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Dataset Paper

Bending Angle and Temperature Climatologies from Global Positioning System Radio Occultations

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The Global Positioning System (GPS) Radio Occultation (RO) technique [1] enables measurements of the global atmospheric density structure under any meteorological condition [2]. As illustrated in Figure 1, the RO technique involves a GPS satellite transmitting the signal and a Low Earth Orbit (LEO) satellite carrying a receiver. The signal transmitted by the GPS satellite is refracted in the atmosphere, and the associated propagation delay, refractive index, and bending angle are measured on the LEO satellite. From the measurements, it is possible to estimate profiles of atmospheric parameters such as temperature, water vapour, and pressure [3]. These parameters are secondary products, derived from the refractivity together with the European Centre for Medium-Range Weather Forecasts (ECMWF) model, and are given with high vertical resolution. The highest accuracy on the refractivity is achieved between 5 and 25 km altitude with average errors estimated in the range 0.3%–0.5% [4]. The RO technique has improved the weather forecast in regions of the globe that is poorly covered by standard measurements, such as the southern hemisphere which is dominated by oceans [5]. For instance, forecasting the track of tropical cyclones (energized over the oceans) has greatly improved [6]. Also the upper atmosphere is better forecasted as in the case of the ECMWF Upper Troposphere Lower Stratosphere (UTLS) model [7].

However, the use of a model to derive atmospheric parameters involves implicit assumptions on the state of the atmosphere. Therefore, during special atmospheric conditions, the assumptions break down and the atmospheric parameters are poorly estimated. Such conditions arise during extreme storms such as tropical cyclones [8]. Consequently, the direct measurement of the primary parameters of the GPS signal can be more sensitive to atmospheric variations and better reflect the physics of the region, if studied directly.

For example, using the bending angle directly, accurate and detailed information can be estimated for the atmosphere above severe storms [9].

Several GPS RO missions are working at present. They include the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) six-satellite constellation [10], the Gravity Recovery And Climate Experiment
Figure 1: The GPS RO technique scheme (the proportions are not respected) [1]. Dashed and dotted lines are the satellite orbits (LEO and GPS). The dotted line is the signal transmitted from GPS not crossing the atmosphere. The red and dashed lines are two different signals bended by the atmosphere and received from the LEO satellite. With respect to the red signal, $\alpha$ is the bending angle, $a$ is the so-called impact parameter, and $r_p$ is the tangent radius.

(M) twin satellites [11], the Meteorological Operational satellite A (MetOp-A) [12], the Radio Occultation Sounder for the Atmosphere (ROSA) [13] on board of OceanSat-2 [13], Megha-Tropique [14], and the Satellite de Aplicaciones Cientificas-D (SAC-D) [15]). Several new missions are planned for the near future (e.g., COSMIC2, ACES on the International Space Station, and MetOp-B/C).

The number of transmitters will also increase in the near future with the European GALILEO system, with the availability of the Russian GLObal NAvigation Satellite System (GLONASS), and with the new projects from China (COMPASS), India (Indian Regional Navigational Satellite System, IRNSS), and Japan (Quasi-Zenith Satellite System, QZSS).

The new missions will increase the spatial measurement resolution of the Earth, which is especially needed in the tropical region [16], and the temporal resolution.

2. Methodology

We downloaded the GPS ROs from the COSMIC Data Analysis and Archive Center (CDAAC) website [17]. We collected all the level 2 product profiles in Network Common Data Form (NetCDF) format covering the period 1995–2009 coming from the following missions: the Global Positioning System/Meteorology (GPS/MET, 1995–1997) satellite [18], the CHAllenging Minisatellite Payload (CHAMP, 2001–2008) [18], the Satellite de Aplicaciones Cientificas-C (SAC-C, 2000-2001) [19], the COSMIC (2006–2009) six-satellite constellation, and the GRACE (2007–2009) satellite.

In total more than 2,700,000 ROs were used (Table 1), mostly coming from COSMIC.

All the products are provided from CDAAC in a common standard format.

(i) Atmospheric Profile (atmPrf). It is a product containing the bending angle, refractivity, impact parameter, and the so-called dry pressure and dry temperature (derived assuming no water vapor). All the parameters are reported versus the geometric height above the mean sea level from the surface to 60 km of altitude and the coordinates of the perigee point with vertical resolution from 60 meters in the lower troposphere to 1.5 km in the stratosphere [4].

(ii) Wet Profile (wetPrf). It is an interpolated product sampled every 100 meters and obtained using a nonstandard IDVar (one-dimensional variational) technique [16] together with ECMWF low-resolution analysis data. This profile contains latitude and longitude of the perigee point, pressure, temperature, water vapor pressure, refractivity, and mean sea level altitude of the perigee point from the surface to 40 km of altitude.

Using all the GPS ROs collected from the CDAAC website from 1995 to 2009, we have created a grid with one-degree resolution containing the average bending angle profiles (from the atmPrf product) and the average temperature profiles (from the wetPrf product). This grid becomes our reference and is defined in the text as “climatology” [20].

Figure 2 shows the map with the number of occultations used for any box. The density of measured vertical profiles of atmospheric parameters is higher at the midlatitudes,
between ±27 and ±60 degrees, and it decreases between the tropics, which is a key region for atmospheric circulation [8].

The full process to compute the climatology fundamentally consists in 3 steps.

(i) Interpolation. The vertical distribution of atmPrf acquisitions is not fixed, providing anytime a different number of measurements in the altitude range 0–60 km. To create a standard reference to be comparable with other products, we decided to interpolate the atmPrf data with a common vertical sampling of 50 meters. The wetPrf products are already provided by CDAA with a sampling of 100 meters.

(ii) Geolocation. The interpolated profiles were indexed with respect to the tangent point latitude and longitude at 16 km of altitude (average altitude of the tropical tropopause) with one-degree resolution. We have created this dataset specifically for studying the upper troposphere/lower stratosphere; for this reason, the GPS RO profiles are categorized into the one-degree box corresponding to the RO coordinates at 16 km of altitude.

(iii) Average. In each geolocated box, we averaged all the values at the same altitude obtaining one reference profile for every latitude/longitude degree: this becomes the climatological reference (climatology) for the corresponding coordinates.

3. Dataset Description

The dataset associated with this Dataset Paper consists of 3 items which are described as follows.

Dataset Item 1 (Binary Data). The bending angle climatology structure in matlab format (.mat) formed by 180 × 360 cells corresponding to the one-degree latitude/longitude grid boxes in the following order: row 1 is latitude −90°; row 180 is latitude 90°; column 1 is longitude −180°; column 360 is longitude 180°. Whenever a value is missing, it is replaced by Not a Number (NaN). When the number of profiles for a certain grid box is n and the NaN at each altitude is m, the climatological value for the box and related altitude is computed averaging n–m values. If n = m, the climatological value is NaN. Each cell contains an array of 1200 single values representing the climatological bending angle profile from the surface to 60 km of altitude with a vertical resolution of 50 meters.

Dataset Item 2 (Binary Data). The bending angle climatology structure in matlab format (.mat) formed by 180 × 360 cells corresponding to the one-degree latitude/longitude grid boxes in the following order: row 1 is latitude −90°; row 180 is latitude 90°; column 1 is longitude −180°; column 360 is longitude 180°. Whenever a value is missing, it is replaced by Not a Number (NaN). When the number of profiles for a certain grid box is n and the NaN at each altitude is m, the climatological value for the box and related altitude is computed averaging n–m values. If n = m, the climatological value is NaN. Each cell contains an array of 400 single values representing the climatological temperature profile (in Celsius) from the surface to 40 km of altitude with a vertical sampling of 100 meters.

Dataset Item 3 (Binary Data). The number of profiles used to get the final climatologies in matlab format (.mat) formed by 180 × 360 cells corresponding to the one-degree latitude/longitude grid boxes in the following order: row 1 is latitude −90°; row 180 is latitude 90°; column 1 is longitude −180°; column 360 is longitude 180°. Whenever a value is missing, it is replaced by Not a Number (NaN). When the number of profiles for a certain grid box is n and the NaN at each altitude is m, the climatological value for the box and related altitude is computed averaging n–m values. If n = m, the climatological value is NaN. Each cell contains an integer representing the number of profiles used to compute the climatological temperature and bending angle for the corresponding one-degree box.

4. Concluding Remarks

We have already used this dataset for studying the atmospheric physics during convective systems [9] and tropical cyclones and for detecting the tropical cyclones cloud top [21]. The results were very satisfactory revealing the capabilities of GPS ROs detecting a detailed atmospheric structure in the upper troposphere. In Figure 3, we report a schematic thermal structure of convective systems (red line) obtained using 53 cases [9] in comparison with the average
standard temperature profile (from wetPrf data) colocated with the systems (blue line). During convective systems, the temperatures decrease from the surface with a moist adiabatic lapse rate until a few kilometers from the cloud top. At this altitude, the lapse rate increases revealing a relative temperature minimum (cold point) near the top of the system. Above the cloud top, a strong inversion occurs, reestablishing a climatological temperature profile at higher altitudes.

The GPS RO climatology is useful for climatological [22] atmospheric physics [9] and meteorological [6] studies. The bending angle and temperature climatology can be used as reference for detecting anomalies from the standard atmosphere. The horizontal and vertical sampling of the temperature and bending angle is high enough to study mesoscale processes.

The future development of this dataset, including new missions acquisitions and the extension of the reference period, will provide a solid background for seasonal or monthly climatologies (not possible at the moment due to the small number of profiles at certain latitudes). Several new deliverables have already been planned for the next 2 years within the project CONvective SYstems DEtection and analysis using Radio occultations (CONSYDER) within the EU Program FP7-PEOPLE-2012-IEF, including specific datasets for different type of clouds.

Dataset Availability

The dataset associated with this Dataset Paper is dedicated to the public domain using the CC0 waiver and is available at http://dx.doi.org/10.7167/2013/795749/dataset. In addition, the dataset is available in the DTU server at http://outer.space.dtu.dk/~ribi/.

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