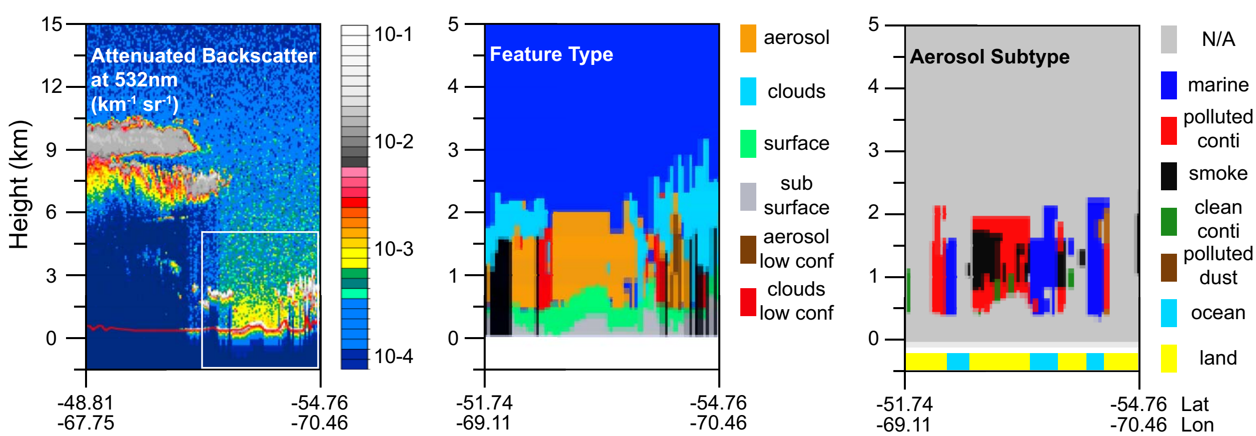


Figure 4. Left: Height–time display of the lidar attenuated backscatter at 532 nm of the CALIOP observation at 4:47 UTC on 13 January 2010. Center: Feature mask of aerosol, clouds, and surface. Right: Aerosol subtype mask differentiating between five aerosol types. The surface type is given at the bottom.

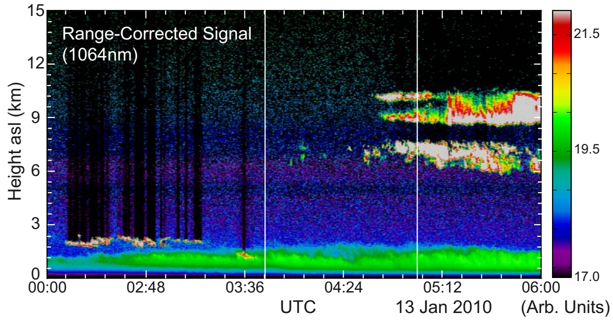


Figure 5. Height–time display of the ground–based lidar measurement on 13 January 2010. White lines indicate the time period chosen for the comparison to CALIOP measurements (see Fig. 4, left).

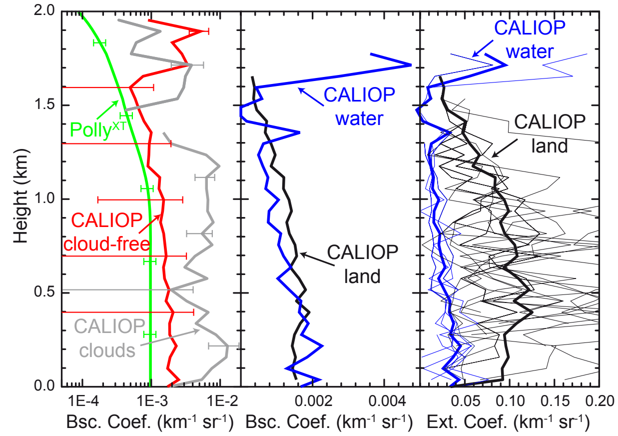


Figure 6. Left: Averaged vertical profiles of the particle backscatter coefficient at 532 nm as determined by Polly$^{XT}$ (green) from 3:45 to 5:00 UTC and CALIOP at around 4:47 UTC on 13 January 2010. Profiles determined from CALIOP measurements are distinguished into cloud–free profiles (red) and cloudy profiles (grey). Center: Averaged cloud–free profiles of the particle backscatter coefficient at 532 nm over land (black) and over water surface (blue) as determined by CALIOP measurements. Right: Averaged cloud–free profiles of the extinction coefficient at 532 nm according to the center panel (thick lines), single profiles are indicated by thin lines.

aerosol. Thus, the extinction coefficient is calculated with a lidar ratio of 35 (clean continental) or 70 sr (polluted continental and smoke). As a result, the extinction coefficients determined in a more or less homogeneous aerosol layer over land are about 3.5 times higher than over the water surface (Fig. 6, right). An estimation of the solar radiative impact was performed by 1–D, plane–parallel radiative–transfer calculations with libRadtran [7] above IGBP grassland. For 13 January 2010 at 53°S, 71°W a difference of 10 W m$^{-2}$ for the daily mean solar radiative impact was estimated because of the change in AOT values from 0.02 (marine, $-3$ W m$^{-2}$) to 0.07 (polluted continental, $-13$ W m$^{-2}$) and the aerosol properties. Taking into account that the difference in the aerosol typing above land and ocean belongs to the prohibited possibility of marine aerosol over land by CALIOP's data algorithm, a significant bias on global estimates with CALIOP measurements cannot be ruled out. Besides an overestimation of the abundance and the radiative effect of continental aerosol by CALIOP's data in coastal regions, a misinterpretation of cloud–aerosol effects might happen as well.

## 6. OUTLOOK

The recent findings give evidence on discrepancies of the automatic data algorithm of CALIOP in coastal regions. On the one hand, we found out that the definition of the aerosol subtype discrimination in direct dependence of the surface type might lead to an underestimation of the presence of marine aerosols above land and discrepancies in the estimation of the global aerosol radiative effect. Further, we used the recommended quality flags of the level 2 version 3 data and found nevertheless questionable aerosol profiles that might be affected by overlying or mistreated clouds. In the future we will use our multiwavelength Raman lidar measurements at Punta Arenas for an intensive comparison study between ground–based and spaceborne lidar measurements. To our knowledge this approach will be unique in terms of the southern midlatitudes, clean marine aerosol conditions throughout the year, and the vicinity of multi–layered clouds.

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