

Establishing a long-term cloud record from a combination of space-borne lidar observations

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Abstract: This study presents a methodology to merge cloud data from different spaceborne lidar platforms, aiming to establish a long-term cloud record. By compensating for differences in wavelength, overpass time, and measurement gaps, the study reconciles data from CALIPSO, ALADIN/Aeolus, and AT Lid/EarthCARE. The approach enables the comparison and analysis of cloud datasets spanning from 2006 to present time, providing insights into cloud properties crucial for climate prediction. The findings highlight advancements in understanding cloud dynamics and offer valuable implications for future spaceborne lidar observations.

1. Introduction

Clouds exert multifaceted radiative effects on Earth's energy budget by reflecting the incoming solar radiation while also trapping the outgoing infrared radiation. Consequently, clouds contribute to both surface and atmosphere cooling and warming processes, exerting a profound influence on regional and global climate dynamics. Despite their crucial role for the Earth's energy balance, uncertainties persist regarding their feedback mechanisms.

A comprehensive understanding of clouds, including their spatial coverage, vertical distribution, and optical properties, is imperative for accurate climate prediction. Satellite-based observations, particularly those from active sounders, offer continuous monitoring of clouds with high vertical and horizontal resolution, starting from 2006. But, comparing cloud data from different spaceborne lidars presents challenges due to variations in wavelength, pulse energy, detector type, and local time of observation. It's evident that there is an obvious need to ensure the continuity of global space-borne measurements and to get a smooth transition between the satellite missions [1–3].

This study discusses a methodology aimed at reconciling cloud data derived from several disparate spaceborne lidar platforms: CALIPSO (Cloud-Aerosol Lidar and Infrared

Pathfinder Satellite Observation), which was operating from 2006 to 2023, ALADIN/Aeolus (Atmospheric Laser Doppler Instrument) operating in 2018–2023, and AT Lid/EarthCARE (ATmospheric LIDar), which should be launched this year.

2. Lidar data used in the study

CALIPSO-GOCCP

CALIOP, a two-wavelength polarization-sensitive near nadir viewing lidar operating at 532 and 1064 nm, provided high-resolution vertical profiles of aerosols and clouds [4–6]. The General Circulation Model (GCM) Oriented Cloud Calipso Product (CALIPSO-GOCCP) is derived from CALIPSO L1/NASA products at Laboratory of Dynamic Meteorology (LMD) and Institute of Pierre-Simon Laplace (IPSL) with the support of NASA/CNES, ICARE Thematic Center (Lille, France), and ClimServ data service (IPSL) and it contains observational cloud diagnostics including the instantaneous scattering ratio (profiles) at the native horizontal resolution of CALIOP (333 m) and at 480 m vertical resolution [7–9].

ALADIN lidar onboard Aeolus satellite

The Aeolus satellite carried a Doppler wind lidar called ALADIN, which operated at 355 nm wavelength and was composed of a transmitter, a Cassegrain telescope, and a

receiver capable of separating the molecular (Rayleigh) and particular (Mie) backscattered photons (high spectral resolution lidar, HSRL). Its main purpose was measuring winds, but it also provided information on optical properties of the atmosphere. In this study, we used Aeolus L2A aerosol optical properties product [10]. We have to stress here that when using the ALADIN's measured backscattered radiance in the retrieval of atmospheric optical properties, it is crucial to compensate for a loss of cross-polar backscattered component, which is not registered by ALADIN's detectors.

ATLID lidar onboard EarthCARE platform

The goals of the EarthCARE mission are “to retrieve vertical profiles of clouds and aerosols, and the characteristics of their radiative and microphysical properties to determine flux gradients within the atmosphere and fluxes at the Earth's surface, as well as to measure directly the fluxes at the top of the atmosphere and also to clarify the processes involved in aerosol-cloud and cloud-precipitation-convection interactions” [11,12]. The ATLID instrument onboard the EarthCARE satellite will measure the attenuated atmospheric backscatter with a vertical resolution of ~100 m and ~500 m in the altitude ranges of 0–20 km and 20–40 km, respectively. ATLID is a polarization-sensitive, high-spectral resolution lidar (HSRL), which can separate the thermally broadened molecular backscatter (Rayleigh) from the unbroadened backscatter from atmospheric particles (Mie). This helps ATLID retrieve extinction and backscatter vertical profiles without assuming the extinction-to-backscatter ratio (as in CALIOP retrievals), which is poorly known, especially for aerosols.

3. Cloud merging approach

Compensating for wavelength difference

For historical reasons, we use the Scattering Ratio at 532 nm (SR532) as a baseline for our cloud definition. In the numerator, we put the Attenuated Total Backscatter at 532 nm (ATB532), and the denominator contains a would-be Attenuated Molecular Backscatter at 532 nm (AMB532), which is calculated in an assumption of cloud-free atmospheric profile. To consider the layer as cloudy, we require the fulfillment of two conditions: $SR532 > 5$ and $(ATB532 - AMB532) > 2.6e-6 \text{ m}^{-1} \text{ sr}^{-1}$ [7, 13]. Correspondingly, for the measurements

performed at other wavelengths we make a conversion of the retrieved optical properties to SR532 and ATB532 to compare apples to apples. We show that using this approach one can retrieve comparable clouds both for CALIOP and ALADIN using real measurements and for CALIOP and ATLID using synthetic measurements.

Compensating for difference in overpass time

If the lidars do not overfly the same area at the same local solar time (LST), the cloud products should be corrected for differences in cloud cover associated with the diurnal cycle. For example, CALIOP crossed the equator at 01:30 and 13:30 LST, whereas for Aeolus these times were 06:30 and 18:30 LST. Based on the previous studies [14–16], one can say that the cloud diurnal cycle is strong for the high tropical clouds and for low-level clouds over the ocean, reaching 20% in certain areas. In addition, the phase of diurnal cycle is not the same for all clouds. For a combination of CALIOP and ATLID, the LST difference is smaller, but the approach we propose is general: we use a diurnal cycle climatology retrieved [16] either from a combination of two passive sounders, AIRS and IASI, which have been operating in space for more than 15 years, or from CATS observations [17]: Cloud-Aerosol Transport System (CATS) lidar on the International Space Station (ISS), which was operating for more than 2.5 years and collected a good statistics on the diurnal cycle of clouds. For the correction, we use a gridded monthly dataset retrieved from these observations.

Compensating for a gap between measurements

For a pair of lidars overlapping in time, it is straightforward to fine-tune the aforementioned cloud detection parameters to ensure a seamless transition between the datasets: the data are collocated in time and space and the collocated dataset is analyzed with respect to cloud fraction at different latitudes, altitudes, and seasons. The differences are explored and the correction is introduced, which might be linked to a sensitivity of a given instrument or to its noise. However, if the instruments do not overlap in time, then an intermediate step is needed, which might be either a comparison with a set of ground-based stations, or a climatological comparison, assuming a small interannual variability.

4. Summary

For a series of completely different space-borne lidars, we have developed a method of compensating for (a) wavelength, (b) lack of depolarization, (c) cloud diurnal cycle, (d) differences in noise levels, (e) gap between observational periods. With these corrections, we have produced and analyzed the joint CALIOP-ALADIN cloud dataset for the period of 2006–2023 and we estimated cloud observability for synthetic ATLID data w.r.t. CALIOP.

5. References

- [1] D. Winker, H. Chepfer, V. Noël, and X. Cai, "Observational constraints on cloud feedbacks: The role of active satellite sensors," *Surveys in Geophysics*, **38**, 1483–1508 (2017).
- [2] H. Chepfer, V. Noël, D. Winker, and M. Chiriaco, "Where and when will we observe cloud changes due to climate warming?," *Geophys. Res. Lett.*, **41**, 8387–8395 (2014).
- [3] H. Chepfer, V. Noël, M. Chiriaco, B. Wielicki, D. Winker, N. Loeb, and R. Wood, "The potential of multi-decades space-born lidar to constrain cloud feedbacks," *J. Geophys. Res. Atmos.*, **123**(10), 5433–5454 (2018).
- [4] D. M. Winker, W. H. Hunt, and C. A. Hostetler, "Status and Performance of the CALIOP Lidar," *Proc. SPIE*, **5575**, 8-15 (2004)
- [5] D. M. Winker, W. H. Hunt, and M. J. McGill, "Initial performance assessment of CALIOP," *Geophys. Res. Lett.*, **34**, L19803 (2007).
- [6] D. M. Winker, M. A. Vaughan, A. H. Omar, Y. Hu, K. A. Powell, Z. Liu, W. H. Hunt, and S. A. Young, "Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms," *J. Atmos. Ocean. Tech.*, **26**, 2310–2323 (2009).
- [7] H. Chepfer, S. Bony, D. Winker, M. Chiriaco, J.-L. Dufresne, and G. Sèze, "Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model," *Geophys. Res. Lett.*, **35**, L15704 (2008).
- [8] H. Chepfer, S. Bony, D. Winker, G. Cesana, J.-L. Dufresne, P. Minnis, C. J. Stubenrauch, and S. Zeng, "The GCM Oriented Calipso Cloud Product (CALIPSO-GOCCP)," *J. Geophys. Res.*, **115**, D00H16 (2010).
- [9] H. Chepfer, G. Cesana, D. Winker, B. Getzewich, M. Vaughan, and Z. Liu, "Comparison of two different cloud climatologies derived from CALIOP attenuated backscattered measurements (Level 1): the CALIPSO-ST and the CALIPSO-GOCCP," *J. Atmos. Oceanic Technol.* (2012).
- [10] T. Flament, D. Trajon, A. Lacour, A. Dabas, F. Ehlers, and D. Huber, "Aeolus L2A aerosol optical properties product: standard correct algorithm and Mie correct algorithm," *Atmos. Meas. Tech.*, **14**, 7851–7871 (2021).
- [11] A. Hélière, R. Gelsthorpe, L. Le Hors, and Y. Toulemont, "ATLID, the Atmospheric Lidar on board the EarthCARE Satellite," *Proceedings of the ICSSO (International Conference on Space Optics)*, Ajaccio, Corse, France, Oct. 9-12, 2012, paper: ICSSO-065 (2012).
- [12] A. J. Illingworth et al., "The EarthCARE satellite: the next step forward in global measurements of clouds, aerosols, precipitation, and radiation," *Bull. Am. Meteorol. Soc.*, **96**, 1311–1332 (2015).
- [13] A. G. Feofilov, H. Chepfer, V. Noël, R. Guzman, C. Gindre, P.-L. Ma, and M. Chiriaco, "Comparison of scattering ratio profiles retrieved from ALADIN/Aeolus and CALIOP/CALIPSO observations and preliminary estimates of cloud fraction profiles," *Atmos. Meas. Tech.*, **15**, 1055–1074 (2022).
- [14] V. Noël, H. Chepfer, M. Chiriaco, and J. Yorks, "The diurnal cycle of cloud profiles over land and ocean between 51° S and 51° N, seen by the CATS spaceborne lidar from the International Space Station," *Atmos. Chem. Phys.*, **18**, 9457–9473 (2018).
- [15] H. Chepfer, H. Brogniez, and V. Noel, "Diurnal variations of cloud and relative humidity profiles across the tropics," *Scientific Reports*, **9**, 16045 (2019).
- [16] A. G. Feofilov and C. J. Stubenrauch, "Diurnal variation of high-level clouds from the synergy of AIRS and IASI space-borne infrared sounders," *Atmos. Chem. Phys.*, **19**, 13957–13972 (2019).
- [17] M. J. McGill, J. E. Yorks, V. S. Scott, A. W. Kupchock, and P. A. Selmer, "The Cloud-Aerosol Transport System (CATS): A technology demonstration on the International Space Station," *Proc. Spie.*, 9612 (2015).