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Global Climatologies Based on Radio Occultation Data: The CHAMPCLIM Project

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Abstract. The German/US research satellite CHAMP (CHAllenging Minisatellite Payload for geoscientific research) continuously records about 230 radio occultation (RO) profiles per day since March 2002. The mission is expected to last at least until 2007, thus CHAMP RO data provide the first opportunity to create RO based climatologies on a longer term. CHAMPCLIM is a joint project of the Wegener Center for Climate and Global Change (WegCenter) in Graz and the GeoForschungsZentrum (GFZ) in Potsdam. It aims at exploiting the CHAMP RO data in the best possible manner for climate research. For this purpose, CHAMP excess phase data provided by GFZ are processed at WegCenter with a new retrieval scheme, especially tuned for monitoring climate variability and change. The atmospheric profiles which pass all quality checks (~150 profiles/day) are used to create climatologies on a monthly, seasonal, and annual basis. Here, we focus on dry temperature climatologies from the winter season (DJF) 2002/03 to the summer season (JJA) 2004, obtained by averaging-and-binning. The results show that useful dry temperature climatologies resolving horizontal scales >1000 km can be obtained even with data from a single RO receiver. RO based climatologies have the potential to improve modern operational climatologies, especially in regions where the data coverage and/or the vertical resolution and accuracy of RO data is superior to traditional data sources.

1 Introduction

The provision of accurate, long-term, consistent data to sustain and expand the observational foundation for climate studies is one of the high priority areas for action to improve the ability to detect, attribute and understand climate variability and changes (e.g., IPCC 2001). A promising climate monitoring tool meeting these requirements is the Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique. The self-calibrated nature, high accuracy, all-weather capability, and global coverage of RO data suggest them as well suited for global short- and long-term monitoring of atmospheric change.

The German/US research satellite CHAMP was launched in July 2000 into low Earth orbit (LEO), since March 2002 it continuously records about 230 RO profiles per day (Wickert et al. 2001, 2004). Out of these ~230 daily profiles, about

160 can be successfully calibrated and are of sufficient data quality, ~150 of these pass the quality checks during the WegCenter retrieval. The CHAMP mission is expected to last until 2007, CHAMP RO data thus provide the first opportunity to create RO based climatologies for a multi-year period of >5 years.

In Section 2 we summarize the properties of RO data, with respect to the CHAMP mission and climate monitoring. Section 3 deals with appropriate atmospheric parameters for climate monitoring. In Section 4 the CHAMPCLIM project is presented, with selected results in Section 5, followed by concluding remarks.

2 Properties of Radio Occultation Data

Many satellite-derived data records are degraded by problems such as changes in instrumentation and satellites' orbits, insufficient calibration, instrument drift, and poor vertical resolution (Anthes et al. 2000). Because of these shortcomings, the magnitude of temperature trends in the troposphere is still under debate (e.g., Christy and Spencer 2003; Vinnikov and Grody 2003; Mears and Wentz 2005; Stendel 2006, this issue). GNSS RO data have the potential to solve many of these problems due to their combination of specific properties.

Highest quality of RO observations is achieved in the upper troposphere/lower stratosphere region (UTLS), a domain re-acting very sensitive to climate change (see Section 3). Compared to weather analyses CHAMP RO temperature data show an ensemble mean agreement of <0.4 K between 10 km and 35 km height with a standard deviation of ~1 K at 10 km increasing to ~2 K at 30 km height (Wickert et al. 2004). The active use of L-band signals with wavelengths of 19.0 cm and 24.4 cm (in case of GPS), respectively, allows for measurements during day and night and for the penetration of clouds.

2.1 Long-Term Stability due to Intrinsic Self-Calibration

Regarding climate monitoring, the long-term stability of RO data is of particular importance (see also Leroy et al. 2006, this issue). It can be achieved since atmospheric profiles are not derived from absolute values (phase delays) but from Doppler shift (phase change) profiles. Therefore, RO measurements require no external calibration and only short-term measurement stability over the occultation event duration (1 – 2 min), which is guaranteed by very stable oscillators onboard the GNSS satellites. Given this "self-calibration", data from different sensors and different occultation missions can be combined without need for inter-calibration and overlap, as long as the same data processing scheme is used.

The long-term stability of RO data could not be tested so far due to the lack of long-time observations. An intercomparison study by Hajj et al. (2004) based on data from CHAMP and SAC-C (Satélite de Aplicaciones Científicas-C), however, showed a remarkable consistency of the data obtained from these two different satellites with temperature profiles found consistent to 0.1 K in the mean between

5 and 15 km. While CHAMP and SAC-C are equipped with very similar receivers, leaving the possibility of common systematic errors, future RO missions will help assess whether these results can also be obtained with data from completely different receivers, like the GRAS instrument (GNSS Receiver for Atmospheric Sounding) onboard MetOp (Meteorological Operational satellite, launch expected for April 2006) (Loiselet et al. 2000).

2.2 Spatial and Temporal Coverage

The number of RO events depends primarily on the number of available transmitters and receivers. A single receiver in low Earth orbit (LEO), which is capable of tracking GPS signals during setting occultations (like on CHAMP) can collect ~250 RO profiles per day (for a nominal constellation of 24 GPS satellites). LEO satellites with an additional antenna for rising events can achieve twice that amount. The 6 COSMIC satellites (Constellation Observing System for Meteorology, Ionosphere, and Climate), which are scheduled to be launched in March 2006, can be expected to obtain ~3000 setting and rising occultations per day, providing a valuable database for RO based climatologies (Rocken et al. 2000). With the upcoming European Galileo system (nominal constellation of 30 satellites), the number of transmitters will more than double; the operational status of Galileo is expected to be reached in 2008/09.

The geographic distribution of the RO events depends on the geometry of the satellite orbits. Global coverage can only be obtained with a high-inclination orbit of the LEO satellite. This orbit geometry leads, however, to a high RO event density at high latitudes with comparatively fewer events at low latitudes. Figure 1 shows, as an example for this situation, the typical coverage of CHAMP RO data during one season. LEO satellites with a low inclination orbit, on the other hand, provide a better sampling at low latitudes, but do not reach global coverage.

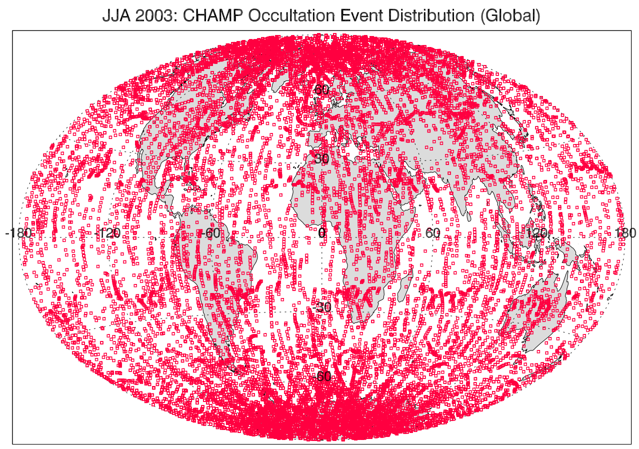

Fig. 1. Geographic distribution of 13 553 CHAMP RO events during the northern summer season (June-July-August) 2003 (orbit inclination = 87.3°).

The LEO orbit geometry determines furthermore the local times of the RO events. Satellites in sun-synchronous orbits, like MetOp, always cross the equator at the same local times. As a consequence, MetOp RO events will be clustered around 9:30 a.m. and 9:30 p.m. local time, respectively. All non-sun-synchronous LEO orbits are subject to a drift in equator-crossing time. The resulting local time drift of the CHAMP RO data is about 1 hour in 11 days.

When attempting to build RO climatologies, we have to consider that any uneven spatial and temporal sampling of the "true" evolution of the atmospheric fields can lead to sampling errors (see Section 5.2).

3 Atmospheric Parameters for Climate Monitoring

In contrast to applications of RO data in numerical weather prediction, where the focus is clearly on RO products which are as close as possible to the raw measurements (e.g., Poli 2006, this issue), ideal parameters for climate monitoring are those which change most in a changing climate. Refractivity (Vedel and Stendel 2004) and geopotential height (Leroy 1997) have recently been identified as good indicators for climate change.

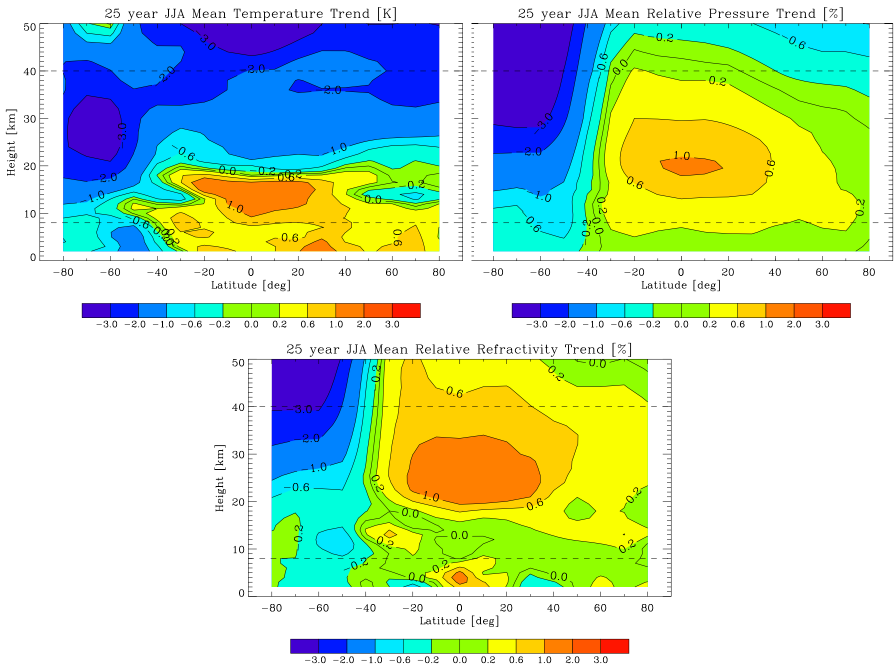

Fig. 2. Trends in atmospheric parameters over the 25-year period 2001–2025 as modeled with ECHAM5 (IS92a emission scenario with CO_2 concentration doubling between 1990 and 2100). Temperature trends (upper left panel), relative pressure trends (upper right panel), and relative trends in microwave refractivity (lower panel).

Results from climate model runs can be used as indicators for expected trends in atmospheric parameters. As an example, Figure 2 shows 25-year-trends (2001–2025) of temperature, pressure, and microwave refractivity as results of runs of the ECHAM5 model (Roeckner et al. 2003) in “middle atmosphere mode” with anthropogenic forcing. For this experiment, the vertical domain of the model was extended to 80 km. A dominant feature, which is only partly visible in “normal” climate model runs with a vertical domain up to 30 km, is the pronounced cooling in the stratosphere. Given the accuracy of RO data in the lower stratosphere it is likely that “global cooling” will be the first consequence of anthropogenic climate change that can be detected with the aid of the RO technique.

An interesting feature of Fig. 2 is the lack of change in refractivity in the upper tropical troposphere. Microwave refractivity N is related to temperature T, total pressure p, and water vapor partial pressure e, via (Smith and Weintraub 1953):

$$N = k_1 \frac{p}{T} + k_2 \frac{e}{T^2} \tag{1}$$

where k_1 is 77.6 K/hPa and k_2 is $3.73 \cdot 10^5$ K^2/hPa. When atmospheric humidity is small, the second term on the right-hand-side of Eq. 1 can be neglected. We immediately see that in this case, the same relative increase in T and p will result in no change in refractivity. Figure 2 shows that different atmospheric parameters are sensitive in different regions of the atmosphere. Climate monitoring with RO data should therefore, in principle, comprise all parameters that can be retrieved with the RO technique.

4 The CHAMPCLIM Project

CHAMPCLIM is a joint project of the Wegener Center for Climate and Global Change (WegCenter) in Graz and the GeoForschungsZentrum (GFZ) in Potsdam. The overall aim of CHAMPCLIM is to contribute to the best possible exploitation of CHAMP RO data, in particular for climate monitoring. The results of this project provide a starting point for RO based climatologies, which can be continuously expanded with data from other RO missions. The main objectives of CHAMPCLIM and some initial results have been described in Foelsche et al. (2005). Here we just briefly recall the three main objectives (Sections 4.1 to 4.3) and focus on new results.

4.1 RO Data Processing Advancements for Optimizing Climate Utility

The essential outcome of this work was a robust CHAMPCLIM retrieval scheme (WegCenter/CCRv2), building on the EGOPS4 software tool (Kirchengast at al. 2002) and a reasonable error characterization for CHAMP/GPS RO data in meeting the aim to improve the maturity and utility of the data products especially for climatological purposes. Main aspects of WegCenter/CCRv2 are:

- Geometric optics retrieval. The implementation of a wave optics retrieval scheme for the troposphere is planned for CCRv3.
- Ionospheric correction via linear combination of bending angles.
- Transparent input of a priori information via statistical optimization of bending angles. For the results shown here, ECMWF (European Centre for Medium-Range Weather Forecasts) data have been used for background bending angles.
- No further background information for initialization of the hydrostatic integral.
- Dry air retrieval (Syndergaard 1999). A 1DVar retrieval for humidity and temperature in the troposphere is planned for CCRv3.

Further details of the CCRv2 retrieval can be found in Gobiet and Kirchengast (2004), Steiner et al. (2004), and Borsche et al. (2006, this issue). Results of a related error analysis can be found in Steiner and Kirchengast (2005) and of an error analysis using CHAMP refractivity profiles in Steiner et al. (2006, this issue).

4.2 RO Data and Algorithms Validation Based on CHAMP/GPS Data

The WegCenter/CCRv2 retrieval scheme was validated against a modeled atmosphere in an end-to-end simulation study, the GFZ operational RO retrieval scheme, numerical weather prediction analyses from ECMWF, and remote-sensing instruments onboard ENVISAT (MIPAS and GOMOS). Results of these validation studies can be found in Gobiet et al. (2004, 2005a).

4.3 Global RO Based Climatologies for Monitoring Climate Change

In this part we focus on building global climatologies based on the validated datasets obtained by advanced retrievals of atmospheric parameters from CHAMP RO data. In a first approach, we perform direct (model independent) monitoring of the evolution of climatological atmospheric fields through averaging and binning of RO profiles. The setup for these climatologies is described in Borsche et al. (2006, this issue). Seasonal dry temperature climatologies are presented in Section 5. In a second approach we assimilate CHAMP RO-derived refractivities into ECMWF short term forecast fields (via 3D-Var) to obtain global climate analyses with higher horizontal resolution. Results of this approach are the focus of Löscher and Kirchengast (2006, this issue). The current record of RO occultations is still too short to actually monitor trends, but comparison with other climatologies shows the value and the potential of the climatologies based on RO data.

5 Seasonal CHAMP Dry Temperature Climatologies

For the results shown here, we sampled CHAMP profiles in 18 latitude bands (10°latitudinal extent). As examples, Fig. 3 shows the zonal mean dry temperatures for the boreal winter season (Dec-Jan-Feb) 2003/04 (left panel) and the summer season (Jun-Jul-Aug) 2004 (right panel), respectively.

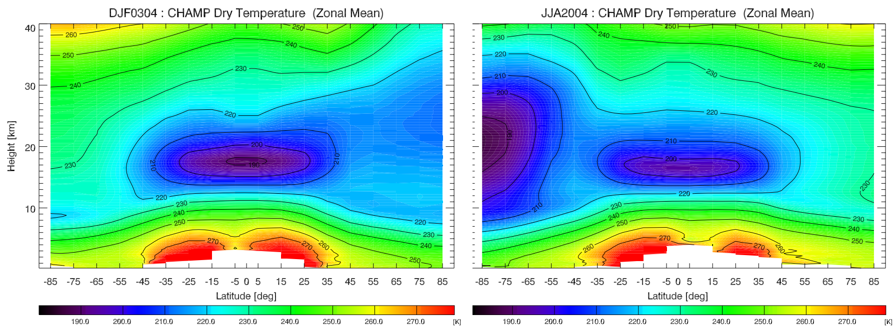

Fig. 3. CHAMP seasonal and zonal mean dry temperature fields for Dec 2003 – Feb 2004 (left panel) and Jun – Aug 2004 (right panel).

5.1 Observational Error

Latitudinally and vertically resolved difference statistics have been computed by comparing each CHAMP RO profile with a co-located ECMWF analysis profile. The systematic differences (sampling errors excluded) for two (northern) winter and two summer seasons (DJF 2002/03, JJA 2003, DJF 2003/04, JJA 2004) are shown in the left panels of Fig. 4 (taking ECMWF as reference). While differences in the lower troposphere can be clearly attributed to RO errors, the differences above 30 km are most probably due to errors in both CHAMP and ECMWF. In the height range, where RO data have the highest quality (~8 km to ~30 km), the agreement between CHAMP and ECMWF is, in general, very good: The absolute bias is <0.5 K, occasionally peaking at 1 K. However, two features are prominent:

- The tropical tropopause region in the CHAMP-derived fields is consistently warmer than the ECMWF analyses. This difference is probably caused by a weak representation of atmospheric wave activity and tropopause height variability in ECMWF fields, but work is ongoing to explain the discrepancies in detail.
- The wave-like bias structure with a magnitude of several degrees in the southern winter polar vortex region (JJA 2003 and JJA 2004) is caused by deficiencies in the representation of the austral polar vortex in the ECMWF analyses. A detailed analysis can be found in Gobiet et al. (2005b). During JJA 2004 this bias structure is less pronounced, due to the addition of new data to the ECMWF analysis scheme in October 2003 (AIRS radiances) and changes in the assimilation scheme like bias adjustments of satellite data (A. Simmons, ECMWF, pers. communication, 2005).

The apparent observational error in the UTLS region is therefore not only caused by errors in CHAMP RO data but contains also considerable errors of the reference dataset (ECMWF).

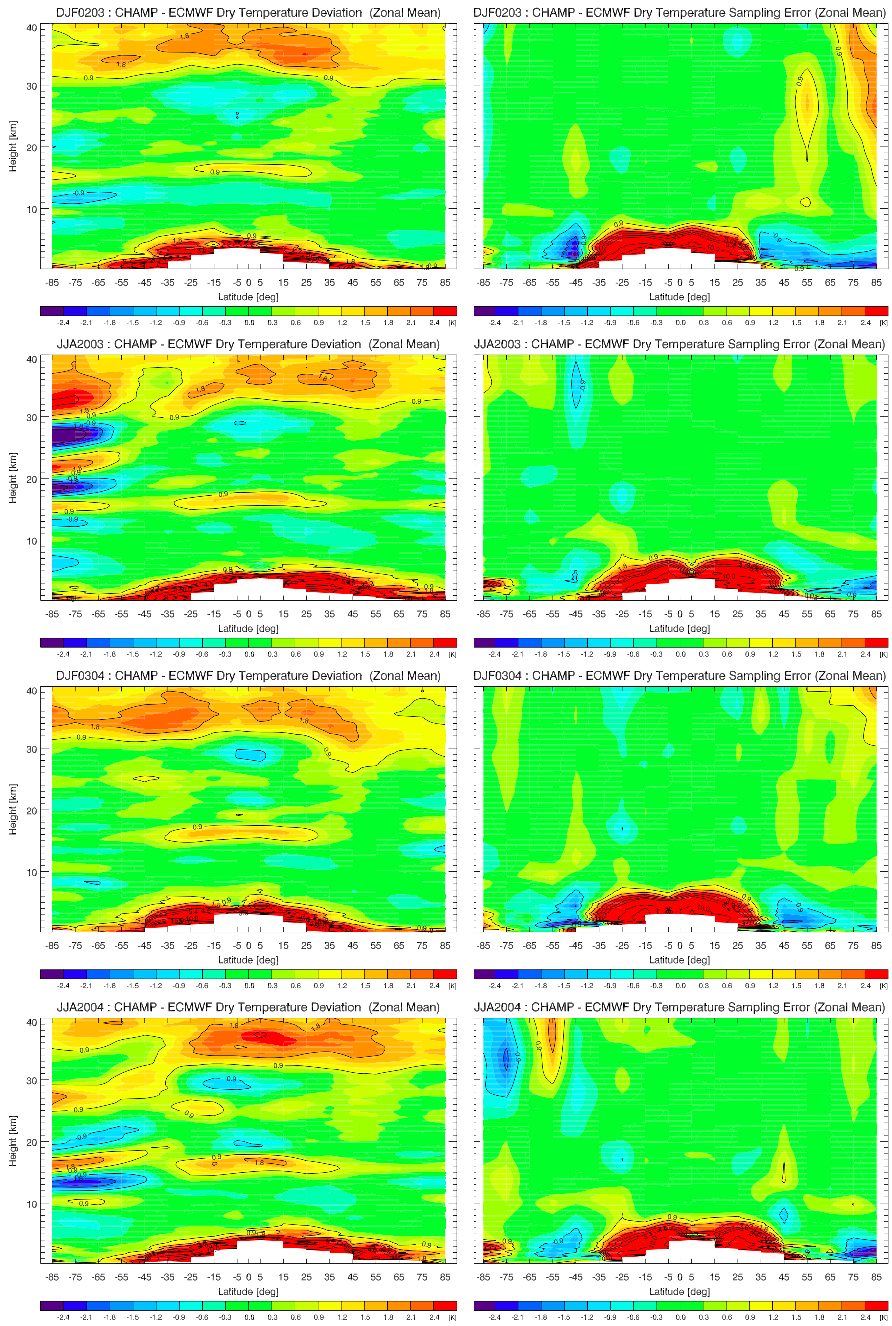

Fig. 4. Seasonal mean and zonal mean dry temperature deviations between CHAMP and ECMWF for DJF 2002/03, JJA 2003, DJF 2003/04, and JJA 2004 (left panels). Estimated CHAMP sampling errors for the same seasons (right panels).

5.2 Sampling Error

The error due to spatial and temporal undersampling of the true evolution of atmospheric fields has been identified as a potential major error source for single-satellite climatologies with the aid of simulation studies (Foelsche et al. 2003). Even with perfect observations at the occultation locations the “measured” climatologies would differ from the “true” ones as the sampling through occultation events is discrete and not dense enough to capture the entire spatio-temporal variability of the atmosphere. Under the assumption that the ECMWF analysis fields (4 time layers per day) represent the true state of the atmosphere, we can estimate the sampling error by comparing climatologies derived from the “true” ECMWF profiles at the RO locations with climatologies derived from the “true” 3D ECMWF fields using the complete field grid. The results are displayed in the right column of Fig. 4. Above ~8 km the sampling error is, in general, <0.5 K.

In the lower troposphere at low and mid-latitudes, however, there is a large “warm” sampling error for dry temperatures. This feature can be interpreted as a selective “dry sampling error”. The tracking of CHAMP signal and the geometric optics retrieval tends to stop at higher altitudes in moist compared to dry conditions. The lowest part of the RO ensembles is therefore biased towards dry conditions, resulting in a systematic under-representation of the true mean refractivity (see Eq. 1). When the refractivities are converted to dry temperatures, this systematic error maps into warm-biased mean dry temperatures. This effect is most pronounced at low latitudes, where the event density is particularly low (see Fig. 1) due to the high inclination of the CHAMP satellite (87.3°). The implementation of a wave optics algorithm in the WegCenter/CCR retrieval will reduce this “dry sampling error”, but it will remain an important error source for RO based climatologies at low latitudes below ~8 km. Operational CHAMPCLIM dry-retrieval climatologies will therefore be provided down to 8 km at low latitudes and down to 4 km at high latitudes (see Borsche et al. 2006, this issue).

The total climatological error, which can be estimated by computing differences of RO based and reference climatologies, is a combination of sampling and observational error (not shown).

6 Concluding Remarks

Our results show that accurate zonal mean seasonal climatologies between 8 km and 30 km height can be obtained even with data from a single RO receiver. Future RO missions like the Taiwan/US FORMOSAT-3/COSMIC constellation with 6 LEOs will provide thousands of RO profiles per day, but already now RO based climatologies have the potential to improve modern operational climatologies in regions where the data coverage and/or the vertical resolution and accuracy of RO data is superior to traditional data sources.

CHAMPCLIM activities will continue in the future. Climatologies of other atmospheric parameters (like refractivity and geopotential height) are currently being prepared and will be validated. Error models for these parameters (currently available for refractivity) will be developed. The next version of the WegCenter/CCR retrieval will include wave-optics based tropospheric bending angle retrieval, and 1D-Var retrieval of temperature and humidity in the troposphere. A provision of CHAMPCLIM climatologies (including error estimates and tropopause parameters) to the scientific community is planned for early 2006.

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