6.2 Climate Change Monitoring by Radio Occultation: From Simulation Studies via CHAMP to COSMIC and ACE+ Constellations

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1. Introduction

The monitoring of climate change, especially of atmospheric change, over the coming decades is highly relevant in view of concerns that the evolution of the Earth's climate system is increasingly influenced by human activities (e.g., IPCC 2001). Considerable efforts are thus currently invested into the setup of a Global Climate Observing System (GCOS), which shall enable significant advances in understanding and predicting climate variability and in detecting anthropogenic climate influences (e.g., GCOS 2001).

A very promising observing system in this context is a suite of spaceborne Global Navigation Satellite System (GNSS) and Low Earth Orbit cross-link (LEO-LEO) radio occultation sensors. Such a system holds potential to become a leading backbone of GCOS for global long-term monitoring of atmospheric change in temperature and other variables with unprecedented accuracy.

The radio occultation (RO) technique is an active limb sounding technique exploiting trans-atmospheric satellite-to-satellite radio links. The method became feasible around 1990 due to the availability of the GNSS with its high-precision L band navigation signals near 1.6 GHz (L1) and 1.2 GHz (L2), respectively (e.g., Gurvich and Krasil'nikova 1990; Ware et al. 1996). The GNSS presently comprises the U.S. GPS (nominally 24 sats) and the Russian GLONASS (24 sats, currently not fully operational). The European system GALILEO (30 sats) is currently under development with full operational status scheduled from 2008 onwards. With these over 50 transmitters well over 1000 occultation profiles can be acquired per day by a single GNSS receiver.

The principal observable of the GNSS RO technique, measured with millimetric precision by a receiver in LEO, is the phase path delay (relative to the straight-line path in vacuum) of the GNSS-transmitted radio signals caused by refraction during passage through the atmosphere in occultation geometry (e.g., Kursinski et al. 1997). The LEO-LEO technique, where radio signals transmitted from other LEO satellites are received, delivers precise amplitude as another key observable. In this way, RO sensors probe refractive and absorptive properties of the atmosphere and profiles of associated fundamental atmospheric variables such as temperature and humidity can be retrieved with high quality (e.g., Steiner et al. 1999; Kursinski et al. 2002).

Despite the (often quoted) promise, the climate change monitoring utility of an RO observing system has not yet been tested nor exploited in any thorough quantitative manner. Main reasons for this are certainly the complexity of the issue and the still very marginal amount of real data for such studies.

In order to help overcome this lack of rigorous efforts, several relevant projects have been started within the IGAM/Univ. of Graz in recent years, in cooperation with various international partners. This paper focuses on these activities which range from simulation studies via climate exploitation of CHAMP RO data to preparations for future constellation observing systems such as the GPS RO mission COSMIC (Lee et al. 2001) and the GNSS- and LEO-LEO RO mission ACE+ (Hoeg and Kirchengast 2002).

After recalling the promise and summarizing the importance of RO data for climate monitoring (section 2), we address in particular an on-going simulation study on the climate trend detection capability of a small suite of GNSS RO sensors (section 3), the current setup of a prototype climate monitoring system based on the continuous CHAMP RO data flow (section 4), and status and main aims of the ACE+ mission (section 5). Concluding remarks (section 6) finally again highlight the overall aim and relevance of building a reliable RO based climate monitoring system within this decade.

2. Climate Change Monitoring Promise

The recent report of the Intergovernmental Panel on Climate Change (IPCC 2001) noted in the "Summary for Policymakers of Working Group I" among the top future priority areas for action: "sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data including implementation of a strategy for integrated global observations" (IPCC-SPM-WGI 2001, p. 17).

Such accurate, long-term, consistent data on the fundamental atmospheric variables temperature (T), humidity (q), and geopotential height can be adequately furnished by a suite of LEO satellites carrying GNSS- and LEO-LEO RO instrumentation. The reason is that RO sounding delivers an unique combination of

- global coverage (equal observation density above oceans as above land),
- all-weather capability (virtual insensitivity to clouds and aerosols due to long wavelengths > 1 cm),
- high accuracy and vertical resolution (e.g., T < 1 K, q < 5% at ~1 km resolution),
- and long-term stability due to intrinsic self-calibration (T drifts < 0.1 K, q drifts < 2%r.h. per decade).

Especially important for climate change monitoring is the self-calibration property (use only of a time-standard reference and of normalized amplitudes), which enables unprecedented long-term stability and smallness of biases in climate datasets. Such datasets can be built from RO data from different satellites and times without inter-calibration efforts.

Given their unique properties, it is fair to expect that RO data can reveal the climate evolution of the atmosphere with an accuracy and consistency never seen before. The nearly unbiased climatologies can, for example, serve as rigorous reference datasets to elucidate weaknesses in climate model physics and forcing formulations or act as powerful observational constraints in climate change detection and attribution schemes.

3. Climate Monitoring Simulation Study

In order to investigate the climate change detection capability of GNSS RO sensors, we are currently performing an end-to-end observing system simulation study over the 25-year period 2001 to 2025. The study involves in a realistic manner all aspects from modeling the atmosphere via generating a significant set of simulated measurements to a statistical analysis and assessment of 2001-2025 climatic trends. Specifically, the study involves five main parts of work as follows:

- Realistic modeling of the neutral atmosphere and the ionosphere over the time period 2001 to 2025.
- Realistic simulations of occultation observables for a small GNSS receiver constellation (6 satellites) for the same time period.
- State-of-the-art data processing for temperature profile retrieval in the troposphere and stratosphere to establish a sufficient database.
- Objective statistical analysis of temperature trends in the “measured” climatology (from the database of simulated RO data) and the “true” climatology (from the model atmosphere).
- Assessment of how well a GNSS RO observing system might be able to detect climatic trends in the atmosphere over the coming two decades.

A detailed description of rationale and design of the study has been given by Steiner et al. (2001), following an introductory description by Kirchengast et al. (2000). Recent results from a meanwhile completed “test-bed” performance analysis on a single year are reported by Foelsche et al. (2002). Figure 1 shows a result of the analysis, comparing errors in a single-season field to climate-model predicted trends. The result indicates that temperature trends expected over the next 20 years have a good chance to be detected with a small suite of GNSS RO sensors in large portions of the atmosphere provided the good performance seen for the “test-bed” year basically holds over the entire 25 year period.

Towards the full 25-year simulation, two dedicated 30-year climate model runs with the new ECHAM5 model of the MPI for Meteorology, Hamburg, have been recently completed; one with anthropogenic forcing by greenhouse gases, aerosols, and ozone, the other being a control run. As a novelty in climate simulations, the modeling domain extended up to the mesopause (0.01 hPa), which is important for use in the present study. Current work focuses on the realistic simulation of the GNSS RO observables for the full 25 years based on this climate model output and on preparation of the statistical analysis and assessment.

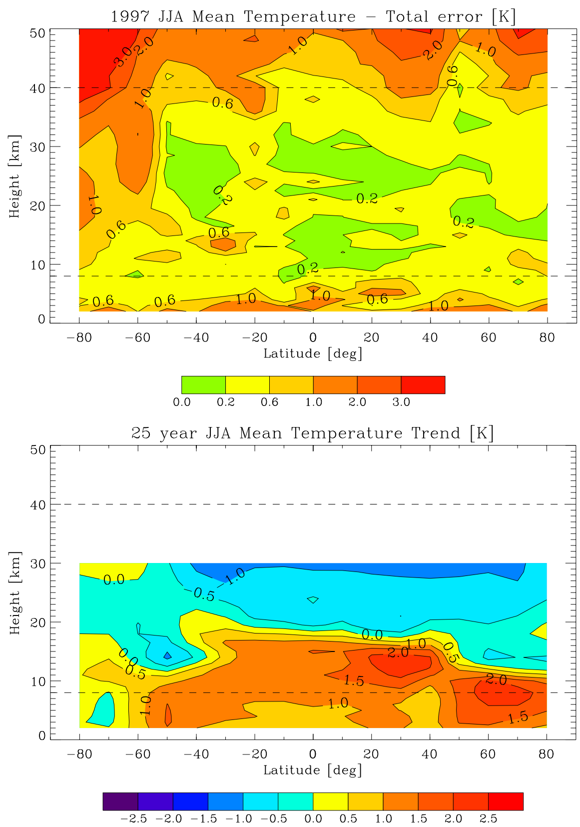

Figure 1. Upper panel: “Test-bed” result, based on ~1000 RO events per season, for the total climatological error (observational error plus error due to spatio-temporal undersampling) in average JJA temperatures in 17 equal-area latitude bins of 10 deg width (15 deg longitude width at equator). Lower panel: 2001-2025 average JJA temperature trends in the same bins based on the ECHAM4 T42L19 GSDIO climate simulation by Roeckner et al. (1999) including transient anthropogenic forcings due to greenhouse gases, aerosols, and tropospheric ozone.

4. Climate Monitoring Based on CHAMP

Over the last years, GNSS RO data processing algorithms have seen significant advancements. While improvement potential still exists both in the troposphere (e.g., via improved tracking concepts and wave optics algorithms) and the stratosphere (e.g., via improved statistical optimization and ionospheric correction), the processing is now sufficiently advanced to start large-scale climatological exploitation of real data. Further algorithmic improvements focused on minimizing biases for optimizing the climate utility of the data need still be performed in parallel, however.

On availability of real data, the German CHAMP (Challenging Minisatellite Payload) GPS experiment, illustrated in Figure 2, delivers GPS RO data of high quality and is the first RO mission, and presently the only one, measuring on a continuous basis (for more details see, e.g., Wickert et al. 2001). Although being a single satellite only, CHAMP thus provides the very first opportunity to create real RO based climatologies.

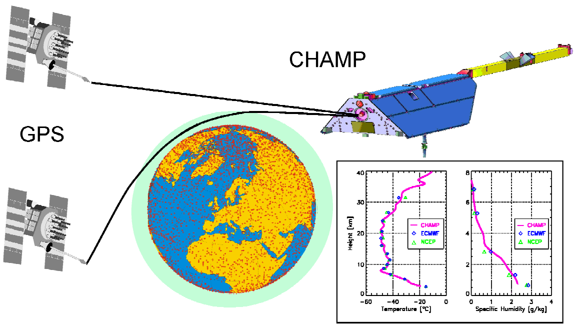

Figure 2. Schematic view of the CHAMP RO experiment and indication of the temperature and humidity retrieval performance (lower-right inset) based on an occultation event from the very first measurement day on February 11, 2001 (graphics: J. Wickert/GFZ Potsdam).

In a recently started project, involving the GFZ Potsdam as main partner, we will use the complete CHAMP GPS RO data flow (nominally > 200 events/day) for month-to-month, season-to-season, and year-to-year climate variability and change monitoring in 2 ways:

- *Model-independent RO-based climatologies.* Direct monitoring of the evolution of climatological temperature, geopotential height, and humidity fields. Both the data processing and the statistical binning and analysis techniques directly utilize the experience and heritage of tools available from the simulation study described in section 3.
- *Climate analyses from assimilation of RO data into ECMWF fields.* Optimal fusion of CHAMP RO data and averaged ECMWF analyses into global climate analyses by 3DVAR assimilation. A dedicated assimilation scheme is developed for this purpose tuned for the high-vertical/low-horizontal resolution analyses foreseen (~T21L60 resolution).

These types of RO climatologies will be a valuable complement to full-fledged climate re-analysis products planned to be generated based on a blend of many observational sources by major meteorological centers (e.g., the ECMWF, as a European example). Mutual validation of the RO climatologies with the re-analyses of such centers will be possible and useful.

Results from initial work on the project, mainly addressing sampling issues and the temperature field, are reported by Foelsche et al. (2002). They indicate that reliable global temperature climatologies can be achieved already with the single CHAMP satellite for season-to-season monitoring at a horizontal resolution scale of > 1000 km (i.e., for large-scale monitoring).

5. ACE+ Atmosphere and Climate Mission

The European Space Agency (ESA) has recently, in May 2002, selected the Atmosphere and Climate Explorer (ACE+) RO mission as its top priority out of 25 proposed ESA Earth Explorer Opportunity Missions, which had addressed all areas of Earth system science.

Detailed information on ACE+ is available via the mission proposal by Hoeg and Kirchengast (2002). Briefly, the ACE+ constellation of four LEO satellites utilises GPS, GALILEO, and LEO-LEO signals for RO sounding of key variables such as temperature and, in particular, humidity. ACE+ will acquire about 5000 GNSS RO soundings per day and demonstrate the novel LEO-LEO concept by about 230 LEO RO soundings per day. ACE+ development is scheduled to last until 2007, with launches 2007/08 followed by a 5 years operational phase. Full implementation will be confirmed after a year of Phase A study in 2002/03 during which no serious issues are expected due to the maturity of the mission.

The climate-related mission goals of ACE+ include:

- to monitor climatic variations and trends at different vertical levels and throughout all seasons. This to improve our understanding of the climate system as well as to detect the different fingerprints of global warming;
- to improve the understanding of climatic feedbacks defining the magnitude and characteristics of climate changes in response to given forcings;
- to validate the simulated mean climate and its variability in global climate models;
- to improve and tune – via data assimilation – the parameterization of unresolved processes in climate models and to detect variations in external forcing of climate.

A series of more direct observational objectives is associated with these goals. In addition, further important goals relate to numerical weather prediction, atmospheric processes research, and space weather (for details see Hoeg and Kirchengast 2002).

The key innovation compared to similar (earlier) missions such as COSMIC is the novel use of GALILEO and LEO-LEO signals. Especially the LEO-LEO signals placed at 3 frequencies within 10 – 23 GHz, from center to wing of the 22 GHz water vapor absorption line, will for the first time allow RO measurements of humidity without temperature-humidity ambiguity and up through the full troposphere.

From a climate research point of view the particular strength to provide highly accurate upper troposphere humidity (UTH) profiles is especially intriguing. Figure 3, showing a result of retrieval error estimates (from Hoeg and Kirchengast 2002), indicates that the expected UTH accuracy is better than 5% in specific humidity.

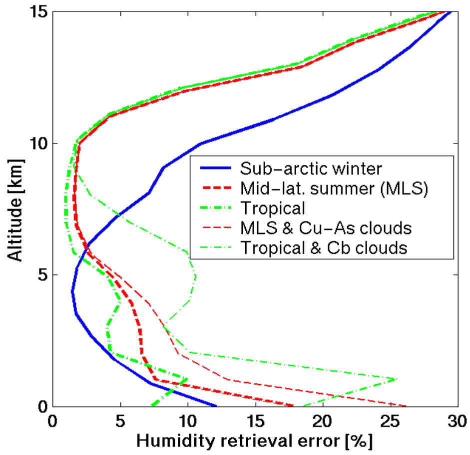

Figure 3. Specific humidity retrieval errors obtained for realistically simulated LEO-LEO RO measurements (adopted measurement noise and gain drift consistent with the ACE+ LEO-LEO RO sensor specifications). Several cases based on different standard atmosphere profiles and different cloud conditions are shown; the vertical resolution involved (estimated via "averaging kernel width" and "Backus-Gilbert spread") is ~1 km.

6. Concluding Remarks

RO sounding of the Earth's atmosphere has seen impressive advances since the launch of the "proof-of-concept" mission GPS/MET in 1995. With the CHAMP mission in orbit, the first GPS RO experiment is now delivering RO data on a continuous multi-year basis. Other missions like GRACE and the European GRAS on METOP, and in particular the COSMIC constellation, will heavily extend this dataset in the coming years. The start of also exploiting GALILEO and LEO-LEO RO sounding with the ACE+ mission from 2008 onwards will be a further key milestone.

These encouraging boundary conditions underpin the importance of efforts to gradually build up a reliable RO based climate monitoring system over the next years. While considerable challenges are still to be mastered, chances are fair that the promise of RO observing systems to become a leading backbone of GCOS for atmospheric climate change monitoring is redeemed within this decade.

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