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An investigation of atmospheric temperature profiles in the Australian region using collocated GPS radio occultation and radiosonde data

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Abstract. GPS radio occultation (RO) has been recognised as an alternative atmospheric upper air observation technique due to its distinct features and technological merits. The CHALLENGING Minisatellite Payload (CHAMP) RO satellite and FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) RO constellation together have provided about ten years of high quality global coverage RO atmospheric profiles. This technique is best used for meteorological studies in the difficult-to-access areas such as deserts and oceans. To better understand and use RO data, effective quality assessment using independent radiosonde data and its associated collocation criteria used in tempo-spatial domain are important. This study compares GPS RO retrieved temperature profiles from both CHAMP (between May 2001 and October 2008) and FORMOSAT-3/COSMIC (between July 2006 and December 2009) with radiosonde data from 38 Australian radiosonde stations. The overall results show a good agreement between the two data sets. Different collocation criteria within 3 h and 300 km between the profile pairs have been applied and the impact of these different collocation criteria on the evaluation results is found statistically insignificantly. The CHAMP and FORMOSAT-3/COSMIC temperature profiles have been evaluated at 16 different pressure levels and the differences between GPS RO and radiosonde at different levels of the atmosphere have been studied. The result shows that the mean temperature difference between radiosonde and CHAMP is 0.39 °C (with a standard deviation of 1.20 °C) and the one

between radiosonde and FORMOSAT-3/COSMIC is 0.37 °C (with a standard deviation of 1.24 °C). Different collocation criteria have been applied and insignificant differences were identified amongst the results.

1 Introduction

Predicting weather and climate change is a challenging task due to the complexity and dynamics of the Earth's atmospheric system and the limitations of current observation methods. Many weather and climate related studies require high quality and high resolution atmospheric information such as temperature, pressure, humidity and wind (World Meteorological Organization, 2008). Currently, radiosonde technique is a dominant method for the acquisition of upper air atmospheric information. A global radiosonde network with about 1500 stations has been established worldwide since the 1950s (Integrated Global Radiosonde Archive, 2011). However, the radiosonde observational method has a limited coverage and low spatio-temporal resolution since it requires suitable geographic locations as well as high operational and maintenance costs. For example, the number (38) and geographical distribution (mainly along the coastlines) of Australian radiosonde station network are limited for the area of about 8.5 millions km² plus large surrounding oceans (Australian Bureau of Meteorology, 2002; Fu et al., 2009). However, it is difficult to improve the situation because of the station maintenance issues in remote areas. Many regions including polar, mountains and unpopulated areas around the world experience similar problems with ground-based observation networks (Kuo et al.,



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2002). Satellite remote sensing technologies are also being used widely for atmospheric observations (Chuvieco, 2008). They generally have a higher horizontal resolution and better global coverage but a low vertical resolution when compared to the ground-based observations. Therefore, there is an increasing demand from the meteorological communities for better observation techniques that can capture the atmospheric structure and processes in a more detailed form.

Recent developments of the Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), Russian Glonass, European Galileo and Chinese Beidou/Compass, have offered exciting potential for meteorological research (Fu et al., 2007; Kursinski et al., 1995; Yunck and Melbourne, 1995; Yunck et al., 2000). Observations from GPS Continuously Operating Reference Stations (CORS) networks have been well utilized for generating useful atmospheric water vapour information (Liou et al., 2000; Rocken et al., 2005). The technique can monitor atmosphere over CORS networks continuously and automatically. The GPS radio occultation (RO) technique is another GPS-based technique that probes the Earth's atmosphere and ionosphere using GPS receivers onboard low Earth orbit (LEO) satellites (Yuan et al., 1993). The first experimental GPS RO mission (i.e. GPS/MET) was launched by UCAR (University Corporation for Atmospheric Research, US) and JPL (Jet Propulsion Laboratory, US) in 1996 and quality atmospheric profiles were retrieved successfully (Ware et al., 1996). Follow on satellite missions such as CHAMP and constellations such as FORMOSAT-3/COSMIC, which were encouraged by the success of the GPS/MET mission, also delivered high quality and resolution information of the atmosphere and ionosphere (Anthes et al., 2008; Wickert et al., 2001).

Compared with the daily or twice a day atmospheric measurements from the 38 Australian radiosonde stations, more than 10 atmospheric profiles are generated daily over the Australasian region by the CHAMP satellite and about 70 profiles from the FORMOSAT-3/COSMIC constellation (Fu et al., 2009). The number of daily RO profiles will be increased while more GNSS and RO satellites become available in the future. GPS RO observations have also better sampling distributions over both space and time when compared with radiosonde measurements. Australian meteorological studies will be significantly enhanced by the large volume of accurate and detailed four-dimensional atmospheric information from the GNSS RO technique. The economic benefits of this space-based atmospheric observation technology can be demonstrated and it is particularly important to Australia due to its distinctive features of a large land mass, sparse population and long coastal areas (Zhang et al., 2009). Evaluation of the GPS RO profiles provides information necessary for the assimilation of the new data sources into the current weather modelling systems and other meteorological applications. Evaluation studies have demonstrated that high quality GPS RO derived atmospheric profiles can be obtained (Healy, 1998; Rao et al., 2009; Wickert, 2004). He

et al. (2009) evaluated GPS RO using radiosonde measurements obtained from different types of radiosonde devices from various worldwide locations and demonstrated good results.

In evaluation studies, collocation criteria to match the RO profiles with other observations or modelled profiles are important for understanding the evaluation results and the data. This study investigates the impact of collocation criteria (specifically, 100, 200 and 300 km radial buffers with 1, 2 and 3 h temporal buffers). It focuses on the Australasian region and uses multiple years of GPS RO data (i.e. CHAMP: between 2001 and 2008 and FORMOSAT-3/COSMIC: between 2006 and 2009). The study regions cover an area of latitude 0–60° South and longitude 30–180° East. Radiosonde data from the 38 Australian weather observational stations including three in the Antarctic have been compared with the CHAMP and FORMOSAT-3/COSMIC RO retrieved temperature profiles. In general, both CHAMP and FORMOSAT-3/COSMIC RO temperature data are in a good agreement with the Australian radiosonde observations. Larger collocation buffers (either spatially or temporally) applied in the comparison result in greater differences in both means and standard deviations. However, insignificant differences are found amongst the comparison studies using different collocation criteria. A detailed study using 300 km and 3 h collocation criteria is presented. The comparisons between radiosonde and GPS RO (both CHAMP and FORMOSAT-3/COSMIC) at different pressure levels were conducted.

The next section of the paper contains the introduction of the evaluation study and discussion of the results. The third section of the paper presents the conclusions.

2 Evaluation study

Australia is one of the key members of WMO and it maintains 16 Global Climate Observing System Upper-air Network stations (GUAN) (Australian Bureau of Meteorology, 2002). These stations provide consistent high quality upper-air information. The data from these stations are used as a benchmark for many Australian meteorological applications and are available to all WMO national members. In addition to the 16 GUAN stations, Australia also maintains another 22 radiosonde stations of high quality that observe the upper-air composition. Australia has been consistently using Vaisala radiosonde system at all the 38 stations. In general, each radiosonde station performs 2 to 4 observations each day. The radiosonde data from the 38 stations were provided by the Australian Bureau of Meteorology. Figure 1 shows the locations of the 38 Australian radiosonde stations. Most of them are located at airports along the Australian coastal lines and a few in central remote areas. There are also three stations in Antarctica, four stations at remote islands and one station in Tasmania. The CHAMP mission

Table 1. Means, standard deviations (STD) and the number of pairs (# Sample) of the temperature (°C) discrepancies 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 FORMOSAT-3/COSMIC (between 2006 and 2009) data over the Australasian region. *P*-values for the tests of discrepancy equivalence between CHAMP and COSMIC are also given separately for the mean and STD.

Collocation criteria		1 h			2 h			3 h		
		CHAMP	COSMIC	<i>P</i> -Value	CHAMP	COSMIC	<i>P</i> -Value	CHAMP	COSMIC	<i>P</i> -Value
100 km	Mean	0.37	0.34	0.81	0.37	0.35	0.83	0.35	0.35	1.00
	STD	1.04	1.09	0.80	1.06	1.10	0.78	1.09	1.12	0.81
	# Sample	93	341	–	170	672	–	239	1002	–
200 km	Mean	0.38	0.35	0.69	0.40	0.35	0.34	0.39	0.35	0.36
	STD	1.10	1.16	0.59	1.13	1.17	0.60	1.15	1.18	0.63
	# Sample	281	1266	–	602	2583	–	884	3851	–
300 km	Mean	0.39	0.36	0.60	0.40	0.36	0.31	0.39	0.37	0.54
	STD	1.16	1.22	0.46	1.18	1.23	0.37	1.20	1.24	0.38
	# Sample	556	2504	–	1189	5118	–	1776	7733	–

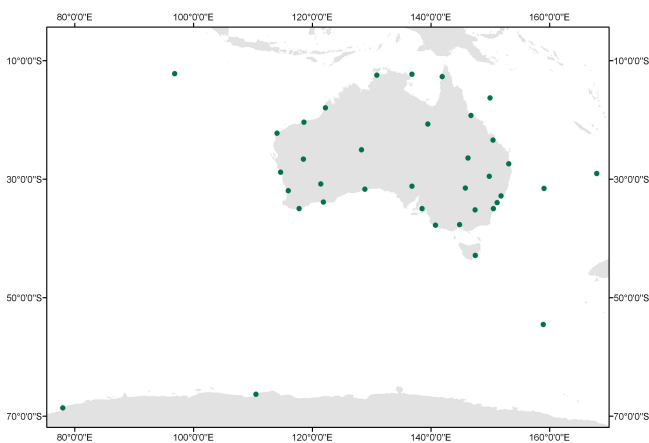


Fig. 1. Locations (dots on the map) of the 38 Australian radiosonde stations (Australian Bureau of Meteorology, 2002).

delivered quality RO data between May 2001 and October 2008 and the FORMOSAT-3/COSMIC constellation started to generate quality RO data from July 2006. Wet temperature profiles from the two missions up to the last day of 2009 were downloaded from UCAR COSMIC Data Analysis and Archive Centre (CDAAC) in early 2010 (product version: 2010:2640) and used in this study. The RO temperature profiles were interpolated at 16 pressure levels (i.e. 30, 50, 80, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 850, 900 and 950 hPa) to match the radiosonde profiles.

Table 1 summarises the statistical means, standard deviations and sample sizes of the temperature differences between the radiosonde measurements and RO profiles from both CHAMP and FORMOSAT-3/COSMIC systems using different collocation criteria. In general, larger buffers (either

spatially or temporally) result in greater differences in both mean and standard deviations. In order to test the differences among the three temporal (1, 2 and 3 h) and three spatial collocations (100, 200 and 300 km), a two-way analysis of variance (ANOVA) was carried out. In two-way ANOVA, the total sum of squared deviations (SS_{total}) from the mean is calculated as $\sum_{j=1}^3 \sum_{k=1}^3 \sum_{i=1}^{n_{jk}} (x_{ijk} - \bar{x}_{..})^2$, where x_{ijk} denotes the i -th temperature discrepancy at the j -th temporal and k -th spatial collocation, and $\bar{x}_{..}$ is the grand mean temperature discrepancy over all observations. The sum of squared deviations from the means (SS) due to temporal, spatial, their interaction and error, however was computed based on the summary statistics given in Table 1, such as the mean, standard deviation and the sample size from each cell, rather than the raw observations. The details of computation can be found from Cohen (2002). Mean squares (MS) are defined as the sum of squares (SS) divided by their degrees of freedom (DF), which is equal to $c - 1$ for c levels of effect. The test statistic F is defined as the ratio between two mean squares, with the numerator due to the effect of interest, and the denominator equivalent to the mean squares error. Our final decision was made based on the resulting *P*-value, which gives the probability of observing a test statistic greater than the observed F -value when assuming no temporal or spatial effects. Table 2 shows the ANOVA results (i.e. sum of squares (SS), degrees of freedom (DF), mean squares (MS), F and P -value) of the temperature (°C) discrepancies between radiosonde and CHAMP data, and between radiosonde and COSMIC respectively.

The result of the ANOVA test suggests that, at the three selected levels of temporal criteria (1, 2 and 3 h), there is no statistical difference detected for the temperature discrepancies between radiosonde and CHAMP (P -value = 0.956). The differences among the three levels of spatial buffers

Table 2. Analysis of variance results (i.e. sum of squares (SS), degrees of freedom (DF), mean squares (MSS), F and P -value) for temperature ($^{\circ}\text{C}$) discrepancies between radiosonde and CHAMP data, and between radiosonde and COSMIC data.

Source	CHAMP					COSMIC				
	SS	DF	MS	F	P -value	SS	DF	MS	F	P -value
Temporal	0.123	2	0.062	0.046	0.956	0.181	2	0.090	0.075	0.928
Spatial	0.490	2	0.245	0.182	0.834	1.337	2	0.669	0.555	0.574
Temporal*Spatial	0.048	4	0.012	0.009	1.000	0.003	4	0.000	0.000	1.000
Error	7790.297	5781	1.348			30 173.364	25 061	1.204		
Total	7790.958	5789				30 174.880	25 069			

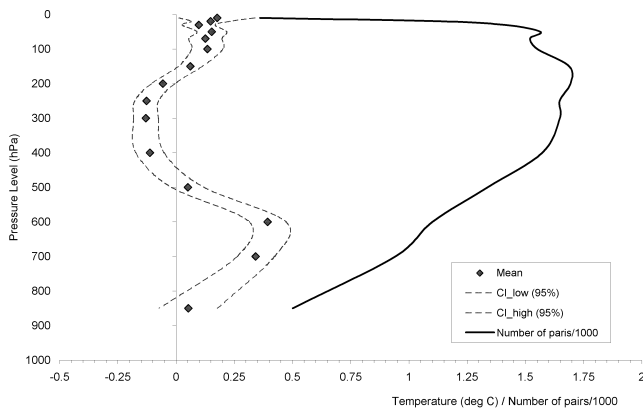


Fig. 2. CHAMP temperature profile comparison results (means, 95 % confident levels and numbers of comparison pairs) at 16 different pressure levels.

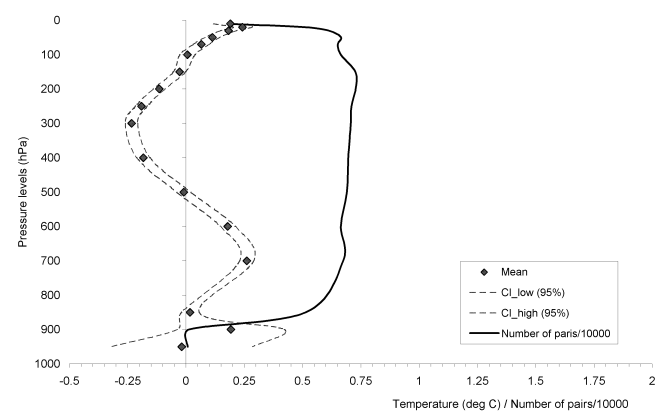


Fig. 3. FORMOSAT-3/COSMIC temperature profile comparison results (means, 95 % confident levels and numbers of comparison pairs) at 16 different pressure levels.

(100, 200 and 300 km) are similarly not significant (P -value=0.834). The result also suggests that there is no interaction between the spatial and temporal effects (P -value=1.000). For the temperature discrepancies between radiosonde and COSMIC, there is also no statistical difference detected at the selected ranges of spatial and temporal collocation criteria within 3 h and 300 km (see Table 2). In this study, FORMOSAT-3/COSMIC shows systematically a smaller mean difference but bigger standard deviation compared with that of CHAMP RO (see Table 1). However all these apparent differences for both means and standard deviations were tested to be statistically insignificant, with the associated P -values given in Table 1.

Xu et al. (2009) evaluated one year FORMOSAT-3/COSMIC refractivity profiles using radiosonde data from the Australian stations. Comparison results with different collocation criteria (1, 2 and 3 h, and 100, 200 and 300 km respectively) were presented. Another study utilised one and a half years global FORMOSAT-3/COSMIC data to examine the impact of different collocation criteria within a window of 7 h and 250 km (Sun et al., 2010). Staten and Reichler (2009) applied a smaller spatial collocation criteria (i.e.

36, 24, 12, 6 and 3 km) using two-year of FORMOSAT-3/COSMIC data in their study. The result of this study is consistent with the above studies. The looser collocation between radiosonde and GPS RO leads to greater differences in the comparison results. The ANOVA result from this study, however, shows insignificantly statistical differences.

Collocation using the 300 km spatial and 3 h temporal buffers are further investigated, as this provides more pairs for the comparison between GPS RO data and radiosonde data. The mean difference between radiosonde and CHAMP data is 0.39°C with a standard deviation of 1.20°C , while the mean difference between radiosonde and FORMOSAT-3/COSMIC data is 0.37°C with a standard deviation of 1.24°C . There is no statistical difference detected between these two temperature differences (P -value=0.461). Figures 2 and 3 show the evaluation study results for CHAMP and FORMOSAT-3/COSMIC atmospheric retrievals at the 16 pressure levels respectively. In these two figures, 95 % confidence intervals for the population mean temperature differences were obtained, along with the sample sizes (in 1000's and 10 000's for CHAMP and FORMOSAT-3/COSMIC respectively) at each pressure level.

Given that all the 95% confidence intervals for the mean differences contain the temperature difference of about $\pm 0.5^\circ\text{C}$, the overall results show significant statistical matches between the GPS RO profiles (from both CHAMP and FORMOSAT-3/COSMIC) and radiosonde measurements. It can also be seen from both figures that the temperature profiles using GPS RO technique have a positive systematic difference between 100 and 500 hPa pressure levels but negative difference in the lower stratosphere (below 100 hPa pressure level) and troposphere (above 500 hPa pressure level) compared to the radiosonde data. At around 100 and 500 hPa pressure levels, both the CHAMP and FORMOSAT-3/COSMIC data are found to match well with radiosonde observations. The results also show that the confidence intervals are in general broader at very low and very high pressure levels compared to the middle range pressure levels, where the samples for evaluation studies are more abundant. Comparing Fig. 2 with Fig. 3, the overall confidence intervals in the FORMOSAT-3/COSMIC comparison are more accurate than those in the CHAMP comparison. With a sufficient length of GPS RO records (about 10 yr and longer), these data can be useful for deriving climatology of atmospheric parameters such as temperature, moisture and pressure for lower stratosphere and upper troposphere, especially over the remote areas where lack of radiosonde observations limits development of such climatology.

3 Conclusions

GNSS RO, as a new GPS space-based atmospheric observation system, overcomes many limitations of current conventional atmospheric observing techniques. In this study, the accuracies of the GPS RO profiles (from both CHAMP and FORMOSAT-3/COSMIC) were evaluated by comparing satellite-derived data with radiosonde observations over the Australasian region. A good agreement between radiosonde and GPS RO data has been found. The influence of the collocation criteria (both space and time) in the comparison study has been also examined. Although the study shows that the tighter collocation criteria lead to smaller differences between radiosonde and GPS RO, statistical analysis presents insignificant differences in the results. The high quality and quantity GPS RO data generated from both CHAMP and FORMOSAT-3/COSMIC have enhanced a number of weather and climate studies. When the new generation GNSS and more RO missions become available, it is envisioned that the GNSS RO technique will deliver good quality atmospheric profiles with improved temporal and spatial resolutions. In this research, we confirmed the findings of earlier studies about the suitability of GPS RO measurements for climate study and demonstrated this conclusion by a case study in the Australian region.

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