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Comparison of stratospheric measurements made by CHAMP radio occultation and Stratéole/Vorcore in situ data

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[1] This paper compares measurements in the Antarctic stratosphere during austral spring and summer made by the CHAMP radio-occultation satellite and in situ long-duration super-pressure balloon (SPB) observations during the Stratéole/Vorcore campaign. Initial analysis compares near-simultaneous and co-located temperature observations made by these instruments and finds excellent agreement between these two very different sets of measurements. The mean bias between the data sets is -0.52 K, CHAMP RO temperature being cooler than the balloon measurements, and the standard deviation of the temperature differences is 1.6 K for the paired observations. This paired data set also allows us to show that an empirical correction used to remove the influence of radiative heating on the balloon sensors does not produce any bias. An initial comparison of the magnitude of gravity wave activity observed by each instrument shows relatively poor agreement. Analysis suggests that this agreement can be improved slightly by accounting for the observational filtering associated with the CHAMP measurements. **Citation:** McDonald, A. J., and A. Hertzog (2008), Comparison of stratospheric measurements made by CHAMP radio occultation and Stratéole/Vorcore in situ data, *Geophys. Res. Lett.*, *35*, L11805, doi:10.1029/2008GL033338.

1. Introduction

[2] Between September 2005 and February 2006 super-pressure balloons (SPB) launched from McMurdo Base in Antarctica were used to observe the Antarctic stratosphere during the Stratéole/Vorcore campaign. The balloons used in these long-duration flights, lasting for more than two months in the majority of cases, behaved as quasi-Lagrangian tracers during periods previous to and after the vortex breakdown in early December. Details on the balloon flights and the instruments carried are given by *Hertzog et al.* [2007]. Long-duration balloon flights have previously carried temperature sensors which have been used to assess the operational ECMWF data in the southern hemisphere tropics and extratropics [*Knudsen et al.*, 2006]. *Knudsen et al.* [2006] observed a mean bias of ECMWF analyses relative to the balloon measurements of -0.9 K and a standard deviation of 1.3 K independent of time of day or latitude. Their study found that much of the scatter in these comparisons is due to small-scale motions in the atmosphere, the dominant small-scale variations in the stratosphere being internal gravity waves [*Fritts and Alexander*, 2003 and references therein]. A number of studies have used measurements from long-duration balloon flights to examine internal gravity waves [*Hertzog and Vial*, 2001; *Vincent et al.*, 2007]. For example, *Vincent et al.* [2007] used SPB data from both northern and southern hemisphere flights to examine gravity wave momentum fluxes in the polar stratosphere. Their study found that the geographical variability in both hemispheres is dominated by large fluxes near mountainous regions. Their study also suggested that the magnitude of the fluxes are different in each hemisphere, with mean values of 3.4 mPa observed in the southern hemisphere compared with 2.6 mPa in the northern hemisphere.

[3] Radio occultation (RO) satellite observations have been used in a very similar manner to examine the quality of analyses [*Wickert et al.*, 2004; *Gobiet et al.*, 2005; *Kuo et al.*, 2005]. In this technique, GPS radio signal bending due to changes in atmospheric refractivity is measured to derive profiles of dry temperature. A good general description of the RO technique is given by *Hajj et al.* [2002]. Comparisons of CHAMP RO measurements with analyses and radiosonde observations have generally shown excellent agreement [*Wickert et al.*, 2004; *Gobiet et al.*, 2005; *Kuo et al.*, 2005]. For example, *Wickert et al.* [2004] compared CHAMP dry temperature with interpolated data from 6-hourly ECMWF meteorological analyses with co-located and near simultaneous radiosonde observations. They found that between 10 and 35 km the bias between ECMWF and CHAMP RO profiles is less than 0.5 K. Comparison using radiosonde observations and RO profiles indicates nearly no bias between 300 hPa (9 km altitude) and 20 hPa (27 km). This lack of bias between the observational data sets suggests deviations of the analyses from the real atmospheric situation. In addition, *Kuo et al.* [2005] compared CHAMP RO soundings, radiosonde soundings, and ECMWF profiles over five geographical areas. Their results indicate that RO soundings are of sufficiently high accuracy to differentiate between the performance of different radiosondes used in the various geographical regions. Gravity waves have also been studied using RO observations. For example, *Tsuda et al.* [2000] derived the potential energy per unit mass, E_p, from RO data and demonstrated the largest wave activity was found over the equator which was suggested to be related to convection. This study compares temperature and potential energy per unit mass measurements made in the Antarctic stratosphere during austral spring and summer made by the CHAMP RO satellite and by sensors carried on long-duration super-pressure balloons flown during the Vorcore campaign. This comparison acts to identify whether these very different measurement techni-

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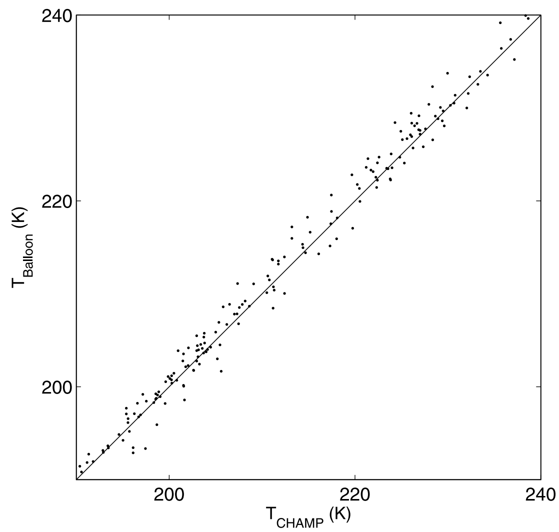

Figure 1. Comparison of coincident and near simultaneous CHAMP RO and Stratéole/Vorcore temperature measurements. The full line indicates the one to one line.

ques observe similar features. Section 2 describes the various measurement methodologies used in the two data sets. Sections 3 and 4 compare temperature measurements made by the SPB and CHAMP RO observations and these instruments measurements of the E_p, respectively. A discussion of the results displayed in Sections 3 and 4 and initial conclusions are detailed in Section 5.

2. Measurements

[4] The SPB used in the Vorcore campaign are helium-filled and, to first order, are advected by the wind on constant-density (isopycnic) surfaces. Two balloon sizes were used in the Vorcore campaign (diameters of 10 and 8.5 m) these two different sizes can sample two different density levels in the stratosphere which correspond approximately to the 50 and 70 hPa pressure surfaces. The comparisons shown later use altitudes derived from balloon pressure data to match CHAMP RO and SPB observations. The measurement package of the Stratéole/Vorcore balloons measured pressure, temperature and velocity. Atmospheric pressure (1 Pa precision) was measured every minute during the flights. Air-temperature observations (with accuracies of 0.25 K at night and 0.3 K in the day) and balloon positions (absolute GPS observations, 10-m accuracy) were obtained every 15 minutes. The horizontal velocities averaged over these 15 minute periods were deduced from the successive balloon positions with a corresponding accuracy of 0.1 ms^{-1}. Air temperature measurements were made with 2 thermistors. The main issue with the temperature data was daytime radiative heating which could reach 1.5 K. This effect is corrected using laboratory-derived empirical corrections [*Hertzog et al.*, 2007].

[5] The RO data from the CHAMP satellite used in this study are the Level 3 version 005 data which was processed and provided by the GeoForschungsZentrum (GFZ) Potsdam. Details of the processing procedure used are discussed by *Wickert et al.* [2004]. The CHAMP satellite has an inclination of 87 degrees and orbits at approximately 450 km altitude. Therefore the data distribution over the globe is nearly uniform. The instrument yields approximately 150–200 profiles of dry temperature each day. From Fresnel diffraction theory it can be shown that the profiles have a true vertical resolution of approximately 1.4 km in the stratosphere. However, the data is over-sampled and provided by the GFZ at a vertical resolution of 200 m. The horizontal resolution of an occultation is 200–400 km along the line of sight (LOS) and on the order of 1–3 km across the LOS.

[6] To reduce the effect of temporal and spatial sampling differences when making comparisons between the CHAMP profiles and the SPB observations we select data that are coincident in both space and time. Thus, in the present study we only examine data from the regions between 60° and 90° S during which the observations were within 200 km of each other horizontally and were separated temporally by less than 2 hours. This restricts the number of available profiles to 182 over the period that SPB measurements were made.

3. Comparison of Temperature Measurements

[7] Figure 1 displays coincident and near-simultaneous temperature measurements made by the Vorcore temperature sensors and the CHAMP RO instrument at the SPB altitude. The coincident observations show excellent correspondence, particularly if we take into account small-scale atmospheric structures which probably dominate the variation around the one-to-one line observed in Figure 1 [*Knudsen et al.*, 2006]. The bias between the matched temperature measurements is −0.52 K, the CHAMP RO measurements are colder than the SPB measurements, and the standard deviation is 1.6 K for the coincidence criterion indicated previously in Section 2. To determine whether the differences observed have a geophysical origin the coincidence criterion used on the data set were changed to examine the impact of spatial and temporal separation. The change in the bias and the standard deviation associated with a range of coincidence criterion is indicated in Table 1. Examination of Table 1 suggests that the standard deviation of the temperature difference between the two measurements increases as the maximum allowable horizontal and temporal separation increases. Values associated with the 95% confidence intervals are also indicated in Table 1. The bias does not change significantly if the 95% confidence intervals for this quantity are examined. This suggests that much of the variation in the observations is potentially due to small-scale atmospheric processes, but that there is likely to be a small but measurable bias between the two instruments.

[8] A possible explanation for the bias between the two measurements is the empirical corrections for daytime radiative heating used on the Vorcore temperature measurements. However, examination of the temperature difference observed between the two measurements as a function of solar zenith angle, which is a factor used in the empirical correction calculation [*Hertzog et al.*, 2007], shows no relationship (not shown). This result suggests that the small temperature differences observed between the two measurements can not be explained by errors in the

Table 1. Summary of Variations in the Bias, Standard Deviation, Number of Coincidences and the 95% Confidence Level Values of the Bias for Different Sets of Spatial and Temporal Coincidence Criterion[a]

Confidence Criteria	Bias	Standard Deviation	Number	95% Confidence Intercal on Bias
<100 km and <1 hours	−0.79	1.0	46	−1.12/−0.48
<200 km and <2 hours	−0.52	1.6	182	−0.76/−0.29
<300 km and <3 hours	−0.64	2.18	414	−0.85/−0.43

[a]All values in Kelvin.

empirical correction for daytime heating and also that the empirical correction used is likely to be valid.

4. Comparison of Gravity Wave Measures

[9] The gravity wave potential energy per unit mass, E_p, is utilized in this study to determine whether the coincident and near-simultaneous data provided by the two instruments match. The calculation of E_p from temperature profiles is described in detail by *Tsuda et al.* [2000]. Briefly, the entire CHAMP derived temperature profile from the ground to 35 km is high-pass filtered with a Hamming window using a cutoff vertical wavelength of 10 km yielding temperature perturbations $T' \cdot T'^2$ was then integrated using a sliding window with a width of 2 km and a step size of 200 m equivalent to the over-sampled vertical resolution of the profile. The mean temperature, $\overline{T}$, and the temperature gradient were calculated using a sliding window with a width of 600 m and from this the Brunt-Väisälä frequency, N, was computed. Finally, the E_p was estimated as:

$$E_p = \frac{1}{2}\frac{g^2}{N^2}\overline{\left(\frac{T'}{\overline{T}}\right)^2} \quad (1)$$

[10] The temperature measurements from the SPB data were used to derive E_p in a similar manner. However, in this case temperature perturbations were derived by applying a high pass filter which removed all periods greater than the local inertial period. Comparison of the E_p derived from CHAMP using a 10km cut-off wavelength and SPB data filtered to remove all motions longer than the local inertial period, shown in Figures 2a and 2b, only display qualitative agreement. In particular, the periods where very large values of E_p are observed with coincident observations show good agreement, but less correspondence is observed between regions with low E_p values. This relatively poor agreement is slightly surprising given the excellent agreement observed between the two instruments temperature measurements (see Section 3). However, a number of potential reasons for this disparity can be suggested and are discussed in Section 5.

5. Discussion and Conclusions

[11] Previous work by *Alexander* [1998] indicated that the broad-range of scales associated with gravity waves means that different observational techniques can potentially observe different fractions of the whole spectrum. Thus, observational filters associated with different instruments

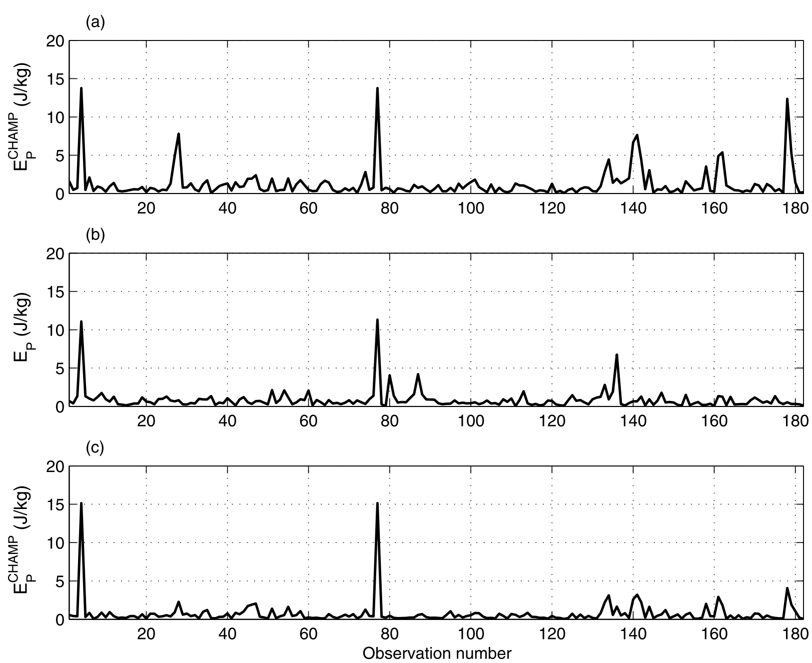

Figure 2. Derived potential energy per unit mass from (a) and (c) CHAMP RO observations and (b) Stratéole/Vorcore super-pressure balloon measurements. The temperature perturbations in Figure 2a are associated with using a high pass filter with a cut-off wavelength of 10 km, and those in Figure 2c are associated with using a cut-off wavelength of 7 km. The Stratéole/Vorcore measurements shown in Figure 2b are associated with using a high pass filter which passes all periods smaller than the local inertial period.

can select waves with certain propagation characteristics which makes the interpretation of any single observation and thereby comparisons non-trivial. A study by *Lange and Jacobi* [2003] shows that while the weighting function of the RO measurements is 200–400 km along the LOS, the GPS measurements are sensitive to gravity waves with horizontal wavelengths greater than 100 km and vertical wavelengths between approximately 1.4 and 10 km. This is partially associated with the LOS having a parabolic path in the atmosphere and also the fact that the plane waves visible will depend on the angle between the LOS and the wavefronts. When the LOS is perpendicular to the wavefronts then spatial averaging will significantly affect the wave activity observed. In particular, work by *de la Torre and Alexander* [2005] has shown that the observability of mountain waves, which have horizontal wavelengths of tens to hundreds of kilometers, can be significantly impacted. Further work by *Baumgaertner and McDonald* [2007] suggested that the preponderance of LOS within 30 degrees of the north/south axis in the Antarctic region means that the viewing geometry over the Antarctic Peninsula and the Trans-Antarctic Mountains potentially favoured the detection of the mountain waves by CHAMP in these regions. However, all this previous work suggests that CHAMP RO measurements observe a limited portion of the gravity wave field. Work on the SPB observational filter detailed by *Hertzog et al.* [2008] indicates that a good approximation to the observational limit of the SPB measurements can be written as:

$$\lambda_z \leq \frac{\lambda_h}{12} \qquad (2)$$

where λ_z and λ_h are the vertical and horizontal wavelength. Comparison of the observational limits for CHAMP ($\lambda_h >$ 100 km and λ_z between 1.4 and 10 km) with this observational limit suggests that at long vertical wavelengths (greater than $\approx$8 km) CHAMP can observe waves with shorter horizontal wavelengths than those observable by the balloons. Thus, by limiting the range of wavelengths observed by CHAMP to vertical wavelengths less than 7 km (Figure 2c), we should improve the relationship between the fraction of the wave field that both instruments observe. Comparison of Figures 2b and 2c shows a slightly improved relationship as expected, in particular the large peak observed for coincidence number 178 has now been removed, however the relationship is still relatively poor. The match between the measurements of E_p for the CHAMP and Vorcore observations is improved at the 90% significance level when the CHAMP data is filtered with a 7 km rather than a 10 km cutoff. With the 7 km cutoff wavelength applied to the CHAMP data set, the Vorcore SPB should observe a wider part of the gravity wave field than the CHAMP RO observations. Consequently, the CHAMP observations of E_p should be smaller than the Vorcore values, this is generally the case (see Figure 2). In a few cases however, the converse is true indicating that other factors must be considered.

[12] Given that these waves are three-dimensional (and time varying) and that the horizontal orientation of constant phase lines relative to the LOS of the satellite observations is unknown we can not remove all of these spatial averaging problems without knowing the propagation direction of the wave. If we assume that the propagation direction of most of the waves is in the zonal plane we can examine LOS information to determine whether LOS makes any difference to the match between the two sets of observations. It should be noted that *Vincent et al.* [2007] supports this simple assumption since they found that meridional momentum fluxes are generally much smaller in magnitude than zonal momentum fluxes. If we examine the difference between the E_p measurements for different LOS we find that the largest relative difference between the two instruments occurs for satellite observations with LOS in the east-west direction suggesting that the instrument visibility filter associated with the CHAMP RO observations is important in explaining the differences between the E_p observed. In particular, the CHAMP data underestimates the E_p compared to the Vorcore derived values as expected. For LOS that are more nearly zonal the underestimation is on average 0.22 Jkg^{-1} while for LOS that are more nearly meridional the underestimation is on average only 0.02 Jkg^{-1}. However, due to the relatively large standard deviations on these values, these differences are not statistically significant. The previous discussion highlights the fact that the E_p measured by the CHAMP observations is larger than that derived from the Vorcore observations in some cases suggesting that observational filtering is unlikely to explain all the differences observed between the two data sets.

[13] Other possibilities which may contribute to the differences are that waves with small spatial scales may be within the field of view of only one instrument because of the coincidence criteria utilized in this study and that the determination of temperature perturbations in the CHAMP data may be contaminated by changes around the tropopause [*Tsuda et al.*, 2004]. However, it should be noted that the impact of the tropopause on the temperature perturbations derived from CHAMP RO associated with the range of altitudes of the balloons of 16–18 km is likely to be small based on previous analysis detailed by *Baumgaertner and McDonald* [2007], particularly given the well-defined relatively low tropopause altitude observed between October and December. Interestingly, the mean difference between the E_p observed by CHAMP and SPB observations is significantly smaller at the 95% level when a 200 km and 2 hour coincidence criteria is used rather than a 300 km and 3 hour criteria. This suggests that stringent requirements are necessary to compare different instruments and that the intermittency of the gravity wave field is important in this type of study.

[14] In conclusion, comparisons of CHAMP RO and SPB temperature observations show excellent agreement, but display a measurable bias and variation around that bias associated with spatial and temporal separation. An initial comparison of the magnitude of gravity wave activity observed by each instrument shows relatively poor agreement and when observational filtering effects are reduced this agreement improved. Another important point from the observations displayed in Figure 2 is that the largest E_p are related to measurements near the Antarctica Peninsula which suggests that CHAMP measurements may be observing mountain waves when the CHAMP LOS is orientated correctly. Further work will focus on using propagation direction information derived from SPB measurements to

gain a greater understanding of the RO observational filter and determining under what circumstances mountain waves may be observed by CHAMP RO data.

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