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Assessing COSMIC GPS radio occultation derived atmospheric parameters using Australian radiosonde network data

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Abstract

Due to the high-uncertainty and high-dynamics of climate and weather changes, the monitoring and forecasting of meteorological conditions have been a challenging task, especially for the southern hemisphere and polar areas where ground-based data are very sparse and only limited meteorological information is available. GPS radio occultation (RO) is an emerging, new and robust Earth atmospheric remote sensing technology and it has overcome many limitations of the conventional meteorological observation techniques. It is critical to analyse the error characteristics of GNSS RO retrievals as a fundamental step for this new research initiative. COSMIC atmospheric products are evaluated extensively by using radiosonde records from 35 Australian and Antarctic weather stations for a period of thirteen months (between July 2006 and July 2007). This analysis is based on a variety of geographical settings (i.e., inland, costal and ocean; three latitude zones). Good agreement between COSMIC profiles and radiosonde measurements is achieved in general and some interesting geo-statistical findings are also identified.

Keywords: GPS; radio occultation; meteorology; COSMIC; validation; spatial

1. Introduction

South eastern Australia experienced unprecedented and consecutive heatwaves with disastrous consequences including severe bushfire in Victoria and loss of about 200 lives during late January and early February 2009. A number of climate extremes have been recorded during this period. This includes the highest temperature of 46.4 °C recorded in Victorian history on Feb 7th, the highest minimum temperature of 33.9 °C in Adelaide and historical droughts in these areas [1]. These extreme weather events are not only regional and individual events, but also global phenomena occurring concurrently around the world (e.g. snow storms in UK and USA, flooding in Indonesia and droughts in China). The impacts of these extreme events on global environment, society and economy are severe and have caused great concerns. However, monitoring and forecasting of extreme meteorological phenomena have been a challenging task due to the high-uncertainty and high-dynamics nature of weather and climate. This is particularly true in the southern hemisphere and polar areas where only limited atmospheric/

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meteorological observations are available.

In the past decades, a number of pilot studies and experimental missions have been carried out and GPS (Global Positioning System) radio occultation (RO) has been demonstrated to be a robust Earth atmospheric remote sensing technology with a great potential for meteorology [2-7]. Comparing with the conventional Earth observation technologies (i.e. radiosonde), GPS RO is advantageous including its global coverage, high vertical resolution, high accuracy, all weather capability and calibration-free [7-9]. In addition, this space-based remote sensing technology is not limited by geographical accessibility and location, time, and weather conditions. The distributions, frequencies and resolutions of the GPS RO atmosphere profiles are only dependent on satellite constellation and orbit design [2]. With this new technology, continuous and stable upper-air information can be obtained across the large unpopulated and difficult-to-access areas (i.e. mountain, desert, ocean and polar). The GPS RO technology has been recognized as a new mechanism for boosting various meteorological and climate related studies and applications [10-15].

Comprehensive evaluations of the GPS RO retrievals provide helpful information for the assimilation of the new data sources into current meteorological systems and other weather and climate related applications [16-20]. However, different evaluation studies select different collocation criteria to match the RO retrievals with atmospheric observation records (i.e. radiosonde). An earlier study conducted by the group investigated the impacts of window sizes using 9 different collocation scenarios (100, 200 and 300 km spatial buffers, and 1, 2 and 3 hour temporal buffers). The study found that 1) the collocation scenarios with smaller windows provide better results, and 2) the window’s size in spatial domain has a greater impact than those in the temporal domain.

This paper firstly introduces the GPS RO technology and related satellite missions (especially COSMIC). Statistical studies that assess COSMIC atmospheric products (temperature and pressure) by using Australian and Antarctic radiosonde station observations are then presented. A period of thirteen months data has been analysed. Collocation windows of 100km and 2 hours are used to pair the COSMIC and radiosonde data. The overall finding demonstrates that there are none significant differences between the two data sets. As for the impacts of different geographical zones, inland and high latitude areas have smallest differences comparing with other areas. This behaviour is confirmed in a further spatial statistical analysis using map representation some interesting findings are revealed.

2. GPS RO technology and experiment missions

The GPS RO utilises GPS receivers onboard a low earth-orbiting (LEO) satellite to capture the atmospheric information. When a GPS satellite sets or rises behind the Earth’s atmospheric limb related to a LEO satellite, the onboard LEO GPS RO receiver captures the delayed and bended GPS signals through the Earth’s atmospheric limb. The bending angle profile of GPS signals over the occultation points is then derived from the recorded GPS excess phase, amplitude, position and velocity of LEO and GPS satellites. Further processing of the bending angle profiles provides valuable information on refractivity, temperature, water vapor and pressure in the neutral atmosphere and electron density in the ionosphere.

The FORMOAST-3/COSMIC is the first mission that uses a constellation of six LEO satellites for GPS RO meteorological studies. Currently, it has been in good operational condition since its launch in 2006 and its atmospheric products (about 2000 daily profiles worldwide) have been extracted by many international meteorological research groups such as NASA (National Aeronautics and Space Administration) and UCAR (University Corporation for Atmospheric Research) in USA, and ECMWF (European Centre for Medium-Range Weather Forecasts) in Europe. The COSMIC LEO satellite is equipped with a GPS RO payload for tracking GPS signals, a tiny ionospheric photometer payload for measuring ionospheric total electron content from the satellite’s nadir direction, and a tri-band beacon payload for generating high resolution satellite to ground-station TEC. The COSMIC GPS RO receiver is a BlackJack receiver from NASA/JPL which was also used by CHAMP and other early GPS RO programs. The integrated GPS receiver system consists of five units, namely a scientific grade receiver, dual occultation antennas, dual precision orbit determination antennas, a payload controller and a solid state recorder. With a robust space-borne GPS receiver system, the LEO satellites’ precise orbit can be well determined and both the rising and setting GPS RO events can be captured.

There are about 100 daily COSMIC derived atmospheric profiles can be captured in the great Australian region. It covers all the current 38 Australian radiosonde stations (two observations per day at each station generally). Moreover, the COSMIC RO observations have a better sampling distribution, higher vertical resolution, higher quality and stability. Obviously, the new atmospheric profiles from COSMIC are an important source of information to Australian weather and climate studies.

3. Statistical assessments

A comprehensive study was undertaken to assess the COSMIC RO retrieved atmospheric profiles (temperature and pressure) for the whole Australian area for a thirteen-month period (from 1st July 2006 to 31st July 2007). Radiosonde records from 35 radiosonde stations were used for this evaluation. A radial buffer of 100 km and a temporal buffer of 2 hours were chosen to match COSMIC profiles with Radiosonde records in this assessment. A total number of 204 collocated pairs of COSMIC derived atmospheric profiles and radiosonde observations were identified.

For an effective management and analysis of the mega and complicated datasets, a database has been developed and implemented in a central-based Oracle database management system (located in a UNIX server system). SQL (Structured Query Language) database functions are designed for automatic data processing, such as data input and unit conversion. Interpolation and transformation of the atmospheric profiles into a comparable format are necessary since the profiles from different sources (i.e. CHAMP, COSMIC, radiosonde and numerical weather models) are different in heights. It is noted that COSMIC has a much better vertical resolution (about 100 meters) than the radiosonde observation which has an approximate vertical resolution of 400 meters.

Atmospheric temperature and pressure are analysed and evaluated. The overall results have demonstrated good agreements between the two datasets. Table 1 summaries the means and standard deviations (STD) of the differences between COSMIC retrievals and radiosonde observations over the 204 pairs. The mean difference in temperature is -0.43° with a STD of 1.53°. Negative mean values represent that COSMIC

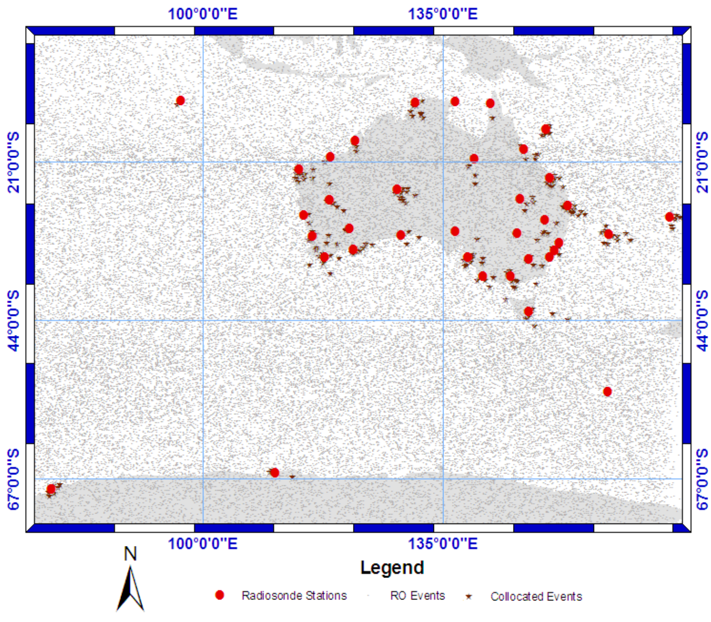

Fig. 1. A schematic map shows the location of the 35 radiosonde stations (in red dots), 64,599 COSMIC derived atmospheric profiles (in dark dots) and 204 collocated pairs (in brown stars) in the thirteen-month period (1st July 2006 to 31st July 2007)

retrievals are general cooler than radiosonde. Pressure profiles also show a good agreement (mean at 1.39°and STD at 1.71°). The positive mean values indicate that COSMIC pressure retrievals are generally greater than radiosonde.

Spatial characteristics of the new data sources are vital for meteorological research and practical applications. In this study, the 204 pairs are classified into three geographical zones (i.e. inland, costal and ocean) and three latitude zones (i.e. low altitude zone [0°-23°], middle latitude zone [23°-67°] and high latitude zone [67°-90°] respectively). Those three smallest mean and STD values are highlighted in Table 1.

Table 1. The mean and STD of the differences (in temperature and pressure) of COSMIC and radiosonde. The bold numbers are the lowest values in each column

	Temperature (°)		Pressure (mbar)	
	Mean	STD	Mean	STD
Overall	-0.43	1.53	1.39	1.71
Coastal	-0.43	1.48	1.42	1.80
Inland	-0.20	1.77	1.26	1.44
Ocean	-0.48	1.35	1.94	2.11
Low Latitude (0°S to 23°S)	-0.30	1.57	1.78	1.57
Mid Latitude (23°S to 67°S)	-0.43	1.53	1.37	1.87
High Latitude (67°S to 90°S)	-0.29	1.36	0.03	0.45

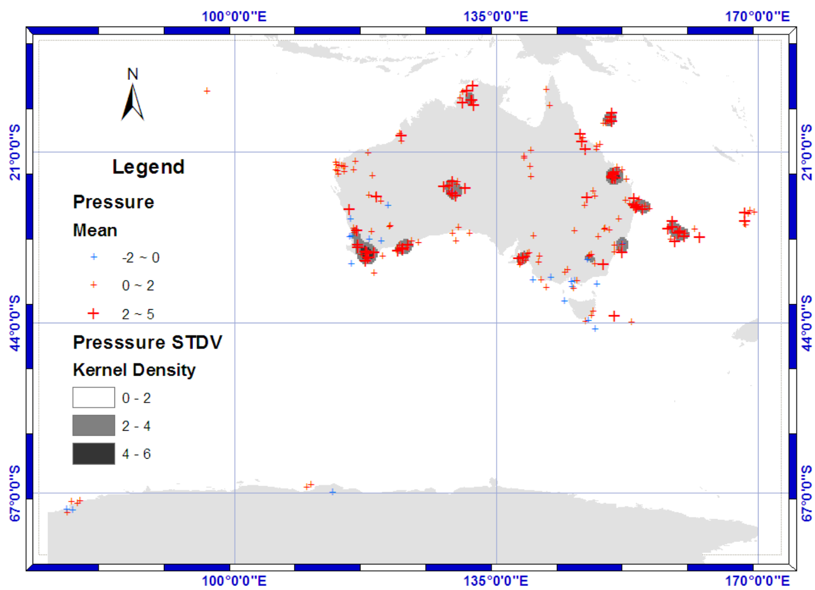

Fig. 2. The means and STD of the pressure differences between COSMIC and radiosonde are represented on the map. Those pairs with negative mean values (between -2 mbar and 0 mbar) are shown as blue crosses; while those with positive mean values are shown as red crosses (bigger crosses indicate bigger absolute mean values). The pressure STD differences are represented as density maps (i.e. converting STD values to kernel density index, e.g. 0~2 represent STD 0-2 and 4~6 represent STD 4-6).

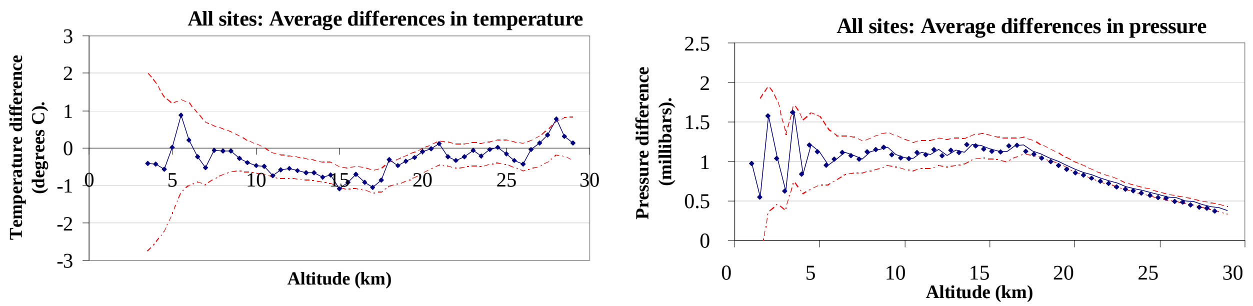

Fig. 3. Average differences in temperature (upper plot) and in pressure (lower plot) against the altitudes from surface to 30 km. The red dash lines are the 95% confidence intervals of all samples.

The inland group has the smallest values except its STD being the highest. The high latitude zone (Antarctic area) has the smallest values in both temperature and pressure. It is found that the discrepancies between RO derived and radiosonde measurements are smaller in the dry areas (inland and high latitude areas).

Fig. 2 is the spatial representation of the mean and STD of pressure differences between COSMIC and radiosonde. It can be seen that both the inland and high latitude areas have smaller values since these areas are relatively dry. These spatial analysis results also indicate a number of 'hot' spots with bigger mean and STD values (i.e. south-west and east Australia). Another interesting phenomenon found from the map is that all the negative mean values clustered in the south east and south west Australia. This may suggest that there are meteorological reasons behind.

Fig. 3 shows the differences (between COSMIC profiles and radiosonde records) of both temperature (upper plot) and pressure (lower plot) against the heights with 95% statistical confidence intervals (CI). These graphs present errors' characteristics and patterns along the altitudes between surface and 30 km. In the upper plot, it can be seen from the average line and 95% CI that the lower attitudes from surface to about 7-8 km have general bigger differences in temperature, and altitudes between 10 km and 20 km have negative differences which reflect cooler COSMIC data. For pressure (lower plot) in the lower altitude regions, similar to the temperature profiles, bigger differences are found. The average line is always above zero which means that COSMIC has greater measurements in pressure comparing with radiosonde. The differences increase dramatically above ~17 km since the atmospheric pressure is very low above that level.

4. Conclusive statements

The global navigation satellite systems (GNSS) RO derived atmospheric profiles have been considered as a good data source for atmosphere related research. In this study, the quality of the GPS RO data is assessed with detailed statistical methods and the outcomes of this study show very good agreements with the Australia regional radiosonde data. Detailed studies in different geographical areas and different altitudes provide usefully information for the assimilation of the new data source into the new Australian weather forecasting framework. Such a large volume of stream-in new high resolution atmospheric profiles will no doubt have great impacts on future meteorological studies and applications. Many countries, such as USA, German, Austria, Russia, Finland, Italy, Denmark, Argentina, Brazil, South Africa and Korea, are investigating GNSS RO technique for meteorological purposes. The importance of applying the GNSS RO meteorological technique in Australia will be never underestimated since Australia has large but unpopulated areas (limited weather observation stations), dry continent (better retrieval results in troposphere) and large areas surrounded by ocean. Satellite Positioning and Navigation (SPAN) research group at RMIT is currently collaborating with scientists from The Australian Bureau of Meteorology, University of New South Wales, USA, China and Canada to identify key issues for a long-term research effort in order to exploit the potential and full benefits of this emerging and enabling technology for the Australian community. Further research with the newly released COSMIC data will be used for long-term and more detailed evaluation studies. Research on the core data retrieval techniques that transfer GPS measurements to atmospheric profiles are being implemented in RMIT University.

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