GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L12806, doi:10.1029/2005GL022617, 2005

Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data

A. Gobiet,[1,2] U. Foelsche,[1,2] A. K. Steiner,[1,2] M. Borsche,[1,2] G. Kirchengast,[1,2]
and J. Wickert[3]

Received 3 February 2005; revised 21 April 2005; accepted 25 May 2005; published 18 June 2005.

[1] A climatological validation of the thermal structure of European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses with a new 2.5-year dataset derived from the CHAllenging Minisatellite Payload (CHAMP) radio occultation (RO) satellite mission was performed. Close overall agreement was found in the 10–30 km altitude region, with seasonal zonal mean temperature biases generally smaller than 0.5 K. Apart from that, discrepancies in the Austral polar vortex region (cold biases up to −2.5 K, warm biases up to +3.5 K) and a cold bias of the analysis at the low-latitude tropopause (up to −2 K) were revealed. The polar vortex bias can be clearly attributed to the ECMWF analysis and data assimilation system and the tropopause bias is strongly indicated to be related to the smaller tropopause variability and the lower vertical resolution in the analysis. The study underlines the utility of RO data as global long-term climate reference datasets. **Citation:** Gobiet, A., U. Foelsche, A. K. Steiner, M. Borsche, G. Kirchengast, and J. Wickert (2005), Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data, *Geophys. Res. Lett.*, *32*, L12806, doi:10.1029/2005GL022617.

1. Introduction

[2] Operational global analyses from the Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) are used as initial conditions for the forecast system and in addition for numerous applications in atmospheric sciences such as the validation of new remote sensing systems, as forward model or background information in the simulation or retrieval of remote sensing data, as basis for atmospheric process studies like dynamics of trace gases, troposphere-stratosphere exchange, or stratospheric ozone depletion. This wide field of applications of ECMWF analyses (often as reference dataset) makes it difficult, but at the same time particularly important, to evaluate the analysis itself.

[3] Especially the stratospheric part, which is weakly constrained by observations, is barely validated. Most operational upper air observation systems like radiosondes and the Advanced Microwave Sounding Unit A (AMSU-A) are unsuitable as reference for this purpose since they are part of the analysis itself. One way to cope with this problem is to evaluate short-range forecasts instead of analyses [e.g., *Knudsen*, 2003] but this approach has limited significance for the analyses. Direct comparison of analyses with ground based or airborne research observations provide valuable insights but are rare and provide information only discretely in space and time [e.g., *Hertzog et al.*, 2004]. Intercomparison studies provide insights into relative errors between analyses from different institutions but not into absolute errors. For example, *Manney et al.* [2003] showed that in the Arctic winter stratosphere the area featuring temperatures below the threshold for polar stratospheric cloud formation (∼195 K) can vary by up to 50% between different analyses.

[4] The radio occultation (RO) technique is an active satellite-to-satellite limb sounding concept using global navigation satellite system (GNSS) signals to probe the Earth's atmosphere. It offers new possibilities for the evaluation of analyses (see *Schrøder et al.* [2003] for a first demonstration) by providing globally distributed profiles of temperature and geopotential height ranging from the lower troposphere to the middle/upper stratosphere with high long-term stability. The German-U.S. research satellite CHAMP has provided RO data continuously since 2002 [*Wickert et al.*, 2004] and offers the first opportunity to create multi-year RO-based reference climatologies which is currently realized in the framework of the CHAMPCLIM project [*Foelsche et al.*, 2005]. First results from CHAMPCLIM show good agreement with various validation data [*Gobiet et al.*, 2005] but also, regarding ECMWF analyses, some salient deviations in southern polar winter and near the tropical tropopause. This paper demonstrates and discusses the latter discrepancies.

2. Data

2.1. CHAMP RO Data

[5] The RO measurement principle exploits atmosphere-induced phase delays of GNSS signals recorded at a satellite platform in low Earth orbit to derive profiles of atmospheric refractivity, density, pressure, geopotential height, temperature, and humidity [e.g., *Kursinski et al.*, 1997; *Kirchengast et al.*, 2004]. The RO technique provides high vertical (∼0.5–1.5 km) and low horizontal (∼200–300 km) resolution, and high accuracy (temperature bias <0.5 K, standard deviation <1–3 K for CHAMP [*Wickert et al.*, 2004]). It is very stable (<0.1 K drift per decade expected) and capable of providing data under virtually all weather conditions.

---

[1] Wegener Center for Climate and Global Change (WegCenter), University of Graz, Graz, Austria.

[2] Also at Institute for Geophysics, Astrophysics, and Meteorology (IGAM), University of Graz, Graz, Austria.

[3] Department Geodesy and Remote Sensing, GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany.

0094-8276/05/2005GL022617$05.00

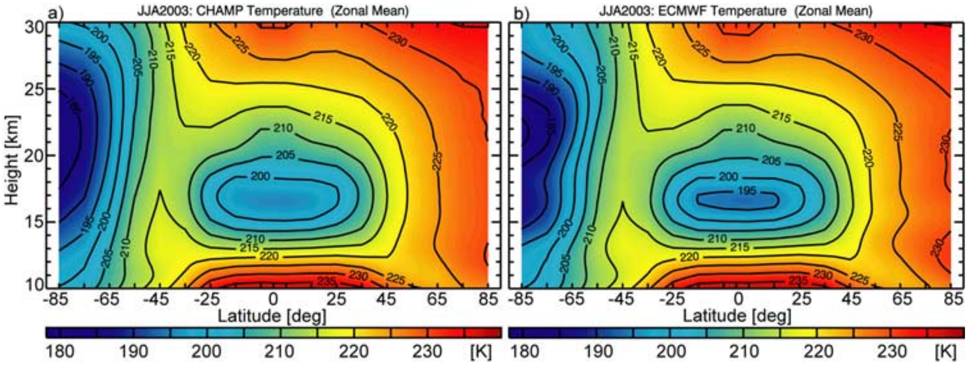

Figure 1. JJA 2003 seasonal zonal mean temperatures in 10° latitude bands derived from (a) CHAMP RO data and (b) ECMWF operational analyses.

[6] All RO temperature profiles used in this study were retrieved from CHAMP phase delay data provided by GFZ Potsdam using the CHAMPCLIM retrieval scheme (version 2) [*Gobiet et al.*, 2005]. At high altitudes the observed data were optimized by combining them in a statistically optimal way with background information (bending angles derived from the ECMWF analyses) considering the error characteristics of the observations and the background [*Gobiet and Kirchengast*, 2004]. This results in a background-determined profile at altitudes above the stratopause and an observation-determined one at altitudes below 30 km. In this study we only use data between 10 and 30 km, a range where no direct background information is used and where the effect of downward propagation of background information from the analysis through the RO retrieval is small to negligible in the differences discussed (<0.2 K at 30 km, quickly decreasing below 30 km).

[7] The CHAMPCLIM retrieval scheme generally yields 130–180 globally distributed temperature profiles per day resulting in ~12,500 profiles per season. The study is based on 2.5 years of CHAMP data (March 2002 to August 2004) comprising 124,355 profiles, of which the year 2003 and June–July–August (JJA) 2004 are shown here. The CHAMP JJA 2003 seasonal zonal mean temperatures in 10° latitude bands are depicted in Figure 1a demonstrating the general features of the Austral winter stratosphere with a well-developed olar vortex (minimum in 90°S–80°S band: 181.7 K at 21.5 km).

2.2. ECMWF Operational Analyses

[8] The IFS of ECMWF uses a semi-Lagrangian model with 60 vertical levels (L60) up to 0.1 hPa, spectral representation in the horizontal with triangular truncation at wave number 511 (T511) for upper air fields and horizontal derivatives, and a Gaussian grid in the horizontal for dynamic tendencies and diabatic physical parameterizations. This setup corresponds to horizontal grid spacing of ~40 km. IFS provides 10-day forecasts started twice a day from an initial state (i.e., the analysis) produced via four-dimensional variational data assimilation dynamically combining a short-range forecast with observational data [*ECMWF*, 2004]. It operationally generates analyses for 00, 06, 12, and 18 UT every day. The ECMWF JJA 2003 zonal mean temperature is shown in Figure 1b.

[9] Though a vast amount of observations is assimilated, the analysis is still weakly constrained by observations in some regions like the polar stratosphere where radiosondes are sparse and the main observational information source are AMSU-A radiances with low vertical resolution [e.g., *Thépaut and Andersson*, 2003] and, since October 2003, Advanced Infrared Sounder (AIRS) radiances [*ECMWF*, 2003].

3. Validation Methodology

[10] The ECMWF-CHAMP comparison is based on statistics of temperature difference profiles. ECMWF analyses were used on model levels (L60 grid) with reduced horizontal resolution (T42, ~300 km), roughly corresponding to the horizontal resolution of RO data, in order to avoid spatial representation errors. For each RO profile a coinciding profile was extracted from the analysis, i.e., spatially interpolated to the locations of the RO data using the nearest time layer of the analysis. This approach ensures that potential sampling errors due to non-uniform distribution or limited coverage of RO observations cannot perturb the difference statistics. For this study, the 2.5 years of difference profiles were divided into 10 seasons, with each season sampled into eighteen 10° latitude bands allowing computation of seasonally, latitudinally, and vertically resolved difference statistics.

[11] For each latitude band the ensemble mean (bias) and standard deviation profiles were computed. The discussion below mainly exploits the bias profiles, i.e., the biases of ECMWF vs. CHAMP. This means the RO data were chosen as reference but does not imply they are the "truth". Due to ensemble sizes of several hundred to beyond a thousand profiles per latitude band, the uncertainty of the bias is very small (standard deviations of bias <0.1–0.2 K).

4. Results and Discussion

[12] All results are presented in latitude (pole-to-pole) versus height (10–30 km) slices. Figure 2 depicts the seasonal zonal mean temperature bias in four seasons from March-April-May (MAM) 2003 to December-January-February (DJF) 2003–2004. Generally, the absolute bias is below 0.5 K, occasionally peaking at 1 K, but two features stand out: A cold bias at the low-latitude

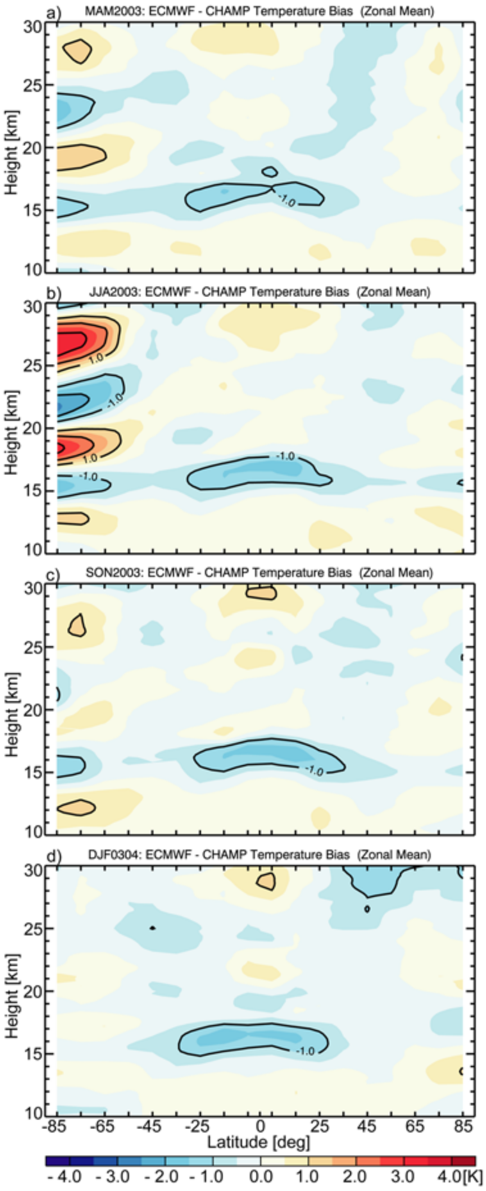

Figure 2. Seasonal zonal mean temperature bias (10° latitude bands) of ECMWF analyses vs. CHAMP RO data throughout four seasons (MAM 2003–DJF 0304).

tropopause and a wave-like bias structure in the southern winter polar vortex.

4.1. Tropopause Bias

[13] A cold bias of up to −2 K at the low-latitude tropopause is systematically visible in all seasons. The inspection of single profiles (not shown) [see also *Hajj et al.*, 2004] indicates that this effect might be related to the different vertical resolution of the analyses and the RO data (RO resolution ~1 km at that altitude, ECMWF analyses > 1.3 km). *Gorbunov and Kornblueh* [2003] suggested the bias to be induced by the lower vertical resolution of the tropopause in ECMWF analyses. Though we as well find indication for this interpretation, we find it complicated by the fact that single difference profiles do not exhibit uniform shapes around the tropopause, i.e., ECMWF profiles cannot simply be described as smoothed versions of the CHAMP RO profiles. Figure 3 illustrates this by the enhanced random temperature deviations near the low-latitude tropopause. Differences in representation of atmospheric wave activity and tropopause height variability, both weaker in the analysis, can be expected to play a relevant role (a closer study will be reported elsewhere).

4.2. Antarctic Polar Vortex Bias

[14] The wavelike bias in the JJA 2003 polar vortex, with a magnitude of −2.5 to 3.5 K (Figure 2b), is resulting from the different representation of the vortex' zonal mean shape in both data sets (Figure 1). Similar, but less pronounced, bias-patterns can be found in MAM and SON 2003 (Figures 2a and 2c). In year 2002 (not shown), a year with a considerably warmer polar vortex (minimum in the 90°S–80°S band: 185.0 K at 20 km, 3.3 K warmer than 2003) and a vortex split in late September [e.g., *Allen et al.*, 2003], the situation is qualitatively the same, but the bias magnitude is smaller compared to 2003 (maxima JJA 2002: −1.9 and +2.3 K), suggesting that the bias is related to very low temperatures. In opposite to the tropopause bias, the vortex bias is not accompanied by any remarkably increased random deviations (Figure 3). It can be clearly attributed to the ECMWF analysis since its magnitude is far beyond the error characteristics of the RO method and it cannot be attributed to resolution-induced effects or sampling errors. Furthermore, there is no physical reason why the RO method should perform worse at lower temperatures or southern polar latitudes.

[15] It is remarkable that the nodes of the "bias wave pattern" at ~20, 25, and 30 km are very close to the maxima of the temperature weighting functions of AMSU-A channels 10, 11, and 12 [e.g., *Staelin and Chen*, 2000], indicating that the bias may be related to the assimilation of AMSU-A radiances. However, an oscillatory vertical bias structure has also been found in ECMWF's re-analysis ERA-40 in the 1992–1997 January zonal mean temperatures [*Randel et al.*, 2004], a period with AMSU-A not yet available.

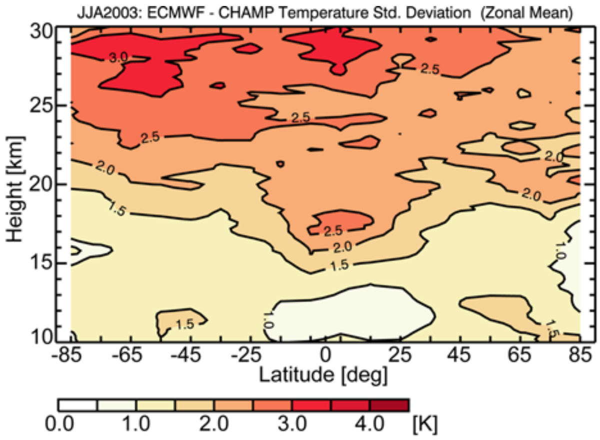

Figure 3. JJA 2003 random temperature deviations (standard deviation of ECMWF vs. CHAMP differences).

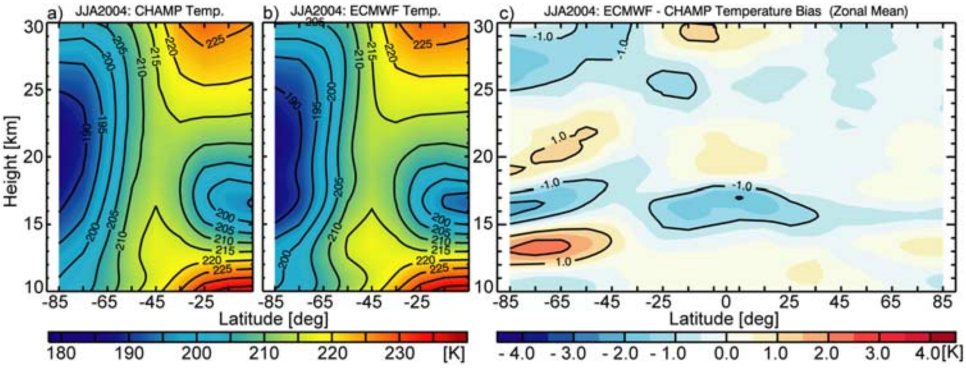

Figure 4. JJA 2004 seasonal zonal mean (a) CHAMP RO and (b) ECMWF temperatures and (c) ECMWF vs. CHAMP bias.

[16] Figure 4 shows the ECMWF and CHAMP RO seasonal zonal mean temperature and the associated bias for JJA 2004. The polar vortex still features a bias but its shape has changed compared to JJA 2003: The wave pattern above 20 km is reduced in magnitude and the sign of the bias is partly reversed. Below 20 km the bias kept its shape and is even more pronounced than in 2002 and 2003. These changes are probably related to the addition of new data to the ECMWF analysis scheme in October 2003 (AIRS radiances) [*ECMWF*, 2003] and changes in the assimilation scheme like bias adjustments of satellite data (A. Simmons, ECMWF, personal communication, 2005).

5. Conclusions

[17] The results presented in this paper generally show very good agreement between ECMWF analyses and CHAMP RO temperatures in their seasonal zonal means between 10 and 30 km (bias <0.5 K) but also demonstrate deficiencies in the representation of the Austral polar vortex in the analyses (bias up to 3.5 K). Recent changes in the ECMWF assimilation scheme obviously reduced these problems in the 20–30 km region but below 20 km the biases remain; further studies including additional data are foreseen to obtain more clear insight. The bias can have considerable impact, for example, on stratospheric ozone depletion studies.

[18] Additionally, a systematic cold bias at the low-latitude tropopause was found. Though a minor contribution to this bias may root in the RO data, there is strong indication and independent evidence (A. Simmons, ECMWF, personal communication, 2005) that it can be mainly attributed to the analyses. It is probably caused by weak representation of atmospheric wave activity and tropopause height variability, which is currently under closer study.

[19] The utility of RO data as climate reference dataset has been demonstrated. Furthermore, the results reinforce evidence from recent and on-going impact experiments [*Healy et al.*, 2005] (S. B. Healy, ECMWF, personal communication, 2005), that RO data will have significant positive impact when included in ECMWF's and other operational weather prediction systems.

[20] Currently only the CHAMP RO instrument is in continuous operation, resulting in relatively coarse geographical resolution of RO climatologies. But near-future missions such as the European MetOp and the US/Taiwan COSMIC mission will soon provide a wealth of RO data enabling to create much finer resolved climatologies.

[21] **Acknowledgments.** We thank A. Simmons, S. B. Healy (both ECMWF Reading), and S.S. Leroy (Harvard University) for valuable scientific discussions and T. Schmidt (GFZ Potsdam) and J. Fritzer (Univ. of Graz) for technical support. GFZ Potsdam is thanked for operating the CHAMP mission and providing the RO data, ECMWF Reading for providing access to their operational analysis data. A.G., U.F., and A.K.S. received financial support from the Austrian Science Fund (START Award of G.K., Program Y103-N03) and M.B. from the Austrian Space Agency (CHAMPCLIM Project ASAP-CO-004/03).

References

Allen, D. R., R. M. Bevilacqua, G. E. Nedoluha, C. E. Randall, and G. L. Manney (2003), Unusual stratospheric transport and mixing during the 2002 Antarctic winter, *Geophys. Res. Lett.*, *30*(12), 1599, doi:10.1029/2003GL017117.

European Centre for Medium-Range Weather Forecasts (ECMWF) (2003), Changes to the operational forecasting system, *ECMWF Newsl.*, *99*, 1–2.

European Centre for Medium-Range Weather Forecasts (ECMWF) (2004), *IFS Documentation CY28r1*, Reading, UK.

Foelsche, U., A. Gobiet, A. Löscher, G. Kirchengast, A. K. Steiner, J. Wickert, and T. Schmidt (2005), The CHAMPCLIM project: An overview, in *Earth Observations With CHAMP: Results From Three Years in Orbit*, edited by C. Reigber et al., pp. 615–620, Springer, New York.

Gobiet, A., and G. Kirchengast (2004), Advancements of Global Navigation Satellite System radio occultation retrieval in the upper stratosphere for optimal climate monitoring utility, *J. Geophys. Res.*, *109*, D24110, doi:10.1029/2004JD005117.

Gobiet, A., G. Kirchengast, J. Wickert, C. Retscher, D.-Y. Wang, and A. Hauchecorne (2005), Evaluation of stratospheric radio occultation retrieval using data from CHAMP, MIPAS, GOMOS, and ECMWF analysis fields, in *Earth Observations with CHAMP: Results From Three Years in Orbit*, edited by C. Reigber et al., 525–530, Springer, New York.

Gorbunov, M. E., and L. Kornblueh (2003), Analysis and validation of Challenging Minisatellite Payload (CHAMP) radio occultation data, *J. Geophys. Res.*, *108*(D18), 4584, doi:10.1029/2002JD003175.

Hajj, G. A., C. O. Ao, B. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. de la Torre Juarez, and T. P. Yunck (2004), CHAMP and SAC-C atmospheric occultation results and intercomparisons, *J. Geophys. Res.*, *109*, D06109, doi:10.1029/2003JD003909.

Healy, S. B., A. M. Jupp, and C. Marquardt (2005), Forecast impact experiment with GPS radio occultation measurements, *Geophys. Res. Lett.*, *32*, L03804, doi:10.1029/2004GL020806.

Hertzog, A., C. Basdevant, F. Vial, and C. R. Mechoso (2004), The accuracy of stratospheric analyses in the northern hemisphere inferred from long-duration balloon flights, *Q. J. R. Meteorol. Soc.*, *130*, 607–626, 597.

Knudsen, B. M. (2003), On the accuracy of analysed low temperatures in the stratosphere, *Atmos. Chem. Phys.*, *3*, 1759–1768.

Kirchengast, G., U. Foelsche, and A. K. Steiner (Eds.) (2004), *Occultations for Probing Atmosphere and Climate*, Springer, New York.

Kursinski, E. R., G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy (1997), Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res.*, *102*, 23,429–23,465.

Manney, G. L., J. L. Sabutis, S. Pawson, M. L. Santee, B. Naujokat, R. Swinbank, M. E. Gelman, and W. Ebisuzaki (2003), Lower stratospheric temperature differences between meteorological analyses in two cold Arctic winters and their impact on polar processing studies, *J. Geophys. Res.*, *108*(D5), 8328, doi:10.1029/2001JD001149.

Randel, W., et al. (2004), The SPARC intercomparison of middle-atmosphere climatologies, *J. Clim.*, *17*, 986–1003.

Schrøder, T., S. Leroy, M. Stendel, and E. Kaas (2003), Validating the microwave sounding unit stratospheric record using GPS occultation, *Geophys. Res. Lett.*, *30*(14), 1734, doi:10.1029/2003GL017588.

Staelin, D. H., and F. W. Chen (2000), Precipitation observations near 54 and 183 GHz using the NOAA-15 satellite, *IEEE Trans. Geosci. Remote Sens.*, *38*, 2322–2332.

Thépaut, J.-N., and E. Andersson (2003), Assimilation of high-resolution satellite data, *ECMWF Newsl.*, *97*, 6–12.

Wickert, J., T. Schmidt, G. Beyerle, R. König, C. Reigber, and N. Jakowski (2004), The radio occultation experiment aboard CHAMP: Operational data analysis and validation of vertical atmospheric profiles, *J. Meteorol. Soc. Jpn.*, *82*, 381–395.

M. Borsche, U. Foelsche, A. Gobiet, G. Kirchengast, and A. K. Steiner, Wegener Center for Climate and Global Change (WegCenter), University of Graz, A-8010 Graz, Austria. (andreas.gobiet@uni-graz.at)

J. Wickert, Department Geodesy and Remote Sensing, GeoForschungs-Zentrum Potsdam (GFZ), D-14473 Potsdam, Germany.