Climate Data Based on GPS Radio Occultations

from the GRAS/MetOp instrument

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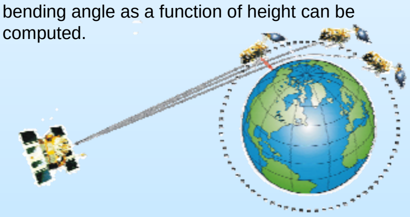
The GPS radio occultation (RO) technique utilizes the refraction of radio waves to probe the Earth's atmosphere. The observed phase delay of a radio wave as a transmitting GPS satellite sets or rises behind the Earth is converted to a vertical profile of refrac-tivity, pressure, temperature, and humidity. The GRAS RO instrument onboard the polar orbiting MetOp satellite provides around 600 profiles per day distributed across the globe. This constitutes an important source of global climate data. Understanding the properties of these data, e.g. the observational and sampling errors, is essential for a correct use of such data in climate research.

The GPS radio occultation technique

The GRAS instrument onboard the Metop near-polar, Sun-synchronous satellite measures the arrival time and frequency of the radio signals emitted from GPS satellites that are setting or rising behind Earth. From the phase shift as function of time, when the radio signal successively traverses deeper and deeper layers of the atmosphere, the bending angle as a function of height can be computed.



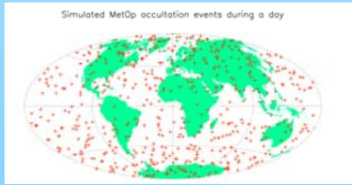
Next, the bending angle can be converted to refractivity, *N,* as a function of height, which itself can be regarded as an atmospheric state variable,

$$N \equiv (n-1)\cdot 10^6 = a\frac{p}{T} + b\frac{p_w}{T^2}$$

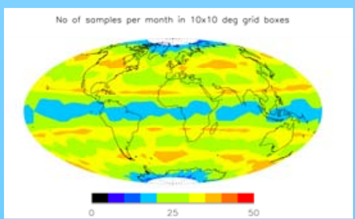
since it is a simple function of the more commonly used geophysical variables pressure (p), tempera-ture (T), and water vapor pressure (p_w). The end-products of the RO observations are vertical profiles of refractivity, pressure, temperature, and water vapour.

Global sampling

Each day, around 600 vertical profiles are observed by the GRAS/Metop instrument. The profiles are irregularly distributed across the globe, providing a good spatial coverage.



This gives between 15 and 35 samples per grid box and month for 10x10 degree grid boxes.



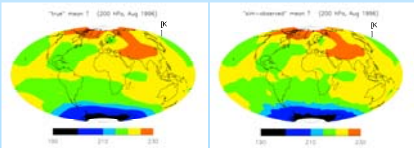
Observe that this is the ideal case where no profiles are deemed bad. Whether the data are sufficient to produce monthly or seasonal averages with small enough errors and biases depends on the observational errors and on the temporal sampling characteristics in relation to the variability of the climate system.

Global RO based climatologies

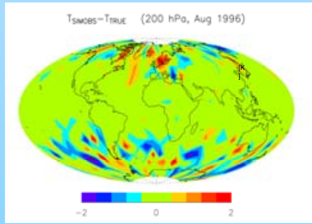
Many of the characteristics of RO data suggest them as a near-ideal source of data for climate studies. We are currently investigating two different methods to construct climatologies from the atmospheric RO profiles irregularly distributed across the globe:
(1) relatively standard aver- aging in grid boxes, and
(2) bayesian fitting of global spherical harmonics to the observational data.

Averaging in equal-angle grid boxes

In preparation for the Metop mission, we have studied the straight-forward method of averaging into equal-angle grid boxes. Simulated "observed" data can be obtained by sampling the ERA-40 reanalysis data set at the locations of simulated GRAS/Metop observations. Such "observed" monthly mean temperatures in 10x10 degree grid boxes (right figure below) can easily be compared to the corresponding "true" mean temperatures (left figure below).



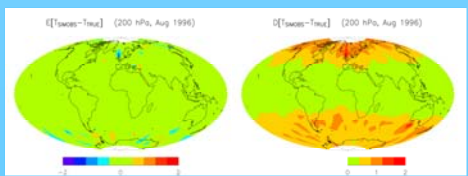
These simulated "observations" are ideal in the sense that there are no observational errors. The differences (shown below) between the two maps are entirely due to sampling effects.



For 10x10 degree grid boxes, the errors form elongated structures in the meriodional direction, indicating the need for grid boxes that cover larger longitude intervals.

Observational and sampling errors

There are two types of errors that need to be considered: *observational errors* and *sampling errors*. The observational errors include all differences – due to the instrument or due to the data processing – between the observed profiles and the truth. The truth is hidden to us, and all we can do is to investigate the inconsistencies between data sets, which may, or may not, indicate observational errors.



In the figures below we show a statistical comparison between observed data from the CHAMP satellite and model data taken from the same times and locations in ECMWF analysis fields; the tropics in the right and outside the tropics in the left panel. Apparently, the observational errors may vary, not only with height, but also with latitude. In climate studies, it is the biases or systematic errors that are the most important. Biases that vary over time may render the data useless for important climate studies, such as detection of climate trends.

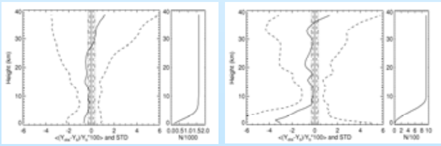


Figure: Mean and standard deviation of normalized differences between CHAMP RO data and model data, here ECMWF analysis data. The mean difference can be interpreted as an observational bias that strongly affects any derived climate data. Note the loss of observational data below 5 km (right panel) and the strong bias at low levels in the tropics.

Even though the GRAS/MetOp data have a good spatial coverage, the Sun-synchronous orbit of the Metop satellite gives a very uneven sampling in local time with related structures in universal time. In the plots below, we show the scatter of simulated GRAS/Metop observations for a full month. We find that over a broad mid-latitude interval, the climate system is only sampled at two local times whereas at high latitudes, either day-time or night-time observations tend to dominate.

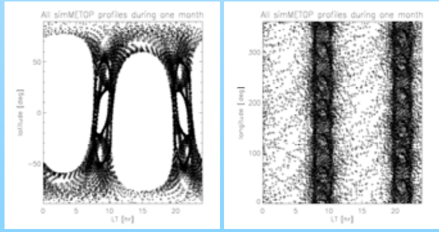


Figure: Scatter of simulated GRAS/Metop observations in local time, latitude (left panel) and longi-tude (right panel). These characteristics are typical for a satellite in a polar, Sun-synchronous orbit.

The effects of sampling on the observed RO based climate data may be simulated in the following way: we sample a model field at the same locations and times as a set of observed data, and compute an error field. By using model data from many years (many August months if we have observed data from August) we can now produce many errors fields from which biases and random errors can be estimated. The plots to the left show an example of realistic distributions of biases and random errors when averaging RO data in 10x10 degree grid boxes