FINAL REPORT

VERTICLIM

Atmospheric Vertical Structure and Trends in Climate Data

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Assoz. Prof. Dr. Andrea Karin Steiner

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Abstract – VERTICLIM

The Earth's atmosphere is governed by a range of natural variability modes, which need to be well characterized to be able to accurately separate them from anthropogenic climate trends. Precise observations for climate monitoring are therefore required, meeting the quality criteria of the Global Climate Observing System (GCOS) program. In this respect, Radio Occultation (RO) measurements based on Global Navigation Satellite Systems (GNSS) signals have the beneficial properties of long-term stability, all-weather capability, global coverage, high accuracy and vertical resolution in the upper troposphere and lower stratosphere.

Here we present results on the characterization of the vertical thermal structure of variability and trends, and relevant processes from the surface to the stratosphere, using RO and other upper-air observations in comparison with reanalyses and climate models.

We confirm the climate quality of RO observations by quantifying the structural uncertainty of multi-satellite RO records from different processing centers. RO records are consistent within 8 km to 25/30 km at low to mid-latitudes. Structural uncertainty for temperature is <0.05 K per decade nearly everywhere in this region, and <0.1 K per decade including high latitudes. The maturity of RO has further improved towards a climate data record meeting the GCOS criteria. We made the Wegener Center RO OPSv5.6 record publicly available for use in climate and other high-accuracy applications.

We provide novel altitude-resolved atmospheric variability proxies constructed directly from RO temperature measurements. They represent main atmospheric modes such as El Niño–Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO), and are greatly beneficial in trend regression analyses. Furthermore, we investigate various other sources of variability such as tropopauses, gravity waves, or volcanic explosive eruptions.

We find substantial improvement in the agreement of temperature trends from reprocessed stratospheric observations with chemistry-climate model data, showing that the stratospheric cooling over the satellite era weakens after 1998. Vertically resolved trends from RO in the period 2001 to 2018 show warming in the whole troposphere and above the tropical tropopause, while cooling is observed in the tropical stratosphere. Arctic amplification is seen to affect the equator-to-pole temperature differences. Trends from RO are found largely consistent with those from radiosondes and reanalyses, though some differences are revealed. The results have been provided for the upcoming Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC).

RO as a unique data source enables an improved representation of the vertical thermal structure and atmospheric trends. This is crucial for studies of atmospheric physics and dynamics, climate trend detection, and the evaluation of next-generation climate models.

1. Report on research work

1.1 Information on the development of the research project

The central aim of the project VERTICLIM was the exploration and evaluation of the vertical structure of atmospheric climate variability and trends, and relevant processes from the surface to the stratosphere. In this respect, evaluation of upper air data sets on consistency and use as climate records was performed. As core data set we employed observations of vertically high resolved Global Positioning System (GPS) Radio Occultation (RO) for rigorous short-term studies, evaluation of climate model performance, and comparison of upper air records from observations and reanalyses.

1.2 Most important results and brief description of their significance

Specific goals and final results include the evaluation of (i) the consistency of multi-satellite RO data and use as climate data records, (ii) the interconsistency of atmospheric observations, (iii) atmospheric modes in observations, reanalyses, and models, and (iv) atmospheric short-term climate trends and vertical structure.

1.2.1 Evaluation of the consistency of multi-satellite RO records and use as climate data records

Consistency and long-term stability are mandatory requirements for a climate data record (CDR) of essential climate variables (ECV). It can be assessed by quantifiying structural uncertainty of the data arising from different processing schemes. In this context, collaboration in the ROTrends group, co-chaired by the PI, is ongoing on the intercomparison of RO data.

The core data set of the VERTICLIM project is our Wegener Center (WEGC) RO record OPSv5.6, which we rigorously validated. Analyzing satellite-dependent quality aspects showed that data from different satellites are highly consistent in the altitude range from 8 km to 25 km, with mean temperature deviations less than 0.1 K. Highest quality data are found for MetOp and GRACE, and also for FORMOSAT-3/COSMIC. At higher altitudes the OPSv5.6 RO temperature record is increasingly influenced by background information, depending on the receiver quality (Angerer et al., 2017).

In the VERTICLIM project we performed an assessment of the structural uncertainty of multi-year RO observations from multiple missions and different processing centers. We systematically analyzed the full time series 2001–2016 of multi-satellite RO data from four different RO missions, CHAMP, COSMIC, GRACE, and METOP, provided by five international RO processing centers, DMI Copenhagen, GFZ Potsdam, JPL Pasadena, UCAR Boulder, and WEGC Graz. Structural uncertainty was quantified for nine variables (non-optimized/optimized) bending angle, refractivity, dry pressure, dry geopotential height, dry temperature, pressure, temperature, and water vapour. In the course of this work, several issues in some of the data sets were detected and reported back to the processing centers. This helped to improve the data sets and resulted in reprocessing of some records.

Structural uncertainty was found lowest from 60°S to 60°N within 8 km to 25/30 km for most inspected RO variables. Structural uncertainty for temperature is <0.05 K per decade nearly everywhere in this region for all satellites and <0.1 K per decade including high latitudes. Compared to CHAMP, the later RO missions show smaller structural uncertainty at altitudes above 25 km due to improved receiver technology. High consistency is found for bending angle and refractivity up to 35/40 km altitude. Larger structural uncertainty at higher altitudes and latitudes is due to different initialization approaches implemented at each center including different high altitude background information (Mochart, MSc thesis 2018; paper is in preparation).

Our results confirm the climate quality of multi-satellite RO observations in the upper troposphere and lower stratosphere. The multi-satellite RO records are consistent within 8 km to 25/30 km at low to mid-latitudes meeting the criteria for climate stability of the Global Climate Observing System (GCOS). Our efforts helped improving the maturity of the RO for establishing an RO climate data record, whose creation is a recommendation of the IROWG and a goal of the WMO/SCOPE-CM programme. It is of relevance not only for the RO community, but for all data users in the atmosphere and climate community.

The WEGC GNSS RO OPSv5.6 record including globally distributed, multi-satellite RO data usable for climate and other high-accuracy applications has been made publicly available (https://doi.org/10.25364/WEGC/OPS5.6:2019.1).

1.2.2 Evaluation of the interconsistency of atmospheric observations

The consistency of different upper-air records is important when analysing climate changes. Rigorous comparisons of RO records with microwave soundings (AMSU) and radiosondes showed overall good consistency between the datasets (Ladstädter et al., presented at COSMIC-IROWG 2017). Small differences between WEGC RO and AMSU are regarded most probably to be due to the initialization of the WEGC RO record with ECMWF forecasts at high altitudes, as the latter show step-like changes due to model version changes.

In the stratosphere, a comparison of reprocessed observations of the stratospheric sounding unit (SSU) with new chemistry-climate model data showed substantial improvement between modeled and observed stratospheric temperature trends over the satellite era (Maycock et al., 2018). This is mainly due to the efforts of the community on improving observations. Weaker stratospheric cooling takes place since about 1998 when ozone-depleting substances have been declining in the atmosphere.

This work was published as frontier article and substantially contributed to the aim of the WCRP/SPARC ATC activity (co-chairs Steiner and Maycock) on improving knowledge on atmospheric climate variability and trends and has provided important input for the IPCC AR6.

1.2.3 Evaluation of atmospheric modes in observations, reanalyses, and models

We exploited the high quality and vertical resolution of RO observations for assessing the atmospheric variability modes and characteristics, also compared to reanalyses and climate models.

Wilhelmsen et al. (2018) demonstrated that information on significant modes of natural climate variability in the tropical troposphere and stratosphere can be derived from RO temperature observations. They introduced, for the first time, new height-resolved atmospheric variability proxies constructed directly from RO temperature measurements, representing main atmospheric modes of El Niño–Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO). These altitude-resolved indices are beneficial in trend regression analysis, having no time-lag and capturing the atmospheric variability better than conventional indices. The work was featured as highlight article.

A study on tropopause characteristics with focus on double tropopauses and how they connect to atmospheric variability due to ENSO, QBO, gravity waves, and jet streams is in preparation for publication. Atmospheric gravity waves over the Alps and the Andes mountains due to convection and/or orography were also investigated (Hierro et al. 2018).

The evaluation of tropical convection regimes in atmospheric climate models with RO observations revealed model biases of 4 K in temperature near the tropopause. In moist convection regions, models tend to underestimate moisture by 10% to 40% over oceans, whereas in dry downdraft regions they overestimate moisture by 100 % (Steiner et al. 2018).

Another novel application of RO is the detection of the top height of volcanic clouds (Biondi et al. 2016; 2017). Cooling was detected in the upper troposphere for the Puyehue volcanic ash cloud case whereas warming was found in the stratosphere for the Nabro SO_2 cloud, indicating that the cloud reached the stratosphere in the latter case. The results are encouraging for future large-scale use of RO data supporting the monitoring of volcanic clouds. The work was featured as research highlight.

RO is a unique data source combining precise altitude location and a range of atmospheric variables (Scherllin-Pirscher et al., 2017) to be exploited. Good representation and better knowledge of atmospheric and climate variability is of importance for studies of atmospheric physics and dynamics, the analysis of climate variability and trends, and for the evaluation and advancement of next-generation climate models.

1.2.4 Evaluation of atmospheric short-term climate trends and vertical structure

Taking advantage of the derived novel RO atmospheric indices (Wilhelmsen et al., 2018), enables detection of robust trends in vertically high resolved data sets. We investigated vertically resolved atmospheric change signals in the troposphere to lower stratosphere based on the WEGC RO OPSv5.6 record. Applying multiple linear regression methods we separated the different contributions to atmospheric variability, including the seasonal cycle, QBO, ENSO, volcanic eruptions, and solar variability from the linear trend signal. The climatic effect of post-2000 volcanic eruptions are robust warming signals in the lower stratosphere from explosive volcanoes. We find that minor volcanic eruptions can substantially alter the short term linear trend of up to 20% in the lower stratosphere (Stocker et al., submitted to GRL).

Over the inspected period 2001 to 2018, a warming is detected in the whole troposphere and above the tropical tropopause while cooling is observed in the tropical stratosphere. The effect of Arctic amplification on temperature differences between the tropics and the Arctic manifests as decrease in the lower troposphere, increase in the upper troposphere, and decrease in the lower stratosphere (Peter, MSc thesis 2019). Resulting trends from RO were found largely consistent with those from radiosondes and reanalyses, though some differences were revealed (Ladstädter et al., EGU 2017; Steiner et al., AGU 2018). The results have been submitted for the IPCC AR6 first draft (publication in preparation).

Our work provided detailed knowledge of the vertical structure of trends. Quantifying atmospheric variability is crucial for comprehensive trend analysis in order to separate natural from anthropogenic temperature changes. Furthermore, cooperation within the SPARC ATC activity resulted in a publication on stratospheric temperature trends (Maycock et al. 2018), and an update of atmospheric temperature trends from atmospheric observations.