Observations of a middle atmosphere thermal structure over Durban using a ground-based Rayleigh LIDAR and satellite data

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Studying the middle atmospheric thermal structure over southern Africa is an important activity to improve the understanding of atmospheric dynamics of this region. Observations of a middle atmosphere thermal structure over Durban, South Africa (29.9°S, 31.0°E) using the Durban Rayleigh Light Detection and Ranging (LIDAR) data collected over 277 nights from April 1999 to July 2004, including closest overpasses of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) and Halogen Occultation Experiments (HALOE) satellites, are presented in this paper. There seems to be good agreement between the LIDAR and satellite observations. During autumn and winter, the temperatures measured by the LIDAR in the height region between 40 km and 55 km were 5 K to 12 K higher than those measured by the satellites. The data from the LIDAR instrument and the SABER and HALOE satellites exhibited the presence of an annual oscillation in the stratosphere, whereas in the mesosphere, semi-annual oscillations dominated the annual oscillation at some levels. The stratopause was observed in the height range of ~40 km – 55 km by all the instruments, with the stratopause temperatures measured as 260 K – 270 K by the LIDAR, 250 K – 260 K by the SABER and 250 K – 270 K by the HALOE. Data from the SABER and HALOE satellites indicated almost the same thermal structure for the middle atmosphere over Durban.

Introduction

Temperature monitoring in the atmosphere is important as temperature controls the rate of chemical reactions and thus ozone abundance. The middle atmospheric temperature is an important parameter as it is a combined manifestation of the dynamic, radiative and chemical processes that occur in the middle atmosphere.[1] The temperature structure in the middle atmosphere has been studied for several decades using a variety of techniques. The first studies used rocketsondes and falling spheres to measure the temperature profiles up to 60 km – 90 km, but with relatively poor accuracy as a result of uncertain radiative and aerodynamic heating corrections.[2] However, the first experimental[3] and systematic[4] temperature profiles derived from Rayleigh Light Detection and Ranging (LIDAR) measurements of the relative density of the middle atmosphere provided improved accuracy and vertical resolution.

Although there are many instruments used to study middle atmospheric temperature (e.g. rockets, satellites and radiometers), the LIDARs have been found to be more accurate and efficient than other instruments. LIDARs also provide long-term data series which are relatively absent of instrumental drift and an integration of the measurements over several hours filters away most of the gravity wave-like short-scale disturbances. Thus, the Rayleigh LIDAR has emerged as the ground-based technique with the most potential to study the structure and dynamics of the middle atmosphere.[5,6,7,8,9]

The climatology of the middle atmospheric temperature has been studied over the past decades using LIDARs and other instruments.[9,10,11,12,13,14] Hauchecorne et al.[15] used Rayleigh LIDAR from two stations in France (OHP: 44°N, 6°E and BIS: 44°N, 1°W) to study the climatology of the mid-latitude middle atmosphere temperature. Sivakumar et al.[9] studied the thermal structure of the middle atmosphere over Gadanki, India (13.5°N, 79.2°E) using Rayleigh LIDAR data and also compared the LIDAR results with Halogen Occultation Experiments (HALOE) on board the Upper Atmosphere Research Satellite (UARS), the CIRA-86 model and the Mass Spectrometer Incoherent Scatter Extended-1990 (MSISE-90) model. More recently, Li et al.[16] applied linear regression analyses to a 13.5-year long (January 1994 to June 2007) de-seasonalised monthly mean temperature time series for each 1 km altitude bin between 15 km and 85 km, measured by the Jet Propulsion Laboratory Rayleigh-Raman LIDAR at Mauna Loa Observatory, Hawaii (19.5°N, 155.6°W). Their regression analysis included components representing the Quasi-Biennial Oscillation (QBO), the El Niño-Southern Oscillation (ENSO) and the 11-year solar cycle. The analyses revealed the dominance of the QBO (1 K − 3 K) in the stratosphere and mesosphere, and a strong winter signature of ENSO in the troposphere and lowermost stratosphere (~1.5 K per Multivariate ENSO Index).

Comparisons between LIDAR temperature observations and observations made using other well-established methods or techniques provide a very good opportunity to better understand the middle atmosphere thermal structure. Satellite measurements offer the best method for providing the temperature structure over the globe with good spatial coverage. However, their height resolution is poor compared to most ground-based instruments. Thus, comparing and quantifying the differences between space-based and ground-based instruments can overcome their differences. There have been a number of studies that have reported comparisons between Rayleigh LIDAR observations and those of other instruments.[9,14,17,18,19] Namboothiri et al.[12] compared LIDAR-measured temperature profiles with rocket-measured and satellite-measured profiles, as well as the COSPAR International Reference Atmosphere 1986 (CIRA-86) model, and found that the LIDAR profiles are in fair agreement with the rocket and satellite measurements and the CIRA-86 model. Recently, Dou et al.[19] studied the seasonal oscillations of the middle atmosphere temperature observed using Rayleigh LIDARs at six different locations, from low to high latitudes, within the Network for the Detection of Atmosphere Comparison Change and performed comparisons with the results derived from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on board the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, and found good agreement at similar latitudes.

The most recent studies that employed the Durban LIDAR temperature data include a study by Moorgawa et al.[20], in which the authors gave a description of the Durban LIDAR system for temperature measurement, and also reported good agreement between the LIDAR and South African Weather Service (SAWS) radiosonde temperature for the lower stratosphere (about 20 km – 27 km). Bencherif et al.[21] used Durban Rayleigh-Mie LIDAR data, data from MeteoSat, SAGE-2 experiments and ECMWF meteorological analysis to study the lower stratospheric aerosols over South Africa, as well as their link to large-scale transport across the southern subtropical barrier. Also, Bencherif et al.[22] performed the first validation of the stratospheric temperature profiles obtained by the Durban Rayleigh LIDAR.

In the present work, we used Rayleigh LIDAR measurements made over Durban (29.9°S, 31.0°E) for 277 nights from April 1999 to July 2004 for the first time, to study the stratospheric–mesospheric thermal structure over Durban. We also compared LIDAR monthly temperature mean profiles with SABER observations and temperature data from HALOE.

Data source

Durban Rayleigh LIDAR

The atmospheric LIDAR instrument employs a laser as a source of pulse energy of useful magnitude and suitable short duration. The laser beam is transmitted vertically into the sky, and interacts with air molecules and aerosols in the lower and middle atmosphere. Backscattered photons are collected by parabolic mirrors and transmitted to the photomultiplier detector. Data acquisition is carried out in a photon counting mode. The returning signal is integrated to generate a photon count versus altitude profiles. Subsequently, a temperature profile is derived from the relative density profile using the hydrostatic equations and ideal gas law by taking an upper level pressure value from an atmospheric model.[4] The error in derived temperature depends upon the relative error in the density measurements and the error in the model pressure value used in the temperature calculation.[4] Temperature measurement uncertainty as a result of the model pressure value fitted on top of the profile decreases rapidly and after 10 km – 15 km it is less than 1%.[4] Sivakumar et al.[9] studied the sensitivity of the derived temperature profile by using different atmospheric models (CIRA-86 and MSISE-90) and introduced perturbation in the model pressure value taken at the top reference height. They observed that the derived temperature profiles based on the two models differed by approximately 1 K – 2 K for the height range extending up to 70 km and approximately 5 K – 6 K over the height range of 70 km – 80 km. They also observed that the perturbations (of about ±10%) in the model parameters had little effect on the retrieved temperature profile (less than ±1 K) at heights below 70 km, whilst it caused differences of ±5 K at 80 km. This discrepancy is because of the fact that an uncertainty in the model parameter at the top of the height range would result in a temperature uncertainty that falls off exponentially with decreasing height. A study by Hauchecorne and Chanin[4] showed that LIDAR improvements involving the reduction of the divergence and the field of view increased accuracy in the LIDAR measurements. This increased accuracy reduced errors at higher altitudes, and thus increased the measurable range. The power of the laser transmission should also be considered as an important variable to improve the return signal strength.

The Durban LIDAR system was operated during the night and only during clear sky conditions. This requirement is because the intensity of the LIDAR echo is quite weak and therefore counting individual photons to retrieve the LIDAR echo is indispensable. Sunlight is considered a serious problem when operating a LIDAR as it limits the LIDAR operating period. The Durban LIDAR is a Rayleigh-Mie system capable of making measurements of vertical profiles of relative density, temperature and aerosol scatter.[20] The laser used is a pulsed Nd:YAG with a repetition rate of 30 Hz and a fundamental wavelength of 1064 nm. The emitted light source is a frequency-doubled (using a potassium dihydrogen phosphate crystal) laser at 532 nm, with a power of ~500 mJ/s. The system started operating in April 1999 with a Spectra Physics Nd:YAG laser at a repetition rate of 10 Hz delivering an average power of 3 W.[22] In early 2002, the 10-Hz laser was replaced with a more powerful Nd:YAG laser operating at a frequency of 30 Hz and delivering at least five times more power. The instrument uses a dichroic mirror at the emission point of the laser to separate the second harmonic from the fundamental laser beam.

The system operates with two acquisition channels: a high altitude channel (Channel A) and a low altitude channel (Channel B). The receiver system contains three parabolic mirrors – two mirrors with diameters of 445 mm and one mirror with a diameter of 200 mm, integrated with the LIDAR. The mirrors are held inside two long tubes which protect them from luminous interference. The larger parabolic mirrors (Channel A) are used to receive backscattered photons from the upper atmosphere, whilst the smaller mirror (Channel B) receives backscattered photons from the lower atmosphere. The received photons are collected at the telescope focus and transmitted by optical fibres to the detection box, which consists of an interference filter, a collimator and a photomultiplier. The two-channel photon-counting system converts the backscattered photons into a numerical signal as a function of altitude, using 1 μs integration which corresponds to a vertical resolution of 150 m. Specifications of the laser transmitter and optical receiver of the system are summarised in Table 1. The histogram in Figure 1 illustrates the monthly distribution of the Durban LIDAR data plotted alongside the HALOE data and SABER data, irrespective of the year. As a consequence of occasions when the observing conditions were not favourable (i.e. convective and cloudy conditions over Durban), the LIDAR observations were necessarily restricted to shorter periods or could not take place at all. These periods are noticeable during the rainy summer months of January, February and December where there are few or no observations during the entire month (Figure 1). More information about the Durban LIDAR and the temperature retrieval method and validation are given by Bencherif et al.[22] and Moorgawa et al.[20]

HALOE instrument

The Halogen Occultation Experiment (HALOE) instrument is on board the UARS launched on 12 September 1991. The instrument uses a solar occultation measurement technique, providing 15 sunrise and 15 sunset vertical measurements of ozone, hydrogen chloride, hydrogen fluoride, methane, water vapour, nitric oxide, nitrogen dioxide, temperature and aerosol extinction at four infrared wavelengths per day, with each daily sunrise or sunset group near the same latitude on a given day. This instrument uses the atmospheric transmission measurements in the 2.8 μm carbon dioxide band for the retrieval of temperature profiles. Retrieval of temperature profiles involves removal of aerosol contamination, assuming that the aerosol concentration above 30 km is negligible. It provides day and night temperature profiles in the altitude range from ~45 km to 85 km.[23,24] A detailed discussion related to the validation of HALOE data can be found in a number of papers.[1,23,24,25]

SABER instrument

In the present study, the vertical temperature profiles were derived from data from version 1.07 of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) level 2A (downloaded from the website http://saber.gats-inc.com) which is one of the four instruments on board the TIMED satellite. The TIMED satellite was launched on 07 December 2001 into a 625 km orbit of 74.1° inclination, and the SABER instrument began taking measurements in late January 2002. By step-scanning the atmosphere limb, SABER measures height profiles of kinetic temperature and selected chemical species in the 10 km – 180 km altitude range, with a horizontal resolution of 400 km and a vertical resolution of ~2 km. The SABER instrument obtains profiles from 52°S to 83°N during its north-looking mode (for about 60 days), switches to an analogous south-looking mode, and then repeats that sequence for subsequent months. Nearly continuous coverage is achieved equatorward of the 52° latitude in each hemisphere. Vertical scans are measured every 52 s, giving a profile spacing along the orbit of 3° of latitude for 15 orbits per day. Details about the SABER temperature data and SABER sampling are given by Remsberg[26].

TABLE 1: Characteristics of the transmitter and receiver systems of the Durban Rayleigh Light Detection and Ranging.

Hardware system	Hardware type	Characteristic	Measurement
Transmitter	Spectra Physics GCR-3	Emitted wavelength	λ_c = 532 nm
		Repetition rate	30 Hz
		Energy per pulse	500 mJ
		Pulse width	5 ns – 7 ns
		Beam divergence (FWHM)	0.50 mrad
Receiver	Newtonian telescope	Channel A: two parabolic mirrors	–
		Diameter of each mirror	445 mm
		Focal length	2000 mm
		Channel B: one parabolic mirror	–
		Diameter of mirror	200 mm
		Focal length	1000 mm
Photomultiplier tube	Hamamatsu R 1477 S	Maximum voltage	1000 V
		Gain	107
		Quantum efficiency at 532 nm	17%
		Cathode sensitivity	72.9 μA/W
		Rising time	2.2 ns
		Transit time	22 ns
		Anode dark current	Typical 2 nA, maximum 5 nA

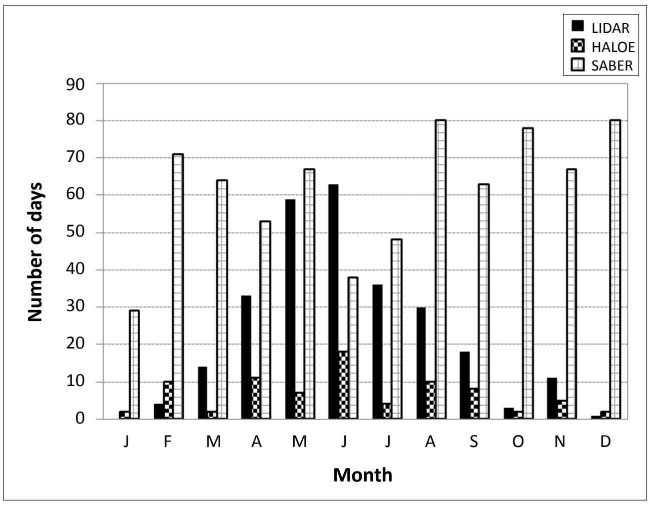

FIGURE 1: A comparison of the monthly distribution of data obtained by the Durban LIDAR and the HALOE and SABER satellites.

Comparisons between LIDAR, SABER and HALOE

Climatological temperature

The contour maps of monthly mean temperature distributions obtained from the Durban LIDAR, SABER and HALOE data plotted in a grid of month versus altitude are depicted in Figure 2. In all three contour plots, high temperatures at a height region between ~40 km and 55 km can be clearly seen and are as a result of the absorption of ultraviolet radiation from the sun by ozone. The LIDAR, SABER and HALOE temperatures do not seem to change significantly from month to month below an altitude of about 40 km. This pattern is similar to the findings of Chandra et al.[27] for middle atmospheric temperature over Mt Abu, India (24.5°N, 72.7°E). However, it must be mentioned that, in their study, there were no measurements during the months of July and August because of the monsoon season. The thermal structure observed by the LIDAR over Durban at the stratopause (at ~42 km – 50 km) shows two distinct maxima with one during the period from February to July and the other during the period from September to December. The maximum temperature is found to be about 270 K. The minimum temperature (about 260 K in the stratopause) is observed during the period from August to September.

The SABER stratopause temperature during the extended summer season (from October to February) had a maximum temperature of 260 K. During the winter period the stratopause temperature was found to be ~250 K. Data from the HALOE satellite for the stratopause during summer, autumn and spring showed a maximum temperature of 260 K. In essence, the stratosphere structure, as seen by the three instruments (LIDAR, SABER and HALOE), depicted a familiar feature (an annual oscillation) in the mid-latitude regions. Previous studies have also shown the presence of an annual oscillation in the mid-latitudes and high-latitudes.[6,15,28] Batista et al.[29] also reported a domination of annual oscillations in the stratosphere in their study using Rayleigh LIDAR measurements obtained from 1993 to 2006 at São josé dos Campos, Brazil (23.2°S, 45°W). In contrast to the annual oscillation in the stratosphere of the mid-latitudes and high-latitudes, the sub-tropical latitude observations show a strong semi-annual oscillation.[9] The Durban station is situated at ~30°S, and the middle atmosphere at this latitudinal position can be influenced by the sub-tropical and mid-latitude meridional exchanges (including the surf zone). The observation of maximum temperatures during the summer and minimum temperatures during the winter stratosphere is in phase with the solar flux.

There were fluctuations observed in the LIDAR temperature climatology as a result of dynamic events, which were smoothed in the satellite (SABER and HALOE) observations. The LIDAR observations were about 10 K warmer in height regions between 40 km and 55 km, compared to the satellite data for the majority of the months. This temperature difference may have been because of dynamic activities which could not be detected by the satellites. In fact, the ground-based LIDAR experiment allows a better vertical resolution (0.3 km) than the satellites. Indeed, the LIDAR is more sensitive than the satellites to small-scale dynamic disturbances, such as gravity waves and atmospheric tides. The SABER and HALOE data exhibited almost the same thermal structure for the middle atmosphere over Durban. Both SABER and HALOE indicated a cold mesospheric winter, above ~63 km. Similar results were also reported by Batista et al.[29] on their study of monthly climatology and trends in the 35 km – 65 km altitude over São josé dos Campos, Brazil.

For a better comparison between the LIDAR and satellite observations, it is necessary to calculate the temperature differences between the measurements obtained from each instrument. The contour plots in Figure 3 and Figure 4 illustrate the temperature differences between the LIDAR and SABER and LIDAR and HALOE measurements, respectively, plotted as a function of month versus height. These differences were obtained by subtracting the satellite (SABER and HALOE) climatology from the LIDAR climatology data, (T_{LIDAR}-T_{SABER}) and (T_{LIDAR}-T_{HALOE}). The differences between the LIDAR and SABER measurements and between the LIDAR and HALOE measurements are similar. Generally, both contour plots are dominated by higher LIDAR temperature values throughout the middle atmosphere, except at heights above 50 km during the equinoxes. The differences between the LIDAR and SABER measurements (Figure 3) were higher (~20 K) in the height range of 40 km – 50 km during the months from March to July. On the other hand, the differences between the LIDAR and HALOE measurements (Figure 4) were greatest (~10 K) in the 35 km – 45 km height range during the months from February to July. Another peak of ~10 K can be seen during August–September. The same feature is also observed in Figure 3, which shows the difference between the LIDAR and SABER data. The double lobe structure of minimum temperature in February–April and September–November over 50 km reflects the presence of a semi-annual oscillation. The smaller differences in both SABER and HALOE data during November and December may be associated with a lack of LIDAR observations during these months.

Studies such as Leblanc et al.'s[30] included comprehensive comparisons of the LIDAR and HALOE satellite observations and found differences between the two instruments to be as large as 15 K in the mesospheric inversion region. Hervig et al.[23] compared LIDAR-measured temperature profiles to those of HALOE-measured and rocket-measured profiles and found that the measurements typically have random differences less than 5 K for heights below ~60 km. The differences shown in Figure 4 indicate that the greatest difference (10 K) was in the 35 km – 45 km height range during the months from February to July.

We have also compared the Durban LIDAR temperature profile with the closest overpass temperature data measured by the SABER satellite. Figure 5 illustrates the SABER

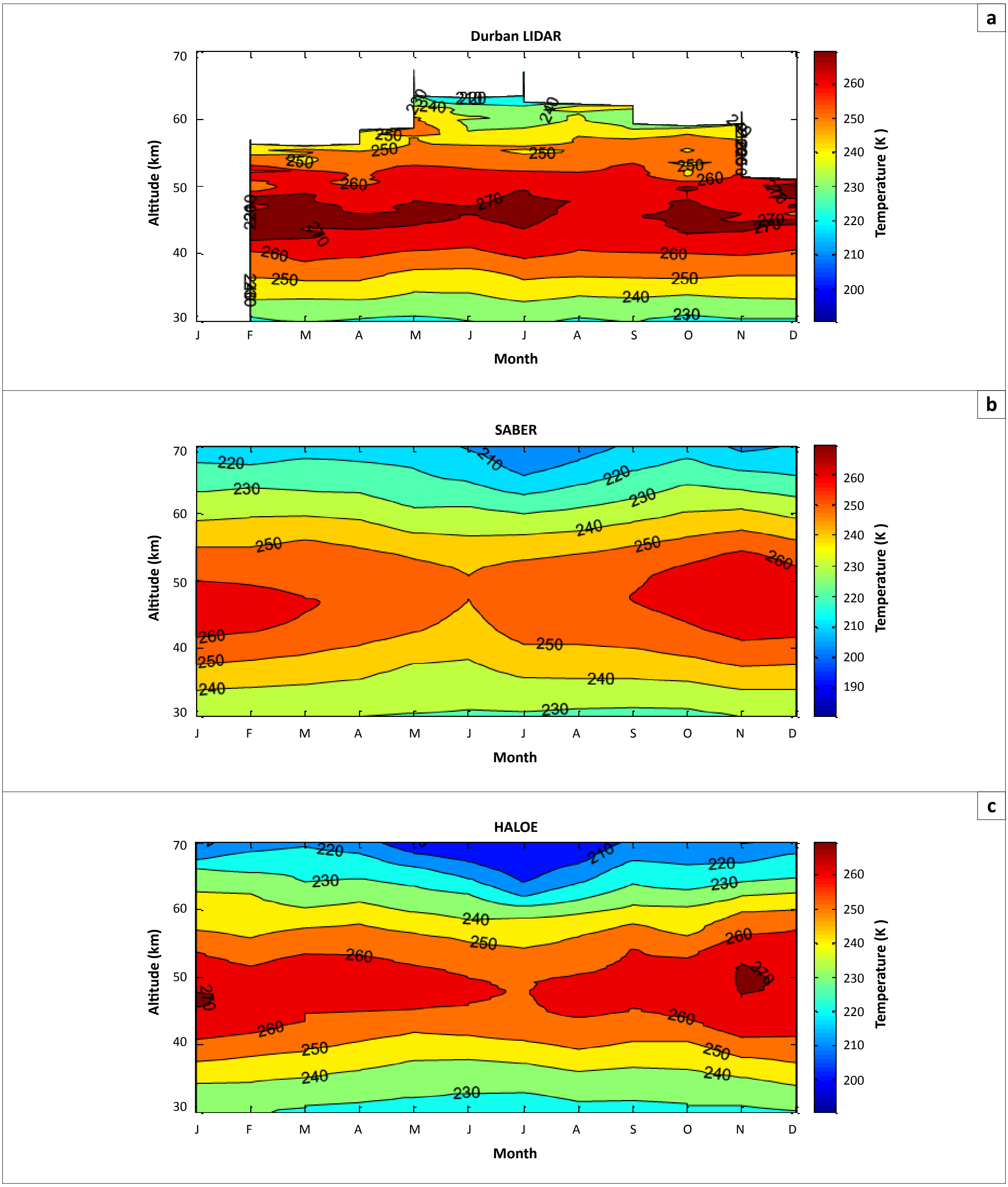

FIGURE 2: Contour plots of monthly climatological temperature variations with altitude (in kilometres) over Durban obtained by the (a) Durban LIDAR, (b) SABER satellite and (c) HALOE satellite.

temperature profile and the Durban LIDAR temperature profile for the night of 27–28 November 2002. The LIDAR profile shows fluctuations in temperature as a result of vertical propagating planetary and gravity waves. However, the figure indicates a good agreement between the LIDAR and the SABER instruments. At a height of between 46 km and 53 km, the SABER temperature profile seems to be about 5 K – 7 K warmer than the LIDAR profile. At a height region between 34 km and 45 km, the SABER-measured temperatures seem to be about 4 K warmer than the LIDAR-

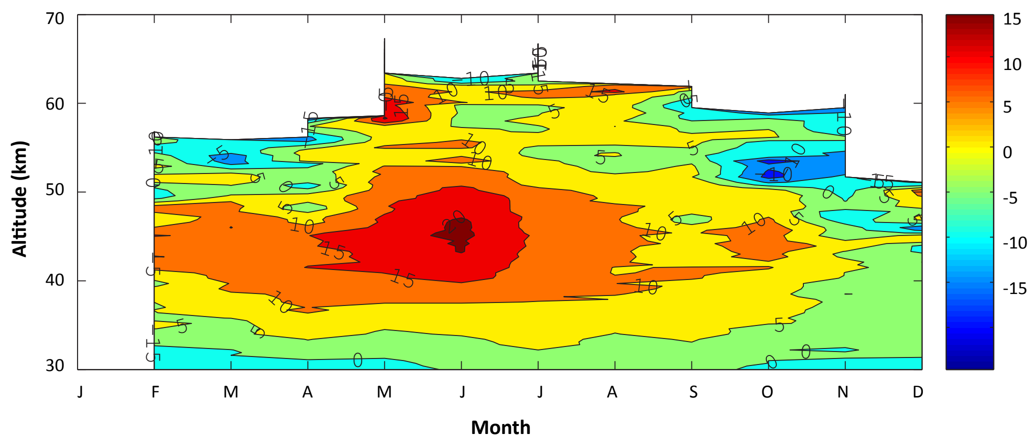

FIGURE 3: Contour plots of temperature differences between the data obtained by the Durban LIDAR and the SABER satellite.

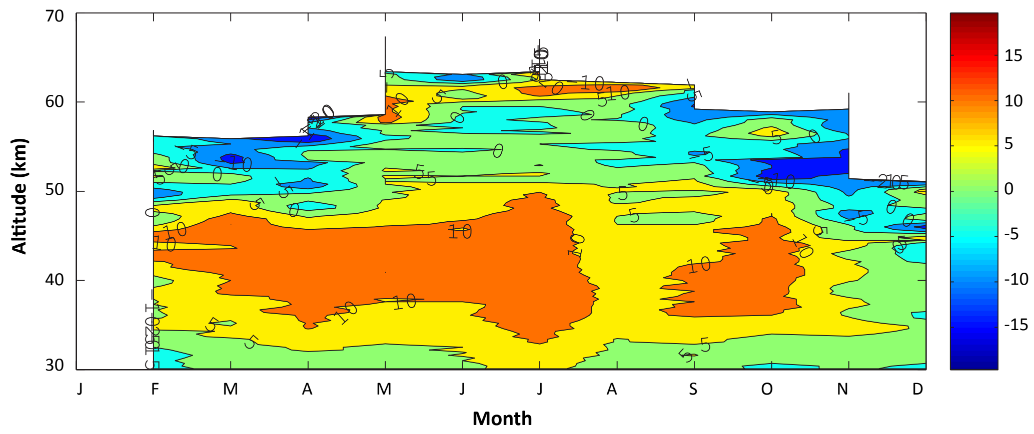

FIGURE 4: Contour plots of temperature differences between the data obtained by the Durban LIDAR and the HALOE satellite.

derived temperatures. The observed differences in the middle atmosphere over Durban are understandably because of the two different techniques used by the two instruments and the actual observation time,[9] and also because some middle atmospheric dynamics can be pictured by the LIDAR, but not by the satellite.

Comparison of seasonal temperature profiles

In order to examine the seasonal characteristics of temperature over Durban, and also to compare the seasonal means measured by the LIDAR against those measured by the satellites, the temperature profiles derived from the LIDAR, HALOE and SABER over Durban were grouped per season; the summer, autumn, winter and spring temperature profiles were derived from daily profiles averaged for the December–February, March–May, June–August and September–November periods, respectively. Figure 6 illustrates the seasonal averaged LIDAR temperature profiles with standard deviations. Superimposed on Figure 6 is the seasonal averaged closest overpasses temperature profiles measured by the HALOE and SABER satellites.

Generally, the temperature profiles obtained from the LIDAR were found to be systematically higher than those obtained from the two satellites in the stratospheric height region

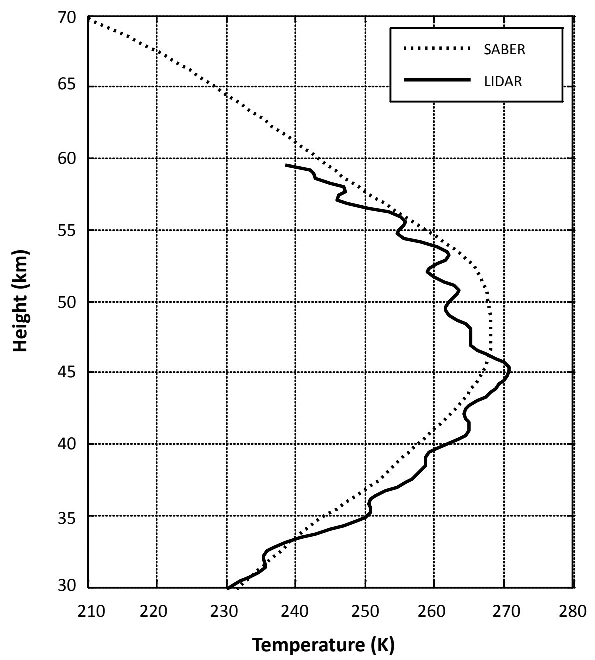

FIGURE 5: A quasi-simultaneous height profile of the temperature observed by the Durban LIDAR and the SABER satellite over Durban, South Africa for the night of 27–28 November 2002.

between 33 km and 55 km. The stratopause is depicted at the same height in the LIDAR, SABER and HALOE profiles in summer and winter. However, during the autumn and spring seasons the LIDAR stratopause height was found to be ~5 km lower than those shown by the two satellite profiles. The HALOE temperature profiles were found to be systematically colder than the SABER temperature profiles for the height region below 40 km in autumn, winter and spring. Above 50 km, the satellite measurements had good agreement with the LIDAR measurements, apart from

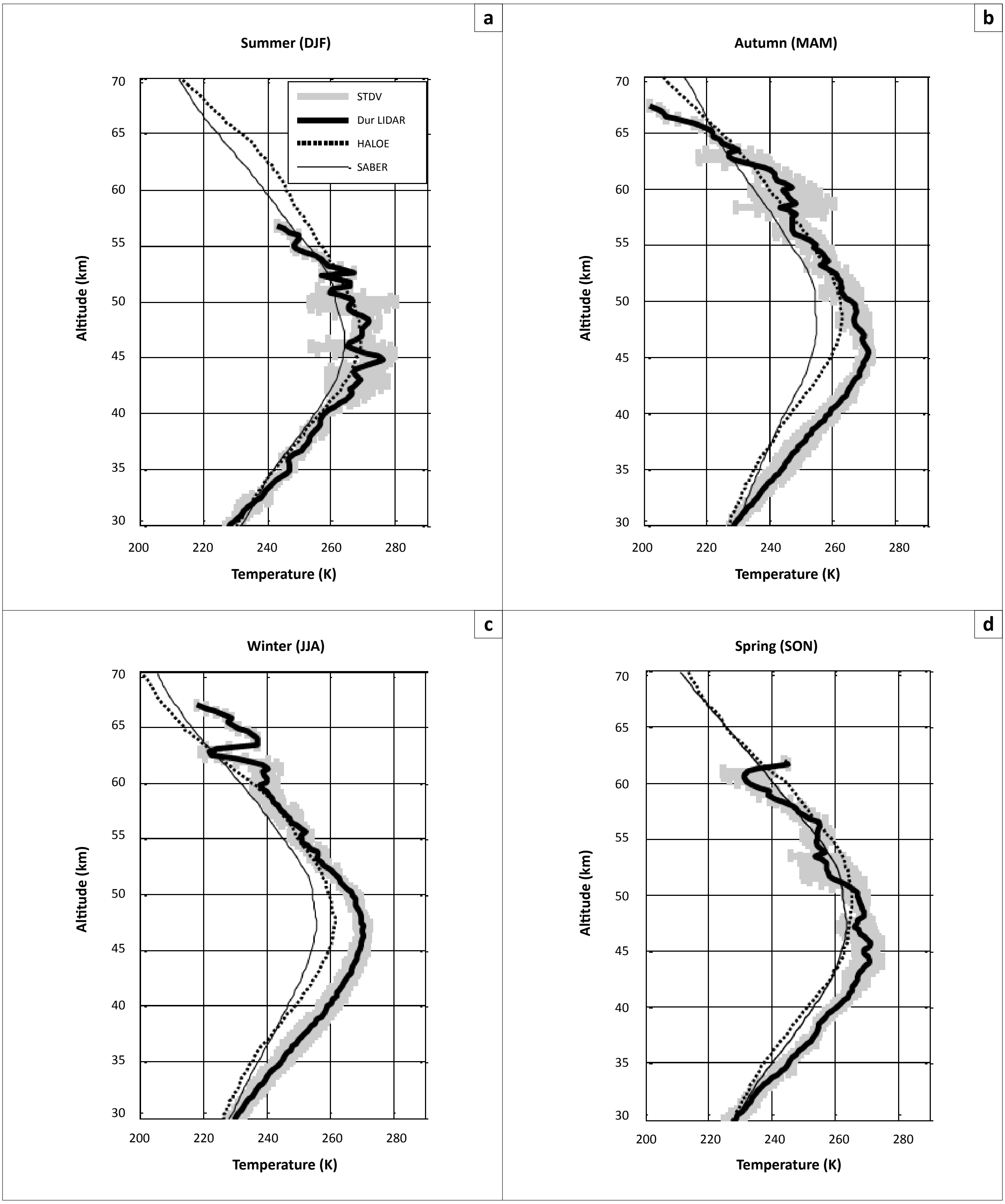

FIGURE 6: Seasonal mean temperature profiles obtained from the Durban LIDAR and the HALOE and SABER satellites for (a) summer (December–February), (b) autumn (March–May), (c) winter (June–August) and (d) spring (September–November).

visible fluctuations within the LIDAR profiles, which can be associated with unusual spectacular events in the middle atmosphere that cannot be detected by satellites (e.g. upwards propagating gravity or planetary wave braking, stratospheric warmings and tidal waves).[31] The differences in stratospheric temperature measurements between the LIDAR and the two satellites were found to be very small during summer and spring compared to those during winter and autumn.

The observed differences are consistent with the findings of Sivakumar et al.[32] in their study comparing Rayleigh LIDAR measurements with satellite (HALOE, SABER, GPS-CHAMP and COSMIC) measurements of the stratosphere and mesosphere temperature over a southern sub-tropical site, Reunion Island (20.0°S, 55.5°E). The temperature differences between the LIDAR and SABER seem to be larger than the differences between the LIDAR and HALOE. Temperature differences between the LIDAR and SABER at the height region between 40 km and 50 km were found to be 5 K – 12 K in autumn and 5 K – 10 K in winter. However, the temperature differences between the LIDAR and HALOE were found to be 3 K – 6 K at the height region between 35 km and 50 km, in both autumn and winter. These differences between the LIDAR and the two satellites may be as a result of the difference in the techniques used to retrieve the temperature, the observational time difference or the poor height resolution of SABER (~2 km) and HALOE measurements (3.7 km) in comparison with the resolution of LIDAR measurements (0.3 km). There are some events that appear to have been detected by the LIDAR but were smoothed out in the observations from the satellites. In the southern hemisphere autumn and winter, eastward propagating waves with periods between 7 and 23 days (usually with zonal wavenumber 2) and quasi-stationary planetary waves co-exist in the stratosphere. These planetary waves can lead to the occurrence of different processes in the stratosphere (e.g. wave–wave interactions, wave–mean flow interactions, mean flow reversals and stratospheric warmings). Thus, it is possible that the LIDAR measurements detected these processes, which led to the increase in the temperature difference during the autumn and winter seasons. Similar results were also reported by Randel et al.[33] for the northern hemisphere where they compared data sampled at four LIDAR sites to Met Office stratospheric analyses.

Moreover, the HALOE and SABER satellite data are for day and night-time observations, whilst the LIDAR measurements were made during the night only. Hervig et al.[23] compared the sunrise and sunset observations of HALOE temperature measurements and found sunrise values to be 1 K – 5 K lower than the sunset values. They also compared the HALOE-measured temperature profiles (sunrise and sunset) to those of LIDAR-measured and rocketsonde-measured profiles and noticed that the measurements typically had differences less than 5 K for the height region below 60 km. The differences between the LIDAR and HALOE measurements reported in this study are in agreement with results from Hervig et al.[23] Earlier results on an intercomparison study by Randel et al.[33] based on different middle atmospheric temperature measurements also indicated that the LIDAR-measured temperature profiles differed by ±5 K. Recently, a study by Sivakumar et al.[32] comparing Rayleigh LIDAR and satellite temperature measurements over a southern sub-tropical site (Reunion Island) reported a temperature difference of 5 K – 10 K in the stratosphere.

Summary and conclusion

Based on 5 years (1999–2004) of Rayleigh LIDAR measurements over Durban, a sub-tropical latitude station in South Africa in the southern hemisphere, the climatology of the temperature of the atmosphere between 30 km and 70 km has been studied and compared with the 4-year (2000–2004) and 5-year (1999–2004) observations from SABER and HALOE satellite instruments, respectively, for the first time.

The LIDAR temperature measurements of the stratopause (at ~42 km – 50 km) showed two distinct maxima of 270 K – one during the period from February to July and the other during the period from September to December. All instruments indicated an annual oscillation in the stratosphere. These findings are consistent with previous observations made by Chanin and Hauchecorne[6], Hauchecorne et al.[15], Gobbi et al.[28] and Batista et al.[29] The satellites, SABER and HALOE, exhibited the same thermal structure of the middle atmosphere over Durban. Comparisons of seasonal mean temperatures obtained from the Durban LIDAR with HALOE and SABER seasonal mean temperatures were in good agreement. However, during autumn and winter the LIDAR measurements were 5 K – 12 K higher in the height region between 40 km and 55 km. The stationary planetary waves that usually propagate into the stratosphere during winter may be the main cause of a higher temperature difference between the LIDAR and satellite observations in winter and autumn.

The difference in methods of data retrieval between the ground-based and space-based instruments, as well as the location and time of the measurements, might contribute to the overall differences between the LIDAR and satellite measurements. In all seasonal profiles, the LIDAR temperature measurements fluctuated above 50 km, indicating a wave-like structure which may be as a result of gravity and tidal waves. The effects of gravity waves and tidal waves over Durban will be examined in detail in a future study.

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Competing interests

We declare that we have no financial or personal relationships which may have inappropriately influenced us in writing this article.

Authors' contributions

N. Mbatha performed the data analysis and produced the results of the paper. V. Sivakumar, H. Bencherif, S. Malinga and S.R. Pillay assisted in analysing the results and provided input during the construction of the manuscript. A. Moorgawa and M.M. Michaelis assisted in the operation of the instrument.

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