Atmospheric Climate Monitoring and Change Detection using GPS Radio Occultation Records

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Kumulative Habilitationsschrift
Juni 2012

Kurzzusammenfassung

Abstract

Observations for atmospheric climate monitoring and change detection have to meet stringent quality requirements. Conventional observations from weather satellites and balloons have several shortcomings since they were originally not intended to serve climate monitoring needs. Radio Occultation (RO) based on Global Positioning System (GPS) signals provides measurements of long-term stability with beneficial characteristics in the upper troposphere and lower stratosphere (UTLS).

This "Habilitation Thesis" includes eighteen publications on my contributions to the field of atmospheric climate monitoring and change detection with GPS RO during the recent years. The introduction gives an overview on the main topics where I have significantly contributed, comprising the error characterization of RO data, the structural uncertainty of atmospheric climate data sets, and the detection of climate change based on RO records.

Precise knowledge of errors is an important prerequisite for the utilization of data in atmospheric and climate studies. We provided observational error estimates for individual atmospheric profiles based on simulated **[S01]** and observed RO data **[S02]**. We developed a simple analytical error model and enhanced it **[S03]**. For RO-based climatological fields **[S04]** we quantified the total error budget including statistical error, (residual) sampling error, and systematic error **[S05]**. Climatologies from different RO missions were found highly consistent to combine it to a single record, which is a key property of climate benchmark data.

Another feature is the knowledge of structural uncertainty in a record arising from different processing schemes. An assessment of lower stratospheric temperature records from different observation systems, (Advanced) Microwave Sounding Unit ((A)MSU), radiosondes, and RO **[S06]**, and analysis of error sources **[S07]** revealed a statistically significant trend difference between (A)MSU and RO **[S08]**. The high quality of RO and the good agreement with radiosondes indicated that these differences are not caused by RO. Structural uncertainty was quantified for the RO record from main processing centers, first for refractivity **[S09]**, then for all variables based on individual profiles **[S10]** and gridded climatological fields **[S11]**. Structural uncertainty in trends was found lowest within 50°S and 50°N from 8 km to 25 km meeting the stability requirements of the Global Climate Observing System (GCOS).

The capability of RO for climate change monitoring was tested with observing system simulation experiments **[S12]** inferring that RO is of high value for climate studies **[S13]**. Exploration of climate data sets with interactive visualization revealed parameters and regions reacting sensitive to climate change **[S14]**. Statistical analysis showed that RO parameters cover the whole UTLS with complementary indicators of climate change **[S15]**. The utility of RO for climate change detection was demonstrated in a first study **[S16]** and investigated in detail **[S17]**. An emerging climate change signal was detected for geopotential height and temperature, reflecting warming of the troposphere and cooling of the lower stratosphere. Though current use for climate trend assessment is bound to 50°S to 50°N, the quality, consistency, and reproducibility of RO data was found favorable for use in climate monitoring and change detection **[S18]**, and for becoming a climate benchmark record.

A.2 List of Selected Papers

A.2.1 Error Characterization of RO Data

Error Characterization of RO Profiles

[S01] **Steiner, A. K.**, and G. Kirchengast (2005), Error analysis for GNSS radio occultation data based on ensembles of profiles from end-to-end simulations, *J. Geophys. Res.*, *110*, doi:10.1029/2004JD005251. (21 pp)

[S02] **Steiner, A. K.**, A. Löscher, and G. Kirchengast (2006), Error characteristics of refractivity profiles retrieved from CHAMP radio occultation data, in *Atmosphere and Climate – Studies by Occultation Methods*, U. Foelsche, G. Kirchengast, and A. K. Steiner (Eds.), Springer, Berlin-Heidelberg, 27–36, doi:10.1007/3-540-34121-8_3. (10 pp)

[S03] Scherllin-Pirscher, B., **A. K. Steiner**, G. Kirchengast, Y.-H. Kuo, and U. Foelsche (2011), Empirical analysis and modeling of errors of atmospheric profiles from GPS radio occultation, *Atmos. Meas. Tech.*, *4*, 1875–1890, doi:10.5194/amt-4-1875-2011. (16 pp)

Error Characterization of RO Climatological Fields

[S04] Foelsche, U., M. Borsche, **A. K. Steiner**, A. Gobiet, B. Pirscher, G. Kirchengast, J. Wickert, and T. Schmidt (2008), Observing upper troposphere–lower stratosphere climate with radio occultation data from the CHAMP satellite, *Clim. Dyn.*, *31*, 49–65, doi:10.1007/s00382-007-0337-7 (published online: 2007, appeared in print: 2008). (17 pp)

[S05] Scherllin-Pirscher, B., G. Kirchengast, **A. K. Steiner**, Y.-H. Kuo, and U. Foelsche (2011), Quantifying uncertainty in climatological fields from GPS radio occultation: An empirical-analytical error model, *Atmos. Meas. Tech.*, *4*, 2019–2034, doi:10.5194/amt-4-2019-2011. (16 pp)

A.2.2 Structural Uncertainty of Atmospheric Climate Records

Structural Uncertainty of Temperature Records from Different Observations

[S06] **Steiner, A. K.**, G. Kirchengast, M. Borsche, U. Foelsche, and T. Schoengassner (2007), A multi-year comparison of lower stratospheric temperatures from CHAMP radio occultation data with MSU/AMSU records, *J. Geophys. Res.*, *112*, D22110, doi:10.1029/2006JD008283. (14 pp)

[S07] **Steiner, A. K.**, G. Kirchengast, M. Borsche, and U. Foelsche (2009), Lower stratospheric temperatures from CHAMP RO compared to MSU/AMSU records: An analysis of error sources, in *New Horizons in Occultation Research: Studies in Atmosphere and Climate*, A. K. Steiner, B. Pirscher, U. Foelsche, and G. Kirchengast (Eds.), Springer, Berlin, Heidelberg, 219–234, doi:10.1007/978-3-642-00321-9_18. (16 pp)

[S08] Ladstädter, F., **A. K. Steiner**, U. Foelsche, L. Haimberger, C. Tavolato, and G. Kirchengast (2011), An assessment of differences in lower stratospheric temperature records from (A)MSU, radiosondes, and GPS radio occultation, *Atmos. Meas. Tech.*, *4*, 1965–1977, doi:10.5194/amt-4-1965-2011. (13 pp)

Structural Uncertainty of RO Climate Records from Different Data Centers

[S09] Ho, S.-P., G. Kirchengast, S. Leroy, J. Wickert, T. Mannucci, **A. K. Steiner**, D. Hunt, W. Schreiner, S. V. Sokolovskiy, C. O. Ao, M. Borsche, A. von Engeln, U. Foelsche, S. Heise, B. Iijima, Y.-H. Kuo, E. R. Kursinski, B. Pirscher, M. Ringer, C. Rocken, and T. Schmidt (2009), Estimating the uncertainty of using GPS radio occultation data for climate monitoring: Inter-comparison of CHAMP refractivity climate records 2002 to 2006 from different data centers, *J. Geophys. Res.*, *114*, D23107, doi:10.1029/2009JD011969. (20 pp)

[S10] **Steiner, A. K.**, D. Hunt, S.-P. Ho, G. Kirchengast, A. J. Mannucci, B. Scherllin-Pirscher, H. Gleisner, A. von Engeln, T. Schmidt, C. Ao, S. S. Leroy, E. R. Kursinski, U. Foelsche, M. Gorbunov, Y.-H. Kuo, K. B. Lauritsen, C. Marquardt, C. Rocken, W. Schreiner, S. Sokolovskiy, S. Syndergaard, S. Heise, and J. Wickert (2012), Quantification of structural uncertainty in climate data records from GPS radio occultation, *J. Geophys. Res.*, revised. (16 pp)

[S11] Ho, S.-P., D. Hunt, **A. K. Steiner**, A. J. Mannucci, G. Kirchengast, H. Gleisner, S. Heise, A. von Engeln, C. Marquardt, S. Sokolovskiy, W. Schreiner, B. Scherllin-Pirscher, C. Ao, J. Wickert, S. Syndergaard, K. Lauritsen, S. Leroy, E. R. Kursinski, Y.-H. Kuo, U. Foelsche, T. Schmidt, M. Gorbunov (2012), Reproducibility of GPS radio occultation data for climate monitoring: Profile-to-profile inter-comparison of CHAMP climate records 2002 to 2008 from six data centers, *J. Geophys. Res.*, revised. (31 pp)

A.2.3 Observing Atmospheric Climate Change Using RO

Monitoring and Indicators of Atmospheric Climate Change

[S12] **Steiner, A. K.**, G. Kirchengast, U. Foelsche, L. Kornblueh, E. Manzini, and L. Bengtsson (2001), GNSS occultation sounding for climate monitoring, *Phys. Chem. Earth (A)*, *26*, 113–124. (12 pp)

[S13] Foelsche, U., G. Kirchengast, **A. K. Steiner**, L. Kornblueh, E. Manzini, and L. Bengtsson (2008), An observing system simulation experiment for climate monitoring with GNSS radio occultation data: Setup and testbed study, *J. Geophys. Res.*, *113*, D11108, doi:10.1029/2007JD009231. (14 pp)

[S14] Ladstädter F., **A. K. Steiner**, B. C. Lackner, B. Pirscher, G. Kirchengast, J. Kehrer, H. Hauser, P. Muigg, and H. Doleisch (2010), Exploration of climate data using interactive visualization, *J. Atmos. Oceanic Tech.*, *27*, 667–679, doi:10.1175/2009JTECHA1374.1. (13 pp)

[S15] Lackner, B. C., **A. K. Steiner**, and G. Kirchengast (2011), Where to see climate change best in radio occultation variables – Study using GCMs and ECMWF reanalyses, *Ann. Geophys.*, *29*, 2147–2167, doi:10.5194/angeo-29-2147-2011. (21 pp)

Detection of Atmospheric Climate Change

[S16] **Steiner, A. K.**, G. Kirchengast, B. C. Lackner, B. Pirscher, M. Borsche, and U. Foelsche (2009), Atmospheric temperature change detection with GPS radio occultation 1995 to 2008, *Geophys. Res. Lett.*, *36*, L18702, doi:10.1029/2009GL039777. (5 pp)

[S17] Lackner, B. C., **A. K. Steiner**, G. C. Hegerl, and G. Kirchengast (2011), Atmospheric climate change detection by radio occultation data using a fingerprinting method, *J. Clim.*, *24*, 5275–5291, doi:10.1175/2011JCLI3966.1. (17 pp)

[S18] **Steiner, A. K.**, B. C. Lackner, F. Ladstädter, B. Scherllin-Pirscher, U. Foelsche, and G. Kirchengast (2011), GPS radio occultation for climate applications, *Radio Sci.*, *46*, RS0D24, doi:10.1029/2010RS004614. (17 pp)