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An investigation of seasonal temperature trends in the Antarctic using CHAMP GPS radio occultation data

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Abstract

GPS radio occultation (RO) has been recognized as an alternative atmospheric upper air observation technique due to its distinct features and technological merits. This technique is best used for meteorological studies in remote and/or difficult-to-access areas such as the Polar Regions. The CHAllenging Minisatellite Payload (CHAMP) space mission has provided about eight years of high quality global coverage atmospheric profiles. This study first evaluates the accuracy of CHAMP RO retrieved temperature profiles in the Antarctic region by using radiosonde data. Different collocation criteria have been applied. The overall results show a good agreement between the two data sets. Utilizing seven completed years of CHAMP temperature profiles, the study then investigates seasonal temperature trends at 100 hPa and 500 hPa pressure levels in the Antarctic region. Detailed temperature variations in both spatial and temporal domains are revealed and their implications for climate change are discussed.

1 Introduction

The Antarctic plays a vital role in the global atmospheric and oceanic systems and circulations because of its unique geographical and meteorological features. In recent years, abnormal melting of the Antarctica ice sheets has been considered as a strong evidence of global warming. The phenomenon itself has significant feedback to the weather and climate processes. Regional climate change in the Antarctic, and its impacts on global climate change, has drawn considerable attention of climatologists and environmental scientists. Current studies have suggested a general warming trend of near-surface temperature in the Antarctic but a cooling trend in some regions and seasons (King, 1994; Vaughan et al., 2001; Steig et al., 2009). It has been reported that there is a general warming trend in the upper troposphere and a general cooling trend in the lower stratosphere by examining temperature variations over the Antarctic using radiosonde data (Turner et al., 2006) and MSU data (Johanson and Fu, 2007).

Studies of the Antarctic atmosphere mostly rely on observational data obtained at 18 meteorological stations operated by different countries (see Fig. 1). The majority of the Antarctic stations are located in the coastal regions of the continent with the exception of Amundsen-Scott station at the South Pole. Clearly, the limited number of the stations as well as their predominant near-coastal locations are inadequate to accurately describe temperature variations over the vast continent of Antarctica with an area of approximately 14 000 000 km^2. Moreover, the extreme weather environment in the Antarctic affects the quality of meteorological observations and their frequency. Recently, atmospheric profiles derived using the Global Positioning System (GPS) radio occultation (RO) technique have demonstrated a great potential for advancing atmospheric studies (e.g. Kursinski et al., 1997; Foelsche et al., 2008; Fu et al., 2007), especially for remote areas such as the ocean and polar regions. The CHAMP (CHAllenging Minisatellite Payload) mission (Wickert et al., 2001) has provided nearly eight years (2001–2008) of atmospheric data by using the GPS RO technique. Another space mission, COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) (Liou et al., 2005, 2007; Fu et al., 2009), generates about 2500 daily atmospheric profiles (approximately 10 times the number of daily CHAMP RO profiles) since 2006. Due to the global coverage of the GPS RO observations, a great number of high quality atmospheric parameter profiles can be obtained over the Antarctic area.

In this study, the potential of using the GPS RO technique for the Antarctic climate monitoring is presented. Although there are only eight years of CHAMP data available for the analysis, the results have demonstrated a great potential of the GPS RO technique for reliable and long-term atmospheric monitoring. In the first part of this study, the accuracies of the GPS RO retrievals (from both CHAMP and COSMIC) using radiosonde data in Antarctica are evaluated. In the second part, the temperature change over the Antarctic region using CHAMP RO data is analysed. Temperature trends at the standard pressure levels and their seasonal and spatial variations are investigated and discussed.

2 Evaluation study

Comprehensive evaluations of the GPS RO retrievals are required to assure that satellite-derived data are in a good agreement with the conventional meteorological observations. However, different evaluation studies use different collocation criteria to match the RO retrievals with atmospheric observation records (Zhang et al., 2009). This study investigates the impact of the different collocation criteria (specifically, 100, 200 and 300 km radial buffers with 1, 2 and 3 h temporal buffers respectively) on the level of agreements between GPS RO and radiosonde data. Radiosonde data from 38 Australian observational meteorological stations (including three in Antarctica) were used to compare the RO retrieved wet temperature profiles (wetPrf data product from the UCAR COSMIC Center) from both CHAMP (between 2001 and 2008) and COSMIC (between 2006 and 2009) data.

Table 1 summarises the statistical means (plus standard deviations) of the temperature differences at 16 pressure levels (i.e. 30, 50, 80, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 850, 900, 950 hPa) between radiosonde measurements and RO profiles (interpolated into a 100 m resolution) from both CHAMP and COSMIC observations. In general, larger buffers (either spatially or temporally) result in greater differences in both means and standard deviations. The only exception found is in the CHAMP study with a radius of 200 km and a 2-h buffer, which has the largest mean differences amongst the results. However, there are no significant differences found using these different collocation criteria. This suggests that for the selected range of spatial and temporal collocation criteria the impact on the evaluation results is not statistically significantly different. COSMIC RO show smaller mean differences and standard deviation in general compared with that of CHAMP RO (see Table 1). COSMIC RO results are improved in terms of not only the number and coverage of the RO events but also the quality in comparison with CHAMP RO.

Figures 2 and 3 show the study results with a 300 km radial buffer for a 3-h temporal buffer using CHAMP and COSMIC atmospheric retrievals respectively. The overall results show significant statistical matches between the GPS RO retrievals (both CHAMP and COSMIC) and the radiosonde measurements. The mean difference between radiosonde and CHAMP data is 0.403 °C with a standard deviation of 1.284 °C. The result between COSMIC RO derived and radiosonde data is 0.389 °C in mean difference with a standard deviation of 1.299 °C. It appears that temperature retrievals using GPS RO technique have a cool bias compared to the radiosonde data in the lower troposphere (below 500 hPa) but a warm bias in the upper troposphere (above 500 hPa). In the lower stratosphere, GPS RO data indicate a cool bias. At 500 and 100 hPa pressure levels, the two techniques (i.e. GPS RO and radiosonde) match very well (see Figs. 2 and 3). Small 95% confidence interval ranges around the means enhance the statistical significant in comparison with the two techniques across all levels.

3 Seasonal temperature trends analysis at 500 hPa and 100 hPa pressure levels

In order to quantitatively evaluate annual and seasonal trends, the area-averaged temperature trends over the Antarctic at a particular pressure level are calculated using the following formulae:

$$\sum (T_i\, S_i) / \sum S_i, \text{ for } i = 1, N,$$

where T_i is a temperature trend computed for each 5° latitude by 10° longitude grid, i corresponds to the area S_i, and N is the total number of boxes ($N = 181$ as the area around the South Pole was computed for a 5° circle). The temperature trends are calculated from monthly average temperature at each box by using a multiple regression method with consideration of the monthly variations and the number of observations in each month.

The map of the average annual 500-hPa temperature trend (Fig. 4 Annual) demonstrates a general tropospheric cooling trend over the Antarctic at an average rate of −0.029 °C/year (i.e. annual average value of the temperature trend over all the 181 boxes at 500-hPa pressure level for the period of 2001–2008). However, the spatial distribution of the trend is far from uniform: cooling is observed over a large area of the upper tropospheric between 60° E and 170° W while positive temperature trends are observed over the Antarctic Peninsula between 40° W and 90° W and over the coastal regions between 60° E and 30° W.

Analysing seasonal variations in Antarctic upper troposphere temperature trends for 2001-2008 using GPS RO data has shown warming in winter (0.024° C/year) and spring (0.027° C/year) and then cooling in summer (–0.1 °C/year) and autumn (–0.017° C/year) (Fig. 4). These results in general agree well with the earlier findings. Strong upper-tropospheric summer cooling, even partially compensated by winter and spring warming, is responsible for overall annual upper tropospheric cooling over the Antarctic.

Examining atmospheric temperature changes over interior parts of the Antarctic is of particular interest as (i) long-term upper air complete records for the near-polar regions are available at only one station (Amundsen-Scott) and (ii) the MSU (Microwave Sounding Units) data are not available for latitudes south of 82.5° S. Based on 30 years of radiosonde records, Turner et al. (2006) reported tropospheric warming over the South Pole, with the most significant warming in winter. Note that strong seasonal warming over the area around the South Pole with warming rates of about 0.1° C/year detected by GPS RO method for the winter season (Fig. 4 Winter), are in agreement with the earlier findings.

The map of the average annual 100-hPa temperature trend over the Antarctic for 2001–2008 demonstrates average cooling at a rate of about –0.21° C/year (Fig. 5 Annual). Examining seasonal variations in trends, we found that stratospheric cooling occurred during all four seasons, with the strongest cooling in spring (–0.57° C/year) (Fig. 5 Spring). Analysing the results derived from MSU observations, Johanson and Fu (2007) reported strong cooling in the lower stratosphere in spring at a rate of about –1.5° C/year and explained it by the effects of ozone depletion (the ozone depletion has a maximum during November and lasts until February; Thompson and Solomon, 2002). Discussion about possible causes of the identified cooling trend of the Antarctic

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atmosphere as well as regional warming and cooling trends is beyond the scope of this study and will be a topic of our further investigations.

4 Conclusions

The new GPS-based technique overcomes many limitations of the current conventional atmospheric observing techniques. In this study, accuracies of GPS RO retrievals (from both CHAMP and COSMIC) were evaluated by comparing satellite-derived data with radiosonde observation over Antarctica. It was found that the two data sets have a good agreement and the different collocation criteria (i.e. combinations of 200 and 300 km radial buffers with 1, 2 and 3 h temporal buffers) tested in this study have no statistically significant impact on the evaluation results. An analysis of temperature change over the Antarctic region using CHAMP RO was conducted to estimate temperature trends at the standard pressure levels and their seasonal and spatial variations. Using satellite-derived data, a warming trend during 2001–2008 was found over the West Antarctic and Peninsula and a cooling trend over the East Antarctic respectively. Over the entire Antarctic region, a general warming trend was identified in winter seasons but a cooling trend in summer seasons. These findings are in agreement with previous studies that used the radiosonde and other satellite data. With future Global Navigation Satellite Systems and more GPS RO missions available, it is promising that the GPS RO technique will enhance the Antarctic climatologic studies significantly.

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Table 1. Means and standard deviations of the temperature (˚C) differences between radiosonde and RO data using different collocation criteria (i.e. 100, 200 and 300 km radial buffers with 1, 2 and 3 h temporal buffers); Radiosonde data are from 38 Australian observational meteorological stations and they were compared with RO retrieved temperature profiles from both CHAMP (between 2001 and 2008) and COSMIC (between 2006 and 2009) data over the Antarctic region.

Mean (STD)	1 h		2 h		3 h	
	CHAMP	COSMIC	CHAMP	COSMIC	CHAMP	COSMIC
100 km	0.366 (1.04)	0.34 (1.091)	0.374 (1.088)	0.252 (1.102)	0.376 (1.146)	0.358 (1.158)
200 km	0.39 (1.133)	0.348 (1.19)	0.426 (1.174)	0.35 (1.204)	0.377 (1.197)	0.361 (1.213)
300 km	0.391 (1.214)	0.375 (1.279)	0.398 (1.251)	0.379 (1.3)	0.403 (1.284)	0.389 (1.299)

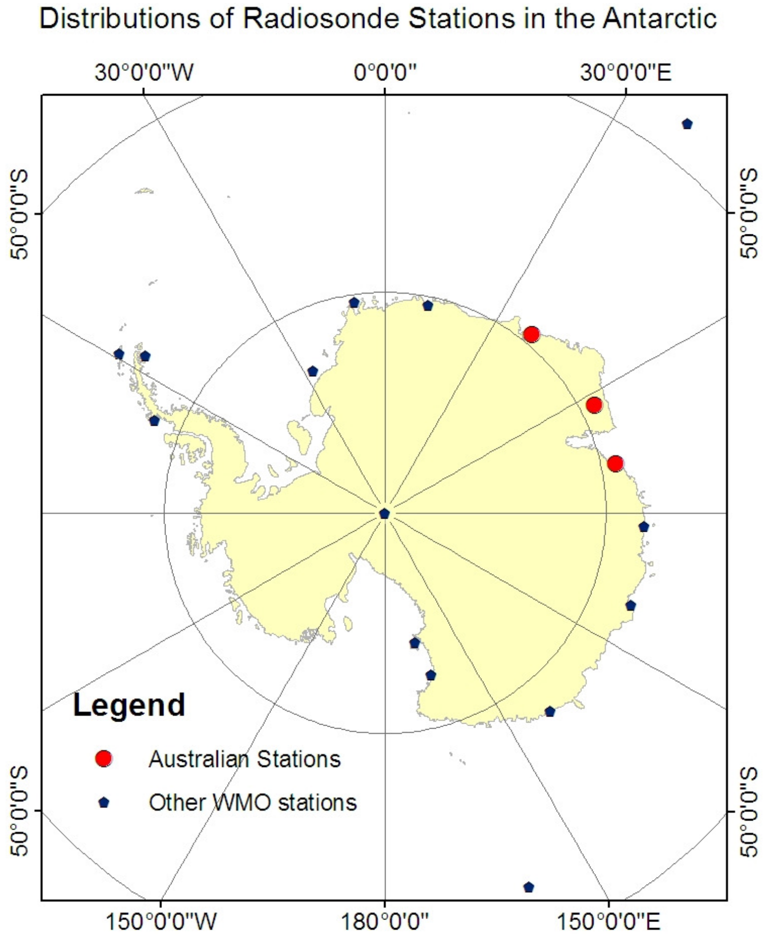

Fig. 1. Distributions of radiosonde stations in the Antarctic.

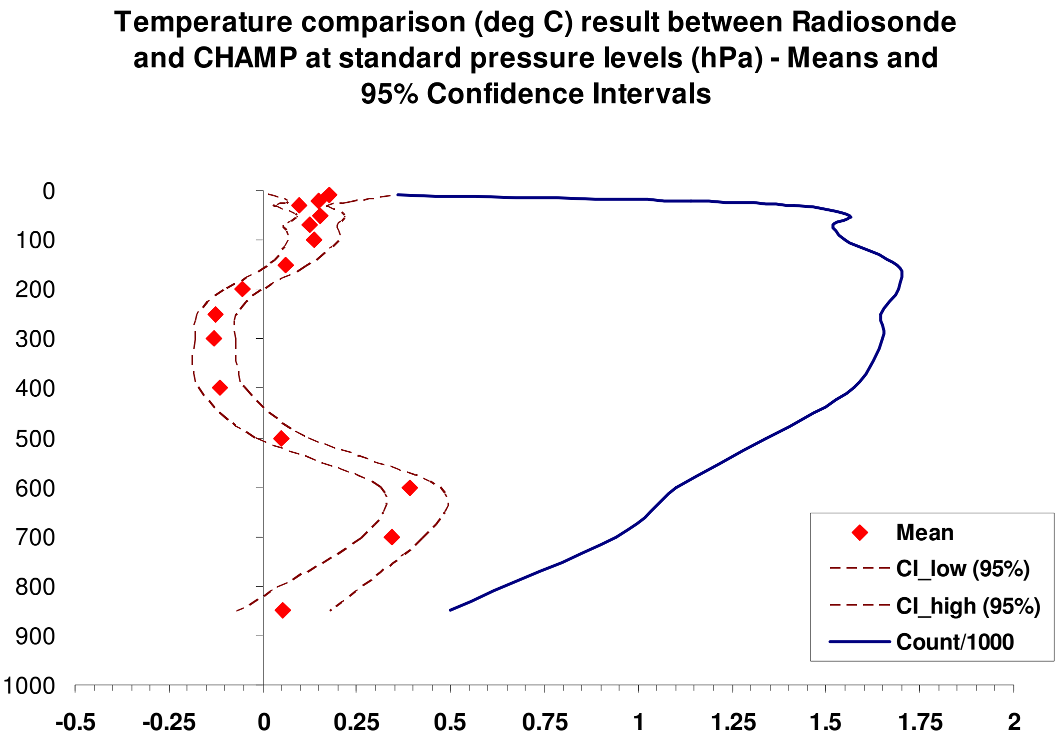

Fig. 2. CHAMP temperature profile comparison result (means, 95% confident levels and counts of comparison pairs) at standard pressure levels.

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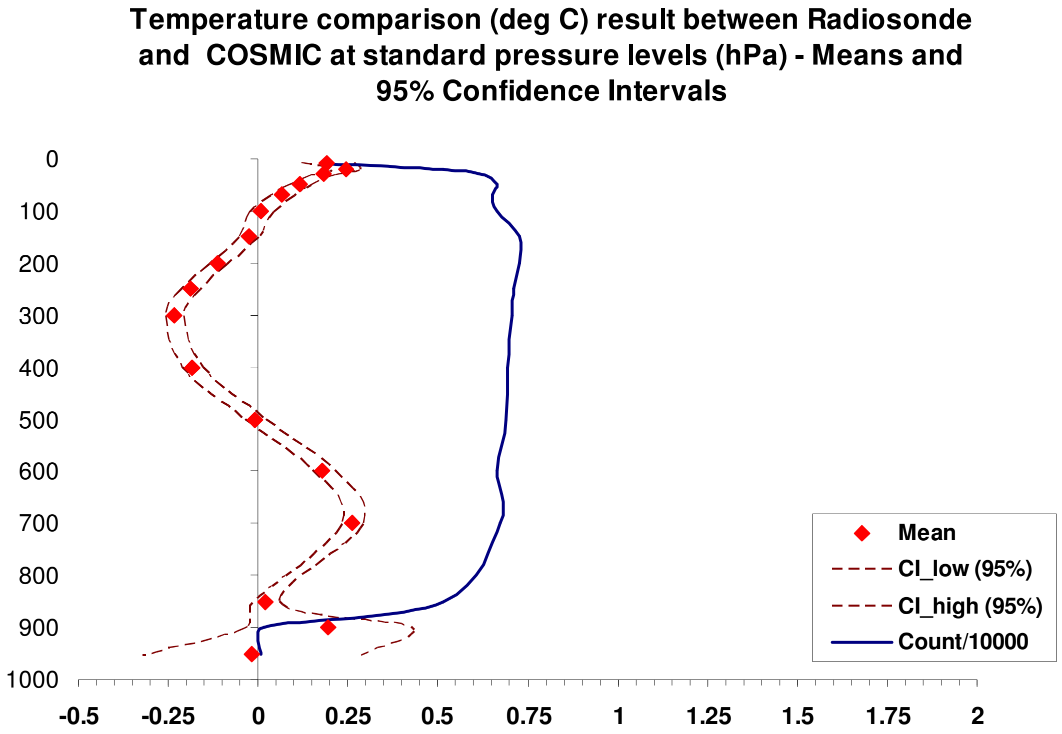

Fig. 3. COSMIC temperature profile comparison result (means, 95% confident levels and counts of comparison pairs) at standard pressure levels.

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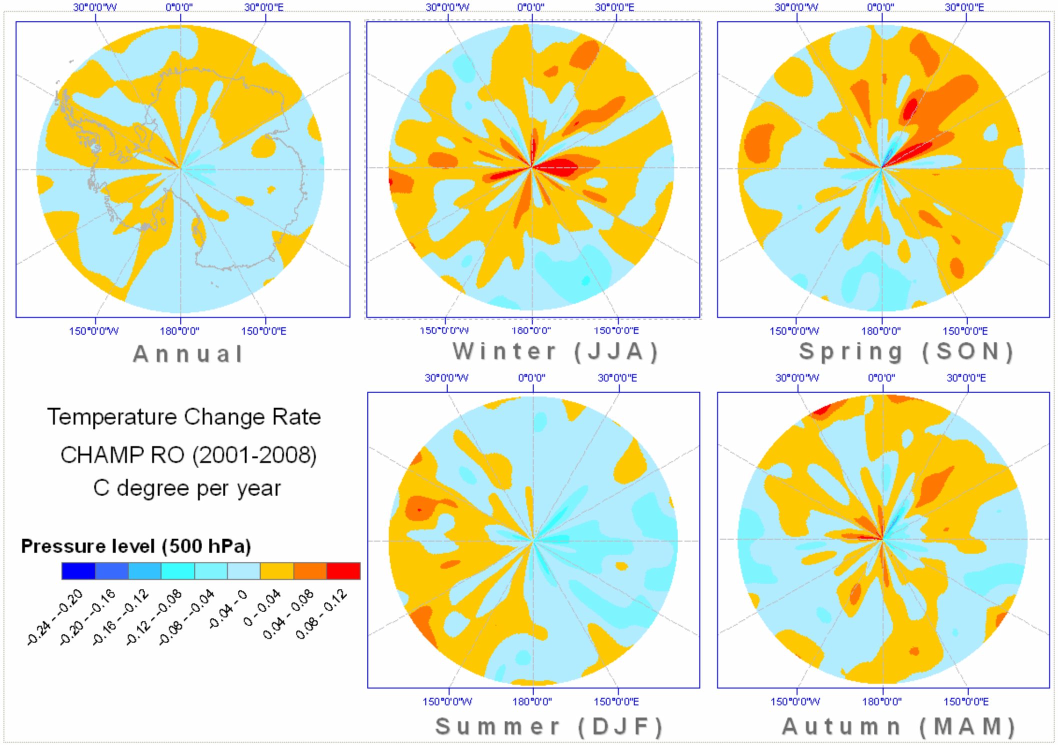

Fig. 4. GPS RO-derived annual and seasonal 500-hPa temperature change rate (°C/year) for 2001–2008.

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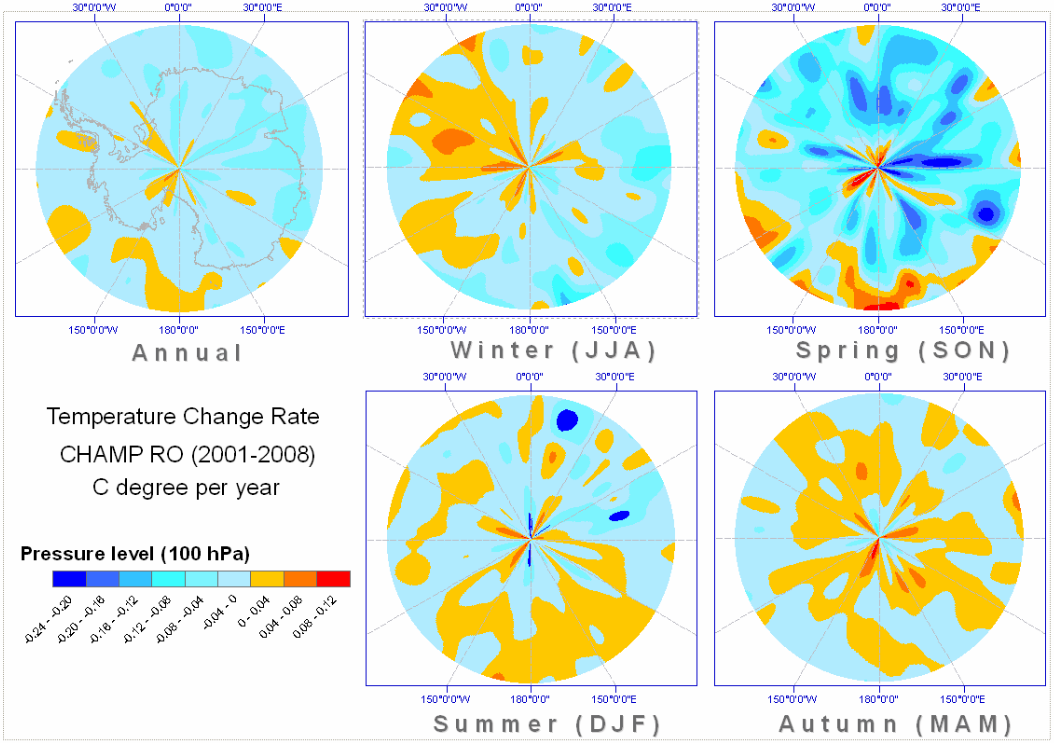

Fig. 5. GPS RO-derived annual and seasonal 100-hPa temperature change rate (°C/year) for 2001–2008.