Questions about the potential value of GPS-RO to the climate observing system and which GPS-RO data are truly benchmark

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Issue 8: Impact of observations scattered across space and time

Most meteorological observations are performed at regular times of day (e.g., 00Z and 12Z) in specific locations.* In situ SST obs are major exception to this rule, but SST changes slowly compared to the atmosphere. Most satellite observations are for wide areas of the globe. GPS-RO is nearly unique because it observes point measurements that change in location and time of observation in a not quite random way. As a result, utilizing them for climate change analyses presents new challenges. Past analyses have averaged the observations into large grid boxes and then into large time segments (e.g., 10x10 degree boxes averaged over a month). An analysis of the errors this technique causes would be helpful in putting the use of GPS-RO for climate into perspective. Perhaps the potential impacts of the errors could be quantified by subsampling a very high resolution model output at the GPS-RO observation locations in time and space (by latitude band and over land and ocean and elevation) and comparing the results to the full model field results.

Answer by K. Trenberth:

* Not true: all satellite soundings are asynoptic.
GPSRO is not actually a point measurement but samples a finite size footprint and this actually makes it more useful to climate and less useful for mesoscale meteorology. Many errors are likely to be random and thus average out, although this needs to be quantified. The exercise suggested may be useful

Answer by U. Foelsche:

Short Answer:

We are well aware of problems that could arise, e.g. through aliasing of diurnal effects in long-term satellite observations. We performed simulation studies and we routinely estimate the sampling error of RO climatologies by comparing climatologies derived from vertical ECMWF profiles at the RO times and locations with climatologies derived from the complete 4D ECMWF field. For climate applications potential systematic components are most important, e.g. through undersampling of the diurnal cycle. The worst case would be a very slow drift in local time (a few hours over many years). No current or planned RO mission is in this unfavorable situation. Most RO missions have precessing orbits. With a precession rate of ~3°/day, the RO measurements from a single COSMIC satellite (in final orbit) drift through all local times within ~60 days, and for the entire constellation (with 30° orbit plane separation) it takes about 10 days to sample the diurnal cycle (at Equator). The European satellite MetOp, on the other hand, is in a sun-synchronous orbit – the measurements are stationary in local time and the diurnal cycle is never fully sampled. We found a constant bias of about 0.04 K in MetOp RO climatologies, which should remain stationary, as long as the shape of the diurnal cycle does not change. For COSMIC we found systematic (but very small) oscillatory local time component of the sampling error in monthly mean climatologies in the extratropics (hemispherically antisymmetric, half cycle ~60 days, ± 0.03 K amplitude) that disappears to < 0.01 K when building seasonal means.

Long Answer:

We compute monthly and seasonal men, zonal mean climatologies with 10°latitudeinal resolution, based on Radio Occultation RO data from CHAMP (*Foelsche et al.*, 2007) and started doing this for RO data from Formosat-3/COSMIC (*Foelsche et al*. 2008a; b).

The sampling error of RO climatologies can be quantitatively estimated, when an adequate representation of the "true" spatio-temporal evolution of the atmosphere is available and the times and locations of RO events are known. As a proxy for this atmospheric evolution we use ECMWF analyses, whose four time layers per day are sufficient to sample the diurnal cycle up to the second harmonic (the semidiurnal cycle). We estimate the sampling error by comparing climatologies derived from vertical ECMWF profiles at the RO times and locations with climatologies derived from the complete 4D ECMWF field (see *Foelsche et al*. 2007, for further details). The dry temperature sampling error profile in each bin is estimated as:

$$\Delta T_{\mathrm{dry}}^{\mathrm{sampling}}(z) = \frac{1}{N_{\mathrm{prof}}}\sum_{i=1}^{N_{\mathrm{prof}}} T_{\mathrm{dry}_i}^{\mathrm{true}}(z) - \frac{1}{N_{\mathrm{grid}}}\sum_{j=1}^{N_t}\sum_{k=1}^{N_\varphi}\sum_{l=1}^{N_\lambda} T_{\mathrm{dry}_{jkl}}^{\mathrm{true}}(z) \quad , \tag{5}$$

where N_{prof} is the number of profiles in the bin, the summation on the right hand side is over all N_λ longitude and N_φ latitude grid points in the bin and over all N_t time layers within the selected time interval (month or season), $N_{\mathrm{grid}} = N_\lambda N_\varphi N_t$.

Figure 1 shows an exemplary season mean CHAMP dry temperature climatology (Dec-Jan-Feb 2003/2004) and the associated estimated sampling error.

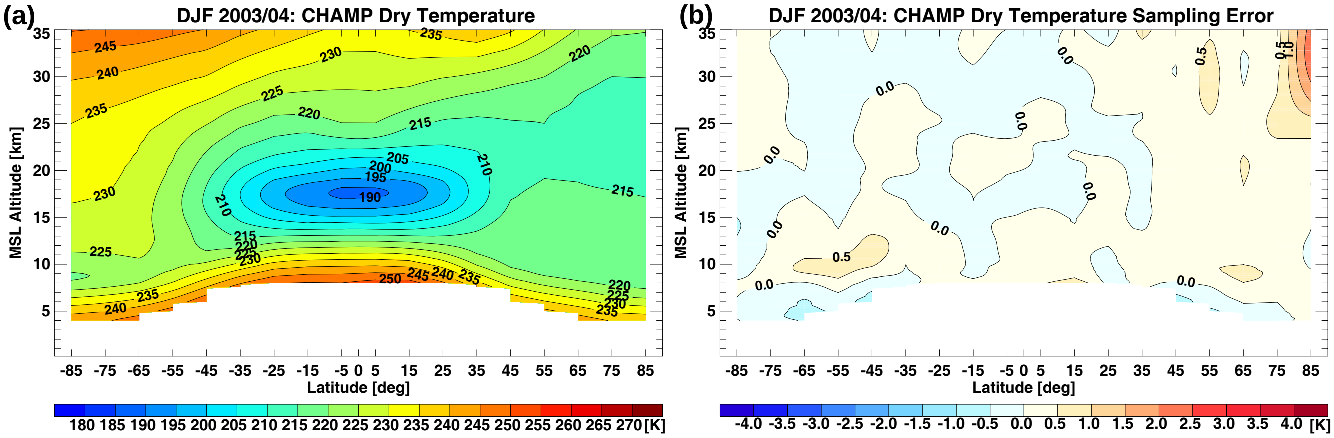

Figure 1 Zonal mean dry temperature fields for the winter season DJF 2003/04: CHAMP dry temperature (a) and estimated CHAMP sampling error (b) (From *Foelsche et al*. 2007).

The mean (absolute) value for the CHAMP (single satellite) sampling error in the UTLS is < 0.3 K for monthly means and < 0.2 K for seasonal zonal means (*Pirscher et al*. 2007). Due to the larger number of profiles, the COSMIC sampling error is considerably smaller – COSMIC monthly mean climatologies are typically at least as good as CHAMP seasonal mean climatologies.

The Sampling error contains a random and a systematic component. The random component of the SE is caused by atmospheric variability, which is not adequately sampled by the satellite. The random component of the sampling error is increasingly reduced by averaging over longer timescales and/or larger spatial regions as well as by increasing spatial and temporal density of observations if so becoming available.

The systematic component of the SE results from systematic spatial and temporal undersampling. The spatial component stems from an inhomogeneous spatial sampling. To give an example, in the early phase of the COSMIC mission (with low orbit heights and measurements within a comparatively small azimuth angle with respect to the orbit plane) very few measurements have taken between 85°N/S and 90°N/S (*Foelsche et al*. 2008a). As a consequence, climatologies for the polar bins where, in general, too warm. This problem has meanwhile been solved due to orbit raising and opening of the azimuth angle (*Foelsche et al*., 2008b).

Another potentially important, systematic component is undersampling of the diurnal cycle. The sampling of the diurnal cycle depends on the satellite orbit geometry (inclination and altitude). The worst case would be a very slow drift in local time (a few hours over many years). No current or planned RO mission is in this unfavorable situation. Most RO missions have precessing orbits. With a precession rate of ~3°/day, the RO measurements from a single COSMIC satellite (in final orbit) drift through all local times within ~60 days, and for the entire F3C constellation (with 30° orbit plane separation) it takes about 10 days to sample the diurnal cycle (at Equator).

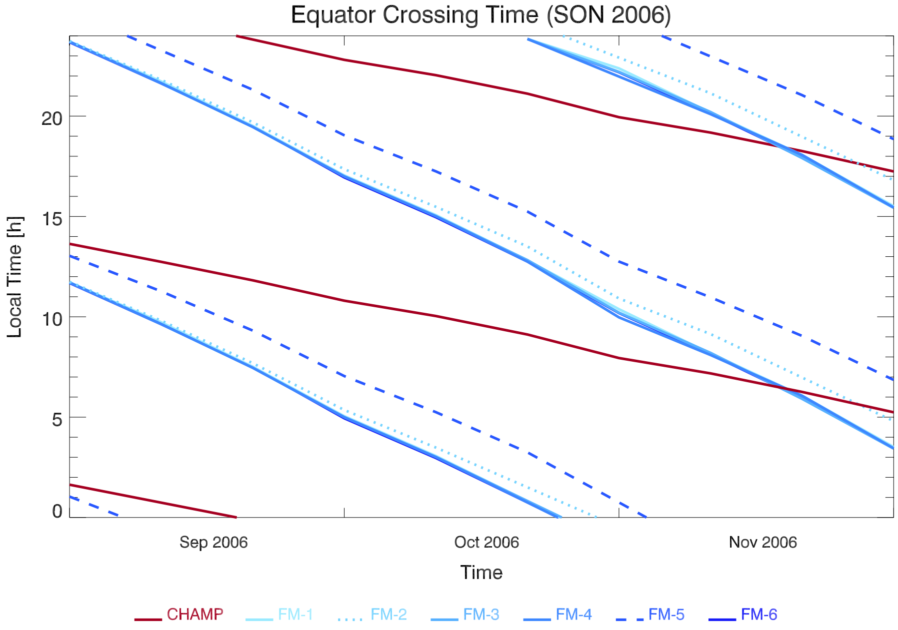

Figure 2 Local time of equator crossing for CHAMP (dark red) and the six COSMIC satellites (different tones of blue) (From *Foelsche et al*. 2008a)

Figure 2 illustrates the local time drift of CHAMP and COSMIC for the early phase of the COSMIC mission: Sep-Oct-Nov 2006, when most COSMIC satellites where still close to each other (note that RO measurements are taken during day and night).

The European satellite MetOp, on the other hand, is in a sun-synchronous orbit – the measurements are stationary in local time and the diurnal cycle is never fully sampled.

Based on simulations, we analyzed the sampling error for CHAMP and MetOp, with focus on the component caused by incomplete sampling of the diurnal cycle. We found that the local time component for CHAMP essentially disappears (< 0.01 K) when averaging over one year, while there remains a constant bias of about 0.04 K in MetOp RO climatologies. We concluded that this local time component should remain stationary, as long as the shape of the diurnal cycle does not change (*Pirscher et al*., 2007).

We have extended this analysis to include COSMIC and found a small but systematic oscillatory local time component of the sampling error in monthly mean climatologies in the extratropics (hemispherically antisymmetric, half cycle ~60 days, ± 0.03 K amplitude) that disappears to < 0.01 K when building seasonal means.

The reason for this is a slight uneven sampling at higher latitudes. Figure 3 (left panels) shows the suborbital points and the corresponding simulated RO event locations for the full COSMIC (F3C) constellation during one month as functions of local time and latitude (for simulation setup details, see *Pirscher et al*., 2007). 2004-2005 was the simulation analysis period and the underlying ECMWF fields for the sampling error estimation are from this period. An interesting feature is the clustering of RO profiles in local time.

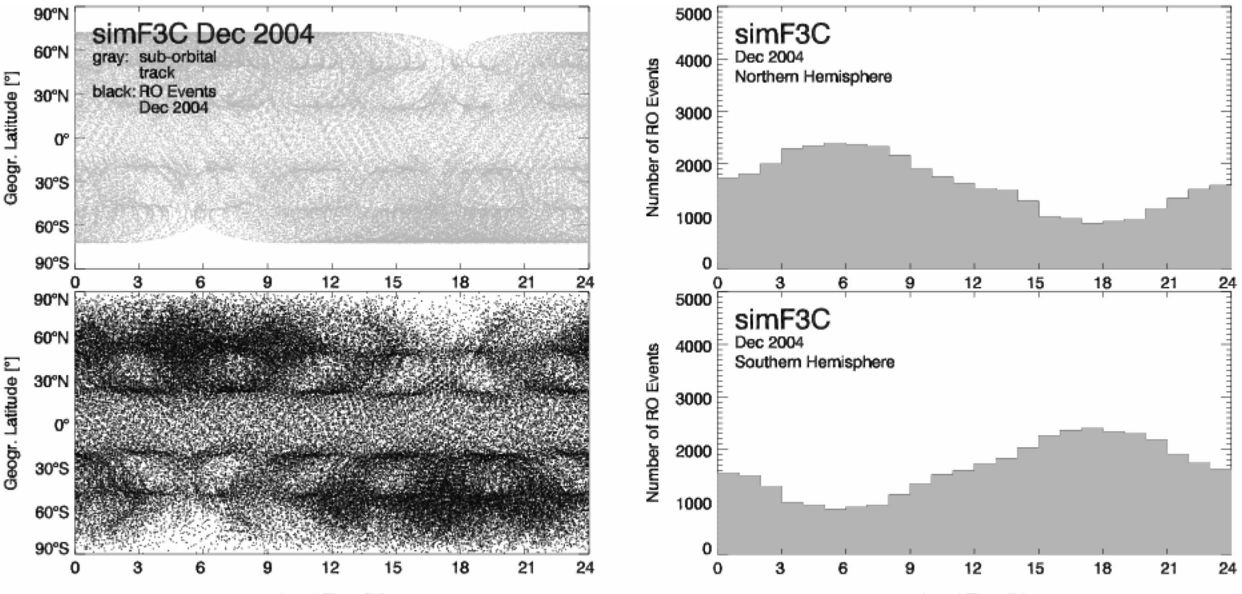

Figure 3 Simulated F3C orbit track (top left, gray dots), occultation event locations (bottom left, black dots) and number of occultation events with respect to local time separated for both hemispheres (Northern Hemisphere top right, Southern Hemisphere bottom right) in December 2004 (2004-2005 was the simulation analysis period).

For the particular month shown in Fig. 3 the RO events are concentrated around 6 LT (local time) on the Northern Hemisphere (NH) and around 18 LT in the Southern Hemisphere (SH) (right panels of Fig. 3, respectively, although the global distribution of RO events with respect to local time is uniform. One month later (not shown here) the constellation has drifted by about 6 hours in local time, resulting in a concentration of RO events around midnight in the NH and around noon in the SH, respectively, while the LT distribution of RO events at low latitudes stays uniform.

At low latitudes, as expected, the local time component is without clear systematic patterns and very small (order 0.01 K fluctuations only). The results for mid and high latitudes are shown in Fig. 4. Here, the sampling situation described above leads to an uneven weighting of day and night temperatures, resulting in alternating small positive and negative deviations (half-cycle period ~60 days) with opposite signs in the local-time component of the sampling error in the NH and SH, respectively (Fig. 14c and 14d). For monthly-mean zonal-mean climatologies with 10° latitudinal resolution, this effect amounts to about ±0.03 K, it disappears (to < 0.01 K) when integrating over longer time periods (at least seasonal means). The full F3C sampling error is generally < 0.1 K (Fig. 4a,b) with an exception in the sampling of the extratropical (NHSM, SHSM) tropopause altitude region where error systematically exceed 0.1 to 0.2 K. The reason is the high space-time temperature variability of this troposphere/stratosphere exchange region which would need even more than six satellites to be sampled to < 0.1 K error.

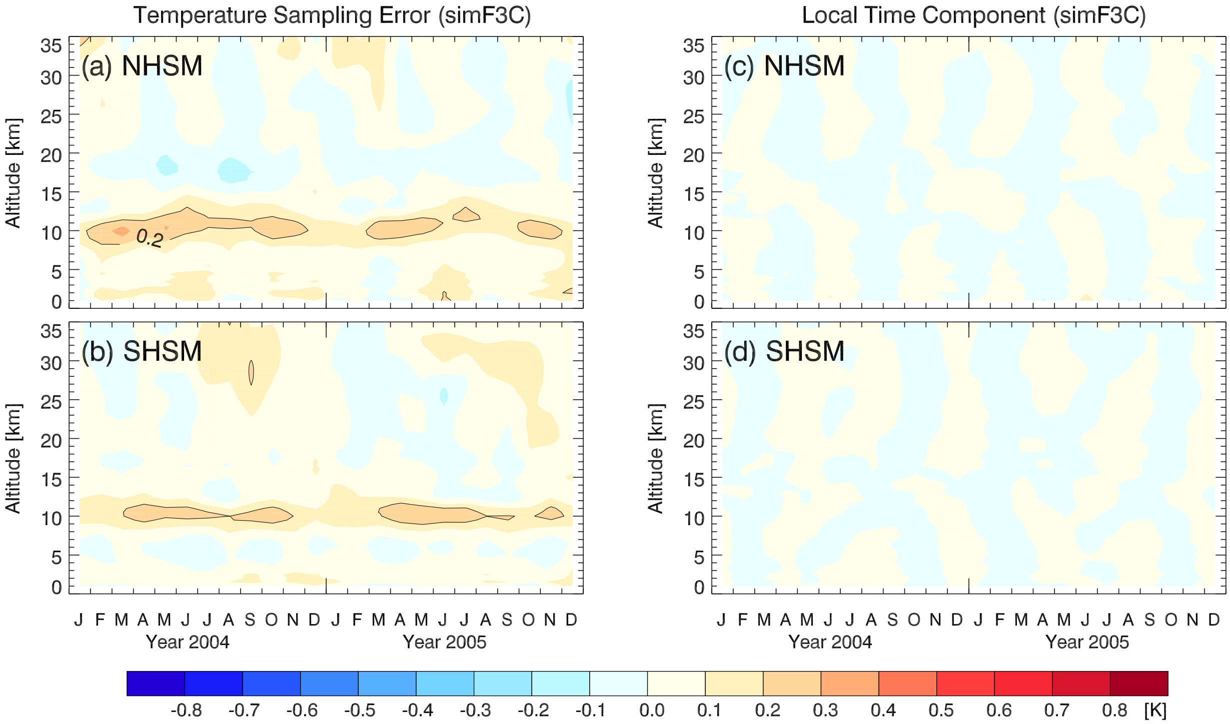

Figure 4. Time series of the monthly-mean temperature sampling error (left) and its local time component for the full F3C constellation for NH sub-tropics and mid-latitudes (20°N -60°N, top) and SH sub-tropics and mid-latitudes (20°S - 60°S, bottom), respectively.

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