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Review article

Monitoring cirrus clouds with lidar in the Southern Hemisphere: A local study over Buenos Aires. 1. Tropopause heights

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ABSTRACT

Cirrus clouds in the upper troposphere and the lower stratosphere have recently drawn much attention due to their important role and impact on the atmospheric radiative balance. Because they are located in the upper troposphere their study requires a high resolution technique not only to detect them but also to characterize their behaviour and evolution. A good dynamic range in lidar backscattering signals is necessary to observe and improve our knowledge of cirrus clouds, and thereof, atmospheric parameters in the troposphere and UT/LS due to their vicinity to the tropopause layer. The lidar system measures, in real time, the evolution of the atmospheric boundary layer, stratospheric aerosols, tropopause height and cirrus clouds evolution.

The aim of the work is to present the main properties of cirrus clouds over central Argentina and to monitor tropopause height together with their temporal evolution using a backscatter lidar system located in Buenos Aires (34.6 °S, 58.5 °W). A cirrus clouds detection method was used to analyze a set of 60 diurnal events, during 2001–2005, in order to estimate tropopause height and its temporal evolution, using the top of cirrus clouds present on the upper troposphere as a tropopause tracer. The results derived from lidar show a remarkable good agreement when compared with rawinsonde data, considering values of tropopause height with differences less than or equal to 500 m, depending on the signal to noise ratio of the measurements. Clouds properties analysis reveals the presence of thick cirrus clouds with thickness between 0.5 and 4.2 km, with the top cloud located at the tropopause height.

Contents

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1. Introduction

Upper tropospheric clouds, such as cirrus, have been identified as one important regulator of the radiance balance of the earth–atmospheric system (Liou, 1986). They cover about 30% of the Earth's surface at any one time, and play an important role in the Earth's climate system owing to their capability of trapping outgoing long-wave (greenhouse effect) and reflecting solar radiation (albedo effect), as well as in the troposphere–stratosphere exchange. The radiative impact can be determined by the balance greenhouse-versus-albedo effects (Liou, 1986; Wylie et al., 1994). The interaction between these two effects is at the core of the radiative budget and therefore the radiation balance depends on the optical properties as well as the thickness, height and temperature of the cirrus layers (Seifert et al., 2007).

As Immler et al. (2008) pointed out: "a clear definition of what should be classified a cirrus clouds is missing to date". Moreover, Ström et al. (2003), emphasizes that what is interpreted as a cloud by one sensor might be interpreted as cloud free air by another. Due the different definition referred to what a cirrus cloud must be, we consider the more general definition to classify the sample presented here, given by the International Coordination group on Laser Atmospheric Studies (ICLAS)(Linch et al., 2002): cirrus clouds derived from lidar measurements are layers of particle above 6 km situated in an air mass with temperature of −25°°C or colder which in addition display a large temporal and spatial variability.

The cirrus clouds appear below the tropopause, especially in the tropics (Beyerle et al., 1998) and they have been observed also above the local tropopause at mid-latitudes (Goldfarb et al., 2001) and polar regions (Formenti et al., 1999; Kärcher and Solomon, 1999). As the mean distance between the tropopause and the hygropause increases from 1 km at low latitudes to 4 km at high latitudes (Chiou et al., 1997), the probability for cirrus to form above the thermal tropopause increases from the equator to the poles, whenever the formation conditions are met. This is coincident with the more recent definitions of the tropopause which view it as a layer of latitudinally varying thickness rather than as a rapid transitions (Bischoff et al., 2007 and references therein). Therefore, monitoring tropopause cirrus clouds height and its time evolution might be considered to be an alternative way, scarcely used at mid-latitudes, with an accuracy equal or higher than rawinsonde., i.e.: tropopause cirrus clouds can be viewed as tropopause tracers.

Due to the high altitude of the cirrus clouds, in situ measurements of their properties are a difficult issue. Moreover, in the Southern Hemisphere, particularly over Argentina, the top of these ice clouds are often located close to the tropopause, which means high altitude observations are a necessity.

Cirrus clouds near the tropopause have been characterized in situ by aircraft (Heymsfield and McFarquhar, 1986; McFarquhar et al., 2000; Pfister et al., 2001; Luo et al., 2003), from space using as examples MODIS and IRIS satellite imagery (Prabhakara et al., 1998; Dessler and Yang, 2003) and limb scanner imagery from space shuttle (Winker and Trepte, 1998; Spang et al., 2002). Finally a global overview was carried out by the Satellite Cloud Climatology Project (ISCCP). Though the satellite observations provide valuable information on cirrus clouds, they have limitations on spectral, temporal and spatial coverage. This stresses the need for local active remote sensing, such as lidar, whose capability to detect high and optically thin cirrus makes it one of the most appropriate instruments for cirrus study (Noel et al., 2007).

Lidar retrievals of atmospheric parameters are an effective tool to characterize the time and spatial evolution of the atmospheric boundary layers as well as to investigate the physics properties of the cloud composing particles (Wang et al., 2005). Physical parameters of primary concern are thickness and altitude of the cirrus clouds. Moreover, mean altitude and mid-cloud temperature play an important role in determining cloud radiative properties (Sunilkumar and Parameswaran, 2005).

Large number of experiments were conducted to investigate and improve our knowledge in different regions of the globe using various techniques employing lidars: Uthe and Russell, 1977; Liou, 1986; Sassen et al., 1989; Ansmann et al., 1992; Wang et al., 1996; Platt et al., 1998, 2002; Heymsfield et al., 1998; Sassen et al., 2000; Goldfarb et al., 2001; Comstock et al., 2002; Keckhut et al., 2005; Sunilkumar and Parameswaran, 2005; Seifert et al., 2007; Immler and Schrems, 2002; Immler et al., 2008, among others. However, over southern mid-latitudes the vertically and temporally resolved measurements of cirrus clouds properties are still scarce. In fact, to the best of our knowledge, except the INCA project concerning cirrus clouds over Punta Arenas, Chile (Immler and Schrems, 2002), there are virtually no studies referring to the tropopause cirrus over the Southern Hemisphere (SH), in particular linking their presence with tropopause height.

This contribution presents the first comprehensive lidar based cirrus cloud analysis for Buenos Aires, Argentina. The primary goal of the present work is to provide insights on two comparable datasets, derived from rawinsonde and lidar system on SH mid-latitude cirrus clouds, respectively, for this region, in order to analyze the tropopause height and its temporal evolution, by analyzing the evolution of the top of these cirrus. Furthermore, the paper describes some of the particular regional properties like thickness, temperature and altitude, of the detected cirrus.

2. Lidar system

The elastic backscatter lidar used for the present work is located in Villa Martelli near Buenos Aires (34.6 S, 58.5 W) and is based on Nd: YAG laser transmitter (Continuun—Surelite II) which delivers around 300 mJ by pulse at 532 nm with a 10 Hz pulse repetition frequency, 5 ns pulse duration, with a tilt angle less than 0.6 mrad. A dual telescope receiver is used to handle the large signal dynamic range. An 8.2 cm diameter Cassegrain telescope covers the range between 50 m and 6 km, while a 50 cm diameter Newtonian telescope covers from 300 m up to 28 km. The two telescopes are pointed at zenith. A field of view less than 1.5 mrad is normally used for both telescopes.

In order to improve the system for future measurements, two interferential filters at 532 nm and 1064 nm were added to reduce the radiometric background during daytime. The 8.2 cm diameter telescope has now two channels at 532 nm Photomultiplier (PTM) and 1064 nm Photodiode (PD), while the 50 cm diameter telescope has three channels: 532 parallel, 532 perpendicular and 1064 nm. The optical part of the detection channel implemented on the 50 cm diameter telescope is based on two optical elements. On one side, a dichroic mirror is used to separate the two probing wavelengths (R=95% in 532 nm and T=85% in 1064 nm) (Lavorato et al., 2004). On the other side, depolarizer unit is used to separate the polarized parallel beam from the perpendicular one at 532 nm. The 1064 nm signal is focused and sent onto a PD detector by a fiber optic link. The fiber optic is coupled directly to a photodiode (YAG-100-Quantum Efficiently=50% at 1064 nm). A large band and high gain photomultiplier amplify the electrical signal, which is sent to the analog to digital converter and data acquisition unit.

After detection by high gain-low noise PMTs and PD at 1064 nm, the lidar signal is low-pass filtered with an 800 MHz

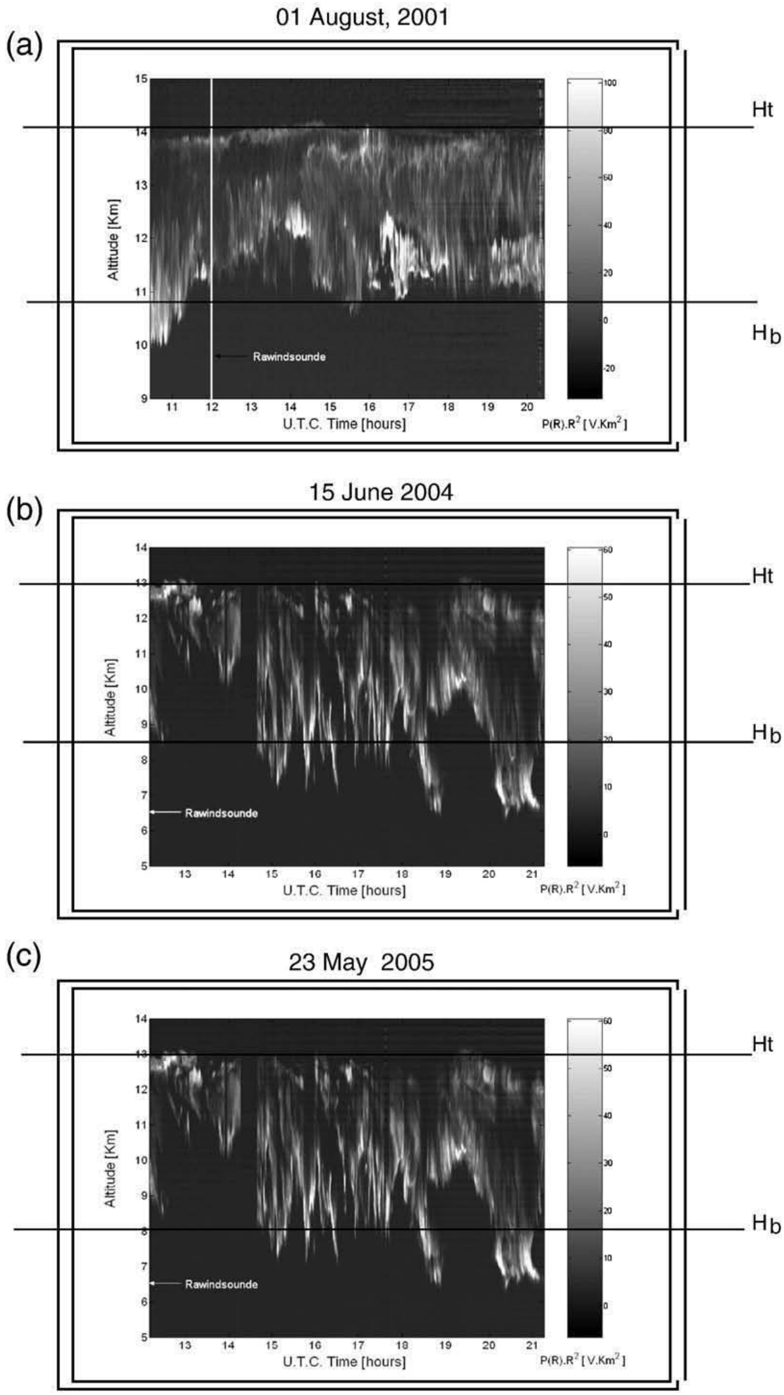

Fig. 1. Three cases of cirrus observations during 2001–2005. Range-corrected 532-nm signals with 50-s and 6-m resolution. Hb and Ht denote mean cloud base and tope, respectively.

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cut-off frequency filter in order to eliminate radio frequency noise. The analogue to digital converter is a 10 bits/25 MS/s numerical oscilloscope. Such a lidar system allows to measure daily lidar signals with a quite good signal to noise ratio in absence of high level cloudiness, pollutants or aerosols.

3. Data and methodology

The selection criterion used to collect data during the present campaign was at first restricted by the availability of measurements; i.e., the visibility of the cirrus from the ground and the absence of aerosols or pollutants between the boundary layer and the tropopause layer. On the other hand, the optical thickness or the optical depth (O.D.) also influences the measurements; i.e., an optical thickness greater than 3 might require other computational process in order to obtain a reasonable extinction coefficient. Hence, only those daily measurements in a clear sky or absence of aerosols, with O.D. less or equal than 3 was considered. Those measurements that do not satisfy this criterion were excluded

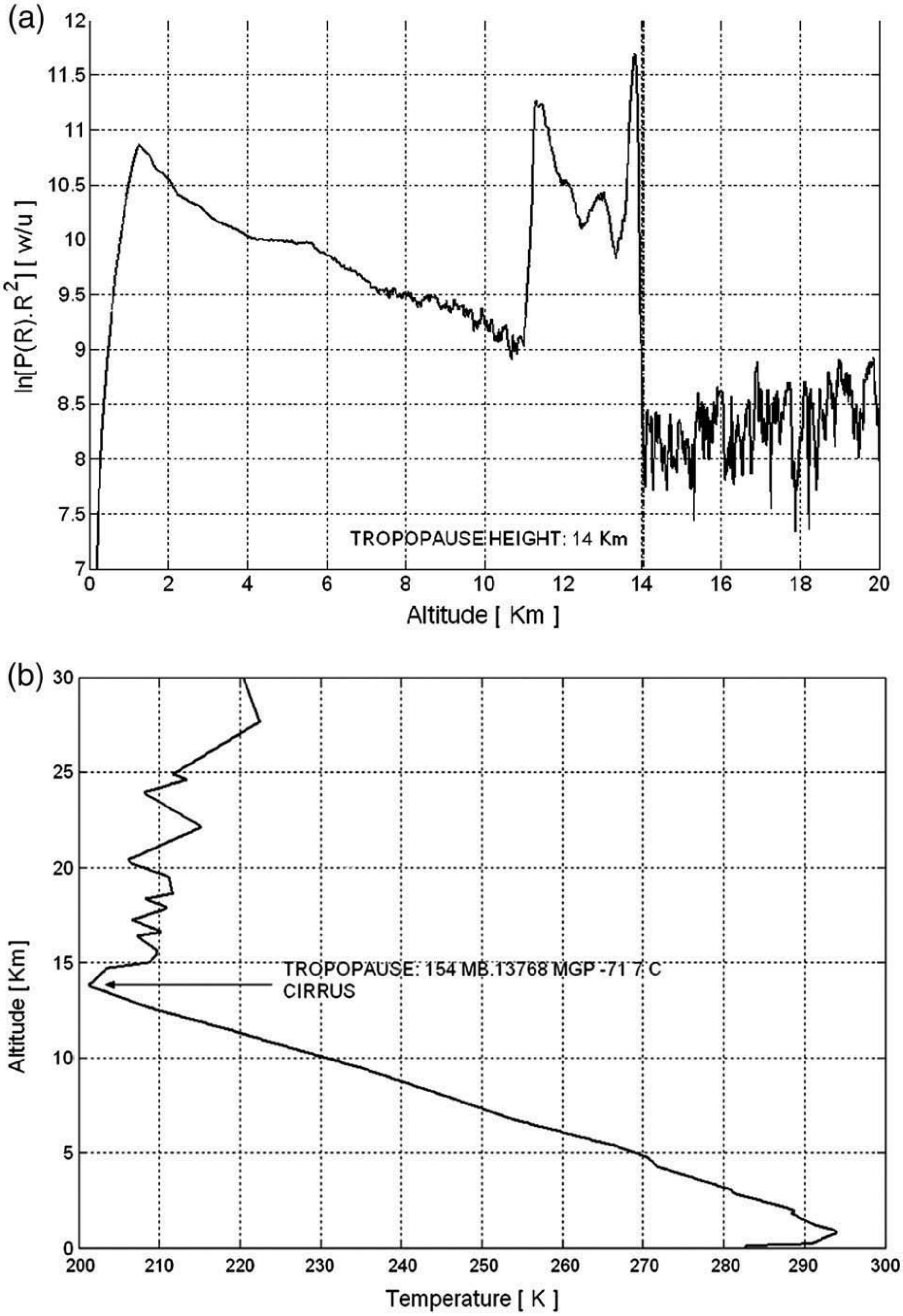

Fig. 2. Tropopause height detection from cirrus cloud (a) dated august 1st, 2001,compared with rawinsonde data (b).

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from this study. The uncertainty caused from the selection criterion is estimated to be 15%.

In order to study tropopause height, only the high resolution lidar signals are considered, which were plotted in a logarithmic scale plot for the electric pulse. These signals are mathematically processed in three stages in order to correct the range of the scale, filter the noise and obtain the best signal to noise ratio. The final lidar signal is averaged with more than 500 laser shots. By adjusting the slope of the high resolution signal with a linear fit up to the point where the cirrus ends, it is possible to detect the tropopause height as the altitude of the last point of the cirrus clouds signal (Klett, 1981; Fernald, 1984). This technique should be considered a graphic method to detect the tropopause height with a confidence interval of about 500 m. Here we use the conventional thermal tropopause height, as given by the World Meteorological Organization (WMO). This is defined as the lower boundary layer of an atmospheric layer in the upper troposphere in which the temperature lapse rate is less than 2 °C km^{-1} and this layer has to be at least 2 km thick (WMO, 1992).

Due to the ambiguity of the thermal tropopause definition with respect to the different processes involved in both hemispheres (Shepherd, 2002) which are also used to define it, e.g., chemical tropopause and dynamical tropopause, it should be noted that when we refer to tropopause, the Extra-

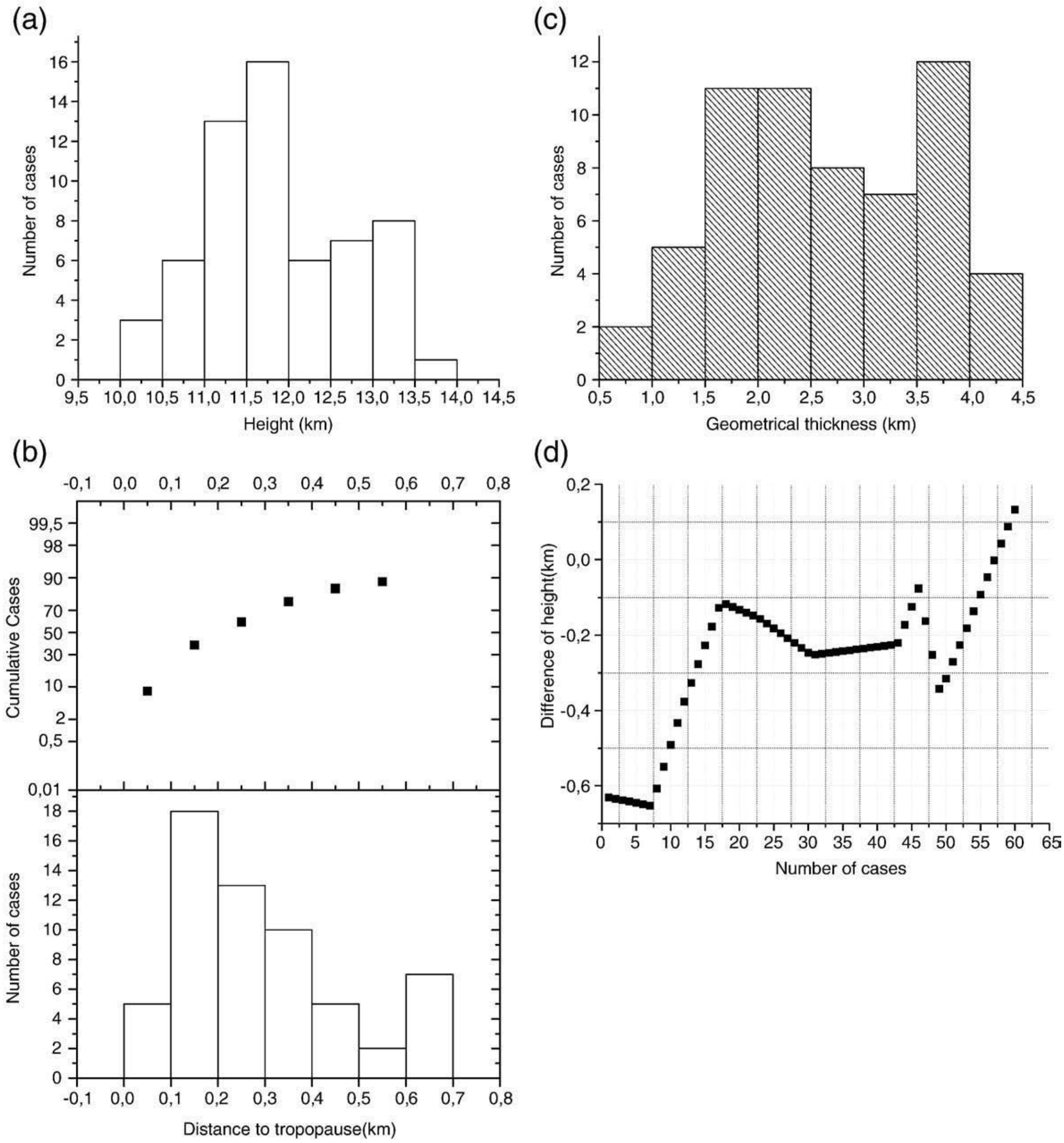

Fig. 3. Distribution of number de cases of cloud parameters: (a) mean Height, (b) thickness (c) Distance between cloud top and the tropopause (d) Differences height (km) of cloud top with respect to the tropopause.

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tropical Tropopause Layer (ExTL) as explained in Bischoff et al. (2007) is considered.

In this study a set of 60 cirrus cloud signals are considered for the period 2001–2005. It is important to note that the profiles collected correspond essentially to diurnal signals. Hereafter these profiles will be called events, where each event represents a profile for a specific year, month, day and hour, i.e., instantaneous measurements.

The measurements derived from lidar system were compared with the local rawinsonde launched at Ezeiza (SAEZ, which is 25 km away to the west the lidar system) and provided by the Argentine Servicio Meteorológico Nacional (SMN), in order to evaluate the accuracy of the lidar system and the detection approach used here. The SMN data set used in this study is restricted to 00 UTC and 12 UTC when available.

4. Results and discussion

Cirrus monitoring was continuously carried out for up to nine consecutive hours for each event. The temporally averaged lidar signal profiles were recorded with 6 m of vertical resolution. Fig. 1 displays three examples of the cirrus cloud dataset collected during the present campaign. In cases of inhomogeneous structures (see Fig. 1b) the mean cloud base and mean cloud top height were calculated during the entire observational period.

In these figures it is possible to observe at first sight, thick cirri in the ~8–11.5 km height range, with thicknesses spanning 2.6–4.2 km.

The tropopause altitude was calculated using the slope method as described in the previous section. Fig. 2 shows the method applied for August 1st, 2001. For this case, the difference in cloud top altitude and tropopause height was about 0.25 km.

Using the data collected during the whole campaign, a preliminary analysis of the morphology of cirrus clouds, over Buenos Aires (34.6 S, 58.5 W) was carried out. Fig. 3 presents the frequency distribution for the clouds parameters of mean height and thickness.

Fig. 3a shows the distribution of the cirrus clouds mean height. The occurrence height of the cirri is confined to the 10–14 km height range. The cirrus cloud heights are very close to the tropopause, in most of the cases, with the maximum occurrence in the range 11.5 to 12.0 km. Fig. 3b, which presents the distribution for occurrence of cirrus cloud top height with respect to the tropopause height, shows that cirrus cloud tops stay aligned with the tropopause height, while the cloud base shows more variability. In this sense, it is important to highlight that Fig. 3b represents not only the cirrus top height, but also the tropopause altitude with differences between cirrus top and the lapse rate tropopause altitude less than or equal to 0.5 km in ~70% of the cases. Fig. 3d displays the difference values between cirrus top height and tropopause altitude. The plot stresses the small difference between lidar measurements and rawinsonde data, which reaches values of less than 0.6 km. This result shows a remarkable agreement between the two datasets under comparison, with a confidence ~95%. Thus, in the light of the altitude behaviour of the cirrus top, it is possible to assume that top cirri over Buenos Aires, can be viewed as tropopause tracers.

Radiative properties of cirrus strongly depend on its temperature. Mid-cloud temperature is the parameter generally used for parameterizing (Heymsfield and Platt, 1984; Sassen and Comstock, 2001) their radiative properties.

Fig. 4a displays the distribution of cirrus occurrence with cloud temperature for the dataset under study. The plot displays a first maximum between −69° and −67 °C, with two secondary maxima at −65° and −61 °C.

In order to identify similarities and differences in the cirrus properties for different latitudinal bands, present results are compared with measurements derived from lidar system at other latitudes. As was pointed out in several papers (e.g., Sassen et al., 1990; Ansmann et al.; 1992; Jensen et al.; 1996; Heymsfield and McFarquhar, 1986; Goldfarb et al., 2001) at mid-latitudes, the occurrence height of thin cirrus clouds is mostly between 8.5 and 11.5 km. Results derived from different research at mid-latitudes carried out by Ansmann et al. (1993), Sassen and Campbell (2001), Sassen and Comstock (2001), Wang and Sassen (2002), Reichardt (1999), show that top heights were found most frequently from 11–13 km, with mean thicknesses around 1.8–2.5 km. Nevertheless, the thickness of the cirri at our southern latitude site seems to be greater

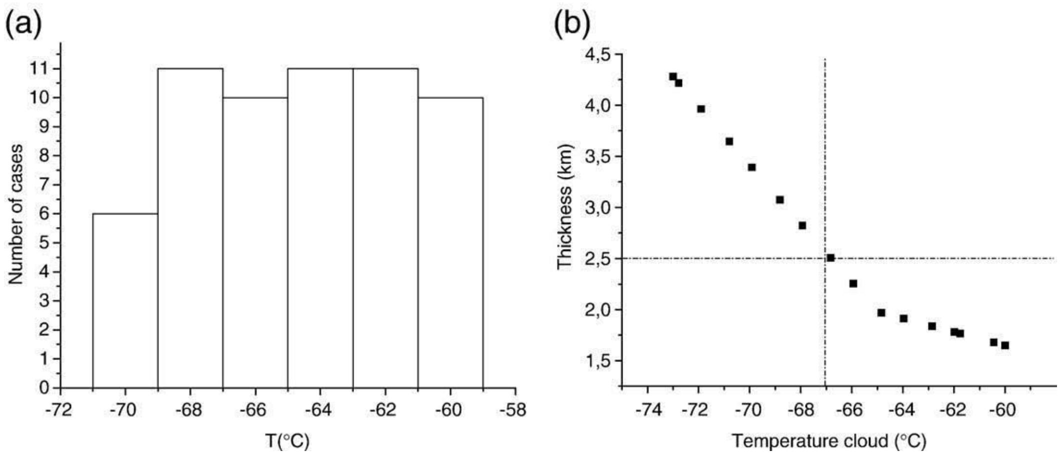

Fig. 4. (a)Distribution of cirrus cloud temperatures, (b) A scatterplot of cloud thickness versus cloud temperature grouped and averaged at 1 °C intervals.

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than those classified as thin in previous work for other sites. Fig. 3c displays the distribution of the cirrus clouds mean thickness. The first maximum occurrence in this case, is found to be in the range 3.5–4 km, and two secondary maxima are located between 1.5 and 2.5 km. Both cases imply cirrus cloud thicknesses greater than previously reported mid-latitude thin cirrus. On the other hand, for tropical latitudes Seifert et al. (2007), Sivakumar et al. (2003), Sunilkumar and Parameswaran (2005), show thickness values around 0.5–2.5 km (75% out of all cases). At the other end of the latitude range, Guasta et al. (1993), reported for high latitude data from Dumount D′Urville (66°S, 140 °E), maximum thicknesses of 6–7 km, with mean value of ~3 km at ~−40 °C. Finally, Immler and Schrems (2002), show a comparison between 55° N, 53° S, as a part of the European INCA 2000 project. They found that mean thickness value is confined to 1.2 and 1.4 km for Prestwick (NH) and Punta Arenas (SH), respectively.

The mean height values for the present data, both in thickness as well as temperature mean value do not agree with the mean values reported above, for various latitudinal bands. Fig. 4b shows the cloud thickness with respect to cloud temperatures. It must be noted that 75% of the clouds of greater thickness are located between −65° and −70 °C, values that also include the tropopause temperature range (Bischoff et al., 2007, International Satellite Cloud Climatology Project (ISCCP)). This corresponds to a cloud thickness greater than 2.5 km. At higher temperatures, the plot shows a small decrease, but the thickness still can be considered a high value. Thus, even when the temperature range is small, it is important to note that while mean temperature and height values derived from our lidar system are closer to those found at tropical latitudes, thickness could be considered much closer to those found for mid to high latitude cirri. These differences must imply differences in the meteorological as well as geographical conditions between the latitudinal bands. On the one hand, the tropopause height and temperature values are in close agreement with those derived from rawinsonde as in the recent tropopause climatology by Bischoff et al. (2007).

The thickness of the cirrus clouds is linked to the formation conditions they found in the atmosphere. In this sense, it is important to point out that the region under study has particular conditions that make the area special with regard to most other regions: there are few land areas in the hemisphere and southern South America virtually is a narrow peninsula surrounded by oceanic basins, i.e., the Atlantic and Pacific oceanic basins. Besides the very unequal land–water distribution, which contributes to the high occurrence of these clouds, the Andes mountain range, with an average height close to 6000 m in the latitude range under study, is a knife-edge obstacle that disrupts the horizontal quasi-westerly flow of the air mass over the Pacific Ocean. It is most probable that because of these particular conditions, that the cirrus detected over southern mid-latitudes over South America can reach greater thickness than the ones over other areas. Table 1 summarize the observational results of cirrus properties and highlights the remarkable differences with other latitudinal band characteristics, confirming that the cirrus cloud properties strongly depends on regional geophysical conditions.

5. Summary

Some mean properties of cirrus clouds over mid-latitudes are investigated using a lidar system located at Buenos Aires, Argentina. The study shows that the top of the cirrus clouds stays aligned very closely with the tropopause, as well as a good agreement between lidar height retrievals and rawinsonde thermal tropopause heights, with a confidence range of 0.5 km. Cloud height values show a maximum occurrence in the narrow 11.5–12.0 km range. With respect to temperature, Fig. 3d and Table 1, display a remarkable correlation between temperature from rawinsonde data and lidar measurements. Therefore, we consider they can be classified as tropopause cirrus clouds, using the same term as Hartmann et al. (2001) and Garret et al. (2004), among others, but for extra-tropical latitudes: Extra-tropical Cirrus Clouds (ExTCC). Thus, in light of the aforementioned behaviour of the top of these clouds, cirrus top can be considered as tropopause tracers. The analysis also reveals that when the cloud top is very close to the tropopause, the cloud thickness is not always as narrow as was generally accepted in the current understanding. In fact, the cloud average thickness derived from our lidar system is ~2.4 km when the temperature is in the range −70 °C to −60 °C. This thickness value classifies them as thick cirrus, considering the standard lidar terminology. Table 1 summarize the representative values for the cirrus clouds under study and the comparison between other recent research of tropical and mid-latitudes cirri. The results derived from lidar measurements over Buenos Aires present particularly characteristics when compared with the others ones. Even when the results in the present study must be considered as preliminary results, it is possible to note that while height and temperature values seem to be similar to those corresponding to tropical cirrus, thickness values are in agreement with mid-latitudes mean values. This stresses the

Table 1
Mean values and standard deviation (parentheses) of cloud properties

	Buenos Aires	Punta Arenas Immler et al., 2002	Prestwick Immler et al., 2002	OHP(fall) Goldfarb et al., 2001	SLC(Oct–Dec means) Sassen and Campbell, 2001	INDOEX Seifert et al., 2007
Location	34.6°S,58.5°W	53.1°S,71°W	55.5°N, 4.6°W	44°N, 6°E	41°N, 112°W	4.1°N, 73.3°E
Cloud base height (km)	9.63(0.92)	8.8(7.9)	8.3(8.5)	9.3	8.5	11.9(1.6)
Cloud top height (km)	11.82(0.86)	9.5	9.6	10.7	11.1	13.7(1.4)
Cloud thickness (km)	2.41(0.95)	1.4	1.2	1.4	1.9	1.8(1.0)
Distance to tropopause (km)	0.38(0.25)	1.7	1.0	0.8(0.2)	0.4	_
Cloud top temperature	−64.5(3.6)	−49	−48		−56	−65(11)
Tropopause temperature	−60.6(4.7)	_	_	_	_	−81(4)

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issue that cirrus cloud properties are strongly correlated with their geographical location and in consequence their climate conditions.

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References

Ansmann, A., Wandinger, U., Riebesell, M., Weitkamp, C., Michaelis, W., 1992. Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar. Appl. Opt. 31, 7113–7131.
Ansmann, A., et al., 1993. Lidar network observations of cirrus morphological and scattering properties during the International Cirrus Experiment 1989: the 18 October case study and statical analysis. J. Appl. Meteorol. 32, 1608–1622.
Beyerle, J., Schäfer, H.-J., Neuber, R., Schrems, O., Macdemid, I.S., 1998. Dual wavelength lidar observation of tropical high-altitude cirrus clouds during the ALBATROSS 1996 campaign. Geophys. Res. Lett. 25, 919–922.
Bischoff, S.A., Canziani, P.O., Yuchechen, A.E., 2007. The tropopause at southern extratropical latitudes: Argentina operational rawinsonde climatology. Int. J. Climatol. 27, 189–209.
Chiou, E.W., McCormick, M.P., Chu, W.P., 1997. Global water vapor distributions in the stratosphere and upper troposphere derived from 5.5 years of SAGEII observations (1986–1991). J. Geophys. Res. 102, 19105–19118.
Comstock, J.M., Ackerman, T.P., Mace, G.G., 2002. Ground-based lidar and radar remote sensing of tropical cirrus clouds at Nauru Island: cloud statics and radiative impact. J. Geophys. Res. 107 (D23), 4714. doi:10.1029/2002JD002203.
Dessler, A.E., Yang, P., 2003. The distribution of tropical thin cirrus clouds inferred from Terra Modis Data. Am. Meteorol. Soc. 1241–1247.
Fernald, F.G., 1984. Analysis of atmospheric lidar observations; some comments. Appl. Opt. 23, 652–653.
Formenti, P., Elias, T., Welton, E.J., Diaz, J.P., Exposito, F., Schmid, B., Powell, D., Holben, B.N., Smirnov, A., Andreae, M.O., Devaux, C., Voss, K., Lelieveld, J., Livingston, J.M., Russell, P.B., Durkee, P.A., 1999. Altitude differentiated aerosol extinction over Tenerife (North Atlantic Ocean) during ACE-2 by means of ground and airborne photometry and lidar measurements. September 6–10, European Aerosol Conference, Prague.
Garret, T.J., Heymsfield, A.J., McGill, M.J., Ridley, B.A., Baumgardner, D.G., Bui, T.P., Webster, C.R., 2004. Convective generation of cirrus near the tropopause. J. Geophyd. Res. 109, D21203. doi:10.1029/2004JD004952.
Goldfarb, L., Keckhut, P., Chanin, M.-L., Hauchecorne, A., 2001. Cirrus climatological results from lidar measurements at OHP (44°N, 6°E). Geophys. Res. Lett. 28, 1687–1690.
Guasta, M.D., Morandi, M., Stefanuti, L., Brechet, J., Piquad, J., 1993. One year of cloud lidar data from Dumont d'Urville (Antartica): 1. General overview of geometrical and optical properties. J. Geophys. Res. 98, 15,575–18,587.
Hartmann, D.L., Holton, J.R., Fu, Q., 2001. The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration. Geophys. Res. Lett. 28 (10), 1969–1972. doi:10.1029/2000GL012833.
Heymsfield, A.J., Platt, C.M.R., 1984. A parameterization of the particle size spectrum of ice 10 clouds in terms of the ambient temperature and the ice water content. J. Atmos. Sci. 41, 84–86–855.
Heymsfield, A.J., McFarquhar, G.M., 1986. High albedos of cirrus in the tropical Pacific warm pool: microphysical interpretations from CEPEX and from Kwajalein, Marshall Islands. J. Atmos. Sci. 53, 2424–2450.
Heymsfield, A.J., McFarquhar, G.M., Collins, W.D., Goldstein, J.A., Valero, F.P.J., Spinhirne, J., Hart, W., Pilewskie, P., 1998. Cloud properties leading to highly reflective tropical cirrus: interpretations from CEPEX, TOGA COARE, and Kwajalein, Marshall Islands. J. Geophys. Res. 103, 8805–8812.
Immler, F., Schrems, O., 2002. Lidar measurements of cirrus clouds in the northern and southern midlatitudes during INCA (55°N, 53° S): a comparative study. Geophys. Res. Lett. 29 (16), 1809. doi:10.1029/2002GL015077.
Immler, F., Treffeisen, R., Engelbart, D., Krüger, K., Schrems, O., 2008. Cirrus, contrails and ice supersaturated regions in high pressure systems at northern mid latitudes. Atmos. Chem. Phys. 8, 1689–1699.
Jensen, E.J., Owen, B.T., Selkirk, H.B., Spinhirne, J.D., Scheberl, M.R., 1996. On the formation and persistence of subvisible cirrus clouds near the tropical tropopause. J. Geophys. Res. 101, 361–375.
Kärcher, B., Solomon, S., 1999. On the composition and optical extinction of particles in the tropopause region. J. Geophys. Res. 104, 27,441–27,459.
Keckhut, P., Hauchecorne, A., Bekki, S., Colette, A., David, C., Jumelet, J., 2005. Indications of thin cirrus clouds in the stratosphere at mid-latitudes. Atmos. Chem. Phys. 5, 3407–3414.
Klett, J.D., 1981. Stable analytical inversion of multiply scattered lidar return. Appl. Opt. 20, 211–220.
Lavorato, M., Flamant, P.H., Porteneuve, J., Pagura, M., Cesarano, P., Canziani, P., 2004. Monitoring of the troposphere by a backscatter LIDAR in Buenos Aires (34.6S/58.5W): overview of the multiyear data set and implementation of new IR channels and depolarization capability. Proceeding: 22nd. International Radar Laser Conference. pp156–159, Matera-Italy.
Linch, D.K., Sassen, K., Starr, O.'C., Stephens, G., 2002. Cirrus. University Press, Oxford.
Liou, K.N., 1986. Influence of cirrus clouds on weather and climate processes: a global perspective. Mon. Wea. Rev. 114, 1167–1199.
Luo, B.P., et al., 2003. Dehydration potential of ultrathin clouds at the tropical tropopause. Geophys. Res. Lett. 30 (11), 1557. doi:10.1029/2002GL016737.
McFarquhar, G.M., Heymsfield, A.J., Spinhirne, J., Hart, B., 2000. Thin and subvisual tropopause tropical cirrus: observations and radiative impacts. J. Atmos. Sci. 57, 1841–1853.
Noel, V., Winker, D.M., Garrett, T.J., Mcgill, M., 2007. Extinction coefficients retrieved in deep tropical ice clouds from lidar observations using CALIPSO-like algorithm compared to in-situ measurements from cloud integrating nephelometer during CRYSTAL-FACE. Atmos. Chem. Phys. 7, 1415–1422.
Pfister, L., et al., 2001. Aircraft observations of thin cirrus clouds near the tropical tropopause. J. Geophys. Res. 106, 9765–9786.
Platt, C.M.R., Young, S.A., Manson, P.J., Patterson, G.R., Marsden, S.C., Austin, R.T., Churnside, J.H., 1998. The optical properties of equatorial cirrus from observations in the ARM pilot radiation observation experiment. J. Atmos. Sci. 55, 1977–1996. doi:10.1175/1520- 0469(1998)055.
Platt, C.M.R., Young, S.A., Austin, R.T., Patterson, G.R., Mitchell, D.L., Miller, S.D., 2002. LIRAD observations of tropical cirrus clouds in MCTEX. Part I: Optical properties and detection of small particles in cold cirrus. J. Atmos. Sci. 59, 3145–3162.
Prabhakara, C., Frase, G., Dalu, G., Man-Li, C.W., Curran, R.J., 1998. Thin cirrus clouds: seasonal distribution over oceans deduced from Ninbus-4 IRIS. J. Appl. Meteorol. 27, 379–399.
Reichardt, J., 1999. Optical and geometrical properties of northern mid-latitude cirrus clouds observed with a UV Raman lidar. Phys. Chem. Earth, Part B 24, 255–260.
Sassen, K., Benson, R.P., Spinhirne, J.D., 2000. Tropical cirrus cloud properties from TOGA/COARE airborne polarization lidar. Geophys. Res. Lett. 27, 673–676.
Sassen, K., Campbell, J.R., 2001. A midlatitude cirrus cloud climatology from the Facility for Atmospheric Remote Sensing. Part I: Macrophysical and synoptic properties. J. Atmos. Sci. 58, 481–496.
Sassen, K., Comstock, J.M., 2001. A midlatitude cirrus cloud climatology from the Facility for Atmospheric Remote Sensing. Part III: Radiative properties. J. Atmos. Sci. 58, 2113–2127.
Sassen, K., Griffin, M.K., Dodd, G.C., 1989. Optical scattering and microphysical properties of subvisual cirrus clouds and climatic implications. J. Appl. Meteorol. 28, 91–98.
Sassen, K., Huggins, A.W., Long, A.B., Snider, J.B., Meitin, R.J., 1990. Investigations of a winter mountain storm in Utah. part II: Mesoscale structure, supercooled liquid water development, and precipitation processes. J. Atmos. Sci. 47, 1323–1350.
Seifert, P., Ansmann, A., Müller, D., Wandinger, U., Althausen, D., Heymsfield, A.J., Massie, S.T., Schmitt, C., 2007. Cirrus optical properties observed with lidar, radiosonde, and satellite over the tropical Indian Ocean during the aerosol-polluted northeast and clean maritime southwest monsoon. J. Geophys. Res. 112, D17205. doi:10.1029/2006JD008352.
Shepherd, T.G., 2002. Issues in stratospheric-troposphere coupling. J. Meteorol. Soc. Jpn. 80, 769–792.
Sivakumar, V., Bhavanikumar, Y., Rao, P.B., Mizutani, K., Aoki, T., Yasui, M., Itabe, T., 2003. Lidar observed characteristics of the tropical cirrus clouds. Radio Sci. 38 (6), 1094. doi:10.1029/2002RS002719.
Spang, R., Eidmann, G., Riese, M., Offermann, D., Preusse, P., Pfister, L., Wang, P.H., 2002. CRISTA observations of cirrus clouds around tropopause. J. Geophys. Res. 107 (D23), 8174. doi:10.1029/2001JD000698.
Ström, J., Seifert, M., Kärcher, B., Ovarlez, J., Minikin, A., Gayet, J.F., Krejci, R., Petzold, A., Auriol, F., Haag, W., Busen, R., Schumann, U., Hansson, H.C., 2003. Cirrus cloud occurrence as function of ambient relative humidity: a comparison of observations obtained during the INCA experiment. Atmos. Chem. Phys. 3, 1807–1816.
Sunilkumar, S.V., Parameswaran, K., 2005. Temperature dependence of tropical cirrus properties and radiative effects. J. Geophys. Res. 110, D13205. doi:10.1029/2004JD005426.

Uthe, E.E., Russell, P.B., 1977. Lidar observations of tropical high-altitude cirrus clouds. Proceedings of Radiative Conference. Int. Assoc. Meteorol. Atmos. Phys., Boulder, Colo., pp. 242–244.
Wang, Z., Sassen, K., 2002. Cirrus cloud microphysical property retrieval using lidar and radar measurements: II. Midlatitude cirrus microphysical and radiative properties. J. Atmos. Sci. 59, 2291–2302.
Wang, P.H., Minnis, P., McCormick, M.P., Kent, G.S., Skeens, K.M., 1996. A 6 year climatology of cloud occurrence frequency from stratospheric aerosol and Gas Experiment II observations (1985–1990). J. Geophys. Res. 101, 29,407–29,429.
Wang, X., Boselli, A., Avino, L.D., Velotta, R., Spinelli, N., Bruscaglioni, P., Ismaelli, A., 30 Zaccanti, G., 2005. An algorithm to determine cirrus properties from analysis of multiple-scattering influence on lidar signals. Appl. Phys. B 80, 609–615.
Winker, D.M., Trepte, C.R., 1998. Laminar cirrus observed near the tropical tropopause by LITE. Geophys. Res. Lett. 25, 3351–3354.
World Meteorological Organization, Scientific assessment of ozone depletion, 1992. 1991, Global Ozone Res. and Monit. Proj., Rep. 25, Geneva.
Wylie, D.P., Menzel, W.P., Woolf, H.M., Strabala, K.I., 1994. Four years of global cirrus cloud statistics using HIRS. J. Clim. 7, 1972–1986.