Analysis of migrating diurnal tides detected in FORMOSAT-3/COSMIC temperature data

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¹ The characteristics of atmospheric tides in the upper troposphere and lower stratosphere region are investigated using radio occultation (RO) measurements performed by the Formosa Satellite Mission-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (FORMOSAT-3/COSMIC) satellite constellation and compared to tides observed in short-term forecast model fields of European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP). Spectral analysis of 2 years of monthly data (2007 to 2008) yields the migrating diurnal tide to be the largest spectral component. This diurnal tide shows similar temporal, latitudinal, and altitudinal characteristics in all data sets equatorward of 50°. Beyond 50°, COSMIC local time sampling is insufficient within 1 month, which prevents space-time spectral analysis from isolating atmospheric waves. Diurnal tides of temperature are characterized by largest amplitudes in the tropics (0.8 K to 1.0 K at an altitude of 30 km). Amplitudes of diurnal tides analyzed in model data are more pronounced by ~20%. An annual cycle of the amplitudes, characteristically linked to the movement of the intertropical convergence zone, is clearly revealed. Tropical diurnal phase features downward progression of waves fronts with a vertical wavelength of 20 km. Extratropical diurnal tides are most pronounced in the model data sets with amplitudes of up to 0.5 K at 30 km. In this analysis we also see the influence of high-altitude initialization of RO data by background information in using data processed by two different centers (University Corporation for Atmospheric Research (UCAR) and Wegener Center (WEGC)). UCAR data, initialized by a climatology without tidal information, exhibit no appreciable extratropical diurnal tides, while WEGC data, initialized by ECMWF forecasts, show more pronounced ones. Overall the results underpin the utility of the local-time resolving COSMIC RO constellation data for monitoring diurnal tide dynamics in the stratosphere. The agreement between observational and model data further confirms that the tidal dynamics is appropriately captured in the models, which is important for other (middle/upper) atmosphere models relying on ECMWF or NCEP dynamics.


1. Introduction

[2] In April 2006 the satellite constellation FORMOSAT-3/ COSMIC (Formosa Satellite Mission-3/Constellation Observing System for Meteorology, Ionosphere, and Climate) [Anthes et al., 2008], COSMIC hereafter, was launched into orbit. The constellation consists of six platforms, which are evenly distributed in space (approximately 30° orbit plane separation). One single COSMIC satellite is able to perform more than 10,000 Global Positioning System (GPS) radio occultation (RO) measurements per month. GPS RO measurements are known to be intrinsically calibrating and long-term stable [Ho et al., 2009; Steiner et al., 2009]. They feature best quality in the upper troposphere and lower stratosphere region (UTLS, ∼5 km to 35 km altitude) where they have a very high vertical resolution (∼0.5 km to ∼1.5 km) as well as high accuracy and precision (e.g., for temperature <1 K) [Kursinski et al., 1997; Steiner et al., 2001; Hajj et al., 2002; Schreiner et al., 2007; Anthes et al., 2008].

[3] RO climatologies (e.g., monthly, seasonal, or annual) are obtained by “binning” and averaging over a large number of vertical profiles [Foelsche et al., 2008]. The quality of a climatology depends on the quality of the measurement itself and of its retrieval [Ho et al., 2009] as well as on the sampling characteristic of the satellite [Pirscher et al., 2007a]. The
satellite orbits, the number of measurements, and atmospheric variability determine the sampling error of a climatology. High atmospheric variability (e.g., at high latitudes during wintertime) demands a large number of measurements to minimize the sampling error, whereas low atmospheric variability (e.g., in the tropics) is captured by a smaller number of measurements. The satellite orbits of transmitters and receivers determine the global distribution of RO events and the local time when measurements are taken [Pirscher et al., 2007a; Foelsche et al., 2009a].

Atmospheric tides are known to have strongest impact on the local–time component of the sampling error. The local–time component of the sampling error of a Sun-synchronous receiving satellite is constant with time if the diurnal tide is constant. A changing diurnal tide or a slowly drifting satellite yields a change in the local time component, in the sampling error, and consequently in the climatology itself. A constellation of satellites in orbits with high drifting rates can overcome this problem by actually sampling diurnal tides. The orbit design of the COSMIC constellation allows the determination and also monitoring of atmospheric tides on a monthly basis, equatorwards of 50°N/S.

Atmospheric tides are global-scale waves, which can be classified into thermal and gravitational tides [Chapman and Lindzen, 1970]. Absorption of solar radiation by tropospheric water vapor and stratospheric ozone as well as tropospheric latent heat release yield migrating thermal tides [Hagan, 1996; Hagan and Forbes, 2002, 2003]. These tides move westward with the apparent motion of the Sun. Zonal wave numbers $k$ of migrating tides, where positive wave numbers correspond to westward motion, therefore equal their frequencies, $n$, in cycles per day (e.g., migrating tides DW1 and SW2, where DW1 is the westward propagating diurnal tide with $k = 1$ and $n = 1$ cycle per day, and SW2 is the westward propagating semi-diurnal tide with $k = 2$ and $n = 2$ cycles per day).

Any longitudinal variation in the absorbing medium such as large-scale regional cloudiness, diurnally varying latent heat release (convective heating), including variations in the Earth’s surface (land-sea contrast and topography) give rise to additional non-migrating tidal components ($k \neq n$, e.g., eastward propagating diurnal tides, DE) [e.g., Tsuda and Kato, 1989; Lieberman, 1991; Williams and Avery, 1996].

The most prominent atmospheric tidal mode is the Sun-synchronous migrating diurnal tide, which has an amplitude of $\sim 1$ K at 30 km at tropical latitudes [Alexander and Tsuda, 2008; Zeng et al., 2008]. Amplitudes of other components are significantly smaller in the UTLS region, which limits the observation, especially of non-migrating tides. In the mesosphere and lower thermosphere (MLT), however, tidal amplitudes are larger. At 115 km, for example, the amplitude of the migrating diurnal tide is larger than 20 K, the amplitude of the migrating semi-diurnal tide amounts to $\sim 16$ K, and the amplitude of the eastward propagating diurnal wave with wave number 3 (DE3) is $\sim 8$ K [Zhang et al., 2006].

We investigate the diurnal tide of temperature in the UTLS region using RO data of the COSMIC satellite constellation. Our main focus lies on the analysis of the migrating diurnal tides at low- and mid-latitudes.

Studies on diurnal tides within the UTLS region have been performed by, e.g., Tsuda et al. [1997], Seidel et al. [2005], Alexander and Tsuda [2008], and Huang et al. [2009] using radiosonde data and by, e.g., Revathy et al. [2001] and Riggin et al. [2002] using radar data. These ground-based data contain global and local signatures of atmospheric tides and it is not possible to separate migrating from non-migrating diurnal tides. Zeng et al. [2008] used CHAMP (CHAllenging Minisatellite Payload) RO measurements to detect migrating diurnal tides within the tropics. The single satellite RO mission CHAMP yields the longest available RO data set with data available from 2001 to 2008. The design of the CHAMP orbit leads to a local–time drift of three hours within one month. Consequently it is not possible to observe diurnal tides within one month or one season. For that reason it is necessary to synthetically merge data from a number of years. With this study we advance the work of Zeng et al. [2008] by investigating the comprehensive COSMIC RO data and applying the same method to isolate atmospheric tides (space–time spectral analysis). The main advantages of the COSMIC data set are the large number of measurements performed by six evenly distributed satellites and the resulting high local–time resolution of diurnal tide analyses, which is possible on a continuous monthly scale.

To provide valuable context, comparisons are drawn to migrating diurnal tides analyzed in ECMWF (European Centre for Medium Range Weather Forecasts) and NCEP (National Centers for Environmental Prediction) data. In an early study, Hsu and Hoskins [1989] have shown that ECMWF analyses depict diurnal and semi-diurnal tides below 50 hPa. Since RO data are operationally assimilated at ECMWF and NCEP, we investigate short-term forecasts (24 h to 45 h forecasts) to look for diurnal tides rather than analyses, which avoids direct inter-dependencies and investigates the models’ dynamics.

Section 2 gives a description of the COSMIC RO data set and of the ECMWF and NCEP forecast data. A brief introduction in space–time spectral analysis, used to extract the tidal modes, and an error analysis are given in section 3. Results are presented in section 4 and section 5 closes with a summary and conclusions.

2. Data

We estimate diurnal tides of temperature on a continuous monthly scale from January 2007 until December 2008. RO data and ECMWF short-term forecasts are used between 8 km and 35 km altitude with a vertical gridding of 0.2 km; NCEP forecast data were available on 26 pressure levels from which we used 10 pressure levels (300 hPa and above).

The RO method, some retrieval information, and the data set itself are introduced in subsection 2.1. COSMIC orbit characteristics and resulting local–time sampling in subsection 2.2 and ECMWF and NCEP data in subsection 2.3.

2.1. COSMIC RO Data

The global positioning system (GPS) RO method [Kursinski et al., 1997; Steiner et al., 2001; Hajj et al., 2002] is an active limb sounding technique, which allows the retrieval of atmospheric profiles of bending angle, refractivity, density, pressure, temperature, and humidity. Measurements are performed when GPS signals are tracked by a low Earth orbit (LEO) satellite. From the LEO’s perspective a GPS
satellite sets behind or rises from the horizon during an occultation event. This is caused by the relative motion of the satellites and results in a near-vertical scan of the atmosphere. The Earth’s atmospheric refractivity field yields an excess phase delay in GPS signals. Briefly summarizing the RO retrieval processing (for details see, e.g., Gobiet et al. [2007]), the derivative of atmospheric excess phase delay with respect to time yields atmospheric excess Doppler-shift. Next, atmospheric bending angle is derived from atmospheric Doppler shift and precise orbit data. The retrieval of refractivity is performed by integrating the bending angle profile by an Abel integral, assuming spherical symmetry. To reduce the effect of error propagation downward into the UTLS region from this integration, the bending angle is initialized at high altitudes >30 km with background information [Gobiet and Kirchengast, 2004] so that the refractivity is background dominated above about 40 km and observation dominated below [e.g., Gobiet et al., 2007].

[15] In atmospheric regions where moisture is negligible, which holds true for altitudes above ~8 km (polar regions) and 14 km (tropics) [Foelsche et al., 2008], the refractivity is directly proportional to dry air density. Pressure is obtained using the hydrostatic integral under the assumption of hydrostatic equilibrium and the application of the ideal gas law allows the calculation of temperature. The neglect of moisture is specified by the term “dry air retrieval”, which yields dry atmospheric parameters, e.g., “dry temperature”. Physical atmospheric parameters and humidity profiles can be derived using auxiliary information obtained from independent data sets [e.g., Healy and Eyre, 2000].

[16] The Wegener Center (WEGC) retrieval (a dry air retrieval, retrieval version OPSv5.4, [see auxiliary material of Steiner et al. [2009]]) uses phase delay and orbit data provided by UCAR/CDAAC (University Corporation of Atmospheric Research/COSMIC Data Analysis and Archive Center). The retrieval utilizes co-located ECMWF short-term forecasts as background information above an altitude of 30 km (24 h/30 h forecasts, four time layers; co-location means nearest time layer and spatial interpolation to mean occultation event location). Dependent on the quality of the COSMIC measurements, most atmospheric profiles are observation dominated below 40 km [Pirscher et al., 2007b; Foelsche et al., 2009b]. However, some background information remains in the refractivity profile as far down as 30 km and it propagates further downwards when calculating atmospheric pressure using the hydrostatic integral. For that reason diurnal tides detected with WEGC RO data are partially influenced by ECMWF short-term forecasts. To quantify this effect we also use UCAR/CDAAC COSMIC dry temperature data (version 2007.3200). Within the high-altitude initialization, CDAAC uses a background model, which is based on NCAR climatology exponentially extrapolated to 150 km [Randel et al., 2002, section 4]. The initialization process involves the optimal mixing of the observed and background bending angle, which is described by Kuo et al. [2004]. The background NCAR climatology does not possess any diurnal variation.

[17] Dependent on the satellites’ health, the COSMIC satellite constellation performs between 1500 and 2500 measurements per day. At WEGC, on average, about 75% of these measurements are of high quality. This means that profiles pass internal quality control (technical aspects and data consistency) and external quality control for “outlier” profiles (applied to retrieval results, where retrieved profiles of refractivity and temperature are compared to co-located profiles extracted from ECMWF analysis fields). Between January 2007 and December 2008 we have always more than 40,000 high quality RO profiles per month.

2.2. COSMIC Orbits and Local-Time Sampling

[18] The satellite’s inclination and its orbit altitude determine the drifting rate of a satellite [Hoffmann-Wellenhof et al., 1997; Larson and Wertz, 1997; Boain, 2005; Pirscher et al., 2007a]. The precession rate $\Omega$ decreases with increasing orbit altitude and with increasing inclination. If it refers to the Earth’s mean motion, $\Omega_\odot$ is calculated from $\Omega_\odot = 0.9856^\circ/d - \Omega$. The precession rate of a satellite determines the sampling behavior with respect to local time. The larger the difference between the orbital precession rate and the mean motion of the Earth, the shorter the time span to sample through all local times.

[19] Shortly after their launch in April 2006, the six COSMIC satellites reached an orbital altitude of ~520 km and an inclination of ~72°, yielding an orbital precession rate of $\Omega \approx -2.34^\circ/d$ and $\Omega_\odot \approx 3.33^\circ/d$. Figure 1 illustrates the subsequent evolution. Consecutive orbit raising from 520 km to 800 km (Figure 1a), with the inclination kept constant, yielded a change in drifting rate to $\Omega \approx -2.04^\circ/d$ and $\Omega_\odot \approx 3.02^\circ/d$ (Figure 1b) and a desired orbit separation of 30° (Figure 1c). In June 2006 the first satellite separated from the others, it was FlightModel-5 (FM-5). In December 2007 the final constellation should have been developed, but since the solar panels of FM-3 were stuck, its orbit raising has been halted at an altitude of 710 km in July 2007.

[20] RO measurements can be performed during day and night. The geographical location of an RO event is situated approximately 3000 km away from the COSMIC satellite (limb-viewing geometry). At the equator, ascending and descending nodes of any satellite track are separated by 12 h. With a precession rate of ~3°/d, which is equal to 6 h/month, RO measurements of a single COSMIC satellite drift through all local times within ~60 days. For the entire COSMIC constellation (with 30° orbit plane separation) it takes about 10 days to sample all local times at low latitudes. Figures 1d to 1f illustrate the local-time sampling in January 2008 for FM-1, FM-2, and the COSMIC constellation.

[21] At higher latitudes, where ascending and descending branches of the orbit move close together (in terms of local-time sampling), measurements are separated by less than 12 h [Leroy, 2001] (Figures 1d and 1e). At 72° latitude ($\sim 72^\circ$), ascending and descending branches of the COSMIC orbital track get together. A satellite constellation consisting of six platforms, which are separated by 30°, is never able to sample all local times beyond ~50° within one month—a small gap remains (Figure 1f). This gap of measurements drifts with the same rate as the satellites themselves. For the same reason, local time sampling is very similar for two months, separated by one year (e.g., for January 2007 and January 2008).

2.3. ECMWF and NCEP Data

[22] Because of the high quality in the UTLS region and their global availability, RO data have significant impact on global/regional weather analysis and prediction [Kuo et al.,...
2000; Liu et al., 2001; Healy and Thepaut, 2006]. Since December 12, 2006 RO data are operationally assimilated at ECMWF [Healy, 2007], since May 1, 2007 the assimilation of RO profiles became operational at NCEP [Cucurull and Derber, 2008], rendering the operational analyses not independent of RO profiles any more. For that reason we investigate ECMWF and NCEP short-term forecast data to look for diurnal tides.

To obtain ECMWF forecast data at eight equally distributed UTC (Universal Time Coordinated) time layers (00 UTC, 03 UTC, 06 UTC, 09 UTC, 12 UTC, 15 UTC, 18 UTC and 21 UTC), we extract 24 h to 45 h forecasts (initial analysis at midnight) with a horizontal resolution of $\sim 2.5^\circ \times 2.5^\circ$ at 91 vertical levels (T42L91). These 91 vertical levels, which range up to $\sim 80$ km, are interpolated to a regular 200 m grid (only used between 8 km and 35 km).

Dry temperature, which is used to estimate atmospheric tides from ECMWF data, is approximated from physical temperature $T$ (in K) and specific humidity $q$ (in kg/kg) [Foelsche et al., 2008] by

$$T_{dry} \approx T(1 - 12q).$$

Operational Global Forecast System (GFS) forecasts are provided by the data archive at NCDC/NOMADS (National Climatic Data Center/NOAA Operational Model Archive and Distribution System). To be on a par with ECMWF, we also use 24 h to 45 h forecasts (3 h forecast interval) with initial analysis at midnight. The data are provided on a regular $0.5^\circ \times 0.5^\circ$ horizontal latitude-longitude grid, with 26 vertical standard pressure levels (GFS 004 domain). We use data at [10, 20, 30, 50, 70, 100, 150, 200, 250, 300] hPa. The main focus of this study is the lower stratosphere region, where dry temperature is essentially equal to physical temperature (negligible water vapor).
Therefore we restrict our analysis of NCEP diurnal tides to physical temperature.

3. Methodology

[26] Information on global atmospheric waves is present in RO data. The spatial and temporal scales of the waves as well as characteristics of the data set determine the method used to extract the waves. This section describes the methodology used to obtain information on atmospheric diurnal tides using COSMIC RO and model data.

[27] Diurnal tides are investigated in different latitudinal regions, where the mean atmospheric profile of each region has to represent typical atmospheric characteristics and the variation of corresponding single measurements must not be too large. Therefore, the optimal extent of the regions to detect diurnal tides is a tradeoff between a sufficiently large number of RO profiles and small atmospheric variability. We found both, a sufficient number of measurements and reasonably similar atmospheric characteristics, in selecting 5° zonal bands. These bands range from 90°S to 90°N resulting in 36 zonal bands. At low- and mid-latitude the number of profiles available within one band varies between 1000 and 2500; at high latitudes, the number of profiles is significantly less.

[28] Monthly averaged local-time variations of dry temperature ("diurnal temperature variations") enable a first view of diurnal tides [Pirscher et al., 2009]. First of all, in data preparation for this purpose, any RO event is allocated to the appropriate 5° zonal bin. To remove synoptic atmospheric variability, the daily-mean 5° zonal mean ECMWF forecast profile is subtracted from each single COSMIC profile. Finally, diurnal temperature variations are calculated by averaging over all profiles belonging to the same local-time bin (we chose eight local-time bins with three hours width) and subtracting the mean profile of all local-time bins. This approach does not contain any confining assumption but it strongly depends on the number of profiles and atmospheric variability. Furthermore, it does not split particular modes of total oscillation but represents the superposition of all waves.

[29] Figure 2 shows diurnal temperature variations of WEGC COSMIC and ECMWF data. Northern hemispheric winter is accompanied by strong atmospheric variability. An unequally distributed number of profiles for each local-time bin (Figure 2, left; see also Figure 1f) results in inhomogeneous diurnal temperature variations. Otherwise, a regular number of measurements and comparably low variability unveil patterns, which are similar to diurnal tides determined with a more sophisticated method.

[30] We use space-time spectral analysis [Hayashi, 1971] to decompose atmospheric tides into zonal wave number and direction (space) and period (time). The space dimension of the data set covers zonal bands with 5° width and is analyzed with respect to wave numbers k. We use 64 grid points in longitude (spatial resolution: 5.625°) for the RO data sets and 32 grid points for the model data sets (spatial resolution: 11.25°). Time is gridded in 64 points in the RO data sets (UTC resolution: 0.375 h) and 8 points (only 8 time layers available, UTC resolution: 3 h) in the model data sets. To sum up, the RO data set X_r(λ, t), with geographical latitude φ, longitude λ, and time t, is gridded into 64 × 64 points and the forecast model data are gridded into 32 × 8 points. Sensitivity tests with different resolutions showed that the results of space-time spectral analysis are stable with these resolutions, i.e., changes of grid density have little effect (±0.05 K) on the analysis results.

[31] Space-time spectral analysis is applied separately for each month, each zonal latitude band, and each height level. Again, the daily mean ECMWF forecast profile is subtracted from each single COSMIC profile. The mean longitude-UT field is calculated by averaging over all profiles, which are available in each grid cell. Grid cells, which do not contain any data, are filled applying bilinear interpolation from neighborhood cells. Mean longitude-UT fields of ECMWF and NCEP are calculated in the same way.

[32] The space dimension is analyzed with Fourier analysis for each single time step t, yielding Fourier coefficients C_k(t) and S_k(F), which correspond to the data series x(λ, t). Examination of temporal variations of one wave number (k fixed) enables us to find temporal periodic behavior. Fourier analyses of the time series C_k(t) and S_k(t) yield the Fourier coefficients A_k(ω) and B_k(ω) and a_k(ω) and b_k(ω), respectively.

[33] After the computation of temporal variations of all wave numbers, the Fourier coefficients of C(k, t) are represented by the matrices A_k(ω) and B_k(ω), combined in the complex quantity F_k; the Fourier coefficients of S(k, t) are represented by the matrices a_k(ω) and b_k(ω), combined in the complex quantity F_a.

[34] The power spectra \( P_+(C) = F_k^*F_k \) and \( P_-(S) = F_a^*F_a \) (\(^*\) denotes the complex conjugate), and the quadrature spectrum (imaginary part of the cross spectrum) \( Q = \text{Im}(F_k^*F_a) \) enable the calculation of the power spectra of the separated waves:

\[
P_{+\omega} = \frac{1}{4}(P_r(C) + P_r(S) + 2Q_r(C, S))
\]

\[
P_{-\omega} = \frac{1}{4}(P_r(C) + P_r(S) - 2Q_r(C, S)).
\]

\( P_{+\omega} \) is the power spectrum for westward traveling waves and \( P_{-\omega} \) for eastward traveling ones. The corresponding waves’ phase is calculated from

\[
\varphi_{+k\omega} = \tan^{-1} \left[ \frac{-b(k, \omega) - a(k, \omega)}{a(k, \omega) - b(k, \omega)} \right]
\]

\[
\varphi_{-k\omega} = \tan^{-1} \left[ \frac{b(k, \omega) - a(k, \omega)}{a(k, \omega) + b(k, \omega)} \right],
\]

where phase denotes local-time of maximum temperature, (i.e., phase of wave crests).

[35] The RO data set is decomposed into 32 wave numbers and 32 frequencies and the ECMWF and NCEP model data are decomposed into 16 wave numbers and 4 frequencies (recall that corresponding longitude-UT resolutions were 64 × 64 and 32 × 8 for the RO and the model data sets, respectively). Waves with wave number \( k = +1 \) and period \( T = 24 \) h (frequency \( n = 1 \) cycle d\(^{-1}\)) travel westward and are called migrating diurnal tides, DW1. The SW2 wave is equal to the migrating semi-diurnal tide, wave number \( k = +2 \) traveling westward with the period \( T = 12 \) h (frequency \( n = 2 \) cycles d\(^{-1}\)).
A Hovmöller diagram shown in Figure 3a, presents the temperature anomaly of COSMIC data in January 2008 at an altitude of 30 km between the equator and 5°N. This 64 × 64 longitude-UT field is decomposed with spectral analysis. The dashed line corresponds to midnight local time. It is obvious that the positive temperature anomalies lie close to the dashed line. This corresponds to the tide DW1 with temperature maximum close to midnight. Confirmation is obtained by calculating the spectrum (Figure 3b). The wave with $k = 1$ and $T = 24$ h, DW1, exhibits the maximum spectral amplitude, all other components show negligible contribution.

Figures 3c and 3d depict the diurnal tides ($T = 24$ h) in terms of altitude and latitude dependence, respectively. In Figure 3c, the height cross-section near the equator shows that the spectral amplitude of DW1 increases with height and all other components yield a negligible spectral amplitude at all height levels. Figure 3d shows that beyond 50°N, spectral amplitude is large for all wave numbers $-8 \leq k \leq 8$. This only means, however, that atmospheric waves cannot be isolated because the spectral analysis fails.

This indicates that high atmospheric variability during wintertime and the comparatively low number of measurements at high latitudes yield significant aliasing errors.

To estimate the errors associated with COSMIC sampling, we extract profiles from ECMWF forecast fields, which are co-located to times and locations of COSMIC events. These profiles are used to estimated atmospheric tides using ECMWF data from a non-optimally sampled field. The sampling error of our atmospheric tides is estimated from the spectral components of the difference field, the co-located longitude-UT ECMWF field minus the full longitude-UT ECMWF field.
Figure 4 depicts the spectral amplitude of the sampling error with $T = 24$ h as a function of wave number and latitude (Figure 4, left) and spectral amplitude of the sampling error with $k = 1$ and $T = 24$ h as a function of latitude and height (Figure 4, right) for January 2008. We find strongest spectral amplitudes of the sampling error in regions with high atmospheric variability (in winter polewards of 50° latitude). Non-negligible sampling errors occur also at mid and high latitudes below approximately 13 km. Spectral phase (not shown) does not show any regular pattern.

Figure 3. (a) Temperature anomaly at an altitude of 30 km as a function of longitude and universal time. This field, the zonal band between 0° and 5°N is spectrally analyzed. (b) Spectral amplitude as a function of wave number and period at 30 km, and spectral amplitude of diurnal tide (period of 24 h) as a function of (c) wave number and height and (d) wave number and latitude, the latter involving all 5° bands. Migrating tides are located along the dashed line.

Figure 4. (left) Spectral amplitude of the sampling error with $T = 24$ h as a function of wave number and latitude in January 2008 and (right) spectral amplitude of the sampling error with $k = 1$ and $T = 24$ h as a function of latitude and height in January 2008.
The systematic retrieval error of radio occultation measurements does not yield any error in spectral amplitudes and phases because it is eliminated when performing spectral analysis. However, the systematic difference originating from different retrieval algorithms is quantified comparing two COSMIC data sets from such different retrievals (CDAAC and WEGC).

4. Results and Discussion

4.1. Characteristics of DW1 in the UTLS

Amplitudes (Figure 5) and phases (Figure 6) of DW1 are shown as a function of latitude and altitude for January 2008, April 2008, July 2008, and October 2008 for WEGC COSMIC (left) and ECMWF (right).

We observe in both data sets maximum amplitudes at high altitudes for all months. Maximum tropical diurnal amplitudes show a latitudinal shift with height. Below ~27 km, they follow the movement of the inter-tropical convergence zone (which is always located in the summer hemisphere) whereas they shift to the opposite hemisphere at higher altitudes. During spring and autumn (equinox) spectral amplitude is nearly symmetric to the equator. This temporally changing vertical structure agrees well with that observed in CHAMP data [Zeng et al., 2008]. A similar latitude-height structure of the amplitude of the diurnal tide was found in the Canadian Middle Atmosphere Model (CMAM) as shown by McLandress [2002a, Figures 3c and 3f]. McLandress [2002b] attributed this seasonal variation to the interference of the latitudinal symmetric and anti-symmetric vertically propagating modes, which have different vertical wavelengths.

Extra-tropical amplitudes are clearly observable above an altitude of 30 km. They are visible in both data sets (smoother in the ECMWF model data) and more pronounced in the summer hemisphere. COSMIC data occasionally show large amplitudes in the extra-tropics, which are not visible or at least not as pronounced in the ECMWF data set.

Tropical diurnal phase exhibits symmetric characteristics with respect to the equator during equinox, where maximum temperatures are observed in the late afternoon at an altitude of ~15 km, in early morning at an altitude of ~20 km, and again in the late afternoon at an altitude of ~35 km. In January and July (solstice) the vertical structure of the tropical diurnal phase is asymmetric about the equator. Extra-tropical phases, which are well-defined in the model data set, predominantly amount to 15 h to 18 h.

4.2. Comparison of DW1 Detected With Four Data Sets

Figure 7 shows amplitudes and phases as a function of altitude/pressure at different latitudes in January 2008 (Figure 7, left) and July 2008 (Figure 7, right) for all four data sets. Altitude-pressure conversion (necessary since NCEP data are only available at pressure levels) is done using the barometric formula \( p = p_0 \exp(-h/h_0) \) with a scale height of \( H = 7 \) km and a surface pressure of \( p_0 = 1013.25 \) hPa. This basic approximation does not account for seasonal pressure variations but works reasonably well for the purpose.

Observational and model data show the same characteristics with small differences between the data sets. Vertical profiles of amplitude clearly show an increase of amplitude with altitude, which results from wave energy conservation and the decrease in density with height, yielding increasing tidal amplitudes with altitude [e.g., Chapman and Lindzen, 1970].

Vertical profiles of amplitudes and phases in mid-latitude winter (30°N to 35°N in January 2008 and 30°S to 35°S in July 2008) are similar in both hemispheres. Amplitudes of observational data sets are more variable with height than amplitudes of model data. Strong variability blurs the altitude level where the increase of amplitude is established. NCEP amplitudes almost coincide with ECMWF data, despite the lower vertical resolution and the approximated pressure-altitude conversion. ECMWF/NCEP show increasing amplitudes above ~16 km/19 km in January 2008 and above ~21 km/19 km in July 2008, respectively. Magnitudes of these tidal amplitudes are in good agreement with those of the Global Scale Wave Model (GSWM-00) [Hagan et al., 2001] and GSWM-02 [Hagan and Forbes, 2002, 2003] as shown by Huang et al. [2009].

Diurnal phase in mid-latitude winter is decreasing with height. Downward propagation of phase corresponds to upward propagation of wave energy. This is one of the fundamental properties of gravity waves, which reveals that phase fronts of gravity waves progress nearly perpendicular to group velocity (energy transport) [Lindzen, 1990]. The vertical wavelength, which can be approximated by inspection of the phase plots, amounts to ~20 km. WEGC COSMIC phase separates from the other data sets at an altitude of ~20 km. The cause of this WEGC COSMIC phase characteristic is unclear at this stage.

In mid-latitude summer (30°N to 35°N in July 2008 and 30°S to 35°S in January 2008) amplitudes of DW1 observed in model data are more pronounced than amplitudes of DW1 detected in observational data above ~27 km. WEGC COSMIC amplitudes are smaller than model amplitudes but stronger than CDAAC COSMIC amplitudes. CDAAC COSMIC data do not show significant amplitudes in mid-latitude summer. Differences in WEGC and CDAAC COSMIC data sets reflect the influence of retrieval differences, in particular the impact of high-altitude initialization of bending angles (see section 2.1) on diurnal tides detected with RO data. As noted above (see subsection 2.1), WEGC bending angle profiles were initialized using ECMWF short-term forecasts (4 time layers) above 30 km. Therefore, WEGC COSMIC and ECMWF data sets are not fully independent, though background information in WEGC COSMIC data is far below 50% at 30 km [Gobiet et al., 2007]. CDAAC COSMIC data are initialized by an NCAR climatology, which does not contain tidal information. Assuming that ECMWF overestimates amplitudes of DW1, some information is transferred to WEGC COSMIC and these data may also overestimate amplitudes of diurnal tides. On the other hand, CDAAC COSMIC data may underestimate them because the initialization using an NCAR climatology tends to suppress any tidal information. Differences between WEGC and CDAAC COSMIC decrease with decreasing altitude. Below 30 km, WEGC and CDAAC COSMIC diurnal amplitudes correspond to ~0.2 K.

Maximum temperatures of diurnal tide in mid-latitude summer are always observed in the afternoon or at night. This is consistent with the phase of the GSWM-00 model, shown by Huang et al. [2009] (though only up to 25 km).
Figure 5. Spectral amplitude of DW1 detected with (left) WEGC COSMIC data and (right) ECMWF data in (top to bottom) January 2008, April 2008, July 2008, and October 2008.
Figure 6. Spectral phase of DW1 detected with (left) WEGC COSMIC data and (right) ECMWF data in (top to bottom) January 2008, April 2008, July 2008, and October 2008.
Figure 7. Spectral amplitude and phase of DW1 as a function of altitude at mid- and low latitudes (top to bottom: North–South) for (left) January 2008 and (right) July 2008.
Phase increases from noon to midnight from 8 km up to ∼14 km/17 km (January 2008/July 2008). Above, it decreases to noon again and after a small increase it remains constant at ∼17 h. The amplitude observed in CDAAC COSMIC data is so small above 25 km in July 2008 (amplitude smaller than 0.1 K) that space-time spectral analysis loses the signal and the phase detaches from the other data sets.

Tropical amplitudes and phases show best agreement of all data sets as profiles closely shadow each other. Amplitudes are very small (0.1 K to 0.2 K only) from 8 km up to ∼16 km. Above the tropopause, amplitudes increase and amount up to 1.4 K between 0° and 5°N (ECMWF amplitude in January 2008) and become even larger. Below ∼15 km, phase shows a trapped wave structure, which peaks in the afternoon; above ∼15 km, phase shows downward progression of waves with a vertical wavelength of ∼20 km. These results are in good agreement with Alexander and Tsuda [2008] and Zeng et al. [2008].

Figure 8 depicts amplitude as a function of latitude. We chose here 31 km, since pressure climatologies based on RO data show that the 10 hPa level (of NCEP data) corresponds to ∼31 km altitude in mid- and low latitudes. We note that 10 hPa equals to 32.3 km using the barometric formula as mentioned above. Table 1 summarizes the amplitude values below 50° latitude.

Table 1. WEGC COSMIC, CDAAC COSMIC, ECMWF, and NCEP Amplitudes of DW1 at 31 km/10 hPa at Low Latitudes and Midlatitudes in January 2008, April 2008, July 2008, and October 2008

<table>
<thead>
<tr>
<th></th>
<th>WEGC COSMIC</th>
<th></th>
<th>CDAAC COSMIC</th>
<th></th>
<th>ECMWF</th>
<th></th>
<th>NCEP</th>
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<tbody>
<tr>
<td>30°N to 50°N</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>15°N to 30°N</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
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<td></td>
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<tr>
<td>0° to 15°N</td>
<td>1.2</td>
<td>0.7</td>
<td>0.3</td>
<td>0.5</td>
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<tr>
<td>0° to 15°S</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
<td>0.6</td>
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<tr>
<td>15°S to 30°S</td>
<td>0.3</td>
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<tr>
<td>30°S to 50°S</td>
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<tr>
<td>15°N to 30°N</td>
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<td>0.1</td>
<td>0.2</td>
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<tr>
<td>0° to 15°N</td>
<td>1.0</td>
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<tr>
<td>0° to 15°S</td>
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<td>0.8</td>
<td>0.4</td>
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<tr>
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<td>0.2</td>
<td>0.4</td>
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<td>30°S to 50°S</td>
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<td>0° to 15°S</td>
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<td>0.9</td>
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<td>15°S to 30°S</td>
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<td>30°S to 50°S</td>
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<td>30°N to 50°N</td>
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<tr>
<td>15°N to 30°N</td>
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<tr>
<td>0° to 15°N</td>
<td>1.1</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>0° to 15°S</td>
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<td>1.1</td>
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<tr>
<td>15°S to 30°S</td>
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<td>30°S to 50°S</td>
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<td>0.3</td>
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CDAAC COSMIC by ∼35%, and NCEP by ∼22%. Tropical amplitudes are smallest in October 2008. Model data sets exhibit maximum amplitude (ECMWF: 0.9 K, NCEP: 0.8 K) in the Southern Hemisphere between 0° and 5°S, but observational data sets show maximum amplitudes in the Northern Hemisphere between 0° and 5°N (WEGC COSMIC: 0.8 K, CDAAC COSMIC: 0.7 K).

[55] Extra-tropical amplitudes of DW1 are distinctively smaller than tropical amplitudes (see also Table 1). Between 30°N/S and 50°N/S at 31 km/10 hPa, amplitudes amount to 0.3 K to 0.5 K in the model data sets. A comparison between ECMWF and NCEP forecast model data yields that extra-tropical amplitudes of DW1 are more pronounced in NCEP data than in ECMWF data. In the same region, CDAAC COSMIC amplitudes are very small, except for January and July 2008 in the winter hemispheres, respectively.

4.3. Monitoring of Diurnal Tide DW1 and Semi-Diurnal Tide SW2

[56] Figure 9 depicts amplitudes of diurnal (Figure 9, top) and semi-diurnal (Figure 9, bottom) migrating tides in WEGC COSMIC and ECMWF data at an altitude of 30 km as function of time. Tropical diurnal tides show a distinctive annual cycle, where maximum amplitudes are observed in hemispheric winter. This annual variation is similar to what has been observed with CHAMP data [Zeng et al., 2008] but different to what has been observed with SABER data in the upper atmosphere [Zhang et al., 2006; Mukhtarov et al., 2009], where maxima occur around equinox. This annual cycle results from latitudinal shift of maximum temperature with time at a constant altitude level (see Figure 5). The annual cycle in the Northern Hemisphere is more pronounced (higher maximum and smaller minimum amplitudes) than that observed in the Southern Hemisphere. Extra-tropical amplitudes of diurnal tides also show an annual cycle (the amplitudes of this annual cycle are above uncertainty level only in the ECMWF data set) but it is much less pronounced than that of tropical diurnal tides and their maximum values are observed in hemispheric summer.

[57] The semi-diurnal tide also shows maximum amplitudes (∼0.3 K) at low latitudes (10°S/N to 20°S/N). The annual cycle is similar to that observed in the tropical diurnal tide, with maximum amplitudes in winter.

[58] Figure 10 shows the temporal evolution of diurnal and semi-diurnal tides at all latitudes and at an altitude of 30 km. Local time sampling at high latitudes is roughly the same every four months (see subsection 2.2). These sampling problems of COSMIC are clearly noticeable in winter beyond ∼40° to 50° latitude. Extra-tropical amplitudes shown in Figure 9 therefore contain small but non-negligible residual sampling errors (<0.2 K) in hemispheric winter. ECMWF data feature small amplitudes of the semi-diurnal tide (up to 0.4 K), which are symmetric to the equator; they can barely be seen in the COSMIC data set.

[59] Differences in amplitudes of diurnal tides between 2007 and 2008 are very small. Table 2 summarizes mean values of amplitudes in 2007 and 2008 at an altitude of 30 km at low- and mid-latitudes. Tropical diurnal tides are distinctively stronger in the ECMWF data set than in the WEGC COSMIC data set by up to 0.2 K, but amplitudes of both data sets do not differ significantly between 2007 and 2008. Amplitudes of extra-tropical diurnal tides are also larger in the model data set. ECMWF diurnal tides at mid-latitudes are stronger in 2008 but WEGC COSMIC data show a stronger diurnal tide at southern mid-latitudes in 2007. That may be due to worse local time sampling in 2007 than in 2008 because COSMIC satellites orbit separation was not fully developed then.

5. Summary and Conclusions

[60] Radio occultation (RO) measurements from the six FORMOSAT-3/COSMIC satellites are of particular utility for observing and monitoring diurnal tides of temperature in
the upper troposphere and lower stratosphere (UTLS). The orbit design of the satellite constellation allows the determination of diurnal tides on a monthly basis equatorwards of $\sim 50^\circ$ latitude. Beyond $50^\circ$ latitude, atmospheric variability in the winter hemisphere is too strong and COSMIC sampling too sparse to adequately resolve the tides. Within $50^\circ$S and $50^\circ$N the error associated with COSMIC sampling was estimated to be less than 0.2 K nearly everywhere.

We performed space-time spectral analysis [Hayashi, 1971] to isolate atmospheric tides in COSMIC data (from January 2007 to December 2008) and draw comparisons to diurnal tides analyzed in ECMWF (European Centre for Medium-Range Weather Forecasts) and NCEP (National Centers for Environmental Prediction) short-term forecast fields (24 h to 45 h forecasts with a temporal resolution of 3 h). Differences in RO retrieval algorithms, which have an impact on diurnal tides, were investigated comparing two sets of COSMIC RO data: a data set retrieved by the Wegener Center (WEGC) and another one retrieved by the COSMIC Data Analysis and Archive Center (CDAAC) of the University Corporation for Atmospheric Research (UCAR). Spectral analysis yields the migrating diurnal tide (DW1) to be the most pronounced spectral component in all data sets. The difference between WEGC COSMIC and CDAAC COSMIC increases with height. At 30 km it reaches values of 0.2 K to 0.3 K.

Typical features of diurnal tides are found in all four data sets and they are consistent with the theory of diurnal tides [Chapman and Lindzen, 1970]. On the one hand, this agreement confirms the utility of COSMIC RO data for monitoring diurnal tide dynamics, on the other hand it confirms that tidal dynamics is appropriately captured in the models, which is important for other (middle/upper) atmosphere models relying on ECMWF or NCEP dynamics.

Best agreement is found at low latitudes. The ECMWF and NCEP model data show a more homogeneous diurnal tide at all latitudes than COSMIC observational data.

Spectral amplitudes are largest at high altitudes since tidal amplitudes generally increase with altitude. At an altitude of 30 km, typical amplitudes of migrating diurnal tides at tropical latitudes amount to 0.8 K to 1.0 K but occasionally they can also become up to 1.5 K (in ECMWF data only).

During solstice months tropical diurnal tides are characterized by a latitudinal shift with height. Below 27 km, maximum diurnal amplitudes follow the inter-tropical convergence zone (summer hemisphere); above that altitude maximum amplitudes shift to the other (winter) hemisphere. During equinox months, amplitudes are symmetric with respect to the equator. Focusing on a single confined low

Table 2. Mean Amplitudes of DW1 in 2007 and 2008 at Midlatitudes and in the Tropics at an Altitude of 30 km$^a$

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30^\circ$N to $50^\circ$N</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$0^\circ$ to $15^\circ$N</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$0^\circ$ to $15^\circ$S</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>$30^\circ$S to $50^\circ$S</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$^a$Midlatitudes: $30^\circ$N/S to $50^\circ$N/S; tropics: $0^\circ$ to $15^\circ$N/S.
latitude band and on a constant altitude level, this latitudinal shift appears as an annual cycle of maximum amplitude. Below 27 km this cycle follows the annual cycle of the intertropical convergence zone, which is more pronounced in the Northern Hemisphere than in the Southern Hemisphere, above 27 km it is opposed to that.

[56] The phase at low latitudes shows the typical feature of downward progression of wave fronts, which corresponds to upward propagation of wave energy. The vertical wavelength seen in observational and model data sets amounts to ~20 km.

[67] Extra-tropical diurnal tides are most pronounced in the model data sets with amplitudes up to 0.5 K at 30 km. At mid-latitudes, the RO data sets reflect the influence of retrieval differences on diurnal tides: CDAAC COSMIC data (high-altitude initialized with a climatology, which does not contain tidal information) do not show noticeable amplitudes of diurnal tide, while WEGC COSMIC data show a tide similar to that detected in the ECMWF data (initialized with ECMWF forecasts). Assuming that ECMWF overestimates the amplitude, we conclude that the actual amplitude of the extra-tropical diurnal tide lies between both observational data sets.

[68] Semi-diurnal tides become more apparent in the ECMWF data set than in the WEGC COSMIC data set, which is likely due to larger amplitudes in the model data set in general, and under-sampling problems in the observational data.

[69] The COSMIC satellite constellation is expected to deliver GPS RO measurements until 2012 and monitoring of diurnal tides utilizing COSMIC RO data can be extended until then (a follow-up multi-satellite mission is currently in planning stage). Inter-annual variations of diurnal tides, dependence on QBO (Quasi-Biennial Oscillation) or other atmospheric waves can be investigated in detail. The present study underpinned the utility of the data for such monitoring of diurnal-tide dynamics.

[70] Acknowledgments. We are grateful to Claudia Borries (DLR, Neustrelitz, Germany) for her advice concerning the space-time spectral analysis technique. We thank UCAR (Boulder, CO, USA) for providing COSMIC data and ECMWF (Reading, UK) and NCDC (Asheville, NC, USA) for short-term forecast data. We specifically thank Jordan Alpert (NCEP, Camp Springs, MD, USA) for his help concerning NCDC data. Celestrack (Colorado Springs, CO, USA) is acknowledged for making available COSMIC Two-Line Element Files. Johannes Fritzer (Wegener Center) is thanked for his efforts in OPS system development. The study was funded by the Austrian Science Fund (FWF) under research grant P18837-N10 (CLIMROCC); OPS development was financed by ESA and the Austrian Research Promotion Agency (FFG-ALR) via projects ProdxCN2 and EOPSLIM. Last but not least, we also acknowledge the careful work of three anonymous reviewers that helped to improve the paper.

References


Cucurull, L., and J. C. Derber (2008), Operational implementation of COSMIC observations into NCEP’s global data assimilation system, Weather Forecasting, 23(4), 702–711.


Hagan, M. E., and G. Kirchengast (2008), Observations of the diurnal tide and planetary waves in the lower atmosphere during the tropical diurnal tide lies between both observational data sets.


Huang, C. M., S. D. Zhang, and F. Yi (2009), Intensive radiosonde observations of the diurnal tide and planetary waves in the lower atmosphere over Yichang (111°18'E, 30°42'N), China, Ann. Geophys., 27, 1079–1095.


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Y.-H. Kuo, University Corporation for Atmospheric Research, PO Box 3000, Boulder, CO 80307-3000, USA.