FINAL REPORT

Project title **Indikatoren des Klimawandels mittels Radio-Okkultation**
Indicators of Climate Change from Radio Occultation

Project number **P18733-N10**

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1. Summary/Zusammenfassung

Anthropogenic climate change manifests itself not only as warming of the Earth's surface but emerges also in the free atmosphere. The INDICATE project provides indicators for monitoring and diagnosing atmospheric climate change based on radio occultation (RO) observations, a novel upper air satellite record. Using signals from Global Positioning System (GPS) satellites, RO achieves best data quality in the upper troposphere-lower stratosphere at about 8 km to 30 km height, a region sensitive to climate change. In a first step we investigated atmospheric fields of reanalysis and global climate model simulations since continuous RO data are only available since 2001. We analyzed the RO accessible parameters refractivity (equivalent to density), geopotential height, pressure, and temperature.

A systematic exploration of the climate datasets with an innovative visualization technique, the SimVis software, identified parameters and regions reacting most sensitive to climate change. SimVis allows to interactively focus on interesting features, to identify data deficiencies and characteristics, leading to new hypotheses. Subsequent statistical analysis revealed most robust indicators in the tropics. Fall and Summer are favorable indicator seasons. Regarding height sensitivity, refractivity turned out as good indicator in the lower stratosphere at about 18 km to 24 km, pressure in the upper troposphere at 13 km to 16 km, and temperature in both regions at 9 km to 12 km and above 20 km height. Together, the set of RO accessible parameters covers the whole upper troposphere-lower stratosphere.

Based on the identified indicators, we tested the trend detection capability of available RO temperature data and found significant climate trends relative to natural variability in the investigated period. While an emerging warming trend in the tropical upper troposphere is obscured by El Nino variability, a significant cooling trend is revealed in the lower stratosphere in February 1997 to 2008. A consistent trend signal is also detected in refractivity. The results are in agreement with trends in radiosonde records though those trends are not significant themselves given the less stable error characteristics. Climate model trends basically agree as well but they show less warming/cooling contrast across the tropical tropopause.

Beside comparison to conventional upper air satellite data, we initiated an RO climate trends intercomparison study in collaboration with the main international RO processing centers. First results confirm the consistency of RO data products fulfilling the needs of climate monitoring for long-term stable, self-calibrated, and well height-resolved global data.

Main scientific advances comprise the identification of RO based indicators that tell us where to see climate change first. They allowed together with a full characterization and accounting of data errors, the worldwide first detection of climate trends in real RO data. Our results contribute to the clarification of open issues on trends from conventional upper air data and models which is of relevance not only for the climate community but also of broader interest.

Der anthropogene Klimawandel zeigt sich nicht nur als Erwärmung der Erdoberfläche sondern zeichnet sich auch in der freien Atmosphäre ab. Im Rahmen des INDICATE Projekts haben wir Indikatoren zur Beobachtung und Diagnose des atmosphärischen Klimawandels erstellt. Als Datengrundlage verwenden wir Messungen aus Radiookkultation (RO), einer neuen satelliten-gestützten Methode welche GPS Signale nutzt. Die beste Datenqualität wird in der oberen Troposphäre und unteren Stratosphäre in etwa 8 km bis 30 km Höhe erreicht, einer Region die sensibel auf Klimaänderungen reagiert. Im ersten Schritt untersuchten wir Atmosphärenfelder aus Reanalysen und globale Klimamodelldaten, da es kontinuierliche RO Beobachtungen erst seit 2001 gibt. Wir analysierten die RO verfügbaren Parameter Refraktivität (äquivalent zu Dichte), geopotentielle Höhe, Druck und Temperatur.

Zum Auffinden von klimasensiblen Parametern und Regionen erfolgte eine systematische Exploration der Klimadatensätze mittels einer innovativen Visualisierungstechnik, der SimVis Software. Diese erlaubt interaktiv Datenmängel- und Charakteristika sowie interessante Phänomene zu finden. Die nachfolgende statistische Analyse zeigte das Auftreten von robusten Indikatoren in den Tropen, in Herbst und Sommersaisonen sowie in bestimmten Höhen. Gute Indikatoren sind Refraktivität in der unteren Stratosphäre von 18 km bis 24 km, Druck in der oberen Troposphäre von 13 km bis 16 km, und Temperatur in beiden Regionen von 9 km bis 12 km und über 20 km. Gemeinsam decken diese Parameter also den gesamten oberen Troposphären- und unteren Stratosphärenbereich als Klimaindikatoren ab.

Darauf basierend untersuchten wir die Detektierbarkeit von Trends in verfügbaren RO Datensätzen und fanden signifikante Trends relativ zur natürlichen Variabilität in den Tropen im betrachteten Zeitraum. Während ein Erwärmungstrend in der tropischen Troposphäre noch durch die El Nino Variabilität überlagert wird, zeigt sich in der Stratosphäre ein signifikanter Abkühlungstrend in den Februarmonaten 1997 bis 2008. Auch in der Refraktivität wurde ein signifikantes Trendsignal detektiert. Unsere Ergebnisse sind mit jenen von Radiosondendaten und Klimamodellen konsistent. Trends aus Radiosondendaten sind jedoch aufgrund ihrer schlechteren Fehlercharakteristik nicht signifikant, Klimamodelle zeigen einen deutlich geringeren Erwärmungs-/Abkühlungskontrast.

Neben Vergleichen mit konventionellen Satellitendaten, haben wir auch eine RO Vergleichs-studie in Zusammenarbeit mit den internationalen RO Prozessierungszentren initiiert. Erste Ergebnisse bestätigen die Konsistenz von RO Datenprodukten und ihre Eignung für Klimabeobachtung durch Langzeitstabilität, Selbstkalibriertheit und guter Höhenauflösung.

Ein wichtiger wissenschaftlicher Fortschritt ist die Bereitstellung von RO-basierten Klima-indikatoren, die uns zeigen wo man den Klimawandel in der Atmosphäre am besten sieht. Ein Meilenstein ist die erstmalige Detektierung von Klimatrends in der freien Atmosphäre mittels RO Daten. Unsere Ergebnisse tragen wesentlich zur Klärung noch offener Fragen bezüglich Trends in konventionellen Atmosphärendaten bei und sind nicht nur für die Klimaforschung von Relevanz sondern von weitreichendem Interesse.

2. Brief project report

2.1 Information on the development of the research work

Anthropogenic climate change manifests itself not only as warming of the Earth's surface but emerges also in the free atmosphere. Radio occultation (RO) measurements based on signals from Global Positioning System (GPS) satellites provide a novel upper air record for atmosphere and climate observations. RO achieves best data quality in the upper troposphere-lower stratosphere (UTLS). Vertical profiles of the atmospheric parameters refractivity, pressure, geopotential height, and temperature are retrieved at the Wegener Center (Graz, Austria) from which monthly-mean zonal-mean climatologies are calculated.

The main aim of the INDICATE project was the exploration and provision of indicators for monitoring and diagnosing atmospheric climate change in the UTLS based on RO accessible parameters. RO data are available continuously since September 2001. In addition, first RO observations of adequate quality and extent exist for October 1995 and February 1997. Given the limited length of the RO record, we also used reanalyses and climate model fields as "proxy" climatologies for exploring the long-term value. Reanalyses from ECMWF (European Centre for Medium-Range Weather Forecasts) and NCEP (National Center for Environmental Prediction) extended the RO observations back to 1979, Global Climate Model (GCM) data for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) until the year 2050. The datasets were systematically explored for finding the most robust and sensitive change indicators both by testing pre-defined potentially useful indicators within a multi-model/multi-ensemble approach and by using the new visual 4D field exploration technique SimVis.

Using the identified indicators our next aim was the investigation of the trend detection capability of RO observations by applying methods of multiple linear regression and optimal fingerprinting. The evaluation of the climate models used in the project, our third aim, was accomplished during the course of work by the different studies. Beside a comparison to conventional upper air records, an RO intercomparison study in collaboration with the main international RO processing centers was initiated to assess the quality and consistency of RO data products for climate applications.

2.2 Most important results and brief description of their significance

2.2.1 Exploration of Atmospheric Data for Trend Indicators with SimVis

Interactive visual exploration was used as an innovative approach to gain information about our large climate data sets. The Simulation Visualization (SimVis) software tool, developed by the VRVis Research Center (Vienna, Austria), allows to iteratively and interactively browse the parameter space, to rapidly get to know the data characteristics, to identify data deficiencies, to easily focus on interesting features, and to come up with new hypotheses.

Main advancements of the SimVis software tool for an effective application to atmospheric data sets were carried out in the INDICATE project in close cooperation with the VRVis team. The following features were implemented: the provision of output data files, the import of two data files at the same time, the choice of specific time layers/height levels enabling the calculation of gradients for trend testing, and the so-called 'curve view' for enhanced interactive visual analysis of the temporal evolution of large time series (*Kehrer* 2007; *Kehrer et al.*, 2008).

SimVis was successfully applied to climate data from different sources including ECHAM5 climate model runs (Max Planck Institute for Meteorology Hamburg), ERA-40 reanalyses (ECMWF), and RO data. Atmospheric fields of temperature, geopotential height, and refractivity were explored to identify parameters and regions reacting most sensitive to climate change, representing robust indicators, which feature regions with trends with high signal-to-noise ratio (SNR) in space and in time (*Kehrer et al*., 2008; *Ladstädter et al*., 2009).

Our results efficiently detected data deficiencies and identified indicators. Deficiencies in the ERA-40 reanalysis were revealed at southern high latitudes and in early years of the pre-satellite era. Regions of high SNR reside in the lower stratosphere (LS) at northern high latitudes and in the tropical upper troposphere (UT) as seen in geopotential height of pressure levels and temperature. Climate model runs show robust trends of temperature and refractivity in the LS over the whole investigated time period, and also in the UT. Differences in RO data from different processing centers were investigated also (*Ladstädter et al*., 2009).

Comparison of SimVis results to those of classical statistics (see section 2.1.2.2; *Lackner et al*., 2009) confirmed its utility and revealed its complementary advantages: No prior knowledge about the data is required by SimVis and the undirected approach reveals features which might be overlooked with pre-defined statistical methods (*Ladstädter et al*., 2010). Combining both, the analytical precision of classical statistics and the holistic power of interactive visual exploration, greatly enhanced our workflow of studying climate data. We see a great potential to apply the presented approach to other climatological and geophysical datasets. Many more applications can be envisioned in helping to handle the vast amount of today's data output in geoscientific research and beyond.

2.2.2 Analysis of Atmospheric Data for Trend Indicators with Classical Trend Testing

Long-term climatologies of RO accessible parameters were analyzed via classical least-squares trend fitting by *Lackner et al*. (2009). Their potential for climate monitoring was investigated by using ERA-40/ECMWF and NCEP/NCAR reanalyes as well as simulations of three representative GCMs of the IPCC AR4 for 1961–2060. Seasonal fields of atmospheric parameters were analyzed for 6 large zonal bands and for 30 geographical regions following IPCC definitions. Refractivity, pressure, and temperature trends were analyzed on geopotential height levels and as layer gradients. Indicators were defined as regions with high trend SNR, which was determined by means of direction of trends, trend significances, and goodness-of-fit.

Results revealed most robust indicators in the tropics. Fall and Summer are favorable indicator seasons. Regarding height sensitivity, refractivity turned out as good indicator in the in the LS at 18–24 km (~70–30 hPa), pressure near the tropopause at 13–16 km (~150–100 hPa), temperature in the UT at 9–12 km (~300–200 hPa). Temperature also emerges as LS indicator above 20 km and refractivity in the UT around 12 km. Layer gradients provide additional information particularly for the tropics (*Lackner et al.*, 2009). Together, the set of RO accessible parameters covers the whole UTLS as most useful climate indicators.

2.2.3 Comparison and Inter-comparison of Upper-Air Data Sets

Concerning real observational data, a first comparison of upper air data sets based on radiosonde data and satellite records from the (Advanced) Microwave Sounding Unit (MSU/AMSU) with RO data was performed by *Steiner et al*. (2007). Equivalent bulk temperatures of the lower stratosphere (TLS) were calculated for September 2001 to December 2006. These synthetic RO TLS temperatures were compared to MSU TLS records from the University of Alabama in Huntsville (UAH, USA) and from Remote Sensing Systems (RSS, USA), as well as to synthetic TLS temperatures from HadAT2 radiosonde data (Hadley Centre/MetOffice, UK) and ECMWF analyses.

Overall very good agreement of RO with MSU/AMSU and ECMWF was found in terms of absolute temperatures and for intra-annual variability. In terms of temperature anomalies, *Steiner et al*. (2007) found statistically significant trend differences of RO to MSU/AMSU TLS data in the tropical region. In a follow-on study *Steiner et al*. (2009a) performed an analysis of known error sources where the total contribution of errors from RO was found to be an order of magnitude smaller than the trend differences and thus insufficient to account for them. The resolution of this discrepancy requires either additional, so far overlooked sources of error in the RO TLS record or the presence of currently unresolved biases in the MSU records.

In this context an international RO intercomparison study to assess structural uncertainty has been initiated with the Wegener Center in a lead role (coordinators G. Kirchengast and A.K. Steiner) in collaboration with the four other main international RO processing centers: GFZ Potsdam, UCAR Boulder, DMI Copenhagen, and JPL Pasadena. A first intercomparison of RO refractivity climatologies from the four centers revealed low structural uncertainty (*Ho et al*., 2009). This result is highly important in the context of a complete error characterization for trend detection studies. It confirms the basic quality and consistency of RO data products fulfilling the needs of climate monitoring and diagnosis for long-term stable, self-calibrated, and well height-resolved global data.

2.2.4 Detection of Atmospheric Trends in RO Observations

Based on the identified indicators together with a full error characterization of RO data we tested the trend detection capability of the RO record. Standard linear regression was applied to temperature time series for February (1997 and 2002–2008) and for October (1995 and 2001-2007) fully accounting for error estimates. In the tropics we also investigated the influence of the El Nino-Southern Oscillation (ENSO) and of the stratospheric quasi-biennial oscillation (QBO) through multiple linear regression (*Steiner et al*., 2009b). The climate variability represented by the de-trended standard deviation (inter-annual variability) and the error of the trend were used to assess the SNR of the trend in the study period. Regarding the anthropogenic signal, we inspect whether the observed trend exceeds long-term natural variability of such trends as estimated from pre-industrial control runs of three representative global climate models of the IPCC AR4. As a second method, an optimal fingerprinting technique was applied to the whole record of the RO parameters to inspect for a forced climate signal, where the response pattern to the external (anthropogenic) forcings is represented by an ensemble mean of the models' A2 and B1 scenario runs (*Lackner et a*l., paper submitted to J. Climate., 2010).

Results revealed a significant cooling trend in the tropical lower stratosphere in February 1997 to 2008 while an emerging warming trend in the upper troposphere is obscured by El Nino variability (*Steiner et al*., 2009b). Optimal fingerprinting also revealed a consistent trend signal in refractivity and temperature (*Lackner et a*l., paper submitted to J. Climate., 2010). The results are in agreement with trends in radiosonde records, especially newly homogenized ones though those trends are not significant themselves given the less stable error characteristics. Climate model trends basically agree as well but they tentatively show less warming/cooling contrast across the tropical tropopause.

We found the RO data capable to start detecting significant UTLS climate trends relative to natural variability over a 10–13 year period, consistent with expected detection times (*Foelsche et al.*, 2008). We regard this worldwide first detection of atmospheric trends in real RO observations as a milestone for the RO community with high relevance for atmospheric and climate science. RO provides an independent climate record of high quality and vertical resolution with long-term stability with the potential to resolve long-standing issues of atmospheric climate trends. Overall the performance of the still short RO record is encouraging that it may become a climate benchmark record in the future.

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All publications are available online via the Wegener Center homepage
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