GPS Radio Occultation Climatologies Retrieved with High-Altitude Initialization by ECMWF Forecasts for the Creation of a Continuous Climate Record

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Introduction

The Radio Occultation (RO) method is an active limb sounding technique. A signal from a GPS (Global Positioning System) satellite is recorded on a satellite in low Earth orbit (**Fig. 1a**) and penetrates increasingly or decreasingly denser atmospheric layers depending on the relative motion of the satellites. In this way the ray is slowed down and bent resulting in "atmospheric phase delays". These can be measured with mm accuracy and inverted to accurate atmospheric profiles of bending angle, refractivity, density, pressure, and temperature, available with accurate height information. **Fig. 1b** schematically shows the RO geometry including the bending angle α and the impact parameter a.

RO measurements are especially suited for climate change studies by providing a combination of: 1) long-term stability, 2) global coverage, 3) virtually all-weather capability during day and night (L-band signals), 4) high vertical resolution (0.5 km to 1.5 km), and 5) high accuracy ($\Delta T < 1$ K).

Data

The German research satellite CHAMP (CHallenging Minisatellite Payload) continuously records about 230 RO events per day since March 2002 (less regularly since September 2001) yielding about 150 high-quality atmospheric profiles daily. With a projected lifetime until 2009, this mission provides the first opportunity to build RO based climatologies.

Measurements from the Argentine research satellite SAC-C (Satéllite de Aplicationes Scientíficas-C) can be used for climate studies from August 2001 to January 2002 and from April 2002 to September 2002 with about 100 to 200 high-quality atmospheric profiles per day.

FORMOSAT-3/COSMIC (F3C) is a Taiwan/US constellation of six satellites launched in April 2006 and data usable since August 2006. The F3C constellation records up to 3000 RO events daily yielding up to 2500 high-quality atmospheric profiles per day. **Fig. 1c** depicts the F3C/FM-1 (flight model one) event distribution of January 2007 with almost 10,000 high-quality atmospheric profiles measured. **Fig. 1d** shows the associated dry temperature climatology derived by zonally averaging into 18 latitude bands .

Method

Atmospheric phase delay and orbit data were provided from UCAR. At the Wegener Center, we have very recently re-processed all available RO data utilizing the End-to-end GNSS Occultation Performance Simulator (EGOPS) version 5.4. Within the retrieval process CHAMP profiles are statistically optimized utilizing background information. For this purpose we use 24 hrs resp. 30 hrs forecast fields of the European Centre for Medium-Range Weather Forecasts (ECMWF). As reference data for comparison we use ECMWF operational analyses. Since December 12, 2006 ECMWF assimilates GPS RO measurements rendering the analyses not independent of GPS RO retrieved profiles anymore.

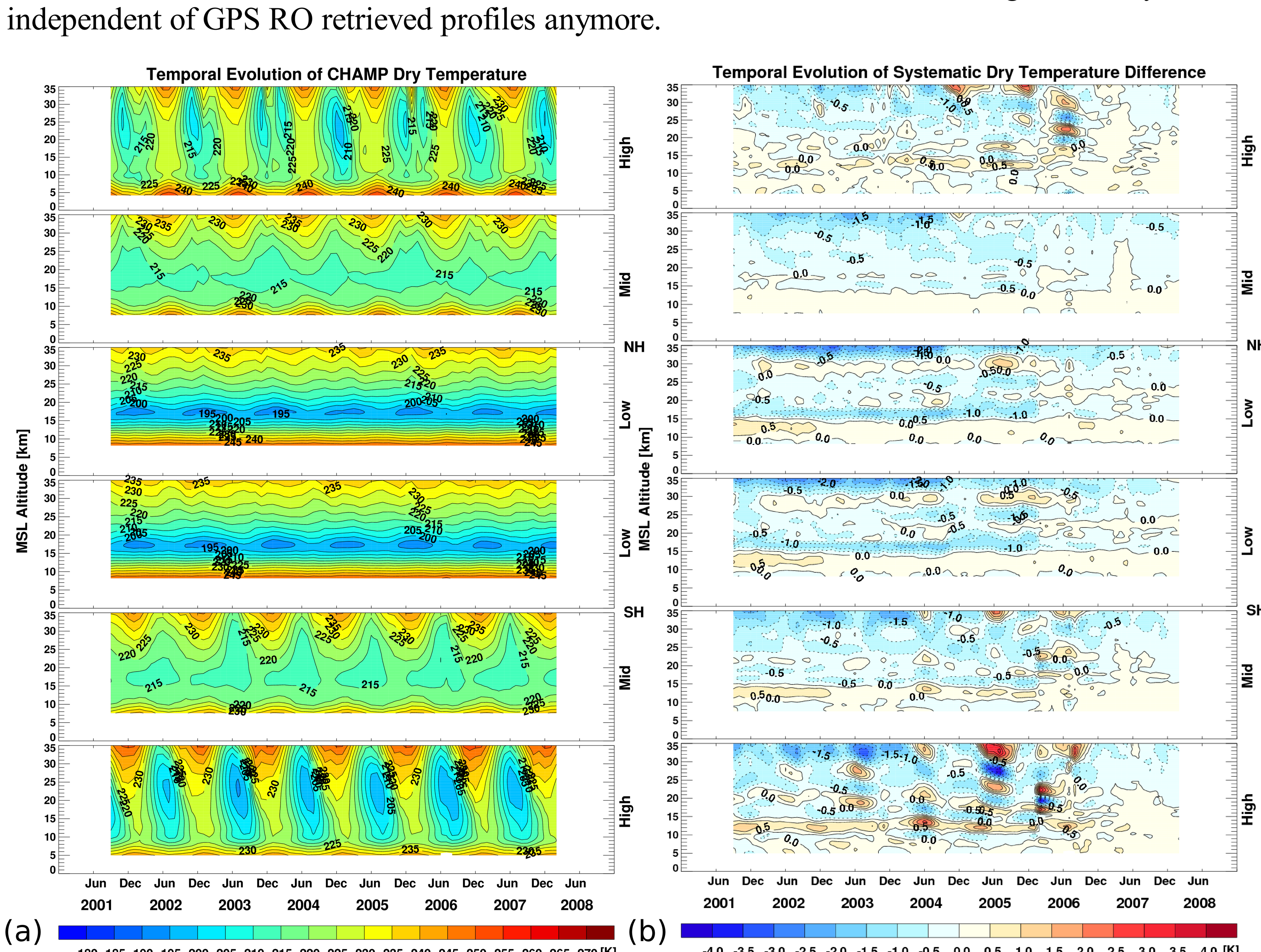

Figure 2: *Temporal evolution of dry temperature for the time period September 2001 to February 2008 as measured by the CHAMP satellite (a). Comparison of CHAMP measurements against ECMWF operational analyses yields systematic dry temperature differences (b). Temperature and systematic differences are divided into six latitude ranges of the northern and southern low-, mid-, and high-latitudes, respectively.*

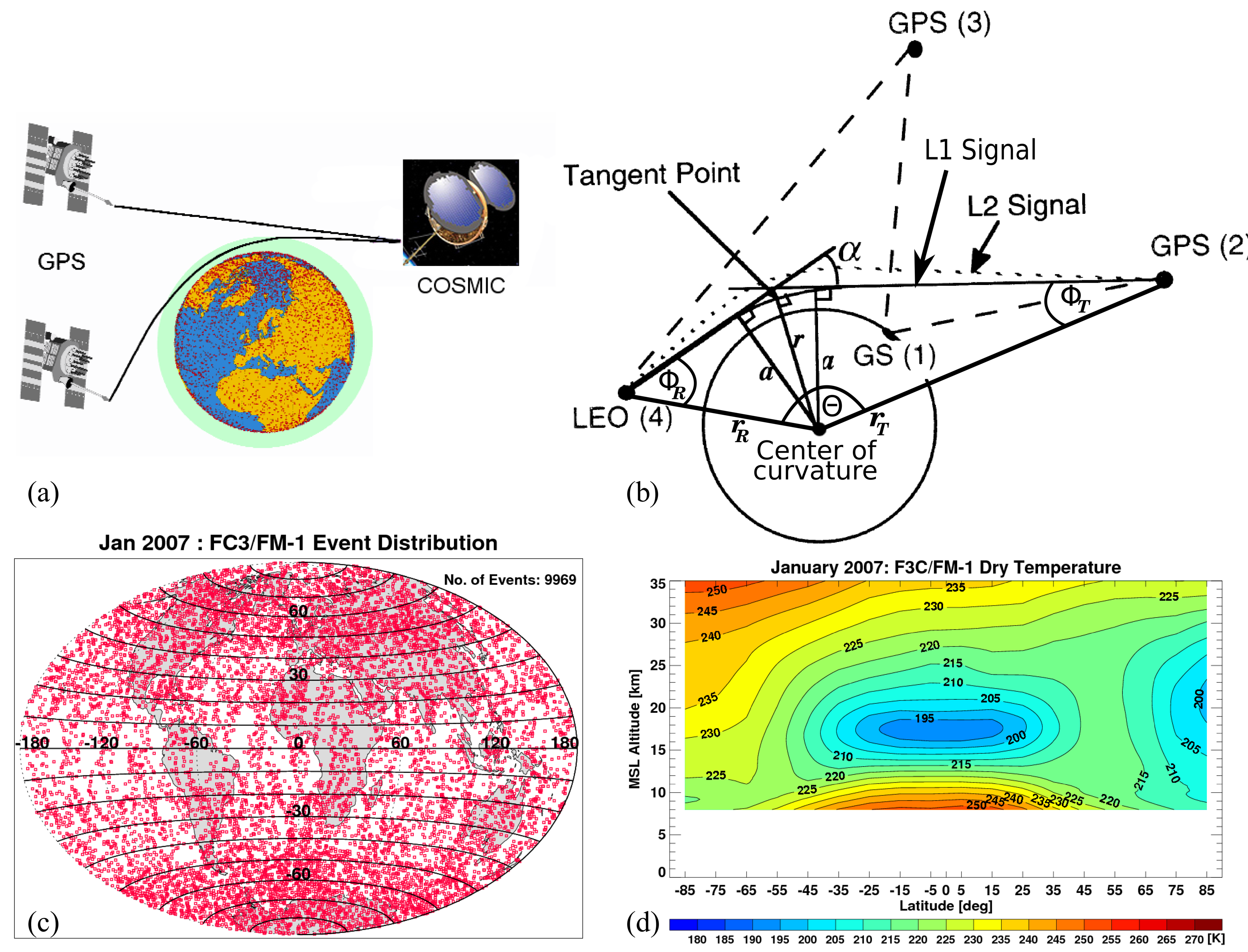

Figure 1: *A F3C satellite (a) and the RO geometry (b), with signals L1 and L2 of the GPS satellite, the bending angle* $\boldsymbol{\alpha}$ *and the impact parameter* $\boldsymbol{a}$*. Event distribution of F3C/FM-1 in January 2007 with the associated dry temperature climatology (d).*

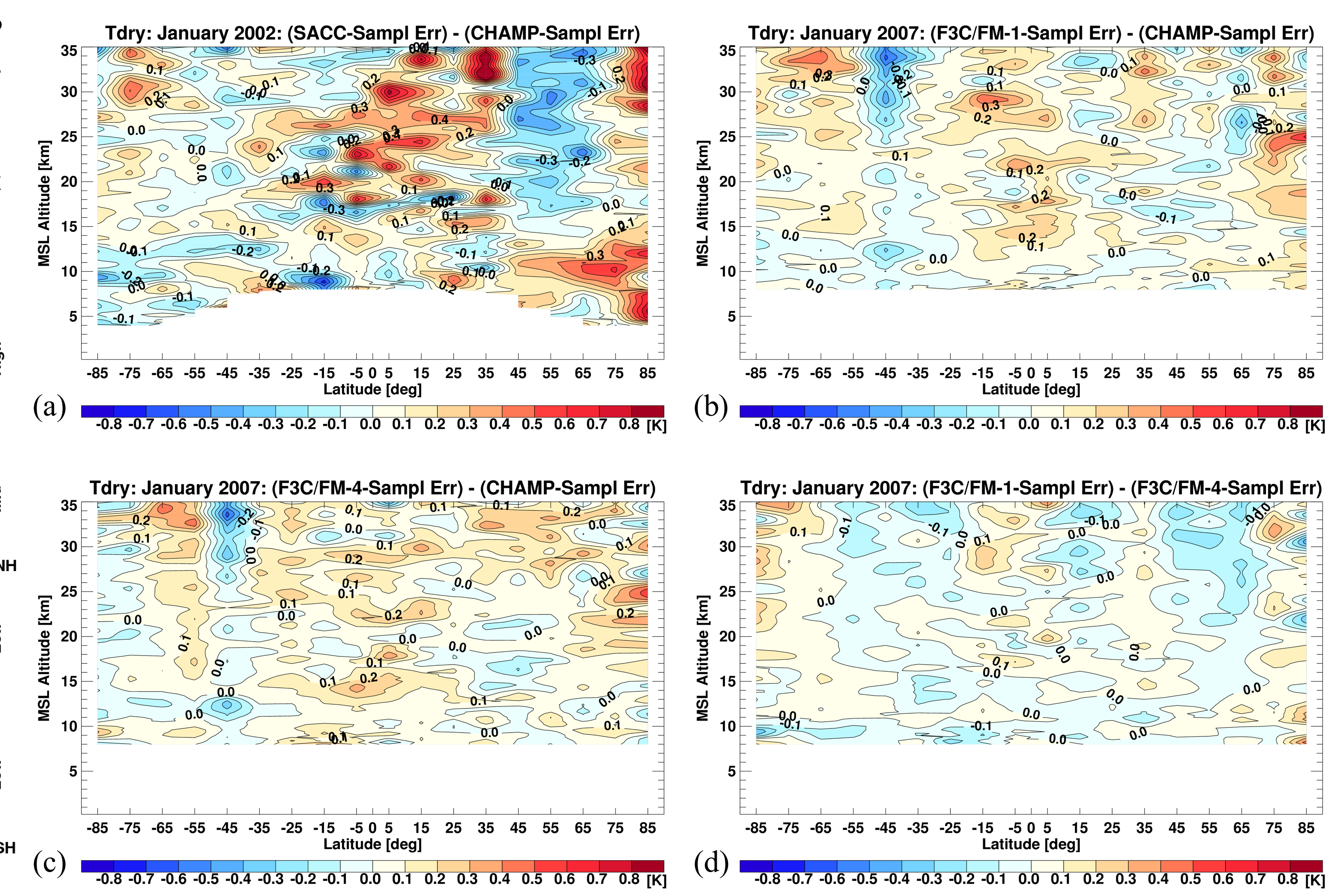

Figure 3: *Difference of the SAC-C dry temperature climatology relative to the CHAMP climatology of January 2002 (a). Differences of the F3C/FM-1 and F3C/FM-4 dry temperature climatology relative to the CHAMP climatology in (b) and (c), respectively, as well as the difference of F3C/FM-1 and F3C/FM-4 climatologies compared to each other (d).*

Results and Discussion

In **Fig. 2** the temporal evolution of zonal monthly mean climatologies of CHAMP GPS RO derived dry temperature **(a)** and the systematic differences between ECMWF analyses and CHAMP **(b)** are shown. At high-latitudes, the temperature intra-annual variation is clearly represented as well as the very low variation at low-latitudes in combination with its cold tropical tropopause. The systematic differences show an overall robust processing. From previous studies, it is known that the analyses exhibit a cold bias at altitudes above ~30 km which amounts to up to –2.5 K at mid- and high-latitudes. The analyses exhibit an additional cold bias around the tropical tropopause of up to –2.0 K terminating with February 2006 and partly varying differences at southern high-latitudes (~ –3 K to +3 K). **Fig. 3** shows monthly mean dry temperature differences between measurements from different RO satellites. The estimated sampling error based on ECMWF analyses is subtracted from each climatology. SAC-C measurements are compared to CHAMP in January 2002 (**Fig. 3a**) revealing an unbiased difference characteristic in the height range and latitude extent shown. On average, differences amount to 0.05 K with a relatively large standard deviation. Climatologies from F3C/FM-1, **Fig. 3b**, and F3C/FM-4, **Fig. 3c**, are compared to CHAMP in January 2007 with a the difference amounting on average to 0.05 K and 0.06 K for FM-1 and FM-4, respectively, and a smaller standard deviation than in the previous comparison. Finally, F3C climatologies were inter-compared, **Fig. 3d**, revealing a virtually non-existent difference of –0.005 K with a similar small standard deviation.

After subtraction of the estimated sampling error, GPS RO measurements from different satellites reveal very small differences which allows them to be used together in climate records making these measurements ideal for climate monitoring and climate trend analyses.

Acknowledgments: The work of MB and BP was supported by the Austrian Science Fund (FWF, CLIMROCC project). UF received financial support from the Max Kade Foundation, New York, NY, and from UCAR, Boulder. UCAR is acknowledged for the provision of CHAMP, SAC-C, and F3C data, and ECMWF Reading, UK, for access to analysis and forecast data.