ON THE DIRECT USE OF GNSS RO REFRACTIVITY MEASUREMENTS FOR CLIMATE MONITORING

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Abstract

By means of data from a climate model simulation we determine the expected change of the height of iso refractivity surfaces (and vice versa) in a situation with global warming. The outcome is compared to two traditional climate monitoring measures: temperature and height variations of isobaric surfaces.

We find that in the stratosphere the height of iso refractivity surfaces is slightly more sensitive to climate change than is the height of pressure surfaces. In the future GNSS RO observations will provide the necessary observations. Because spatial variations are smaller in the stratosphere than further down, fewer observations are needed in order to determine average global and regional properties with a given precision at these notoriously data sparse heights. An important benefit of using an intermediate GNSS RO (radio occultation) product like refractivity, rather than processing the GNSS RO data further into pressure/temperature/humidity profiles, is that the processing of the GNSS RO data becomes more robust, in the sense that it dependent less on auxiliary data and assumptions.

1. INTRODUCTION

GNSS RO measurements will provide high quality measurements of the atmosphere with good global coverage and high vertical resolution. Contrary to some of the currently most important satellite observations the long-time stability of the GNSS measurements is expected to be extremely good. The observations are related to key variables in meteorology and climate research: pressure, temperature and humidity.

However, a sequence of preprossessing steps are necessary to convert the raw data into temperature and humidity profiles. The processing involves assumptions and/or folding with other data, with the potential risk of decreasing the quality of the GNSS RO data and their independence from other data (which they could otherwise be used to validate). One may ask, therefore, whether it is beneficial in climate monitoring to use the GNSS RO measurements in a less processed form, and interpret the results by comparison with climate model simulations. At least as a supplement to the currently envisaged utilisation of the data in less abstract form.

Here we use the outcome of a climate model simulating a situation with future global warming to enlighten that. By means of the model data we study the sensitivity of the GNSS RO product refractivity versus height to global warming compared to the sensitivity of traditional measures, such as the temperature and geopotential height of isobaric surfaces. The use of climate model data for estimation of the expected changes in GNSS RO measurements due to climate change was pioneered by Yuan et al. (1993). The present work takes advantage of the huge improvements of the climate models over the period, enabling us to perform a much more detailed analysis, including local and inter-annual variations.

2. RELATING GNSS RO REFRACTIVITY VERSUS HEIGHT TO METEOROLOGY

Based on an assumption about the atmosphere being spherically symmetric locally the GNSS RO bending angle product can be processed into a profile of refractivity versus impact parameter (see e.g. Meincke (1999)), which can be further processed into a profile of refractivity versus geometric height, z, at the point where the GNSS signal were closest to the surface of earth. In meteorology the most common height measure is geopotential height, h, which is related to the common meteorological variables through,

$$\frac{1}{g_0} R_d T (1 + q(1/\epsilon - 1)) \delta \ln p = - \delta h = - \frac{g}{g_0} \delta z, \quad (1)$$

where p is pressure, T is temperature, q is specific humidity, ϵ is the ratio of the molecular mass of water vapour to that of dry air and R_d is the gas constant for dry air. g is the local acceleration due to gravity and non–inertial forces upon a particle at rest, g_0 is a constant. The model implementation of geopotential height differs slightly from the above textbook definition, and is model dependent. However, it is straight forward to convert from one of the involved height systems to the other (e.g. Vedel (2000)).

Refractivity itself is related to meteorological variables through an empirical relation, Bevis et al. (1994),

$$N = \frac{p}{T}\ \frac{1}{1+q(1/\epsilon - 1)}(k_1 + \frac{q}{\epsilon}(k_2 - k_1/\epsilon + \frac{k_3}{T})), \quad (2)$$

3. MODEL DATA AND ANALYSIS

The climate data come from a simulation performed with a state of the art coupled atmosphere-ocean general circulation model (AOGCM). The atmospheric part of it is ECHAM4. 19 hybrid sigma-pressure levels are used in the vertical, with the upper level at 10 hPa, the horizontal resolution is approximately 300 km. The ocean model is an extended version of the OPYC model, consisting of three sub-models: One for the interior ocean, one for the surface mixed layer, and one for the sea-ice. The ocean model has 11 layers, the horizontal resolution corresponds approximately to that of the atmospheric model. The two components are quasi-synchronously coupled and exchange information once a day. The simulation was performed using the SRES marker scenario A2 for the level of future emissions. See Stendel et al. (2000) and references therein for more details.

The simulation covers 110 year of climate evolution. We compare data from the first 10 years, which we take to represent "current" climate, and the last 10 years, which we take to represent "future" climate. For each variable to be analysed we calculate the annual and seasonal means at 7 pressure levels between 850 and 30 hPa, at the geopotential heights between 2.5 and 22.5 km at 2.5 km steps, and at the refractivity levels: 200, 150, 100, 80, 60, 40, 30, 20, and 15 $[10^{-6}]$. Then the 10 year means and standard deviations are calculated separately for the first ten and the last ten years, and differences are deduced, as future minus current, in order to see the effects of climate change upon the variables.

4. RESULTS

Figures 1 and 2 show the expected evolution of the global means of temperature and geopotential height at isobaric surfaces. Figure 3 shows the behaviour of the global mean of the refractivity at iso height surfaces, whereas figure 4 shows the behaviour of the global means of geopotential height at iso refractivity surfaces. The local behaviour of the refractivity at iso height surfaces is shown in figures 5 and 6 for the 5 and 20 km levels, respectively.

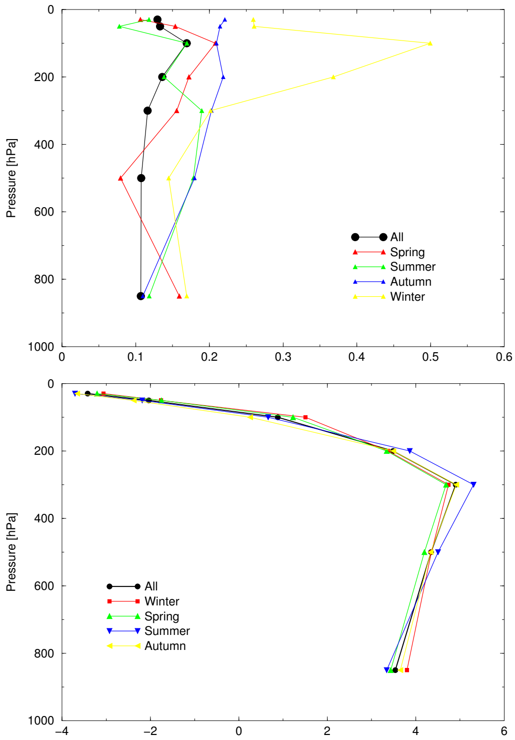

Figure 1. Annual and seasonal global mean temperature versus pressure. Top: Inter–annual variation. Bottom: Climate evolution. In units of K and hPa.

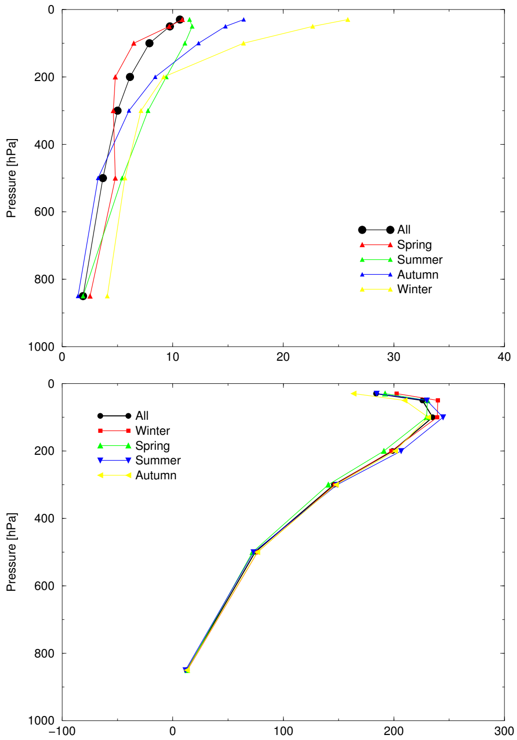

Figure 2. Annual and seasonal global mean geopotential height versus pressure. Top: Inter–annual variation. Bottom: Climate evolution. In units of m and hPa.

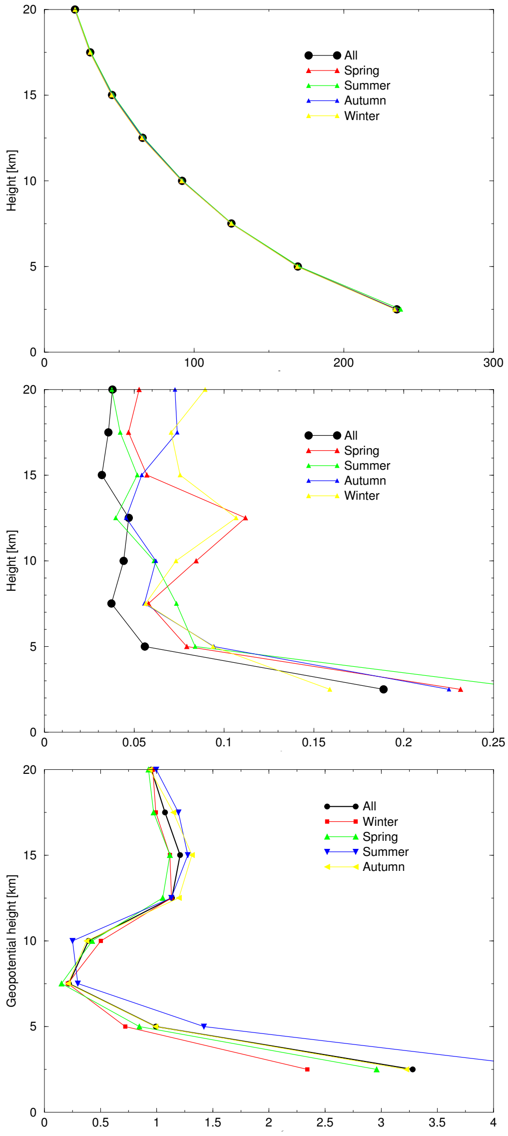

Figure 3. Top: Annual and seasonal global mean refractivity of iso geopotential height surfaces. Middle: Inter–annual variation. Bottom: Climate evolution. In units of 10^{-6} *and km.*

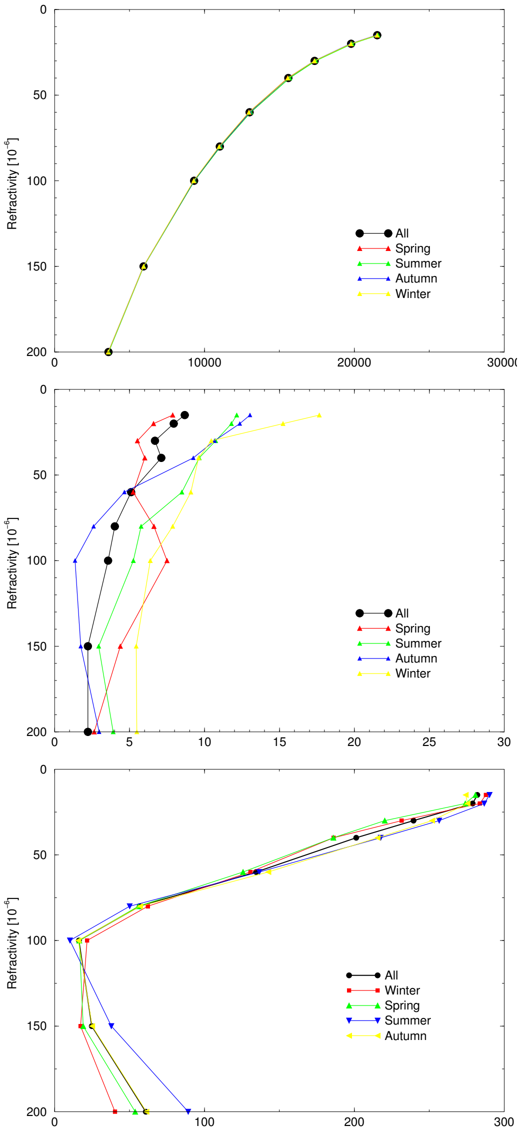

Figure 4. Top: Annual and seasonal global mean geopotential height at iso refractivity surfaces. Middle: Inter–annual variation. Bottom: Climate evolution. In units of m and 10^{-6}

5. DISCUSSION

From Fig. 2 it is clear that the geopotential height of pressure surfaces near the tropopause is a measure well suited for climate monitoring. Unfortunately a solid record of observations is not currently available. GNSS RO observations can be used to provide that, Leroy (1997), by converting the refractivity profiles into profiles of temperature and pressure. That requires an assumption about a boundary condition in the high atmosphere and neglection of humidity.

Our findings for the expected change in refractivity as function of height, Fig. 3, corresponds well to the results found by Yuan et al. (1993). Our expectation for the change in refractivity is slightly larger in the stratosphere, but given the evolution of the climate models the level of agreement is very encouraging. It indicates the results found are robust, which is important when using climate simulation data as input.

From figure 4 one sees that in the stratosphere the heights of refractivity surfaces are apparently even more sensitive to climate change than is the heights of isobaric surfaces. There is a partly theoretical explanation for that: At all levels the heights of isobaric surfaces are increased in response to global warming (Fig. 2) , even in the stratosphere. Specific humidity decreases with height; consider a level above which humidity is negligible to the refractivity, which will be somewhere in the low stratosphere. A decrease in temperature will lead to an increase in refractivity (Eq. 2). The temperature decreases in the stratosphere, the decrease is increasing upward (Fig. 1). To stay on an iso refractivity surface rather than an isobaric surface one therefore has to move even further up in case of global warming, resulting in a

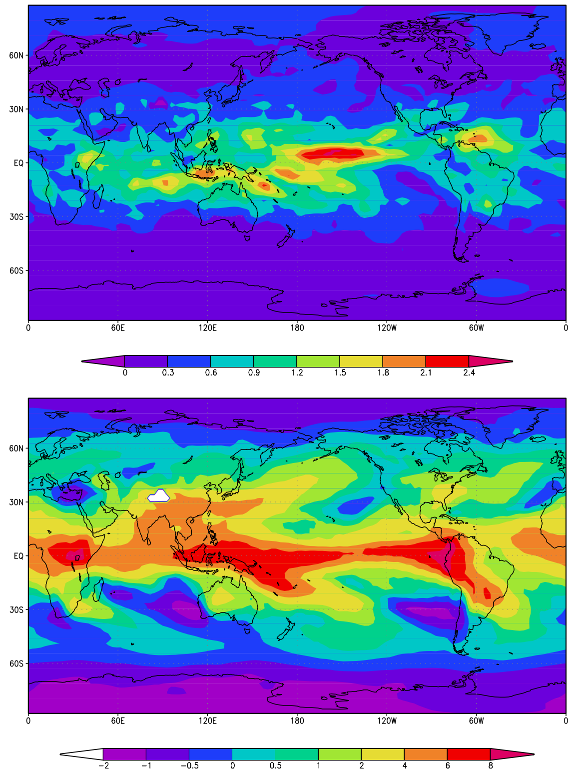

Figure 5. Refractivity at the 5 km surface. Top: Inter–annual variation. Bottom: Climate evolution. Units are 10^{-6}.

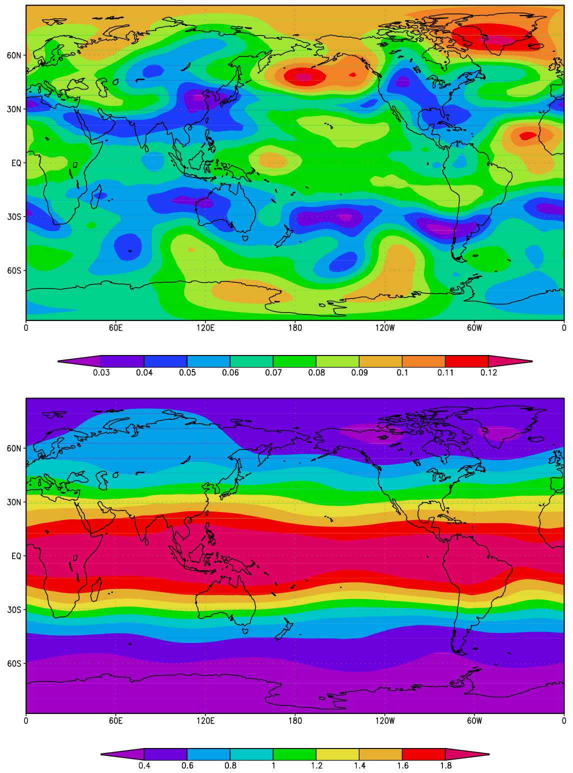

Figure 6. Refractivity at the 20 km surface. Top: Inter–annual variation. Bottom: Climate evolution. Units are 10^{-6}.

larger height increment in this region of the atmosphere.

In the stratosphere the spatial scales for variations are larger than in the troposphere. Fewer observations are necessary in order to determine reliable mean properties. However, from Fig. 6 one sees that the climate induced variation becomes larger toward equator, whereas the inter–annual variations, against which the climate signal must be identified, are largest toward the poles. It may therefore be optimal to use a coarse grained regional analysis for climate monitoring. Further work is needed to enlighten that.

In the troposphere the behaviour of refractivity is much more complex, due to the strong dependence of humidity (Fig. 5). The sign of the climate induced evolution change with latitude, being positive near equator and negative toward the poles.

A more extensive presentation and discussion of the results presented here have been submitted to a scientific journal.

6. CONCLUSION

We have found that refractivity does change as function of climate, and that the level of change makes the use of refractivity as function of height highly useful for monitoring climate change. Direct use of refractivities avoid the temperature/humidity decoupling problem, yielding a relatively robust method, independent from other atmospheric data.

In the stratosphere the height of iso refractivity surfaces is found to increase systematically in response to global warming. The inter-annual variability is relatively low at these levels. In the high part of the model atmosphere our analysis indicates that refractivity is even better suited than pressure as a reference surface for height. A theoretical argument in support of that is given in the discussion. This makes the use of height versus refractivity very promising in the stratosphere. Further adding to this is the fact that in the upper atmosphere the spatial variations are smaller than in the low atmosphere. Thus, besides the sensitivity being larger, fewer observations are needed to determine from observations a mean global (or regional) value with a given precision.

In the mid and low troposphere the time evolution of refractivity varies significantly with latitude. Use of refractivity for climate change monitoring in this volume therefore requires regional analysis rather than global, but may still be useful in certain latitude belts.

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