Revista de Climatología

Vol. 9 (2009): 1-14 ISSN 1578-8768

A comparative analysis of the temperature behavior and multiple tropopause events derived from GPS, radiosonde and reanalysis datasets over Argentina, as an example of Southern mid latitudes.

S.G. Lakkis[1,2] and P.O. Canziani[1,3]

[1] *Equipo Interdisciplinario para el Estudio de Procesos Atmosféricos en el Cambio Global (PEPACG), Pontificia Universidad Católica Argentina (UCA). Facultad de Ciencias Agrarias.*

[2] *Facultad de Ciencias Agrarias. Pontificia Universidad Católica Argentina*

[3] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET).*

(Correspondence to: gabylakkis@uca.edu.ar)

(Received: 29-Jan-2009. Published: 28-Apr-2009)

Abstract

Recent research on climatologies for temperature structure and tropopause parameters in the tropics, based on radiosonde, satellites data and model reanalysis show good agreement between radiosonde (RS) and data derived from remote sounding, such as GPS Radio Occultation (GPS RO), and reanalysis. The agreement is remarkably good over and immediately near the tropics. However, in the southern extra tropical region, especially at medium and high latitudes, there are often considerable differences in the temperature profiles as latitudes increases, which depends on the variability of location and evolution of the tropopause. The purpose of this work is to compare the behaviour of temperature profiles derived from GPS RO, daily and monthly ERA 40 reanalysis means and nearby radiosonde measurements in the southern extra tropical region. Argentina serves as an example of latitudes between 30°- 60°S. The data covers 2001-2002 and analyses parameters such as temperature, pressure, and height derived rom radiosonde and satellite data in order to detect single and multiple tropopause events. The results show that in most cases are GPS RO more closely related to RS measurements than to reanalysis profiles, both for daily values, monthly means and their standard deviations. However, GPS RO deviations increase with respect to RS for heights above the tropopause, i.e., in the stratosphere, and decrease into the troposphere. Radiosonde and GPS appear to be in good agreement for tropopause temperatures and heights estimates when a single tropopause (LRT1) is considered, but with decreasing agreement as latitudes increase. Furthermore, while single and double tropopause events can be detected in RS observations this is less common for the GPS RO retrievals.

Key words: Remote sensing, GPS, tropopause.

Resumen

Investigaciones recientes sobre climatología de la estructura térmica y parámetros de tropopausa en los trópicos, basadas en radiosondas, datos de satélite y productos de reanálisis, muestran una buena concordancia entre los radiosondeos (RS) y los datos derivados de ocultaciones, como las radio ocultaciones del GPS (GPS RO), y los reanálisis. Sin embargo, en la región meridional extratropical, especialmente en latitudes medias y altas, a menudo hay considerables diferencias en los perfiles de temperatura al ir aumentando la latitud, dependiendo de la variabilidad de la altura y evolución de la tropopausa. El propósito del presente trabajo es mostrar el comportamiento de los perfiles de temperatura obtenidos de las ocultaciones GPS y los perfiles diarios y mensuales de reanálisis derivados del ERA 40 comparados con los valores de radiosondeo para eventos detectados en Argentina, como ejemplo de latitudes entre 30° y 60° sur, durante el período 2001-2002. Por otro lado, el estudio analiza también parámetros como la temperatura, altura y presión de los niveles significativos de radiosondeo y de las ocultaciones con el fin de analizar la existencia de eventos con simple y múltiple tropopausa. Los resultados obtenidos de la comparación entre las diferentes bases de datos muestran que en la mayoría de los casos las ocultaciones proveen perfiles de temperatura semejantes a aquellos graficados a partir de datos de radiosondeo, en contraposición a los *obtenidos a partir de los productos de reanálisis, tanto diarios como mensuales. No obstante es posible observar que las diferencias entre las RO y los RS son más notorias para alturas superiores a los niveles de tropopausa, mientras que decrecen en la troposfera. Relacionado con los eventos de múltiple tropopausa, el análisis realizado muestra que los valores de temperatura y altura de la tropopausa de las RS y las RO son semejantes cuando sólo es considerada la LRT1, con diferencias crecientes a medida que las estaciones analizadas están ubicadas en latitudes más altas. A pesar de esta concordancia para la LRT1, los resultados muestran que solo los datos procedentes de radiosondeos son capaces de detectar eventos con LRT2 y LRT3.*

Palabras clave: *Telemetría, GPS, tropopausa.*

1. Introduction

Detecting and monitoring the variability and change in global climate, is one of the most important scientific and technical challenges for the next years, due to the strong evidence that the Earth's climate is changing, as a result of human activities. Understanding global warming and climate variability are topics that concern not only meteorology and climatology studies, but also the advancement of atmospheric chemistry and physics. It is fundamental to establish reliable and stable long-term records of key climate variables such as atmospheric temperature and humidity as well as to understand related physical and chemical processes. The global temperature structure has been studied with different techniques, such as balloons, satellite derived data, different kinds of LIDAR observations and products from various reanalysis models (Reid and Gage, 1984 and 1985; Reichler *et al.*, 1996; Steinbrecht *et al.*, 1998; Hoinka, 1998; Seidel *et al.*, 2001; Randel *et al.*, 2000; Lakkis *et al.*, 2008), which provide a large array of measurements. These data sets are also associated with various limitations or even errors that derives from, e.g. differing vertical and horizontal resolutions, model and assimilation capabilities as well as instruments quality, operational characteristics, inversion algorithms and, in the case of satellite instruments, orbit changes.

Obtaining reliable vertical profiles of atmospheric variables in general and information on their global behaviour in particular of temperature, is one of the most important steps to improve our understanding of troposphere and stratosphere dynamics and climatology, and processes such as coupled stratosphere-troposphere dynamics/climate (Baldwin *et al.*, 2007) and troposphere-stratosphere exchange (STE) of trace species including greenhouses gases. Since the World Meteorological Organization assessment in 1990 (WMO, 1990), there has been a growing impetus for observational and model investigations of the temperature trends. This has occurred owing to increases in greenhouse gases and the now well documented global and seasonal losses of stratospheric ozone, both of which are estimated to have impact on the climate (Langematz, 2000; Rex *et al.*, 2004; IPCC, 2005). Temperature changes also affect the microphysical-chemical processes in the lower stratosphere and upper troposphere (UT/LS region) (WMO, 1999).

On the other hand, the tropopause is recognized as a key feature of the atmospheric structure at all latitudes; i.e., polar, mid latitudes and tropics, and an overall understanding both of the UT/LS and of STE is dependent on our ability to quantify and describe tropopause structures and their evolution over time (Holton *et al.*, 1995; Shepherd, 2002; Stohl *et al.*, 2003; Seidel and Randel, 2006).

The tropopause layer (Pan *et al.*, 2004; Bischoff *et al.*, 2007) in simple terms determines the boundary between the troposphere and stratosphere, which has fundamentally different characteristics with respect to chemical composition and static stability. The tropopause can be thus viewed as the transition zone between the turbulently mixed troposphere and the more stable stratified stratosphere (Hoinka, 1998), affecting both the dynamics and the chemistry. In this scenario the tropopause plays an exceptional role (Shepherd, 2002; Garrett *et al.*, 2005).

Various studies have attempted to elucidate the key factors that determine the latitudinal-altitude distribution of the tropopause (e.g. Held, 1982; Thuburn and Craig, 1997 and 2000; Haynes *et al.*, 2001). Initial studies were based on radiosonde (Labitzke and van Loon, 1999). More recently, data derived from satellite and analyses from numerical weather prediction centres and reanalysis products (Hoinka, 1998; Randel *et al.*, 2000) have provided insights on the behaviour of the tropopause. Although some of these studies are based on linear interpolation of the atmospheric variables they reveal that the tropopause responds to different influences, such as angular momentum, volcanic eruption and solar radiation (Reid and Gage, 1981; Robock, 2000; Shindell *et al.*, 2001). These studies show a variability of the tropopause height over the last decades, either at individual radiosonde stations, stations networks in the tropics or in tropical averages from reanalysis products (Randel *et al.*, 2000; Steinbrecht *et al.*, 1998). Tropopause altitude behaviour is thus an excellent parameter for detection the climate variability. Global tropopause pressure changes in the ECMWF 15-years reanalysis (1979-1993) have been estimated to vary between +0.1 and 1.13 hPa/decade (Hoinka, 1998 and 1999; Santer *et al.*, 2003), while both ECMWF 40-year reanalysis and NCEP/NCAR reanalysis show larger trends of about 2 hPa/decade in 1979-2001 (Santer *et al.*, 2003 and 2004) in the zonal means values. These reported tropopause trends in reanalyses are remarkable given that typical vertical reanalysis resolution publicly available is about 50 hPa near the tropopause, and that the tropopause is calculated by interpolation of lapse rates between model or reanalysis levels (Seidel and Randel, 2006). Therefore direct monitoring and understanding of the temperature structure and the behaviour of the tropopause layer interaction with the upper troposphere and lower stratosphere remain important goals for atmospheric and climate change studies (Baldwin *et al.*, 2007).

The WMO definition of the tropopause is based on lapse ratio criteria. This definition is referred to as the thermal tropopause, being the definition used in the operational radiosonde profiles retrievals. The tropopause can further be defined by more general stability criteria, represented by potential vorticity (PV) (Hoerling *et al.*, 1991). In terms of the lapse rate tropopause, the interface between the tropics and extratropics at a particular longitude is often characterized by a break in the tropopause, rather than a continuous transition. It should be noted that the tropopause can occur as a multiple or layered tropopause (Bjerknes and Palmén, 1937). Multiple tropopause are referred by WMO (1999) as: "A frequent atmospheric condition in which the tropopause appears not as a continuous single surface of discontinuity between the troposphere and stratosphere, but as a series of quasi horizontal "leaves" which are partly overlapping in a step-like vertical distribution".

Many recent studies have sought to analyse and characterize multiple tropopause in the tropics, i.e., the Tropical Tropopause Layer (TTL) (e.g., Seidel *et al.*, 2001) but less so in Polar Regions (e.g., Zängl and Hoinka, 2001). Even fewer studies have been carried out for the mid-latitude regions in particular over the Southern Hemisphere (e.g., Bischoff *et al.*, 2007).

Over the extratropical regions, soundings can reveal the presence of multiple tropopause events. Seidel and Randel (2006) as well as Bischoff *et al.*, (2007) noted that historical radiosonde show the presence of multiple tropopause events and their trends. Multiple tropopause situations have been studied since the advent of upper air soundings (Bjerknes and Palmén, 1937; Kochanski, 1955). However, few studies of the extratropical regions have analysed in detail the characteristics and dynamical and chemical transitions between the troposphere and stratosphere.

The present work analyzes the temperature profiles for radiosonde stations in Argentina as an example of Southern mid latitudes between 30°S - 60°S, using data from radiosonde (RS), retrievals from the Global Positioning System radio occultation (GPS RO), data from similar sensors on board CHAMP (Challenging Minisatellite Payload) and SAC-C (Satélite de Aplicaciones Científicas) satellites, and data derived from ERA40 reanalysis. In order to compare the different datasets, the RS retrievals were considered observational reference. In addition, the study analyzes the presence of single and multiple tropopause events according to the lapse rate tropopause (LRT) definition for GPS remote sounding data and significant levels derived from radiosonde profiles.

This paper is organized as follows. In section 2, we describe the datasets and the methodology. In section 3 we examine the accuracy of the intercomparisons for the selected stations, and show the multiple tropopause events detected by the RS and RO retrievals. Finally, the work is summarized in section 4.

2. Data and methodology

2.1. Data

Operational radiosonde, satellite retrievals from CHAMP and SAC-C and reanalyses data products from ERA 40 are chosen for this study.

2.1.1. Radiosondes

For more than fifty years, radiosondes have been the core of operational and observational datasets. However there are many problems when such datasets are to be used for variability and trend studies. It is very common in atmospheric studies that incomplete datasets have to be used, either because the original complete datasets are no longer available or because there are gaps in the operation of the instruments. In such cases, can potential results be affected by assumptions about the extent to which an incomplete dataset is representative of the full unavailable sample nd various working hypotheses must thus be applied during the analysis. Although the sonde data do not cover the entire globe, there have been several well-documented efforts using varied techniques to obtain temperature data over the global domain. The RS measurements used here are obtained from the database at the Department of Atmospheric Sciences, College of Engineering, University of Wyoming (http://weather.uwyo.edu). A set of 4 stations over Argentina at latitudes between 30°- 60°S (only two are shown), was selected for this study. The criteria include the length and completeness of the archived data records and coincidence with GPS remote soundings events during 2001-2002, in order to more closely compare the different techniques. The chosen stations are Córdoba (SACO), Ezeiza (SAEZ), Santa Rosa (SAZR) and Mount Pleasant (EGYP). Stations will hereafter be referred to using the International Air Transport Association code, e.g., SAEZ, and so forth (table 1). Depending on the sensor and balloon used at each location, the vertical resolution of RS data typically have 40 levels between 1000 and 50 hPa or 0.5 km resolution.

2.1.2. GPS data

The availability of GPS radio signals during the last decade has introduced a promising remote sensing technique for the Earth's atmosphere due to its global coverage, high vertical resolution, self-calibration and ability to operate under all weather conditions. Signals from GPS satellite constellations are received by sensors onboard Low Earth Orbiting (LEO) satellites for atmospheric limb sounding. Signals from GPS measurements are influenced by the atmospheric refractivity field resulting in a time delay and bending of the signal, assuming the validity of geometric optics and local spherical symmetry. The atmospheric shift phase is the observable variable, which is measured with high accuracy and varies from about 0.5 km in the lower troposphere to about 1 km in the lower stratosphere (Kursinski *et al.*, 1994, 1995 and 2001; Kursinski, 1997).

In this study approximately 40 soundings from SAC-C and CHAMP satellites for 2001-2002, provided by Jet Propulsion Laboratory (JPL), are analyzed.

While a complete statistical analysis cannot be carried out due to the restricted number of GPS RO profiles it is still possible to achieve a reasonable comparison of tropopause events in RS and GPS RO profiles. For this purpose, given the WMO definition of tropopause, only significant levels from radiosonde profiles were considered for its determination. By contrast data collected by sensors onboard CHAMP and SAC-C contain many different variable levels due the nature of the technique and their global coverage during the day. We consider here that both methods can be analytically compared if GPS retrievals, since they show a unique and instantaneous retrieval for each station, are taken as significant levels.

2.1.3. ERA 40 reanalysis

Detailed descriptions of model processing and data products provided by The European Centre for Medium Range Weather Forecast (ECMWF) can be found at (http://www.ecmwf.int). For the present work the publicly available model has 16 pressure levels on a 2.5° $\times$ 2.5° grid.

Table 1: Names, IATA and WMO codes, and coordinates of the stations used in the study.

Name	IATA	WMO	Lat.	Lon.
Córdoba	SACO	87344	-31.32	-64.22
Ezeiza	SAEZ	87576	-34.82	-58.53
Santa Rosa	SAZR	87623	-36.57	-64.27
Mount Pleasant	EGYP	88889	-51.82	-58.45

Figure 1: Radiosonde stations located in Argentina. (Source: Department of Atmospheric Science, College of Engineering, University of Wyoming).

2.2. Methodology

All reported levels, both the standard and significant levels in radiosonde observations made within three hours from 00Z to 12Z, were used to compare with the GPS RO and ERA 40 in order to study temperature behaviour over these stations. Data from RS were computed in order to obtain two subsets from the original data set, corresponding to significant and standard levels respectively, so as to determine the location of the lapse rate tropopause (LRT1) for each data set and, if present, the second (or third) tropopause (LRT2, LRT3), using the World Meteorological Organization definitions. Single and double (multiple) tropopause determinations were carried out using the following criteria:

1: The first tropopause (LRT1) is defined as the lowest level at which the temperature lapse-rate is less than to 2 K/km and the lapse-rate average between this level and the next 2 km does not exceed 2 K/km.

2: If above the first tropopause (LRT1) the average lapse rate between any level and all higher levels within 1 km exceeds 3 K/km, then a second tropopause is defined by the same criteria as under the first criterium. This tropopause may be either within or above the 1 km layer.

Regarding the RO retrievals, the globally distributed data were processed to obtain individual profiles of each event, where each event corresponds to a profile for a specific year, month, day and hour, with a selected $2.5^\circ \times 2.5^\circ$ (latitude-longitude) gridbox, around a selected radiosonde station. Temperature, pressure and height are considered among other atmospheric variables.

For the comparison with radiosonde data and GPS retrievals, both monthly means and corresponding daily reanalysis data are used in the present study. Monthly means data within the 30°-60°S latitude band were bilinearly interpolated for 1000 to 10 hPa levels to each station's coordinates.

Daily and mean temperature profiles over the selected stations as well as the corresponding monthly standard deviations were thus calculated for comparison with RS and GPS RO profiles.

3. Results

3.1. Comparison between the datasets

The temperature profiles derived from RS measurements, GPS RO retrievals as well as ERA 40 daily profiles and monthly means are plotted together in the Figures 2 to 6 for SAZR and EGYP, as examples of the stations under study. For reanalysis products daily profiles are named ECMWF D, while ECMWF M stands for monthly means.

Figures 2 to 4 compare, for some randomly selected events, RS data, monthly (daily) means reanalysis and GPS RO measurements for SAZR as example of a station located near the Tropic of Capricorn. Temperature for RS measurements in the upper levels decreases with height due to the fact that proportionately fewer radiosonde launches reach stratospheric levels. By contrast, in the lower troposphere, the situation is different. Here the number of GPS RO data available per height decreases with decreasing altitude. This is related to the refractivity bias (Kursinski, 1997). On the other hand, reanalysis products always contain a fixed amount of data per level. At first sight GPS RO may appear more closely related to RS measurements than to reanalysis profiles, both for daily values as well as for monthly means and their standard deviations. However there are GPS RO differences that increase respect to RS for heights above the tropopause levels (stratosphere) and decrease into the troposphere. These results are in agreement with previous results since GPS RO have their highest accuracy near 100 hPa pressure level (Kursinski *et al.*, 1994 and 1995; Kursinski, 1997).

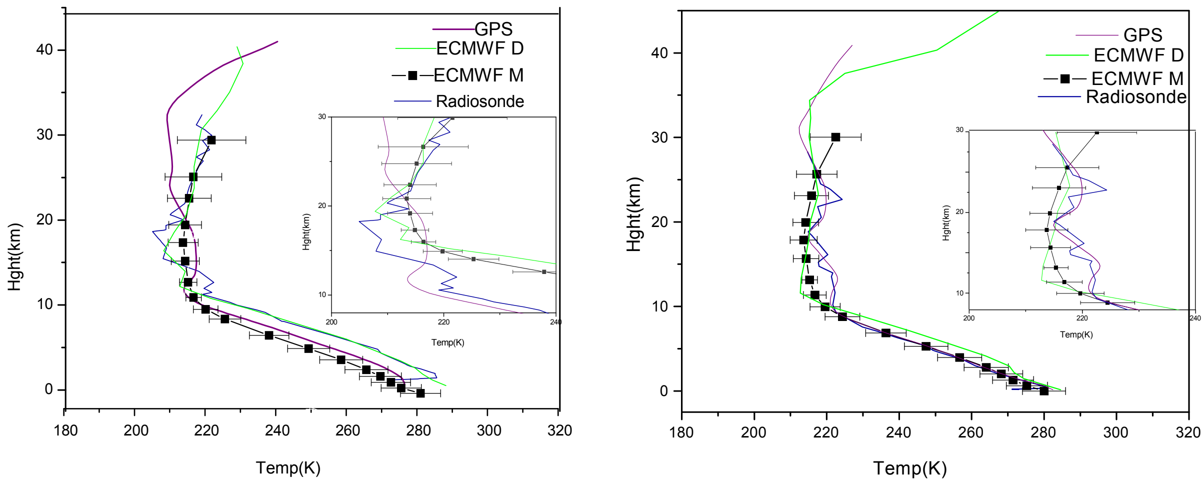

Figure 2: Vertical profile derived from radiosonde data, reanalysis daily values, reanalysis monthly means value and GPS RO for SAZR on June 20, 2001 SAC-C (left) and July 10, 2001 CHAMP (right).

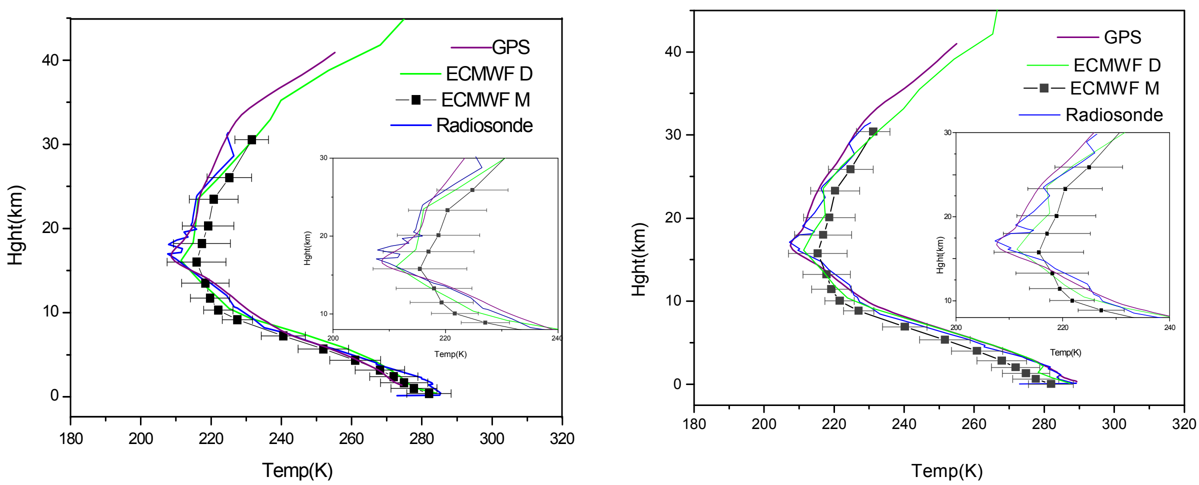

Figure 3: As in figure 2 but for SAZR on November 24, 2001 SAC-C (left) and November 26, 2001 CHAMP (right).

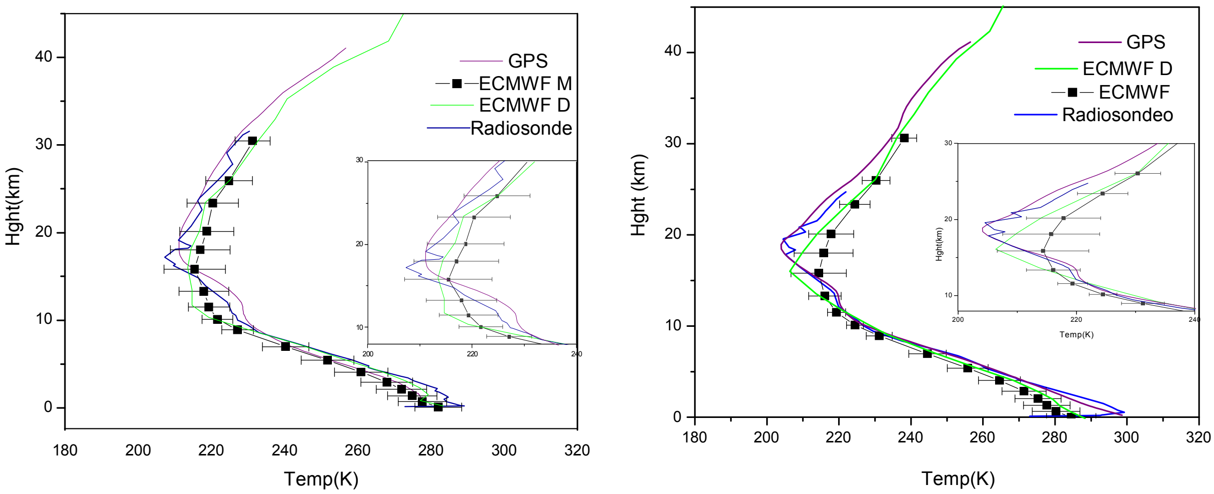

Figure 4: As in figure 2 but for SAZR on November 29, 2001 CHAMP (left) and January 22, 2002 CHAMP (right).

The differences between GPS RO and RS for the set of stations oscillates between 1-10 K. Most differences are warm biases in the lower troposphere and cold biases in the lower stratosphere. On the other hand, for pressure levels at less than 50 hPa, or altitudes higher than 20 km, the performance of the sensor must be taken into account due to their fundamental role at these differences.

Even in the height range of better GPS RO performance, i.e., close to the tropopause and UT/LS, all RS profiles show a height range. This shows, despite variability, a distinct change in the temperature profile that corresponds to the change in the temperature gradient. GPS RO profiles, on the other hand, show a smooth curve as if the data had been fitted at the height range that surrounds the tropopause zone. Thus, while the RS profiles suggest a complex structure in the UT/LS transition height range, the GPS RO profiles would appear to suggest a far smoother, less stratified transition in the STE region.

The ERA 40 profiles, on the other hand, have important differences when compared with RS ones, even at levels below the tropopause. Such differences can be detected not only in daily profiles but also for monthly means profiles. These differences, which can extend beyond the standard deviation of the means, could suggest systematic errors in the processed profiles. Even when there are some cases, as shown in figure 5 (chart (b), station code 88889: EGYP), which carry few differences between profiles from GPS RO and ERA 40 products in the stratosphere, both yield differences with respect to RS.

For almost all the stations in this study, the RS and GPS RO observed temperature profiles are quite close but only up to about 12 kilometres, as well as with ERA 40 profiles (both the monthly mean and the corresponding daily profile). ERA 40 profiles show cold differences at lower troposphere heights in contrast with the stratosphere, where the biases are warm compared with RS and GPS RO observations. These differences appear both in the daily profiles and in the monthly mean values plotted.

Both ERA 40 monthly mean values and their standard deviation show, as expected, different behaviour for each month. In consequence, if monthly mean values, bilinearly interpolated, are considered to reasonably represent the expected daily behaviour, as the plots show it happens in many cases, the detected biases could have a strong temporary dependence.

The profiles obtained from the reanalysis show that monthly mean profiles at these locations have differences at almost all heights, which are particularly important at the upper levels between 1020 km. These differences reach in some cases values as large as 10-14 K in and around the tropopause, showing a trend that underestimates the temperature behaviour compared to RS and GPS RO. Thus, despite differences, either because of bias or smoother structures in particular in the UT/LS region, GPS RO retrievals are overall in better agreement with the observations obtained by the operational radiosonde network than the latter with ERA 40 reanalysis products.

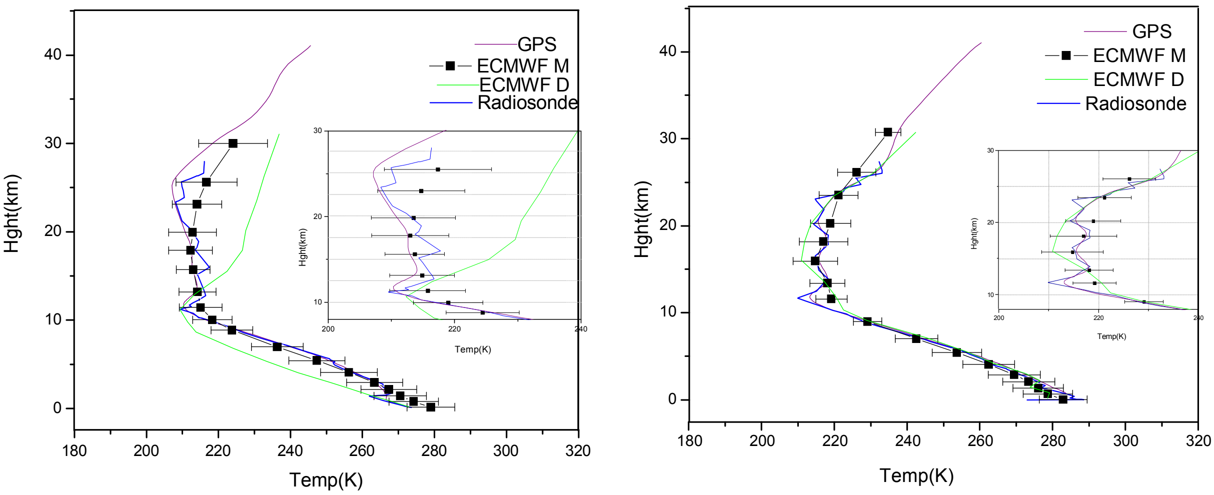

Figure 5: As in figure 2 but for EGYP on: September 15, 2001 CHAMP (left) and December 10, 2001 CHAMP (right).

3.2. Tropopause

In this section only data from RS and GPS RO profiles were used to calculate tropopause parameters for each studied event, considering the notable differences found in the reanalysis profiles with regard to the RS, as shown in the previous section.

The GPS RO and RS data were processed in order to obtain LRT1 and, if present, LRT2 or even LRT3. Values for tropopause pressure, height and temperature obtained by this procedure are shown in table 2 for SAEZ as an example of the approach applied to all stations. As pointed out in the methodology section, the WMO definitions of thermal tropopause and multiple tropopause situations were used in the present analyses. While the number of events considered during 2001-2002 do not permit the analysis of annual variability or a full statistical analysis, a preliminary inspection of the results can suggest important features on tropopause behaviour. As it would be expected, given the smoothness of the GPS retrievals in the UT/LS region shown in the previous section, a preliminary inspection shows that, while single and double tropopause events can be detected in RS observations, this is not as common an occurrence with the GPS RO retrievals.

Examples of temperature profiles where LRT1, LRT2 and, in some cases LRT3, are identified in RS observations but not in GPS RO retrievals are shown in figure 6.

SAEZ is one of the most representative stations for the present study, where frequent occurrences of multiple tropopauses are observed when data from radiosonde, both in low and high resolution, are available. It is possible to note in table 2 that in RS profiles LRT1 height is found on average at around 12.5 km, with a temperature near 210 K. These values are in reasonable agreement with GPS RO retrievals: tropopause height is located at about 13.6 km, and the temperature is near 213 K. In this sense, Kishore *et al.* (2006) found that for these regions tropopause height can vary between 9 and 16 km, while temperature values increase from 199 K to 219 K. Special reference must be made regarding EGYP, as an example of a high latitude station: differences between GPS and RS data can be as large as 6 km for tropopause height, yet temperatures in both datasets are of the same order, i.e., around 213-215 K. This is less than expected for this latitude, but represents a coherent value if the number of occultations available is taken into account. Therefore, both GPS RO and RS datadescribe climatologically reasonable LRT1 heights and temperatures decreasing from 12 km over subtropical/mid latitudes to about 9 km at higher latitudes, i.e., decreasing height values and increasing temperature values towards the Pole.

Therefore, broadly speaking radiosonde and GPS appear to be in good agreement in tropopause temperatures and heights estimates when LRT1 is considered, with a decreasing agreement as latitude and temporal independence for the available retrievals increase at the stations under study. Nevertheless, it is possible to infer a slight overestimation of the tropopause parameters derived from GPS RO, both in height and/or temperature, depending on the location of the studied station. This behaviour is in good agreement with the results previously mentioned in the comparison of temperature profiles.

An important issue regarding tropopause parameters is that of the pressure behaviour: the differences between GPS RO and RS data are independent of station latitude and longitude. These differences vary between a scant 1 hPa to more than 120 hPa (table 2), but in these cases pressure differences are not reflected in height or temperature values to such an extent; i.e., the high variability between tropopause pressure values in each event between the two methods does not imply a similar variability in temperature or height values.

As an example, table 2 includes a row in blue corresponding to SAEZ, on 29 May, 2002, with a pressure difference close to 120 hPa, while the temperature difference is only 4 K; i.e., pressure differences are about 45%, while temperature or height differences are only near 2%. Regarding this point, studies using radiosonde network data have evaluated the tropopause pressure monthly mean anomalies. They concluded that, even when the pressure is independently measured (and it is generally thought that radiosonde pressure observations are more accurate than temperature ones), this argument is unfortunately wrong, and the accuracy is directly related with the performance of the sensor type used at each station (Seidel and Randel, 2006). These anomalies are present too in reanalyses products and satellite data, as mentioned in several previous studies (e.g., Santer *et al.*, 2003). The comparison between the various observation techniques and with the reanalysis further confirms these findings.

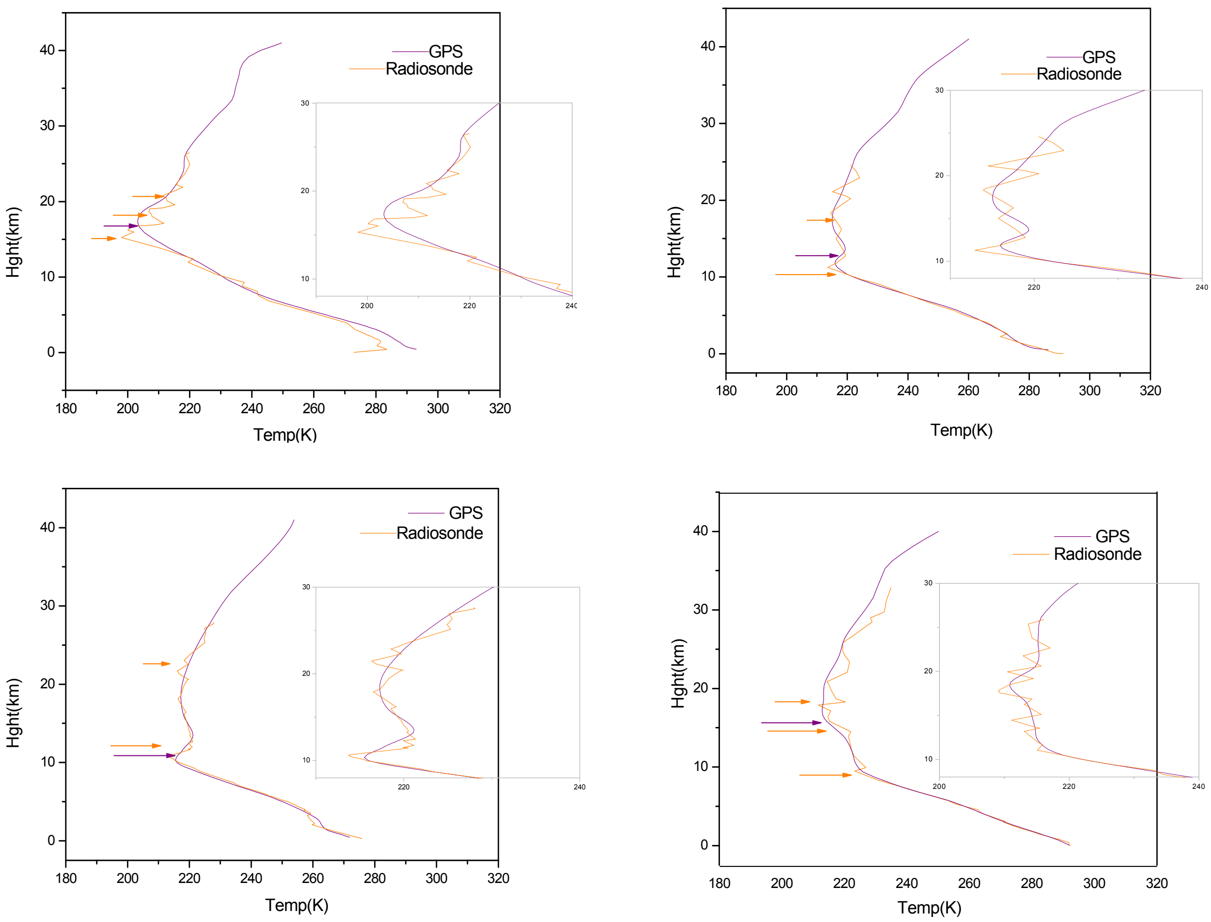

Figure 6: Vertical temperature profiles for SACO, June 05, 2002 (upper left), SARZ, December 15, 2001 (upper right), EGYP, March 18, 2002 (lower left), and SAEZ September 04, 2001 (lower right). (Arrows in orange denote location of tropopauses from radiosonde, while in purple correspond to GPS, both defined by the temperature lapse rate criterion).

Table 2: Tropopause parameters derived from radiosonde and GPS retrievals for SAEZ. Values show the presence of LRT1, LRT2, LRT3 and even LRT4 for some events from data collected from radiosonde, 12 UTC, while values derived from GPS can detect only the first lapse rate.

SAEZ	Date	P1 (hPa)	H1 (km)	T1 (K)	P2 (hPa)	H2 (km)	T2 (K)	P3 (hPa)	H3 (km)	T3 (K)
RS	2001-05-23	104.0	16062.0	205.1	24.0	25178	273.7	13.6	28810	214.3
GPS	14.47	190.6	12364.7	214.4	–	–	–	–	–	–
RS	2001-06-08	179.0	12748.0	207.1	44.6	21214	208.1	–	–	-
GPS	11.37	188.2	12459.6	211.5	–	–	–	–	–	–
RS	2001-09-04	229.0	11077.0	215.1	–	–	–	–	–	–
GPS	16.50	171.9	12919.5	214.8	–	–	–	–	–	–
RS	2001-09-12	194.0	12258.0	210.5	–	–	–	–	–	–
GPS	03.37	147.0	14029.8	208.1	–	–	–	–	–	–
RS	2001-11-04	258	10394.0	222.7	134.0	14652	210.3	–	–	–
GPS	11.45	253.9	10535.9	226.0	–	–	–	–	–	–
RS	2001-11-15	287.0	9496.0	222.3	109.0	15804	215.3	62.0	19372	216.4
GPS	14.41	97.1	16546.0	213.2	–	–	–	–	–	–
RS	2002-03-12	89.1	17259.0	198.9	–	–	–	–	–	–
GPS	10.23	99.6	16628.5	201.9	–	–	–	–	–	–
RS	2002-05-29	229.0	10999.0	217.1	135.0	14345	214.0	64.0	18999	211.8
GPS	13.37	105.5	15908.2	212.4	–	–	–	–	–	–
RS	2002-06-16	210.0	11629.0	211.3	–	–	–	–	–	–
GPS	03.27	205.6	11733.6	215.5	–	–	–	–	–	–

From results reported in table 2, it is possible to infer 44% of occurrences for LRT1 and near 30% for LRT2 in SAEZ for the RS observations considered in this study. This percentage of occurrences is obviously influenced by the limited number of events. However, the results must necessarily consider two important factors that could influence the final profiles derived from the GPS RO: First of all, the quality of the measurement due to the refractivity. During the analyzed years, the performance of GPS sensors was not at its best, e.g., the number of erroneous CHAMP profiles due to different kinds of errors, both in the capture of signals and their processing were around 30% for 2001 and 27% for 2002. And secondly, it is also important to point out the fact that the GPS RO selected for this research were restricted in $2.5^\circ \times 2.5^\circ$ latitude-longitude gridbox and, as a consequence, the number of profiles available for analyses was limited. While this approach restricts the possible statistics analyses, if the region under study had been a large latitude-longitude band instead of a gridbox, the comparison with actual RS profiles would not have been conclusive without an array of statistical test between both data sets. And from a dynamic perspective, such a comparison would not have been reliable, since physical processes affecting the RS profiles may not influence the GPS RO profile located at a distance and vice versa.

Nevertheless, and as mentioned above, the detection of multiple tropopause corresponds only to RS data. The analysis of GPS RO retrievals could only detect LTR1 in most cases and practically no double or multiple tropopause events were detected in the vicinity of the selected stations, even when the RS profile clearly had a double tropopause occurrence. For SAZR and EGYP there were cases where GPS RO lapse rate analysis did not even yield a single tropopause according to the WMO definition (results not shown). Thus, given these results, it made no sense to carry out a detailed analysis of multiple tropopause events with GPS RO profiles. Such behaviour in the satellite retrievals is systematic for all station studied and can be seen in the examples presented in figure 6. Furthermore, when RS data reveals the presence of multiple tropopause situations, the differences between temperatures for LRT1 derived from both methods appears to increase. Moreover, in some cases, the single tropopause temperature derived from GPS RO was close to the non-weighted average of LRT1, LRT2 and eventually, if present, of LRT3 derived from RS measurements.

4. Discussion and conclusions

The comparison of GPS RO measurements and ERA 40 reanalysis products with RS profiles at Argentinian selected sites for the period 2001-2002, provides insights into the capabilities of these different techniques to describe the troposphere and lower stratosphere, and in particular the UT/LS region.

The comparison carried out in section 3 reveals at first sight a better agreement for GPS RO measurements with RS profiles than for reanalysis products, both as daily and monthly mean values. It was shown that, even when the agreement of GPS RO profiles with RS data varies with the location of the stations under study, especially in the stratosphere, the resulting differences derived from remote sounding are practically independent of the latitudelongitude because there are no correlation between the module of the differences and the station locations. Profiles plotted for almost all stations show good agreement with RS measurements up to 15 km, with smaller differences than at upper levels. As it was previously mentioned, the sources of this somewhat less than perfect agreement in the lower troposphere could be related to water vapour (Wickert *et al.*, 2004). From figures 2 to 6 it is possible to note that, in those cases where GPS RO profiles do not have a good agreement with RS data at the lower troposphere, the differences between GPS RO and RS measurements commonly appear as warm biases. It could be thus considered that in the lower troposphere GPS RO have a slight trend to overestimate temperature values at altitudes below 10 km and tropopause vicinity. The lower stratosphere has the opposite performance when GPS RO is compared with RS data. In this case, cold differences are more important, particularly near 20 km. It is important to note that, for these heights, radiosonde instruments may not reach upper levels with high accuracy measurements.

Concerning the ERA 40 reanalysis products, the comparison with the RS data shows that both the daily values and the monthly means have differences larger than GPS RO with respect to RS data. These differences are present in the troposphere as cold biases as well as in the stratosphere where the differences appear as warm biases. Thus ERA 40 analysis yields behaviour with a tendency to underestimate the temperature structure, particularly near the tropopause. The reason for these deviations could be found in several factors, but it is important to note that the output of the ERA 40 data were bilineary interpolated. As the results show, the interpolation must be done with exponential criteria that involve not only obtaining a correct estimate, but also representative standard deviations.

Regarding the accuracy of tropopause detection, temperature and height values for LRT1 derived from GPS RO can globally be considered in a good agreement with RS data (Kishore *et al.*, 2006).

Recently published papers (e.g. Schmidt *et al.*, 2004; Randel *et al.*, 2003) have carried out comparisons between radiosonde measurements and data derived from GPS, considering latitude bands with a much broader coverage in extra tropics region. They could establish, using different techniques, that tropopause folds occur in latitude bands between 30° to 50° over both hemispheres, with more occurrences, on average, over the Northern Hemisphere than over the Southern Hemisphere. There is however a region with enhanced multiple occurrences (at least double tropopause) at eastern South America (35°) during the summer and winter seasons. These latitude bands with multiple tropopause events are related to the location of the jet stream. Furthermore, it was noted that tropopause breaks and double tropopause situations could be associated with the passage of frontal systems (Palmén and Newton, 1971). More recently the subtropical jet was considered as the primary source for double tropopause events. In simple terms, the jets near the tropopause, either the subtropical jet or jets associated with frontal activity, can lead to tropopause break and double or multiple tropopause situations (Wickert *et al.*, 2004). Bischoff *et al.* (2007) provide valuable information about the occurrence distribution of double tropopause at southern extra tropical latitudes using near thirty years of observations from a radiosonde network (i.e., approximately 9000 daily profiles per station). They showed that, over SAEZ (a station sampled in this study as well), seasonal maximum of occurrence of double tropopause events is close to 45%. Notwithstanding an important result derived from our comparison between GPS RO and RS measurements should be noted: Results reveal that currently only RS observations can reliably detect the location of the LRT2 and LRT3, and even LRT4 in some cases (e.g. SAEZ, not shown). This is an important issue given that, despite the fact that the optimum GPS RO resolution is near 15 km or 100 hPa, their profiles cannot detect LRT2, and much less the LRT3.

Figure 6 illustrates examples of such behaviour in the profiles. Furthermore, as it was previously described, tropopause temperatures for LRT1 as derived from GPS RO measurements are an approximate average value of the double or multiple tropopause at the stations where RS profiles show their existence. Reasons for such behaviour could be related with the limited $2.5^{\circ} \times 2.5^{\circ}$ latitude-longitude gridbox; i.e., the number of radio-occultation profiles available is rather less than in a wide latitude band approach. But nevertheless it has the advantage of a more accurate comparison with RS due to their proximity in space and time. However, an overview of a limited sample of profiles, as presented in figure 6, is not sufficient for a detailed analysis and discussion. Therefore the capability of GPS RO to detect multiple tropopause events and their location, and in consequence the percentage of their occurrences, constitutes a controversial issue that must be further analyzed (at least with the algorithm used until 2003).

Acknowledgements

The authors thank the Pontificia Universidad Católica Argentina, Facultad de Ciencias Agrarias, for the Ph.D. grant given in the framework of the *Programa de Incentivo para la Investigación*, and to the *Consejo Nacional de Investigaciones Científicas y Tecnológicas* (CONICET) PIP 2004 5276.

References

Baldwin MP, Dameris M, Shepherd TG (2007): How will the stratosphere Affect Climate Change. *Science*, 316:1576-1577.

Bjerknes J, Palmén E (1937): Investigations of selected european cyclones by means of serial ascents. *Geofysiske Publikasjoner*, 12(2).

Bischoff SA, Canziani PO, Yuchechen, AE (2007): The tropopause at southern extra tropical latitudes: Argentina operational rawinsonde climatology.*Int. J. Climatol.*, 27:189-209.

Garrett TJ, Liu C, Dean-Day J, Barnett BK, Mace GG, Baumgardner DG, Webster CR, Bui TP, Read WG (2005): A redistribution of water due to pileus cloud formation near the tropopause. *Atmos. Chem. Phys. Discuss.*, 5:82098232.

Haynes P, Scinocca J, Greensalde M (2001): Formation and maintenance of the extratropical tropopause by baroclinic eddies. *Geophys. Res. Lett.*, 28:4179-4182.

Held IM (1982): On the height of the tropopause and the static stability of the atmosphere. *J. Atmos. Sci.*, 39:412-417.

Hoerling MP, Schaack TK, Lenzen AJ (1991): Global objective tropopause analysis. *Monthly Weather Rev.*, 126:3303-3325.

Hoinka KP (1998): Statistics of the global tropopause pressure. *Monthly Weather Rev.*, 126:3303-3325.

Hoinka KP (1999): Temperature, humidity, and wind at the global tropopause. *Mon. Weather Rev.*, 127:2248-2265.

Holton JR, Haynes PH, Douglass AR, Rood RB, Pfister L (1995): Stratosphere-Troposphere exchange. *Rev. Geophys.*, 33:403-439.

IPCC (2005): *Safeguarding the ozone layer and the global climate system*. Cambridge University Press, United Kingdom and New York, NY, USA, 488 pp.

Kishore P, Namboothiri SP, Igarashi K, Jiang JH, Ao CO, Romans LJ (2006): Climatological characteristics of the tropopause parameters derived from GPS/CHAMP and GPS/SAC-C measurements, *J. Geophys. Res.*, 111:D20110.

Kochanski A (1955): Cross sections of the mean zonal flow and temperature along 80 W. *J. Meteorology*, 12:95-106.

Kursinski ER, Hajj GA, Hardy KR (1994): Observing Climate Change with the Global Positioning System. *Eos Trans. AGU*, 75:114.

Kursinski ER, Hajj GA, Hardy KR, Romans LJ, Schofield JT (1995): Observing tropospheric water vapor by radio occultation using the global positioning system. *Geophysical Research Letters*, 22:2365-2368.

Kursinski ER (1997): *The GPS radio occultation concept: Theoretical performance and initial results*. Ph.D. thesis, Calif. Int. Of Technol., Pasadena.

Kursinki ER, Hajj GA (2001): A comparison of water vapor derived from GPS occultations and global weather analyses. *Journal of Geophysical Research*, 106:1113-1138.

Labitzke KG, van Loon H (1999): *The Stratosphere: Phenomena, History and Relevance*. Springer-Verlag, Berlin, ISBN 3-540-65784-3, 179 pp.

Lakkis SG, Lavorato M, Canziani PO (2008): Monitoring cirrus clouds with LIDAR in the Southern Hemisphere: a local study over Buenos Aires. 1. Tropopause heights. *Atmospheric Research*, doi:10.1016/j.atmosres.2008.08.003.

Langematz U (2000): An estimate of the impact of observed ozone losses on the stratospheric temperature. *J. Geophys. Res. Lett.*, 27:2077-2080.

Palmén E, Newton CW (1971): *Atmospheric Circulation System: Their structure and physical interpretation*. Academic Press, New York and London, 602 pp.

Pan LL, Randel WJ, Gary BL, Mahoney MJ, Hintsa EJ (2004): Definitions and sharpness of the extratropical tropopause: a trace gas perspective. *J. of Gheophys. Res.*, 109:D23103.

Randel WJ, Wu F, Gaffen DJ (2000): Interannual variability of the tropical tropopause derived from radiosonde data and NCEP reanalyses. *J. Geophys. Res.*, 105:509-524.

Randel WJ, Wu F, Rios WR (2003): Thermal variability of the tropical tropopause region derived from GPS/MET observations. *J. Geophys. Res.*, 108:(D1)4024.

Reichler T, Dameris M, Sausen R, Nodorp D (1996): *A global climatology of the tropopause height based on ECMWF analyses*. Inst. fur Phys. der Atmos. Rep., 57, 23 pp., Wessling, Germany.

Reid GC, Gage KS (1981): On the annual variation in height of the tropical tropopause. *J. Atmos. Sci.*, 38:1928-1938.

Reid GC, Gage KS (1984): A relationship between the height of the tropical tropopause and the global angular Gage momentum of the atmosphere. *Geophys. Res. Lett.*, 1:840842.

Reid GC, Gage KS (1985): Interannual variations in the height of the tropical tropopause. *J. Geophys. Res.*, 90:56295635.

Rex M, Salawitch RJ, von der Gathen P, Harris NRP, Chipperfield MP, Naujokat B (2004): Arctic Ozone Loss and climate change. *Geophys. Res. Lett.*, 31, doi:10.1029/2003GL018844.

Robock A (2000): Volcanic eruptions and climate. *Rev. Geophys.*, 38:191-219.

Santer BD, Sausen R, Wigley TML, Boyle JS, AchutaRao K, Doutriaux C, Hansen JE, Meehl GA, Roeckner E, Ruedy R, Schmidt G, Taylor KE (2003): Behavior of tropopause height and atmospheric temperature in models, reanalyses, and observations: Decadal changes. *J. Geophys. Res.*, 108:D14002.

Santer *et al.* (2004): Identification of anthtopogenic climate change using a second-generation reanalysis. *J. Geophys. Res.*, 109:D21104.

Schmidt T, Wickert J, Beyerle G, Reigber C (2004): Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP. *J. Geophys. Res.*, 109:D13105.

Seidel DJ, Ross RJ, Angell JK, Reid GC (2001): Climatological characteristics of the tropical tropopause as revealed by radiosondes. *J. Geophys. Res.*, 106:7857-7878.

Seidel DJ, Randel JW (2006): Variability and trends in the global tropopause estimated from radiosonde data. *J. Geophys. Res.*, 111:D21101.

Shepherd TG (2002): Issues in Stratosphere-troposphere Coupling. *Journal of the Meteorological Society of Japan*, 80:769-792.

Shindell DT, Schmidt GA, Miller RL, Rind D (2001): Northern Hemisphere winter climate response to greenhouse gas, ozone, solar, and volcanic forcing. *J. Geophys. Res.*, 106:71937210.

Steinbrecht W, Claude H, Koehler U, Hoinka K (1998): Correlations between tropopause height and total ozone: Implications for long-term changes. *J. Geophys. Res.*, 103:19183-19192.

Stohl *et al.* (2003): Stratosphere-troposphere exchange: A review, and what we have learned from STACCATO. *J. Geophys. Res.*, 108:(D12)8516.

Thuburn J, Craig GC (1997): GCM test of theories for the height of the tropopause. *J. Atmos. Sci.*, 54:869-882.

Thuburn J, Craig GC (2000): Stratospheric influence on tropopause height: The radiative constraint. *J. Atmos. Sci.*, 57:17-28.

Wickert J, Schmidt T, Beyerle G, König R, Reigber C, Jakowski N (2004): The radio occultation experiment aboard CHAMP: Operational data analysis and validation of atmospheric profiles. *J. Meteorol. Soc. Jpn.*, 82:381-395.

WMO (1990): Report of the International Ozone Trends Panel: Ozone, 1988. *Global Ozone Res. and Monit. Proj.*, Rep. 18, chapter 6, pp. 443-498, Geneve.

WMO (1999): Scientific Assessment of Ozone Depletion: 1998. *Global Ozone Research and Monitoring Project*, Report No. 44, Geneva.

Zängl G, Hoinka KP (2001): The Tropopause in the Polar Regions. *J. Climate*, 14:31173139.