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 6: Observed refractivity (or delay) vs. retrieved meteorological profiles

Because it is more closely connected to the measured delay, refractivity has some advantages over derived temperature and humidity profiles. But is refractivity itself a useful climate parameter to monitor? How would one use changes in refractivity as a climate indicator (e.g., indictor of what)? Do any other observing systems depend on precise refractivity data for calibration? Does a time series of refractivity tell us anything useful about the evolution of the climate system?

Answer by K. Trenberth:

Refractivity is similar to radiances used widely in NWP. Retrievals from radiances alone are no longer used although the MSU channels have been used as a satellite temperature, but with more uncertainty that using refractivity. I think the refractivity could become a benchmark temperature measurement when estimates of humidity from elsewhere are included above about 6 km. Below that level, the confounding influences of water vapor and its uncertainties make refractivity alone the useful quantity, but given that temperature and moisture are positively correlated, a useful index may emerge.

Answer by U. Foelsche:

Short Answer:

Refractivity itself is already a very useful parameter, since it is directly proportional to **density** in the upper troposphere and stratosphere (in the presence of significant amounts of atmospheric water vapor the relation is more complicated). Projected trends in **bending angle** are very similar to trends in refractivity (which is only a scaled representation of the index of refraction). As bending angle is even closer to the original measurement than refractivity, bending angle climatologies could be very useful. Bending angle (and refractivity) is expected to show significant changes in a changing climate, and the signal can be decomposed into contribution from changes in temperature, pressure, and humidity.

Nevertheless, derived parameters like temperature should not be completely disregarded. RO temperatures are, e.g., very accurate around the tropical tropopause and any potential influence from high altitude initialization or uncorrected ionospheric errors has vanished at these altitudes. Given the good height resolution of RO data, **temperature** climatologies can provide valuable insight in changes in tropopause height and temperature as well as in the transition region between tropospheric warming and stratospheric cooling.

Long Answer:

I have the impression that (microwave) refractivity is sometimes regarded as a very exotic parameter, which somehow depends on many atmospheric parameters. The important point is that refractivity is directly proportional to atmospheric **density** in the absence of significant amounts of water vapor. GNSS RO is therefore one of the very few methods that can provide accurate density information for the stratosphere.

$$\rho(z) = \frac{m_d}{R^* k_1} N(z) \;= b_1 N(z)\,, \tag{1}$$

where ρ is the air density, m_d is the molar masses of dry air, R^* is the universal gas constant, and k_1 is measured to be 77.6 K/hPa. The new constant b_1 is given by:

$$b_1 = \frac{m_d}{R^* k_1} = 4.4892 \cdot 10^{-3} \text{ kg/m}^3\,. \tag{2}$$

Note that k_1 can also be related to more fundamental physical constants (*Foelsche*, 1999):

$$k_1 = \frac{10^6 n_L T_0}{2\varepsilon_0 p_0} \overline{\alpha}\;, \tag{3}$$

where n_L is the *Loschmidt number* (n_L = 2.686 7627 · 10^{25} m^{-3}), p_0 is 1013.25 hPa, T_0 is 273.15 K, ε_0 is the *permittivity of vacuum* (ε_0 = 8.854 187 817 · 10^{-12} $\text{AsV}^{-1}\text{m}^{-1}$), and $\overline{\alpha}$ is the mean polarizability of dry air.

Also **bending angle**, which is even closer to the original measurement, is a useful climate indicator. This has recently been shown by *Ringer and Healy* (2008), using transient coupled model integrations of the Hadley Centre Global Environmental Model (HadGEM1) that follow the SRES A1B scenario. Under this scenario the global mean temperature increase by 2050, relative to the 1961-1990 mean, is approximately 2 K. Figures 1(c)-(f) show the evolution of the climate change signal in the zonal mean bending angle profiles from the present-day through to the 2050s. The signal in the tropical lower stratosphere emerges after a decade, is clearly identifiable by the 2020s and continues to intensify through to the 2050s. It is accompanied by a signal in the tropical mid-stratosphere which, though weaker initially, is of comparable size by the 2050s. The signals at polar latitudes in the mid-stratosphere are more variable over the first 20 – 30 years and are not clearly established until the 2040s. In the upper troposphere a signal of opposite sign emerges, the upper boundary of which follows the zonal variation of the height of the tropopause: this delineates the warming of the troposphere due to increased greenhouse gases from the cooling of the stratosphere. In the lower troposphere the increased water vapor as the climate warms dominates and the bending angle signal is positive.

Using a tangent linear version of the bending angle forward model, the authors have also identified the contributions to the bending angle signal from changes in temperature, pressure and humidity. The results for the 2050s are shown in Fig. 2. It can be seen that the total bending angle signal due to climate change can be neatly decomposed into components due to these different effects and results from their linear combination (cf. Figs. 2d and 1f, which indicates that we are within the linear regime with respect to perturbations considered here).

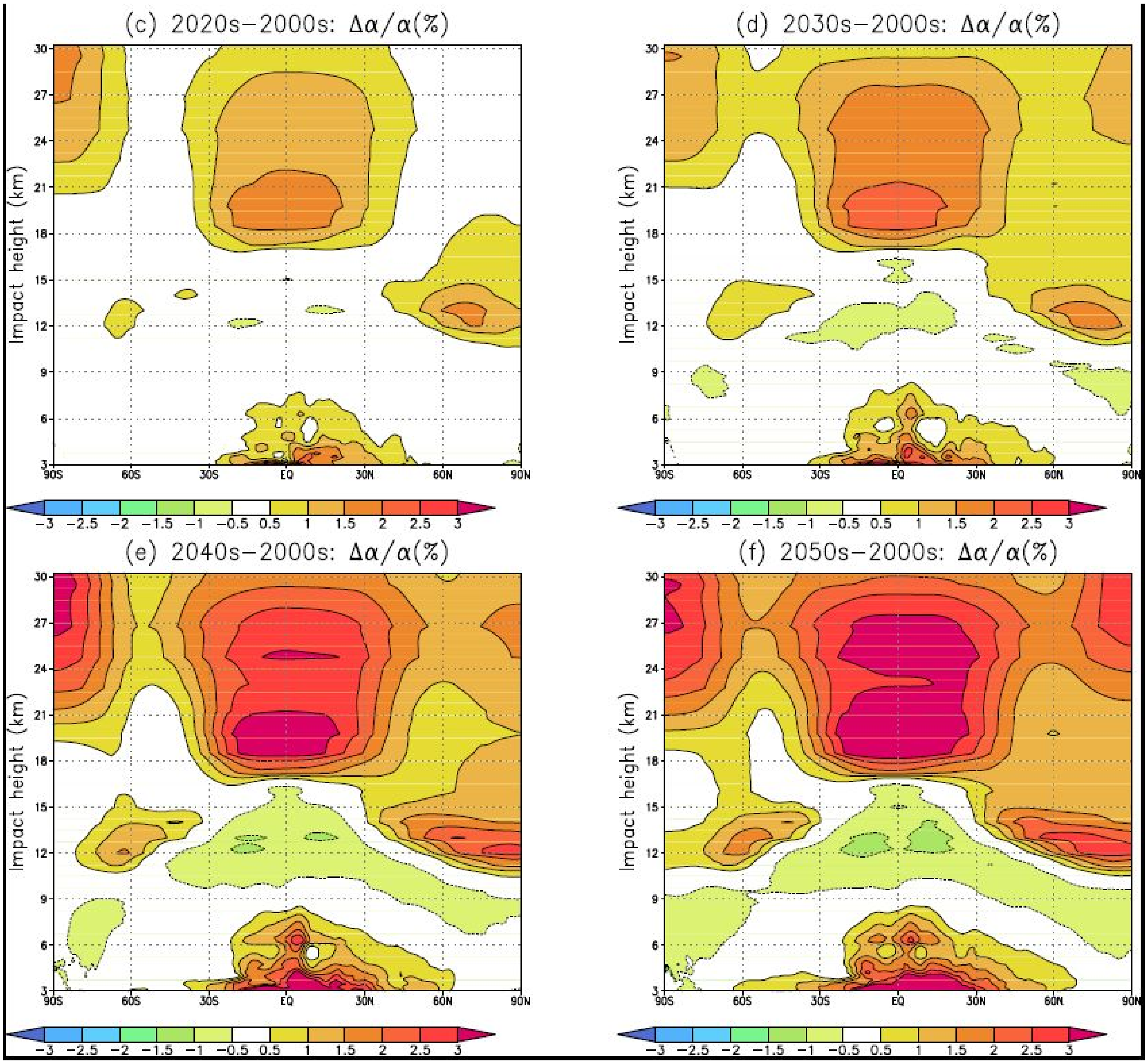

Figure 1 (c) – (f) Evolution of the annual mean bending angle climate change signal from the 2020s to 2050s relative to the 2000 – 2005 mean. The signal for the 2020s is the difference between the 2020 – 2025 mean minus the 2000 – 2005, etc. (From *Ringer and Healy* (2008, their Fig. 1))

Ringer and Healy (2008) found furthermore, that the climate change signal in the tropical upper troposphere and lower and middle stratosphere may become distinguishable from natural variability, i.e. “detected”, after approximately ten to sixteen years of measurements.

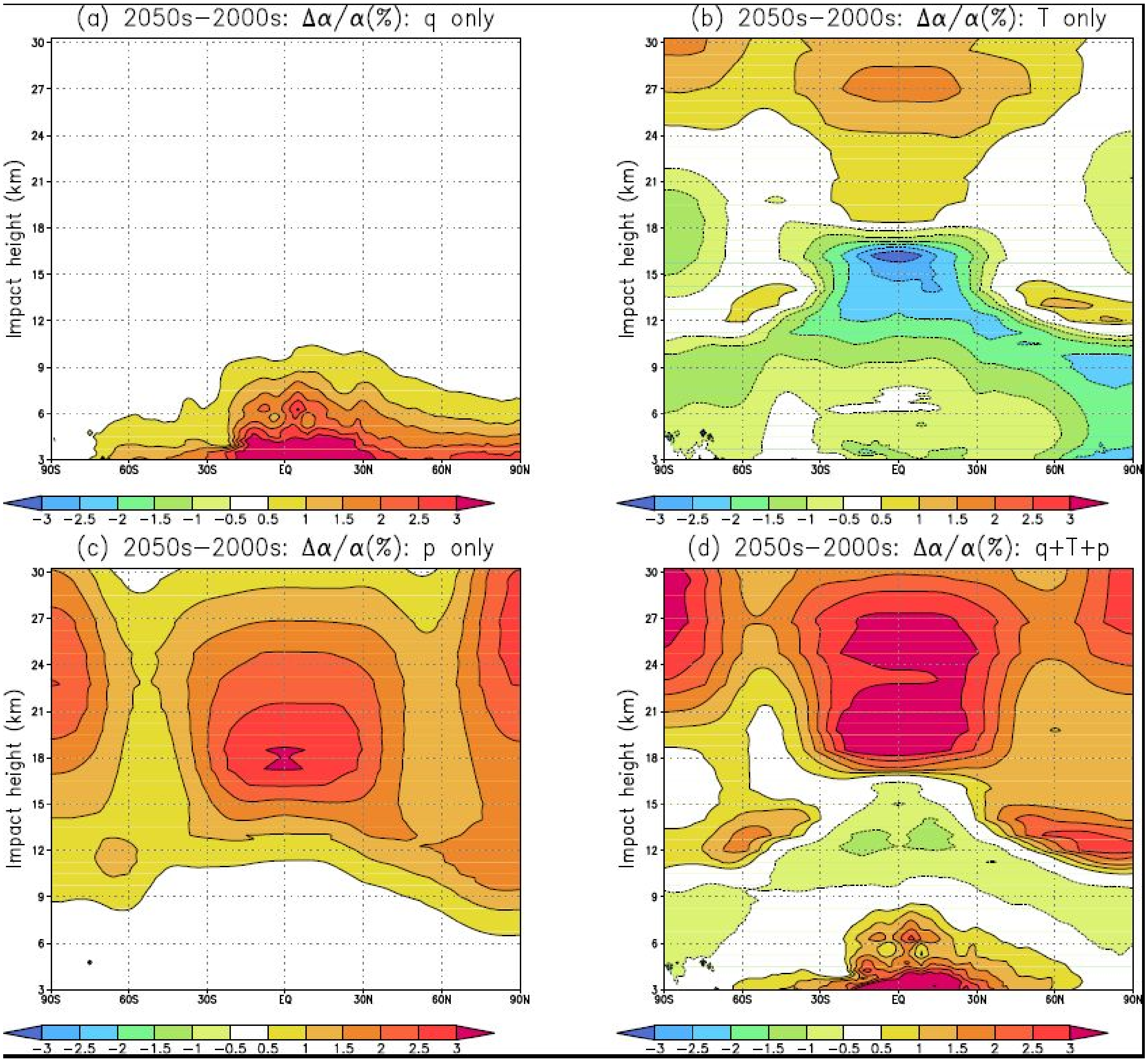

Figure 2 The contribution to the 2050s bending angle signal from (a) humidity, (b) temperature and (c) pressure and their sum (d) (From *Ringer and Healy* (2008), their Fig. 2).

Vedel and Stendel (2003) have identified **refractivity** as a useful parameter for climate monitoring. *Leroy et al*. (2006a; 2006b) have shown that **dry pressure** can be used for this purpose, the the strongest indicator of climate change being the poleward motion of the midlatitude jet. *Leroy* (1997) has analyzed **geopotential height**, where trends in geopotential heights have to be expected because of thermal expansion of the troposphere, a consequence of warming of the troposphere on global scales. (Note: I have not included more detailed results from Stephen Leroy, since he will attend the workshop himself).

We currently perform a large-scale climate observing system simulation experiment (OSSE) over a 25 year period, which aims at testing the climate trends detection capability of GNSS RO sensors. The setup and results from a testbed study, based on an example season, are presented in *Foelsche et al.* (2008a). For this purpose we used the ECHAM5 (European Centre/Hamburg Model) in Middle Atmosphere mode (MAECHAM5) with a resolution of T42L39. The highest of the 39 model levels is located at ~0.01 hPa or ~80 km. The underlying emission scenario is IS92a, which is characterized by comparatively high sulfur emissions and intermediate CO_2 emissions, leading to a projected atmospheric CO_2 concentration of about 700 ppm in 2100. The projection for the globally averaged surface temperature in 2100 is about 2.5 K above the 1990 value. The simulated changes in the neutral atmosphere can therefore be considered relatively conservative estimates of the future evolution.

Figure 3a shows the summer (JJA) **temperature** trends per decade for the geographic domain used in *Foelsche et al*. (2008a), on a 17 x 34 grid (17 equal area 10° latitude bins – 15° longitude at the Equator, 24 altitude levels). A salient feature, which is only partly visible in “normal” climate model runs with a vertical domain up to the 10 hPa level (30-35 km), is the pronounced cooling in the stratosphere. Given the accuracy of RO data in the lower stratosphere it is thus possible that “stratospheric cooling” will be the first consequence of anthropogenic climate change that can be detected with the aid of the RO technique. On the other hand, the largest positive temperature trends, with values up to 0.6 K per decade, are expected below the tropical tropopause, where favorably the RO errors are particularly small.

It is also very interesting to look at other climate variables that can be observed with the RO technique. Along this line, trends in pressure and microwave refractivity are shown in Figure 3b and 3c, respectively. Given the exponential decrease of both parameters with increasing height, and the large dynamic range of the absolute values, we inspect relative trends per decade in these cases (with the year 2001 taken as basis). Note that relative pressure trends are proportional to absolute geopotential height trends, where the proportionality factor is the local scale height (*Leroy et al*., 2006a; b). Thus Figure 3b represents also geopotential height trends. For example, the pressure trend of ~0.5%/decade near 12 km in the tropical upper troposphere (UT) implies a geopotential height trend of ~32 m/decade (assuming a scale height ~6.5 km), indicating that the 200 hPa pressure level is raised by this amount due to the warming of the tropical troposphere underneath.

When we compare the results for the three climate variables in Figure 3a-c, we see salient changes in each parameter, but in different parts of the latitude-height domain. For example in the low latitude UTLS, the largest positive temperature trend occurs near 15 km altitude, the largest relative pressure trend near 20 km, and the largest relative refractivity trend near 25 km, respectively. These trend behaviors are largely consistent with the ones shown by *Leroy et al.* (2006a) based on CMIP2+ (Coupled Model Intercomparison Project) models, and by *Leroy et al.* (2006b) based on IPCC Fourth Assessment Report (AR4) Models, respectively. Regarding the stratosphere above 30 km, the limitations of the CMIP2+ and IPCC AR4 model fields, top-limited by the 10 hPa level instead of the 0.01 hPa level of the fields here, are evident, however.

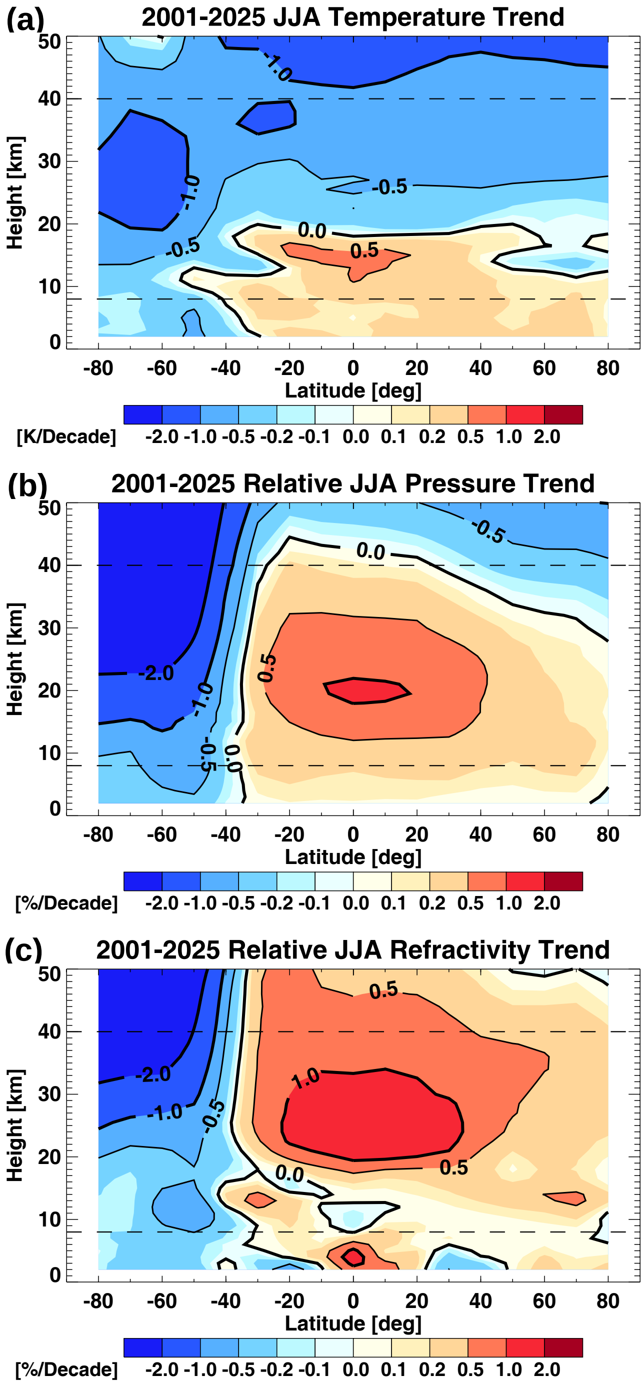

Figure 3 June-July-August (JJA) MAECHAM5 trend results for 2001-2025 (anthropogenically forced run): (a) temperature trend per decade, (b) relative pressure trend per decade, and (c) relative refractivity trend per decade (From *Foelsche et al*. (2008a), their Fig. 8).

An interesting feature of Figure 3c is the markedly small change in refractivity in the tropical UT (< 0.1–0.2%/decade). Microwave refractivity N is related to temperature T, total pressure p, and water vapor partial pressure e, via (*Smith and Weintraub*, 1953):

$$N \equiv 10^6 (n-1) = k_1 \frac{p}{T} + k_2 \frac{e}{T^2}, \qquad (4)$$

where n is the index of refraction, k_1 is 77.6 K/hPa, and k_2 is $3.73 \cdot 10^5$ K^2/hPa. When atmospheric humidity is small (valid at > 10 km), the second term on the right-hand-side of Eq. 4 can be disregarded. We immediately see that in this case the same relative increase in T and p, which is approximately true in the tropical UT, will result in no change in refractivity. The same applies for bending angle trends (c.f. Fig. 1).

The key message of Figure 3 is that different RO-accessible atmospheric parameters are sensitive in different regions of the atmosphere. RO based climate monitoring should therefore carefully exploit **all parameters** that can be retrieved with the RO technique in order to optimize sensitivity to climate change.

Temperatures are, e.g., very accurate around the tropical tropopause and any potential influence from high altitude initialization or uncorrected ionospheric errors has vanished at these altitudes. Given the good height resolution of RO data, **temperature** climatologies can provide valuable insight in changes in **tropopause** height and temperature (e.g. *Borsche et al*., 2007; *Foelsche et al*, 2008b) as well as in the transition region between tropospheric warming and stratospheric cooling.

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