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Diversity on subtropical and polar cirrus clouds properties as derived from both ground-based lidars and CALIPSO/CALIOP measurements

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ABSTRACT

Cirrus (Ci) cloud properties can change significantly from place to place over the globe as a result of weather processes, reflecting their likely different radiative and climate implications. In this work Cirrus clouds (Ci) features observed in late autumn/early winter season at both subtropical and polar latitudes are examined and compared to CALIPSO/CALIOP observations. Lidar measurements were carried out in three stations: São Paulo (MSP, Brazil) and Tenerife (SCO, Canary Islands, Spain), as subtropical sites, and the polar Belgrano II base (BEL, Argentina) in the Antarctic continent. The backscattering ratio (BSR) profiles and the top and base heights of the Ci layers together to their Cirrus Cloud Optical Depth (CCOD) and Lidar Ratio (LR) for Ci clouds were derived. In addition, temperatures at the top and base boundaries of the Ci clouds were also obtained from local radiosoundings to verify pure ice Ci clouds occurrence using a given temperature top threshold (<-38 °C). Ci clouds observed along the day were assembled in groups based on their predominant CCOD, and classified according to four CCOD-based categories. Ci clouds were found to be vertically-distributed in relation with the temperature, forming subvisual Ci clouds at lower temperatures and higher altitudes than other Ci categories at both latitudes. Discrepancies shown on LR values for the three stations, but mainly remarked between subtropical and polar cases, can be associated to different temperature regimes for Ci formation, influencing the internal ice habits of the Ci clouds, and hence likely affecting the LR derived for the Ci layer. In comparison with literature values, daily mean CCOD/LR for SCO ($0.4 \pm 0.4/21 \pm 10$ sr), MSP ($0.5 \pm 0.5/27 \pm 5$ sr) and BEL ($0.2 \pm 0.3/28 \pm 9$ sr) are in good agreement; however, the variability of the Ci optical features along the day present large discrepancies. In comparison with CALIOP data, Ci clouds are observed at similar altitudes (around 10–13 km height); however, differences are found mostly in CCOD values for subtropical Ci clouds, whereas LR values are in a closer agreement. These differences are carefully examined in relation with the closest CALIPSO overpass time and distance from the station (>70 km far), inferring the irregular extension and inhomogeneity of the Ci clouds over each study area. These considerations can be useful for assimilation of the Ci features into climate models and evaluation of future space-borne lidar observations of Ci clouds, especially for the future ESA/Copernicus-Sentinel and ESA/EarthCARE missions.

1. Introduction

Both weather and climate are evidently affected by Cirrus (Ci) clouds. Indeed, their role in the radiation balance of the Earth-atmosphere system can be regionally and globally observed (Liou, 1986; Stephens, 2005; Yorks et al., 2009; Yang et al., 2012) as cooling or heating modulations. What it still a puzzle is the response of Ci clouds to factors related to anthropogenic climate changes, i.e. greenhouse effect (Iacono et al., 2008), or increasing upper tropospheric contamination from enhanced aviation circulation (Boucher, 1999). The Ci cloud radiation transfer properties could alter, either enhancing or negating, the supposed global warming effect linked to aerosols as reported in the last Intergovernmental Panel on Climate Change (IPCC, 2013) (Boucher et al., 2013). In particular, Cirrus aircraft-induced contrails could increase the albedo of the upper troposphere, modifying the warming effect associated to greenhouse gases (Burkhardt and

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Kärcher, 2011). The balance between the infrared greenhouse warming and solar albedo cooling depends on both Ci cloud altitude and their microphysical features (Myhre et al., 2013).

In this context cloud height plays a significant role. Tropical Cirrus located at high altitudes can act as effective greenhouse modulators. In opposition, low-altitude Cirrus over Polar Regions can be more cooling efficient due to their albedo effects (Sassen and Campbell, 2001). Hence, mid-latitude Ci clouds are assumed to reveal radiative implications varying with season (Sassen and Comstock, 2001; Dupont and Haeffelin, 2008; Campbell et al., 2016; Kienast-Sjögren et al., 2016). Regarding microphysical aspects of the Cirrus clouds, namely ice clouds, they are composed of ice crystals that can present different crystal habits, shapes, orientations, sizes, phases, Ice Water content (IWC), among others, in dependence on their formation mechanism: a) directly from the gas phase (in situ origin), and b) by freezing of liquid father below drops, but uplifted into Ci temperature regimes (liquid origin) (more details, see Krämer et al., 2016). Regardless of the determination of the microphysical features is out the scope of this work, they are directly linked to both the optical and macrophysical properties of Cirrus clouds. Indeed, 'in situ' Cirrus are optically thin and present a lower IWC in comparison with the 'liquid' Cirrus, optically thicker and with a higher IWC. In addition, those Cirrus formation mechanisms depend also critically on the weather situations (convective processes, high pressure frontal systems, jet streams, atmospheric waves, …) (Krämer et al., 2016). Hence, Ci clouds are a weather product; their properties and occurrence can differ over diverse regions of the world.

In general, since Ci clouds form at high altitude levels (typically, from 7 km up to the tropopause), active remote sensing instrumentation, as lidar systems, are widely used for their detection, either deployed in ground-based stations (Sassen and Campbell, 2001; Giannakaki et al., 2007; Seifert et al., 2007; Dupont et al., 2010; Kim et al., 2014; Campbell et al., 2016; Kienast-Sjögren et al., 2016) or aboard space platforms (Sassen et al., 2008; Josset et al., 2012; Zhang et al., 2014; Campbell et al., 2015). Lidars appear as the most suitable instrumentation for high-cloud observations, since they can provide vertical measurements with good vertical and temporal resolutions. The studies conducted by Platt and Sassen (Platt and Dilley, 1981; Sassen et al., 1989) pioneered the studies of Ci clouds with lidars and radiometers and pursued a comprehension on intensive and extensive variables which much affect Ci cloud optical properties. These quantities and the geometric properties of such clouds opened a pathway to explore simulations and models built in order to understand their influence on radiative processes. Understanding the properties and morphology of ice crystals in those clouds allowed the understanding of habits, simple and complex, with geographical variability and under different synoptic conditions (Baum et al., 2011). Also regionally the cloud optical properties have been studied such as in Europe (Dupont et al., 2010; Kienast-Sjögren et al., 2016), North America and Pacific Regions (Hawaii) (Yorks et al., 2011; Campbell et al., 2016), Asian areas (He et al., 2013; Kim et al., 2014), the Mediterranean (Giannakaki et al., 2007) and Indian Sea (Seifert et al., 2007; Das et al., 2009). Therefore, our study represents a significant part of the globe with its own mesoscale processes to formation and circulation of Ci clouds. More recently, in the past ten years, satellites platforms (CERES, CALIPSO, MODIS, CLOUDSAT) (Vaughan et al., 2009; Vaughan et al., 2010; Josset et al., 2012; Guo et al., 2016) have provided important insights on the comprehension of Ci clouds and their role in radiative transfer. Lidar studies devoted to cloud identification and optical properties are of great interest and provide together with CLOUDSAT an important cloud database (Zhang et al., 2014) as the generated results are useful to improve cloud parameterizations in climate models and their validation. In addition, a great effort was made towards correcting multiple scattering effects (Wandinger, 1998), and enhancing the understanding on their temperature dependence (i.e., Garnier et al., 2015).

Moreover, the depolarization factor is a lidar parameter usually used to identify ice phases within the clouds, and then providing an estimate of the internal state of Ci clouds. However, some lidar systems cannot support depolarizing capabilities, hence a thermal threshold for cloud top temperature of <− 37 °C (236 K) (Sassen and Campbell, 2001) or − 38 °C (235 K) (Krämer et al., 2016) (below that value liquid water is absent) is proposed to clearly distinguish Cirrus (ice) cloud presence in lidar profiles (i.e., Campbell et al., 2015; Kienast-Sjögren et al., 2016).

This work describes the methodology for retrieving the macrophysical and optical features of Ci clouds detected by lidar observations, using that temperature threshold of <− 38 °C combined with a modified version of recently proposed procedures (Larroza et al., 2013; Barbosa et al., 2014). Ci clouds features observed in late autumn/early winter season at both subtropical and polar latitudes are analyzed for particular case studies. In addition, their potential latitudinal variability is examined. This study is focused on: (1) classifying the daily cloud features into four Ci categories according to their Cloud Optical Depth (CCOD), as adapted from Sassen et al. (1989) and Sassen and Cho (1992): subvisual-1 (svCi-1, CCOD < 0.03, as a threshold for the visible Ci detection in the zenith), subvisual-2 (svCi-2, CCOD: 0.03–0.1, as a less conservative threshold for visible clouds: Platt et al. (1987) proposed a value of 0.06 instead); semitransparent (stCi, CCOD: 0.1–0.3), and opaque (opCi, CCOD > 0.3) clouds; and (2) analyzing the temperature-related Ci formation with respect to altitude. In order to expand this comparative analysis our ground-based (GB) lidar measurements, as carried out along the day, were evaluated together with the space-borne lidar CALIOP aboard CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation, www.calipso.larc.nasa.gov) observations (Winker et al., 2009), as performed only once per day. Their similarities and discrepancies are also discussed.

This study strongly encourages the establishment of a long-term Ci clouds monitoring network, and adding future stations to these existing ones, including mid-latitude observations.

2. Methodology

2.1. Ground-based (GB) lidar observations

2.1.1. Stations and lidar systems

Cirrus (Ci) clouds observations were performed in an Antarctic polar station and two subtropical sites. The polar Belgrano II base (BEL, Argentina, 78°S 35°W), managed by the Instituto Antártico Argentino/Dirección Nacional del Antártico (IAA/DNA), is located in deep Antarctica. The two subtropical stations were the Santa Cruz de Tenerife observatory (SCO, Canary Islands-Spain, 28.5°N 16.3°W) and the Metropolitan city of Sao Paulo station (MSP, Brazil, 23.6°S 46.8°W), managed by the Agencia Estatal de Meteorología (AEMET) and the Instituto de Pesquisas Energéticas e Nucleares (IPEN), respectively. Fig. 1 shows the location of all these stations around the world.

Lidar systems deployed at SCO and BEL sites are two Micro Pulse Lidars (MPL) (Campbell et al., 2002), v.3 (MPL-3) and v.4 (MPL-4, including depolarization capability), respectively. MPLs are the standard lidars that are in routine continuous operation (24 h/7 d) within the NASA/MPLNET (MicroPulse Lidar NETwork, mplnet.gsfc.nasa.gov) (Welton et al., 2001), and belong to the Spanish Institute for Aerospace Technology (INTA, Instituto Nacional de Técnica Aeroespacial, www.inta.es/atmosfera), managed in collaboration with the AEMET (Spain) and IAA (Argentina), respectively. The MSP lidar system (SPL) is managed by the IPEN/Centro de Lasers e Aplicaçoes (IPEN/CLA, gescon.ipen.br/leal), and operates within LALINET a.k.a. ALINE (Latin America LIdar NETwork, lalinet.org) (Guerrero-Rascado et al., 2016). Principal features and acquisition settings of each lidar system are shown in Table 1. Lidar signals detected at above 7 km height up to the tropopause are referred to Ci signatures. In the case of the polar Cirrus, in order to avoid Polar Stratospheric Clouds (PSC) contamination (Córdoba-Jabonero et al., 2009, 2013), only PSC-free conditions observed over Belgrano site are considered. Local radiosounding profiles are also used for Cirrus temperature estimation and tropopause levels determination.