

# Thermosphere Tides as Viewed from Space: CHAMP and GRACE as a “Mini-Constellation”

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## ABSTRACT

In this paper we use accelerometer data from the CHAMP and GRACE satellites to demonstrate the potential contributions of a “mini-constellation” of satellites to the new and emerging study of troposphere-ionosphere-thermosphere-exosphere coupling. Using densities measured by accelerometers on the CHAMP and GRACE satellites, and taking advantage of the local time precession characteristics of these near-polar orbiting satellites, exosphere temperatures are derived as a function of local time, longitude and latitude. Significant longitude variability (e.g.,  $\pm 25\text{K}$  maximum to minimum over the equator) in geomagnetically-quiet exosphere temperatures is shown to exist, and is attributed to a spectrum of diurnal and semidiurnal thermal tides that are excited in the troposphere and strongly influenced by the global land-sea distribution. Since exosphere temperatures are independent of height, this discovery constitutes evidence that exosphere variability is linked to surface variability. We also demonstrate a thermosphere-ionosphere link with the El Nino Southern Oscillation. Swarm will enable new investigations into coupling between the ionosphere-thermosphere system and tropospheric processes over inter-annual scales, and will enable us to tie together neutral atmosphere and electrodynamic aspects of the problem.

## INTRODUCTION

As solar radiation passes over the Earth's surface, the production and convection of water vapor and its subsequent condensation release latent heat over a diurnal cycle. A spectrum of diurnal (24-h) and semidiurnal (12-h) thermal tides is generated that reflect the land-sea distribution and other factors. Some of these tides, namely those with sufficiently long vertical wavelengths to withstand dissipative processes along the way, reach the base of the thermosphere [ca. 100 km][8, 9]. These authors estimated global distributions of latent heating from satellite data, and used a numerical model to predict the spectrum of thermal tides reaching the thermosphere. Forbes et al. [5, 6] and Zhang et al. [18] analyzed temperature measurements from the SABER instrument on the TIMED spacecraft to provide an observational perspective of this tidal spectrum. There is general agreement that the predominant wave-4 longitude distribution of land-sea difference [17], leads to a predominance of tidal components that impose a striking wave-4 longitude distribution on the lower thermosphere.

Vertically-propagating tides reach their maximum amplitudes in the 100-150 km height region where molecular dissipation begins to dominate their behavior [4]. This altitude regime overlaps with the so-called dynamo region, where tidal motions are capable of generating electric fields. The dynamo effect on the ionosphere is “indirect” in that it relies upon the intermediary generation of electric fields, rather than being a direct result of the tidal motions themselves. In the present work, we provide evidence that the tidal perturbations themselves extend all the way to the exosphere, and impose longitude variability there in much the same way that has been documented for the lower thermosphere [18]. We do this through analyses of CHAMP and GRACE accelerometer measurements, that are processed in a way to provide exosphere temperatures over a full range of local times, latitudes and longitudes. In addition, we present new results that demonstrate a connection between inter-annual variability of the ionosphere and that of the El Nino Southern Oscillation that is intimately connected with the neutral dynamics alluded to above. The Swarm mission is then discussed in terms of what it might contribute to furthering our understanding of the above processes and phenomena.

## DATA ANALYSIS AND METHODOLOGY

The basic data to be employed in this study are thermosphere total mass densities inferred from accelerometer measurements on the CHAMP and GRACE satellites, which are in near-polar orbits and have been supplying data since July, 2000 and March, 2002, respectively. Various details relating to the derivation of densities from accelerometer measurements are well documented [2,3]. In order to derive diurnal and semidiurnal tides, sampling over 24 hours of local time is required. CHAMP and GRACE each require more than 4 months to completely sample a solar day. However, due to the relative local time precession rates of the CHAMP and GRACE orbits, there are two periods of time wherein complete local time coverage is obtained within sequential 72-day periods: July, 2005 to June, 2006 (“period 1”), and December 2003 to October, 2004 (“period 2”). The problem remains that CHAMP and GRACE are acquiring data at different altitudes and both of their orbits are not exactly circular. We address this by iteratively deriving exosphere temperatures from the measured densities using the NRLMSISE-00 empirical model [15]; this is possible since total density in the model depends parametrically on the temperature. The densities were first inter-calibrated to remove possible biases due to drag coefficients and other effects by computing the measured/model ratios for both CHAMP and GRACE for each year; this ratio was found to be constant ( $1.23 \times \text{GRACE} = \text{CHAMP}$ ) for both years of analysis, and yielded a ratio close to unity. And because exosphere temperatures are height-independent over the height region of interest (ca. 350-500 km), these data can be mixed together in a least-squares fitting procedure to extract the diurnal and semidiurnal tidal components.

Uncertainty in the drag coefficient is about 5-15% and is the most important systematic error [3]. Errors relating to calibration, resolution, attitude, mass, and the satellite macromodel are all less than 1% for both systematic and noise errors. The largest source of error in inferring densities from in-track accelerations is due to neutral winds. In the following section, in connection with Fig. 2, we show that the effects of winds are small, and validate our derived exosphere temperature structures against tidal theory. What is important for the present analysis is that the exosphere temperatures derived from CHAMP and GRACE are consistent with each other in the context of NRLMSISE-00, although they may collectively contain some bias imposed by NRLMSISE-00. Since we are primarily considering diurnal and semidiurnal *variations* about a background state, we maintain that any such effects will not influence the conclusions of this paper. Moreover, NRLMSISE-00 does not contain the types of tidal longitude variations that we reveal in the next section, so there is no way that our results could originate through the density-temperature conversion process.

## RESULTS

The results presented in the following are obtained by sequentially fitting diurnal, semidiurnal and terdiurnal harmonics to 24 hours of exosphere temperature data in local time and longitude within a 72-day window, and moving this window forward one day at a time. Only measurements when  $K_p < 3$  are considered, and given constraints on time and space, we focus our attention exclusively on the diurnal tide. The first example is shown in Fig. 1, and corresponds to the equator. The left and right panels illustrate the diurnal temperature amplitude as a function of longitude and time during periods 1 and 2, respectively. These results imply max/min longitude variations in exosphere temperature of order  $\pm 20\text{-}25\text{K}$  due to the diurnal tide alone. Furthermore, note that the exosphere temperature transitions from a longitude wave-4 structure during August to more of a wave-3 structure during October-January, consistent with the transition from predominance of a DE3 to DE2 non-migrating tide propagating from the lower atmosphere into the lower thermosphere [6]. (Note: DEs is short-hand notation for the “eastward-propagating diurnal tide with zonal wavenumber  $s$ ”.) Furthermore, DE3 (DE2) gives rise to a wave-4 (-3) longitude structure for the total diurnal wave amplitude when interfering with the migrating or sun-synchronous tide DW1 [18]. For more than two waves interfering with each other, the pattern is more complicated [1].

The patterns in Fig. 1 are quite different from those revealed in the lower thermosphere (i.e., 110 km) from SABER temperature measurements on the TIMED satellite (not shown). The longitude variability of diurnal temperature amplitude evolves with altitude due to several effects. First, there is a strong diurnal exosphere temperature component that is excited in-situ in the thermosphere due to absorption of EUV radiation, and that constructively and destructively interferes differently with the non-migrating tide near 400 km than is the case at 110 km where the in-situ-driven component is much less in comparison. Further, the various vertically-propagating tides, including and in addition to DE3 and DE2, are affected differently by molecular dissipation, such that the relative mixture of tidal components is different between 110 km and ca. 400 km. For instance, DE2 has a longer vertical wavelength than DE3, and it therefore penetrates more efficiently into the thermosphere than DE3. See [4] by Forbes and Garrett in 1979, for a review of these concepts. It is also possible that these upward-propagating tidal components

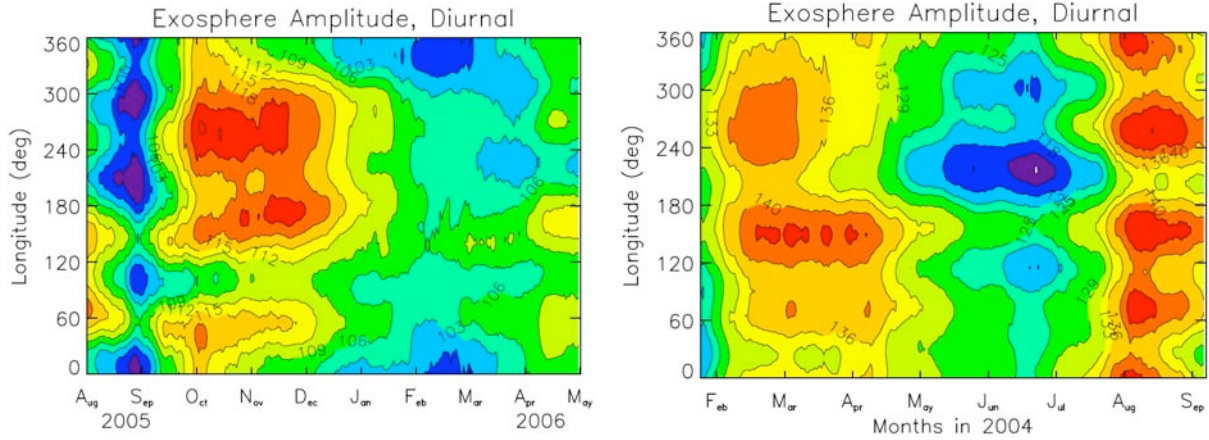


Fig. 1. Left: Equatorial tidal exosphere temperature amplitudes as a function of longitude and month from August, 2005 to May, 2006, ranging from 97K (maroon) to 121K (red). Right: Equatorial tidal exosphere temperature amplitudes as a function of longitude and month from February, 2004 to September, 2004, ranging from 115K (maroon) to 144K (red) [7].

interact with the longitude-dependent ion drag to create other longitude-dependent structures, along the lines of the “ion drag coupling” process reviewed in [4]; or, that in-situ wave-wave nonlinear interactions may induce some longitude structure in the thermosphere [10]. However, as we show below, at least for DE3 and DE2, evidence points to direct vertical propagation into the thermosphere.

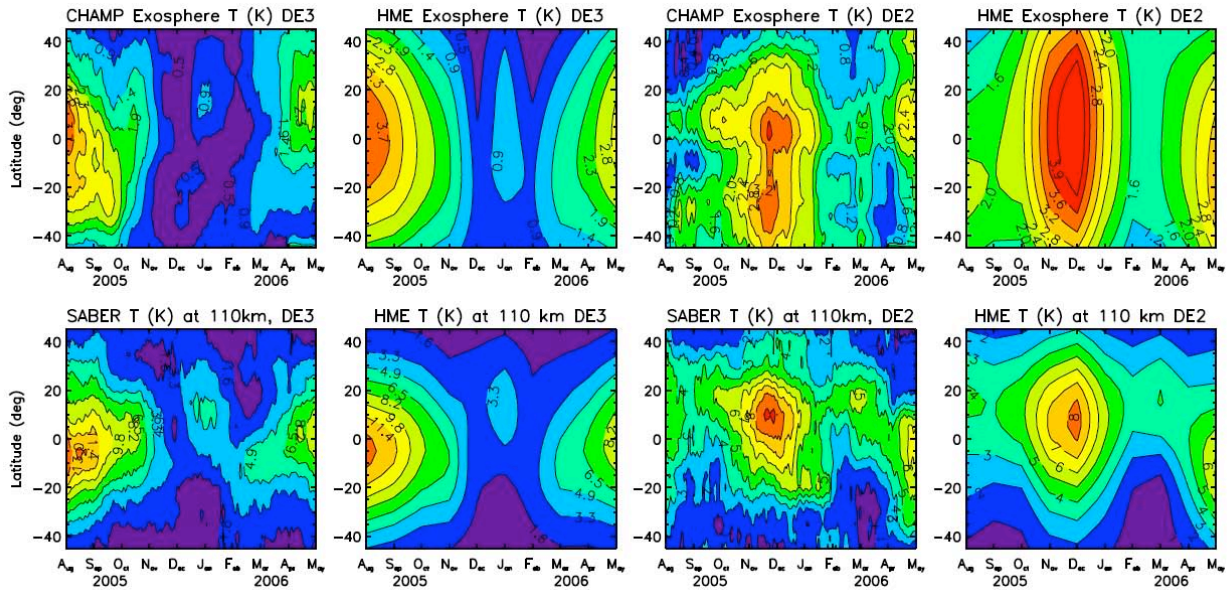


Fig. 2. Latitude structures of DE3 and DE2 non-migrating diurnal tidal temperature amplitudes, and comparisons with Hough Mode Extension (HME) approximations during August, 2005 - May, 2006. Left four panels: Bottom left, SABER DE3 temperature amplitudes at 110 km (max 13K); top left, DE3 exosphere temperature amplitudes (max 3.3K); bottom right, DE3 temperature amplitudes from HME fit to SABER temperatures (max 13K); top right, DE3 exosphere temperature amplitudes predicted by DE3 upward extension (max 3.7K). Right four panels: Same as left four panels, except for DE2, with respective maxima of 9K, 3.2K, 8K, 3.9K. In press [7] by Forbes, Bruinsma, Zhang and Oberheide.

In Fig. 2, we perform a form of validation of our exosphere temperature results while also providing further insight. Here we utilize the methodology of “Hough Mode Extensions (HMEs)” [13, 16] to relate lower-thermosphere tidal structures with those at higher altitudes in the thermosphere. The left 2 panels illustrate the latitude versus time structures of the DE3 tidal component derived from the CHAMP-GRACE data (top) and the SABER temperatures





## CONCLUSIONS

As noted in the introduction, there is a large body of evidence that indicates that the longitudinal variability in tidal oscillations in the lower thermosphere (ca. 110 km) originates from tropospheric heating processes that reflect land-sea distributions, topography, and other factors. We demonstrate here that such influences extend to the exosphere, and we may thus conclude that exosphere variability is linked to processes occurring near the Earth's surface. We furthermore present evidence that significant inter-annual variability exists, and that some of this is attributable to the way that ENSO modulates the excitation of tidal waves that propagate into the thermosphere and are observable by satellite-borne accelerometers.

This paper only concentrates on neutral temperature variations, specifically those connected with the diurnal tide. There are many other interesting aspects of this general problem, ranging from the semidiurnal and terdiurnal tides, to electrodynamic effects produced by the E-region wind dynamo that include the generation of electric fields, the redistribution of ionospheric plasma, and magnetic field variations associated with the Sq system and the equatorial electrojet. The Swarm mission in particular, by providing a continuation of measurements after CHAMP and GRACE, can further elucidate the remarkable connections suggested so far between tropospheric processes and the ionosphere-thermosphere system, and tie together ionosphere, thermosphere, and magnetic field perturbation measurements together into a comprehensive understanding of the “whole atmosphere system”.

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