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Evaluation of uncertainty in gravity wave potential energy calculations through GPS radio occultation measurements

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Abstract

The application of the Global Positioning System (GPS) radio occultation (RO) method to the atmosphere enables the determination of height profiles of temperature, among other variables. From these measurements, gravity wave activity is usually quantified by calculating the potential energy through the integration of the ratio of perturbation and background temperatures between two given altitudes in each profile. The uncertainty in the estimation of wave activity depends on the systematic biases and random errors of the measured temperature, but also on additional factors like the selected vertical integration layer and the separation method between background and perturbation temperatures. In this study, the contributions of different parameters and variables to the uncertainty in the calculation of gravity wave potential energy in the lower stratosphere are investigated and quantified. In particular, a Monte Carlo method is used to evaluate the uncertainty that results from different GPS RO temperature error distributions. In addition, our analysis shows that RO data above 30 km height becomes dubious for gravity waves potential energy calculations.

Keywords: Gravity wave potential energy; Uncertainty; Radio occultation

1. Introduction

The application of the Global Positioning System (GPS) radio occultation (RO) method to the atmosphere enables the determination of height profiles of temperature in the neutral atmosphere. The principle of this remote sensing technique is based on the time delay effect of the neutral atmosphere and ionosphere on propagating radio waves. Data is collected during an occultation through the line of sight between a receiving and an emitting satellite. Due to the relative motion of both satellites, the signal penetrates through the atmospheric limb at different heights and there is a scan from top downwards (setting event) or from bottom up (rising event). GPS RO provides a unique combination of favorable factors: it is a nearly instantaneous snapshot (about 1 min) of the measured zone and it has global coverage, high vertical resolution, good accuracy, all-weather and all-time capability and no need of instrumental drift or bias corrections in time (observations are long-term stable due to permanent self-calibration). We note however that the data retrieval processing can induce errors in addition to the observational ones.

Gravity wave activity is usually quantified by the mean potential energy E_p per unit mass in a layer between vertical positions z_1 and z_2 by the formula

$$E_p = \frac{1}{2}\frac{1}{z_2 - z_1}\int_{z_1}^{z_2}\left(\frac{g}{N}\right)^2\left(\frac{T'}{T_b}\right)^2 dz, \tag{1}$$

where g and N refer to gravity of Earth and the Brunt–Väisälä frequency, whereas T_b and T' correspond to the background and gravity wave components of the vertical temperature profile T usually found by the use of a digital filter.

The choice of the integration limits z_1 and z_2 has some degree of arbitrariness. After the filter is chosen, the

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calculation of E_p also depends on the personal choice of maximum λ_M and minimum λ_m wavelengths to separate the background and the gravity wave fluctuations. The different options in the settings turn comparisons between different studies dubious.

In short, the uncertainty in the calculation of E_p depends not only on the inaccuracy of T, but also on the degrees of freedom in the choice of the z_1, z_2, λ_M and λ_m values.

2. Uncertainties

As previously explained, the value of E_p is not directly measured. Besides its explicit dependence on the values of T, z_1 and z_2 (see Eq. 1), the choice of λ_M and λ_m is also involved in the calculation of the output. In brief, the dependencies are

$$E_p = E_p(T, z_1, z_2, \lambda_m, \lambda_M). \tag{2}$$

A further parameter is the filter itself, as diverse types have different response curves. However, we will not consider this issue here as it is not possible to study every existing filter, so we will keep using in all our analyses the same typical non-recursive tool (Scavuzzo et al., 1998). The filter includes a Kaiser window (Kaiser et al., 1966; Hamming et al., 2004) to minimize filtering artifacts as Gibbs effects due to the non-infinite extension of the data. Each vertical temperature profile was low-pass (wavenumber) filtered with the upper wavelength cutoff, which led to the background temperature. In order to obtain a bandpass which isolated wavelengths between given lower and upper cutoffs, the filter was applied again to the difference between the original and the background profiles, but now with the lower wavelength cutoff.

A standard analysis of the uncertainty, using the well-known law of propagation of uncertainties cannot be applied to this model, given the high non-linearity of Eq. 1. Strictly speaking, the only uncertainty involved is the one corresponding to T. The differences in the other parameters correspond to the choice of different values by the authors in their studies. In this work, we report on the application of a Monte Carlo-based uncertainty propagation technique to evaluate the uncertainty in the calculation of the potential energy per unit mass. A sensibility analysis to the input parameters z_1, z_2, λ_m and λ_M is also presented.

3. Data set

COSMIC (Constellation Observing System Meteorology, Ionosphere and Climate) is a constellation consisting of six low Earth orbit satellites, launched in April 2006. We used 15 396 COSMIC RO evenly distributed over the planet and over time. They correspond to the RO of day 15 of every month from year 2010. They are moisture-corrected atmospheric temperature post-processed profiles provided by UCAR (University Corporation for Atmospheric Research) COSMIC Data Analysis and Archive Center (CDAAC). Fig. 1 displays the histogram of the 15 396 E_p values in the stratosphere calculated with $z_1 = 18$ km, $z_2 = 33$ km, $\lambda_m = 2$ km and $\lambda_M = 10$ km. The distribution obtained is skewed, and follows the usual lognormal shape of gravity wave climatologies (Baumgaertner and A., 2007). For statistical purposes, only values of E_p smaller than 4 J/kg are included in the following, given the very few cases with larger energies. When analyzed in detail we noticed that some of them correspond to ”pathologic” cases. This means that they survived the RO quality control procedures, but exhibit nevertheless above about 30 km significant departures from a typical profile, which may be attributed to initialization issues (Hajj et al., 2004; Gobiet and Kirchengast, 2004; Ao et al., 2006). Those large deviations become in some calculations a significant addition of energy, as noticed in fact below.

4. Uncertainty due to GPS RO temperature errors

Temperature retrievals of RO are known to have an accuracy around 0.5 K (Kuo et al., 2005). Therefore, we considered Gaussian noise with 0.5 and 1 K standard deviation to evaluate the contribution from T to the output uncertainty. Fifty Monte Carlo simulations were performed on each RO profile. The dispersion of the E_ps found for each profile is considered an indicator of uncertainty due to T for that profile. To analyze uncertainties for different energy ranges, we averaged the standard deviations of the profiles of each bin from Fig. 1. The result is displayed in Fig. 2. It may be seen that the absolute uncertainty increases in a nearly linear way for both noise amplitudes. At the highest energies, the relative uncertainty is of the order of 5 or 2.5%, depending on the noise amplitude considered.

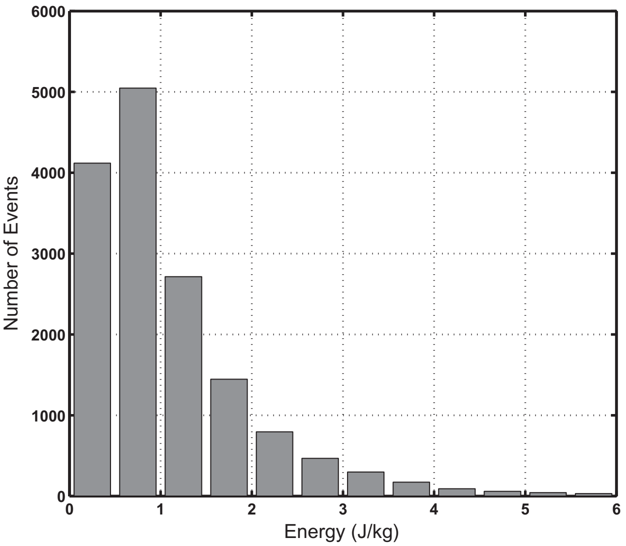


Fig. 1. E_p distribution for all the studied cases ($z_1 = 18$ km, $z_2 = 33$ km, $\lambda_m = 2$ km, $\lambda_M = 10$ km).

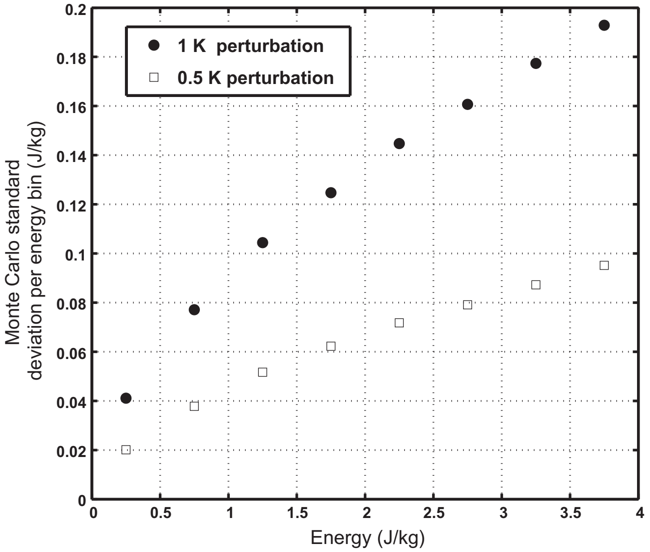


Fig. 2. Absolute uncertainty against E_p ($z_1 = 18$ km, $z_2 = 33$ km, $\lambda_m = 2$ km, $\lambda_M = 10$ km).

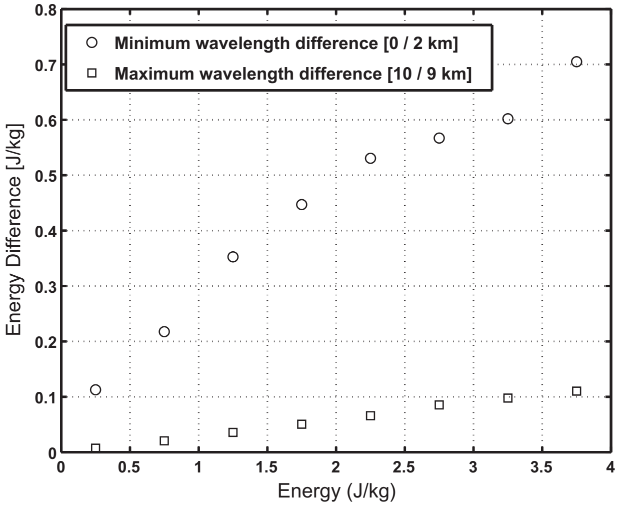


Fig. 3. Circles: E_p calculated with $\lambda_m = 0$ km minus E_p calculated with $\lambda_m = 2$ km against the average E_p per bin. Squares: E_p calculated with $\lambda_M = 10$ km minus E_p calculated with $\lambda_M = 9$ km against the average E_p per bin.

5. Bias due to the choice of the minimum and maximum filter wavelength cutoffs

The adequate choice of the wavelength cutoffs for studying gravity waves through RO measurements is still open. For example, Tsuda and Hocke, 2002 applied no minimum wavelength filter ($\lambda_m = 0$) to the RO profiles used to analyze vertical wavenumber spectra of temperature fluctuations. Marquardt and Healy, 2005 argued that for vertical wavelengths less than 2 km, temperature fluctuations in the profiles may generally be related to measurement noise. They used Monte Carlo simulations of the phase delay noise, and then studied the dry temperature profiles obtained. They found a great contribution of the measurement noise to the power spectral density at wavelengths smaller than 2 km. This measurement noise might be confused with wave activity if it is not properly filtered. These authors evaluated power spectral densities of fluctuations, but they did not calculate potential energy.

In this section, we evaluate the differences that arise in E_p due to the filtering with $\lambda_m = 0$ and 2 km. We used the same RO as in Section 4. Fig. 3 shows that energies calculated with zero wavelength cutoff are always larger than those filtered with $\lambda_m = 2$ km. This result is no surprise but it quantifies the noise effect.

A similar situation occurs with the choice of λ_M. Some authors use a 10 km cutoff (Baumgaertner and A., 2007), while others use 9 km (Alexander et al., 2010). The uncertainty emerging from the difference between these criteria is also shown in Fig. 3.

As in the case of the temperature uncertainty, the difference due to the cutoff choice increases linearly with energy. Among the two wavelength cutoffs, the minimum wavelength criterium is the more important one, generating relative uncertainties between $\lambda_m = 0$ km and 2 km of ~ 20% and ~ 45% at the highest and lowest energies, respectively. The majority of RO have low energies (see Fig. 1)

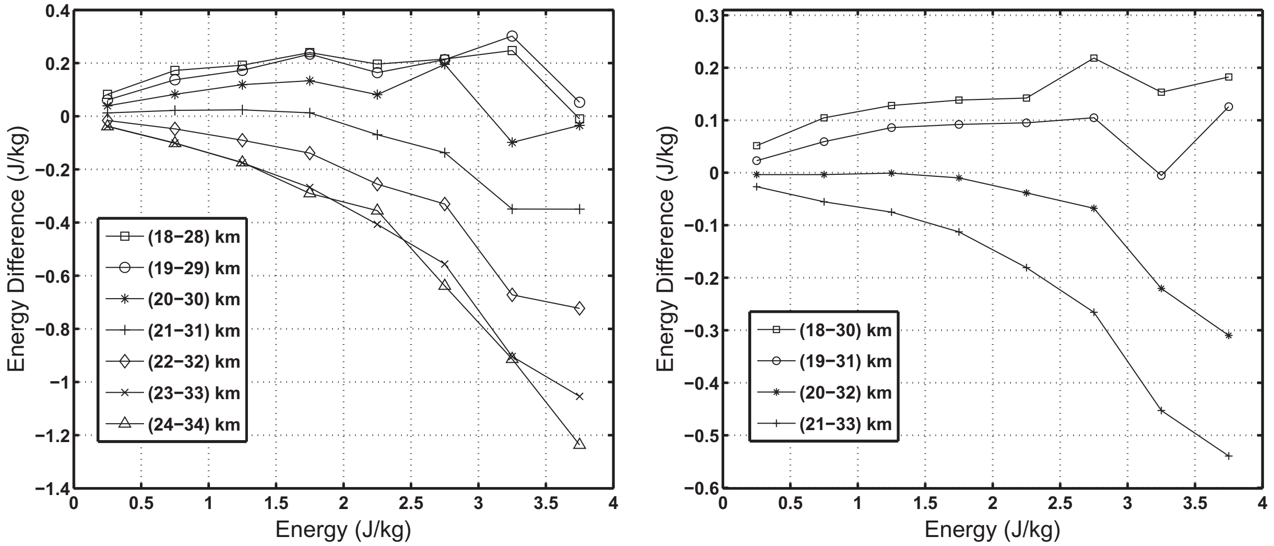
6. Uncertainty due to the choice of the altitude interval

The filtering procedure described above overestimates E_p in the tropopause region. This happens because the tropopause kink may be interpreted by the filter as the surrounding of a large sinusoidal peak (Alexander et al., 2011). To avoid this issue, the integration intervals are usually taken above the expected tropopause height. Again, no unique criterium exists among authors. For example, Jiang et al., 2002 considered temperature variances between 16 and 32 km, while Xiao and Hu, 2010 integrated between 20 and 35 km. Altitude intervals may also depend on the specific geographic region being studied.

RO are accurate up to 0.5 K below 35 km (Kuo et al., 2005). For this reason, the upper limit of integration is usually taken below this level. Other authors were extremely cautious and chose a smaller height, e.g., 27 km (Alexander et al., 2010).

Fig. 4 depicts differences between several integration intervals. A 15 km long reference interval between 18 and 33 km height is compared to 10 km and 12 km long intervals. The differences become significant for integration intervals that include temperature measurements above 30 km. This shows that RO temperature profiles are not reliable for gravity waves potential energy calculations above 30 km. The possible origin of this artifact are that spurious oscillations introduced by the GPS RO initialization procedure of atmospheric profiles have a significant presence up to that altitude. This injects artificial additional energy to the profiles above that height.

The comparisons also show that the length of the integration interval is less relevant than the upper end of the interval.



(a) Energy differences between the reference and 10 km integration intervals.

(b) Energy differences between the reference and 12 km integration intervals.

Fig. 4. E_p calculated with vertical column of 15 km minus E_p calculated with vertical columns of 10 km and 12 km against the average E_p per bin.

7. Concluding remarks

A study performed for COSMIC GPS RO data over the whole globe for one year shows uncertainty values of gravity waves E_p in the stratosphere depending on the different choice of filter parameters to separate background and waves in the temperature profiles. Measurement uncertainties in temperature were shown to be less important than the choice of those parameters. The most sensitive factor is the minimum wavelength: variations of the order of 45% were found between different choices. We have also shown that RO temperature profiles are not reliable above 30 km for E_p calculations. From these results it is clear that extreme care must be taken when comparing E_p climatologies processed with different parameters. This applies not only to GPS–RO temperature measurements, but to any other measurement technique. A future study should also evaluate different digital filters.

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