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Storm-Time Equatorial Density Enhancements Observed by CHAMP and GRACE

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Total atmospheric densities have been simultaneously acquired from accelerometer measurements on the CHAMP (challenging minisatellite payload) and GRACE (gravity recovery and climate experiment) satellites over the past years. Both satellites have observed a large number of geomagnetic storms, most of them simultaneously, offering unique opportunities to study the temporal and latitudinal responses of the thermosphere to geomagnetic disturbances. The equatorial density enhancements observed during fast and significant increases in geomagnetic activity are calculated. The relationship between the density enhancements and local time, and the increase and maximum value of the geomagnetic activity are analyzed. The enhancements top 100% only if geomagnetic activity exceeds a minimum value, are larger on the nightside than on the dayside, and increase with altitude. The largest enhancement observed was 800%. The day-to-night density ratios become smaller during storm periods and are closest to unity for a local time of 0800/2000. The relative delay of the equatorial enhancement with respect to the ones observed at 60°S and 60°N is a function of geomagnetic activity, and it is shorter in the night sector than in the daylight sector. Equatorial propagation speeds of the density disturbance that are derived from the delay are of the order 400–1200 ms^{-1}.

Nomenclature

a	=	acceleration
ap	=	planetary geomagnetic activity index, 2 nT
$F10.7$	=	index of solar radioflux at 10.7 cm, 10^{-22} Wm$^{-2}\cdot$Hz^{-1}
kp	=	3-hourly quasi-logarithmic planetary geomagnetic activity index
z	=	observation altitude, km
z_0	=	reference altitude, km
ρ	=	density, kg/m^3

Subscripts

alb	=	acceleration; Earth albedo
drag	=	acceleration; atmospheric drag
IR	=	acceleration; Earth infrared radiation
M	=	model
sol	=	acceleration; solar radiation pressure
total	=	acceleration; total effect

Superscripts

model	=	acceleration; model computation
STAR	=	acceleration; accelerometer measurement

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I. Introduction

SPACE weather is a relatively new field that bridges both science and engineering in an effort to predict the effects of solar disturbances on the atmospheric and geospace environments, and on human-based assets within these environments, for example, commercial and military spacecraft, aircraft, and their crews and passengers; communication and navigation systems; power grid systems, etc. One focus area of space weather concerns the prediction of atmospheric drag effects on satellites. A primary concern is having sufficiently precise predictions of thermosphere density to keep track of more than 10,000 Earth-orbiting objects of various sizes on a day-to-day basis. Other applications include precise orbit prediction of high-interest satellites or reentry computations. Quite often, many of the difficulties arise under geomagnetic disturbed conditions, when energy of solar wind and magnetosphere origin is dissipated at high latitudes, leading to global perturbations of total mass densities. These density perturbations are time-dependent, globally heterogeneous, and not well delineated by existing empirical models [1].

One shortcoming of past efforts to delineate and model the thermosphere response to geomagnetic disturbances is that the available data are often derived from orbital drag analysis, with typical resolutions of 1–5 days. However, accelerometer measurements from the CHAMP (challenging minisatellite payload) [2] and GRACE (gravity recovery and climate experiment) [3] satellite missions offer new opportunities to delineate the response of the thermosphere density at spatial and temporal scales that have not previously been possible. In this paper, we take advantage of these capabilities to focus on one aspect of the density prediction problem, that of the intensity and time delay of the equatorial response to energy injected at high latitudes. In particular, we aim to categorize the equatorial enhancements as a function of relevant parameters, for example, the fast increase in kp, the absolute value of kp, the solar local time (SLT), and the time delay of the response.

The total mass density observations are derived from accelerometer measurements provided by precise science instruments, carried by the satellites CHAMP [2] and GRACE [3]. These missions are particularly interesting for upper atmosphere studies, because they provide pole-to-pole latitudinal coverage, while complete 24-hour solar local time sampling is achieved approximately every four and five months, respectively. Whereas both missions have as their main mission objective the mapping of the gravity field of the Earth, total atmospheric densities have been derived from the accelerometer measurements: from CHAMP/STAR (spatial triaxial accelerometer for research) since May 2001, and from GRACE/SuperSTAR since March 2002, but for selected events relevant to this study only.

Over the last few years, both satellites have observed a large number of geomagnetic storms, most of them simultaneously, including the largest one ever recorded in October 2003. Because of the approximately 100 km higher orbit altitude of the GRACE satellites than that of CHAMP (June 2005: 480 km versus 365 km), the angular rates of their orbital planes are different; therefore, the density response is generally observed at four local times. These capabilities offer unique opportunities to study the temporal and latitudinal responses of the thermosphere to geomagnetic disturbances. It is also convenient for modeling purposes, because it allows a better separation of local time and seasonal variations. The satellites are in good health, and the missions will be maintained well beyond their nominal lifetime (5 years for both missions), at least up to 2009. These density time series will then become the longest and most complete ever recorded with single instruments. Data will be collected from maximum (2000–2001) to minimum (2006–2007) solar activity conditions, which is important considering the heterogeneity of the density database existing nowadays into account.

Because of the absence of a rigorous physical basis, semi-empirical models such as DTM (drag temperature model) [4,5] rely heavily on the assimilated density and temperature data. Predictions under conditions for which no data were available, or inaccurate data were assimilated, may be in error by an unknown amount. Assimilation of the CHAMP and GRACE data in an updated DTM will significantly increase its accuracy (currently at the 15–20% 1σ level), at least in the 300–500 km altitude range. Satellite drag modeling will be improved thanks to the more accurate density model, which is particularly important in precise orbit computations of satellites lacking precise tracking data such as the global positioning system (GPS). The data used in the present study were processed and analyzed in the framework of the full revision of the DTM-2000 model [5], which will start in the autumn of 2006. All CHAMP and GRACE densities processed at that time will be assimilated in the new model. Although it is not expected that all findings of this and ongoing studies can be taken into account, they will contribute to a better understanding of the model shortcomings and a more realistic error budget.

The next section reviews the data considered in this study and the methods used to derive, compare, and analyze the density profiles. Section III presents the CHAMP and GRACE density comparison and an observed-density error analysis. The equatorial density enhancements using observations from both CHAMP and GRACE are discussed and compared to model predictions in Sec. IV, followed by the conclusions of this study.

II. Data and Analysis Methods

A. CHAMP and GRACE Data

CHAMP was launched in July 2000 in a near-circular orbit at 450-km altitude and an inclination of 87.3°. The GeoForschungsZentrum (GFZ) in Potsdam, Germany, manages the mission. The STAR accelerometer, developed by ONERA (Office National d'Etudes et de Recherches Aerospatiale), is the contribution from CNES (Centre National d'Etudes Spatiales) to the CHAMP mission. The 0.1 Hz STAR level-2 observations, which are free from maneuvers and anomalous spikes thanks to the GFZ preprocessing, are used in this study. The two identical satellites GRACE-A and GRACE-B were launched in March 2002 in near-circular orbits also, but at approximately 500 km altitude and inclinations of 89.5°. GRACE-B orbits approximately 220 km behind GRACE-A. DLR and Jet Propulsion Laboratory (JPL) jointly manage the mission. GRACE carries SuperSTAR accelerometers, also built by ONERA, but the level-1B data contain the attitude maneuvers, which are smeared out over up to tens of seconds. Therefore, the effects of these hundreds of thrusts per day contaminate the drag acceleration we seek to isolate in an irretrievable way. The 1-Hz GRACE-A data (GRACE-B was not used in this study) were downsampled to the CHAMP rate of 0.1 Hz by averaging the accelerations over 10-s intervals.

The densities are derived from the tangential component of the measured nongravitational acceleration only, because the calibration parameters of the normal component cannot be determined with equal and sufficient accuracy [6]. The effective cross-sectional area perpendicular to the velocity vector and the incidence angles to the particle flow are computed accurately using 15-plate and 8-plate macromodels for CHAMP and GRACE, respectively, which are correctly oriented in inertial space owing to the attitude quaternions. The first step in the density retrieval procedure consists of removing that part of the acceleration from the data that is not due to drag, that is, solar radiation pressure and Earth albedo. In the case of GRACE, hundreds of small attitude thrusts per day introduce accelerations (the effect of which cannot be corrected for) that are not due to drag. Averaging reduces the thrust error to a few percent at most, but at the cost of a lesser resolution [7]. In a second step, the total atmospheric density is reconstituted. The following equation, incorporating steps 1 and 2, shows how the "observed" total density ρ^{STAR} is computed by scaling of the modeled density ρ^{model} using only the tangential components of the accelerations a:

$$\rho^{\mathrm{STAR}} = \frac{a_{\mathrm{total}}^{\mathrm{STAR}} - a_{\mathrm{sol}}^{\mathrm{model}} - a_{\mathrm{albedo}}^{\mathrm{model}} - a_{\mathrm{IR}}^{\mathrm{model}}}{a_{\mathrm{drag}}^{\mathrm{model}}} \cdot \rho^{\mathrm{model}} \tag{1}$$

In this equation, the total tangential acceleration measured with an accelerometer, corrected for the instrumental bias and corresponding scale factor, represents the sum of the surface accelerations acting on the satellite. The following a priori bias and scale factors were applied to the CHAMP and GRACE-A tangential accelerometer data:

$$\mathrm{CHAMP: bias} = 2.96\mathrm{E}-6\ \mathrm{ms}^{-2}, \quad \mathrm{scale} = 0.833$$

$$\mathrm{GRACE\text{-}A: bias} = 1.12\mathrm{E}-6\ \mathrm{ms}^{-2}, \quad \mathrm{scale} = 0.957$$

A single correction to the a priori biases is estimated per 24-h orbit (once per day), which is necessary to accommodate the drift of the instrument (for the tangential component, approximately $1\mathrm{E}-7\ \mathrm{ms}^{-2}$ from 2004 through December 2005). The accuracy of the density derivation mainly depends on the uncertainty of the estimated accelerometer calibration parameters (drifting bias, for example), the aerodynamic drag coefficient (using the model of Cook for flat plates), and the unknown thermospheric winds [7]. Although errors in the drag coefficient or the instrumental biases mainly cause the derived densities to have a systematic offset and/or drift of a few percent at most [6,7], the upper atmosphere winds are an important source of geophysical noise that cannot be corrected for using a model. The accuracy of the density observations is always better than 5% when the geomagnetic activity is low to moderate, that is, kp less than 3. The density cannot be derived with equal accuracy for higher geomagnetic activity because of significant upper atmosphere neutral winds. Observations under geomagnetic storm conditions are used in this study despite their poorer accuracy of 5–20% *at low latitudes* due to not modeling neutral wind with speeds of order 200–400 ms^{-1}. These uncertainties are acceptable considering the amplitude of the density perturbations of up to several hundred percent as will be shown later in this paper in Sec. IV.

B. Density Normalization

The CHAMP and GRACE orbit altitudes are not constant due to their small but nonzero eccentricities, the flattening of the Earth, as well as due to natural decay. One has to take the variation of altitude into account when comparing absolute densities. The CHAMP and GRACE densities at some altitude z are normalized to a constant altitude z_0, which is accomplished using an empirical model density according to the following equation:

$$\rho(z_0) = \rho(z) \cdot \frac{\rho_M(z_0)}{\rho_M(z)} \quad (2)$$

For altitude differences of less than 25 km, the errors introduced by this normalization are estimated to be less than 3% [7]. All CHAMP and GRACE densities were normalized to 400 and 480 km (approximately their mean altitudes from 2002 through 2005), respectively, except for the case in which CHAMP and GRACE densities were both normalized to 440 km. For that particular instance the normalization error may be up to 10–15%, and, because it depends on the model scale height, this error is probably quite different on day- and nightsides.

C. Selected Events

Heating events were selected based on a rapid increase of kp of at least 3 over 3 h (i.e., the temporal resolution of the index), and not on an absolute value of kp. Therefore, many storm events were not selected. Because kp is a quasi-logarithmic index, the energy input is not constant in our analysis. Also, because of the condition that an event has to be observed by CHAMP and GRACE simultaneously, some selected events were rejected because of problems with data from either satellite. A total of 28 events complied with the above conditions. Table 1 lists all relevant parameters for each event.

It is obvious from Table 1 that not all possible relations between the density enhancements and certain physical parameters can be established. In particular, the data do not allow a seasonal dependency to be determined. Because solar minimum conditions are not yet reached, a likely relation between (mean) solar activity and the size of the enhancement also cannot be evaluated.

The equatorial density enhancements were determined following the procedure given here:

1) densities are derived 12 to 24 h before and after each (storm) event;

2) per event, they are separated in ascending and descending passes;

3) the densities are normalized to a mean altitude;

4) the average density in the $(-10°, 10°)$ latitude band is computed for each pass;

5) the dayside and nightside enhancements are calculated as the peak-to-before event density ratio.

The last point can be particularly delicate because of significant variability also before the event, as well as the existence of multiple density peaks. Consequently, the uncertainty in the determination of the enhancements is approximately 10–20% in those worst cases.

III. GRACE Compared to CHAMP: Coincident Orbit Planes

We want to verify first that CHAMP and GRACE observe the same variations, that is, the accelerometers of the spacecraft function correctly (no spikes, comparable resolution, etc.). If we want to compare GRACE to CHAMP density profiles with a view toward establishing the above as well as any net offset between the two, then the orbital planes must be coincident or very nearly so. In any other orbit configuration, the variations of density with local time (migrating tides) cause differences. Secondly, the density profiles must be normalized to a constant altitude, which in this study was chosen to be 440 km (the average altitude between the two satellites). An offset due to macromodel errors actually does not hinder this study, which is about relative enhancements, but it must be accounted for in some manner when CHAMP and GRACE data will be assimilated in a model. Usually this is done by estimating a scale factor for each density dataset [4,5].

The difference of the arguments of the ascending node of the CHAMP and GRACE orbits must be 0° (the satellites orbit in the same plane and direction) or 180° (the satellites orbit in the same plane but opposite direction) for their orbital planes to be coincident. The 0° difference took place the end of March 2005, while the 180° difference occurred the beginning of May 2003. The observed densities of 28 March 2005 (dayside SLT of CHAMP and GRACE 13.6 and 13.4 h, respectively) and 3 May 2003 (dayside SLT of CHAMP and GRACE 17.5 and 17.4 h, respectively) were selected for this comparison because the orbit planes were very close *and* the geomagnetic activity was low to moderate ($kp < 3$). Higher activity

Table 1 The dates and relevant information of the 28 selected events

Year	Day of year	Mean $F10.7$	Δkp	Max kp	CHAMP SLT, h Day	CHAMP SLT, h Night	GRACE SLT, h Day	GRACE SLT, h Night
2002	104	200.06	3.3	4.2	16.5	4.5	9.9	21.9
2002	210	164.37	3.3	4.3	6.7	18.7	13.9	1.9
2004	340	106.37	3.3	4.3	12.2	0.2	10	22
2004	346	105.26	3	4.3	11.6	23.6	9.5	21.5
2003	229	126.21	4	4.5	7.6	19.6	9.3	21.3
2004	257	112.22	4	4.5	7.7	19.7	16.1	4.1
2003	97	130.01	3	4.6	7.7	19.7	7.2	19.2
2005	165	93.52	3.7	4.8	6.5	18.5	7.7	19.7
2005	14	104.67	3	5	8.2	20.2	6.7	18.7
2002	138	183.06	4.3	5.2	13.4	1.4	7.4	19.4
2002	230	165.23	3.6	5.2	16.9	4.9	12.4	0.4
2003	310	132.16	3	5.5	12.5	0.5	15.6	3.6
2004	6	140.65	3	6	6.6	18.6	10.6	22.6
2002	113	193.1	3.7	6	15.7	3.7	9.2	21.2
2003	119	126.81	3.3	6	17.8	5.8	17.6	5.6
2004	206	105.64	3	6	12.2	0.2	7.8	19.8
2002	324	173.91	3	6	8.6	20.6	17.7	5.7
2002	131	185.94	3.7	6.7	14	2	7.9	19.9
2003	308	132.58	3	6.8	12.7	0.7	15.7	3.7
2002	107	198.67	3.3	7.2	16.2	4.2	9.7	21.7
2003	287	115.12	3	7.2	14.6	2.6	17.3	5.3
2005	7	106.51	3.3	7.5	8.8	20.8	7.3	19.3
2005	21	104.44	4	8	7.5	19.5	6.2	18.2
2003	149	122.78	4	8	15	3	15.4	3.4
2004	208	106.85	3.6	8.2	12	0	7.6	19.6
2005	235	94.58	3	8.3	11.9	23.9	14.3	2.3
2003	324	131.19	3	8.3	11.2	23.2	14.5	2.5
2003	302	126.65	5	9	13.3	1.3	16.2	4.2

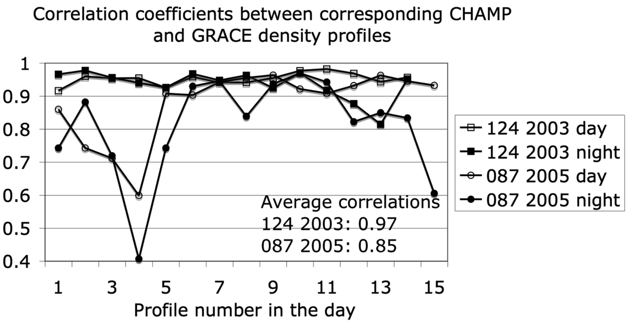

Fig. 1 The correlation coefficients computed for each matching CHAMP and GRACE density profile, for day- and nightsides.

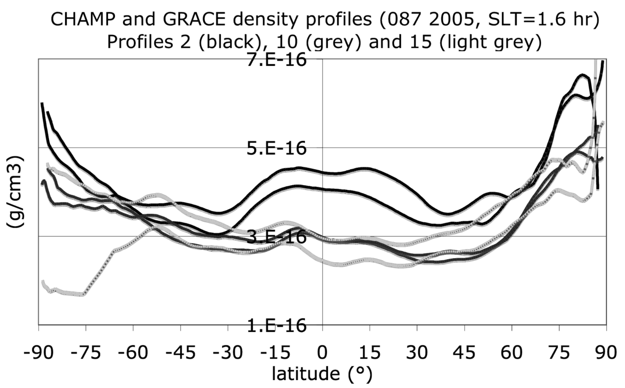

Fig. 2 Examples of three CHAMP and GRACE smoothed density profiles, corresponding to the nightside passes 2, 10, and 15 for day 87 of 2005. The correlation coefficients are shown in Fig. 1.

causes disturbances and waves, which make direct comparison more difficult because in that case some sort of filtering is required.

The compatibility of the GRACE-derived density with that from CHAMP is demonstrated by calculating the correlation coefficients for each corresponding pair of day- and nightside profiles for the selected two days. The results, using profiles smoothed over 70 s (seven points), are shown in Fig. 1. The correlations are 0.97 and 0.85 on average and thus it may be concluded that both satellites indeed observe the same variations. Some examples of normalized profiles, for which the correlation coefficients are shown in Fig. 1, are given in Fig. 2. The offset between the profiles is caused by the ensemble of errors due to normalization, errors in the satellite macromodels, a difference in the time of passing of the same parallel (although always within 1 h), and a higher smoothing of the CHAMP data. We conclude that, within present limitations, no net bias between CHAMP and GRACE densities can be claimed. As the GRACE density database expands, results and conclusions with more statistical confidence may be possible (for example, by comparing a CHAMP-only to a GRACE-only atmospheric density model).

IV. Observed Equatorial Density Enhancements

The relation between the observed enhancements and the planetary geomagnetic index kp is revealed by plotting them versus the peak value of kp, the values of which were listed in Table 1. Figure 3 depicts all enhancements on the dayside (right frame) and the nightside (left frame) versus the peak value of kp for each event, and for both CHAMP and GRACE, as well as the corresponding predictions of the semi-empirical model NRLMSIS-00 [7]. This model was used in this study instead of DTM because of its significantly higher accuracy, thus better representing state-of-the-art modeling. The maximum enhancements observed by CHAMP are for the 24 November 2003 (day 324) storm: 275 and 500% on the day- and nightside, respectively. NRLMSIS-00 underestimates the enhancements, predicting 125 and 225%, respectively. The maximum enhancements observed by GRACE are for the 23 August 2005 (day 235) storm, which are slightly larger than those observed on 24 November 2003: 400 and 800% on the day- and nightside, respectively, while NRLMSIS-00 again underestimates the effect, predicting 90 and 400%, respectively. The (magnitude of) enhancements are less than 100% when kp is less than 7, whereas for larger values they are always greater than 100%. The model predictions are consistent with observations. This behavior is similar to an avalanche effect, that is, it is triggered only when the amount of input energy exceeds a certain minimum. The minimum energy in this case is supplied by solar wind speeds causing the planetary geomagnetic index kp to be larger than 7, which corresponds to geomagnetic perturbations exceeding 264 nT. This behavior is not an artifact of using the logarithmic kp instead of the linear ap index. The few storm events at our disposal in this study, which were monitored at different local times, cannot provide evidence that the enhancements are growing as a function of increasing maximum kp. The amplitudes of the equatorial enhancements shown in Fig. 3

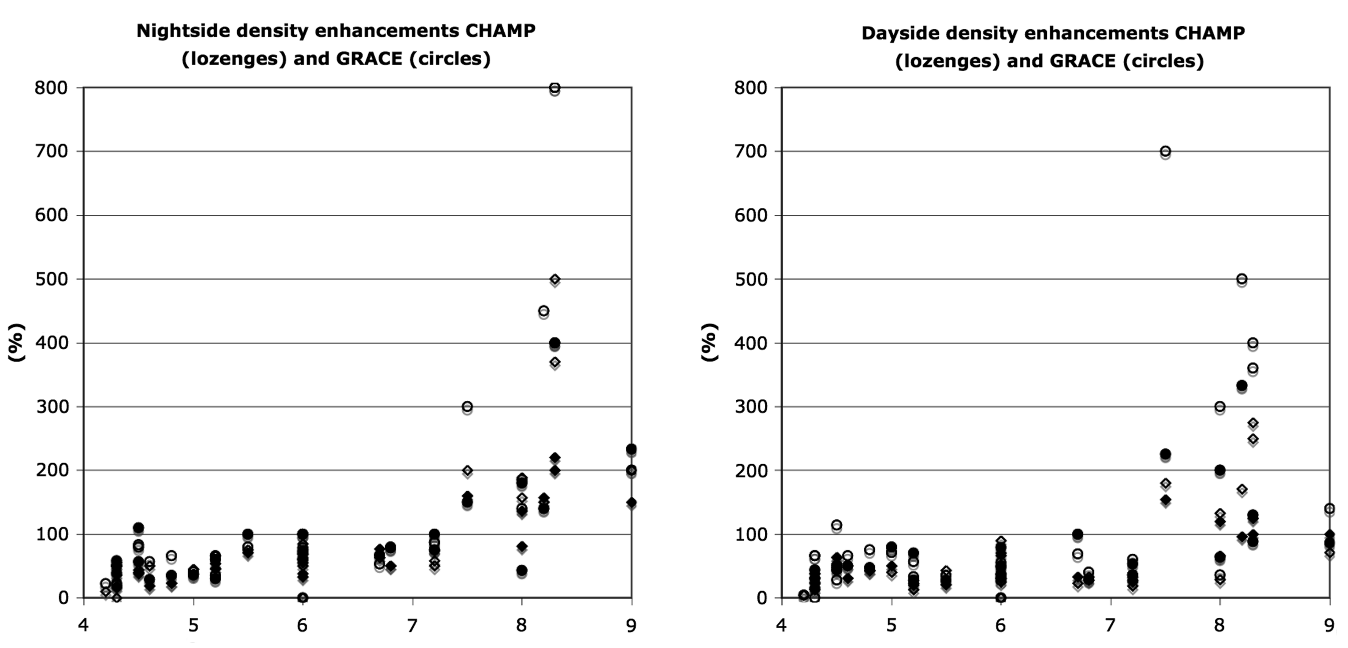

Fig. 3 The equatorial density enhancements as a function of the maximum *kp* of an event, observed during nighttime (left plot) and daytime (right plot).

Table 2 The average size (and standard deviation) of the observed and predicted ("MSIS" = NRLMSIS-00) enhancements as a function of *kp*, altitude, and day- and nightsides

	CHAMP		MSIS		GRACE		MSIS	
	Day	Night	Day	Night	Day	Night	Day	Night
All kp	68 (71)	101 (112)	55 (38)	77 (57)	127 (172)	154 (208)	78 (72)	106 (99)
$kp < 7$	40 (22)	47 (24)	36 (15)	42 (17)	49 (29)	61 (27)	45 (19)	60 (26)
$kp > 7$	110 (96)	180 (142)	80 (45)	125 (57)	240 (227)	289 (277)	122 (94)	170 (127)

become huge for extreme storms; in fact, the amplitudes of large-scale disturbances (>1000 km) are equivalent at all latitudes [8]. Large-scale disturbances only can travel large distances, crossing the equator to the opposite hemisphere, sometimes recombining with a wave coming from the other direction, causing the equatorial enhancements we observe; a medium or small-scale wave has a much smaller radius of action and is practically confined to high latitudes.

Table 2 summarizes the average enhancements for all events, and for the subsets for which kp is larger or smaller than 7. The nighttime enhancements (on average) are significantly larger than those observed and predicted on the dayside. Similarly, the enhancements observed with GRACE, which orbits about 100 km higher, are larger than those observed with CHAMP. NRLMSIS-00 reproduces this effect too. The events for which kp is less than 7 generated enhancements of 50% on average, and Table 2 shows the high fidelity of the NRLMSIS-00 predictions. For both CHAMP and GRACE the nighttime augmentations are on average 20% stronger than those observed on the dayside, and the model establishes approximately the same difference. This proportion remains valid in case of GRACE for the severe to extreme storms too ($kp > 7$); however, for CHAMP the nighttime response is about 60% stronger than those observed on the dayside, probably due to equatorward winds on the nightside that are preexisting due to normal diurnal variations associated with EUV-driven circulation. The effect of altitude is more distinct too: the GRACE enhancements are 80–120% larger than those monitored by CHAMP, compared to about 25% when kp is less than 7. Table 2 reveals that the model, which is accurate up to a kp of 7, vastly underestimates the enhancements in case that kp is larger than 7: about 50% and 80–100% at CHAMP and GRACE altitudes, respectively. However, these cases are relatively rare, and therefore few observations taken under those conditions were assimilated in the model.

The local time plays a role in the magnitude of the enhancement, but a clear-cut relation cannot be gleaned from the data; the enhancements in the morning sector, 6–12 am, appear to be stronger than those detected in the afternoon sector. There does not appear to be a preferred sector on the nightside. The distribution of the events in time did not allow the study of potential seasonal effects. The solar minimum was not attained by the end of 2005 (last part of this dataset) and as a consequence a probable influence of the solar flux could also not yet be studied. Specifically, the enhancements are expected to be clearer and stronger than when solar activity is high [9]. The day-to-night density ratios of the observations and NRLMSIS-00 were calculated just before the event or storm, and at its peak. These ratios are shown in Fig. 4. Inspection of the figure shows that the least variation of both observed and modeled ratios (ratio close to unity) is around 0800/2000 local time. The day-to-night ratios were also calculated at 60°S and 60°N and the least variation was again found around 0800/2000 local time. This kind of configuration would thus require the smallest dynamic range of a drag-free system; however, such a system is more difficult to operate in a partly shadowed orbit. The observed ratios are largest between 0200–0400/1400–1600 at 490 km (GRACE), where they range from 3 to 5. The model ratios are significantly smaller. Figure 4 also clearly shows that the day-to-night differences are decreasing during a storm as a consequence of the more intense augmentation on the nightside, the average ratio decreasing from 1.6 to 1.4 (14% smaller) for CHAMP and 2.1 to 1.6 (25% smaller) for GRACE. The NRLMSIS ratios decrease from 1.7 to 1.3 (29% smaller), and from 1.9 to 1.5 (30% smaller), respectively.

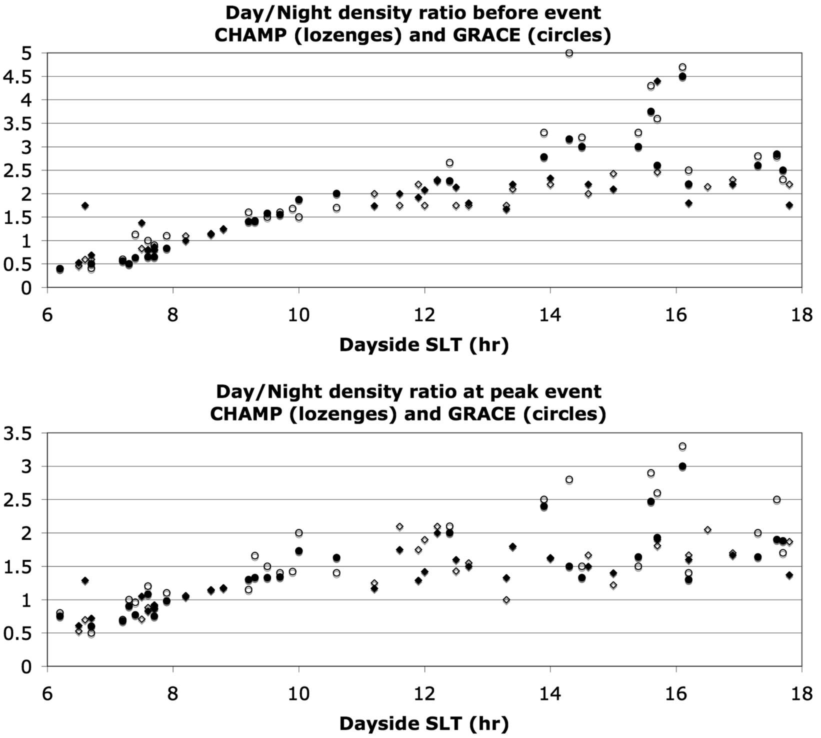

Fig. 4 The day-to-night ratios before (top frame) and at the peak (bottom frame) of the event, observed by both CHAMP and GRACE (but in general at different local times; open symbols), and predicted with NRLMSIS-00 (solid symbols).

Table 3 The average equatorial delay and the standard deviation inferred from CHAMP data, in revolutions (hours), with respect to 60°S/60°N as a function of *kp* and day–night conditions. The bottom line shows the shortest and longest delays measured, in h

	Daytime	Nighttime
All kp	2.21/0.72 (3.4/1.1)	2.00/0.84 (3.1/1.3)
$kp > 7$	1.88/0.35 (2.9/0.5)	1.29/0.49 (2.0/0.8)
$kp < 7$	2.38/0.81 (3.7/1.3)	2.33/0.72 (3.6/1.1)
Shortest/longest, h	1.6/7.8	1.6/6.2

In the present analysis, using CHAMP data only, we attempt to establish if the delay of the thermospheric response at the equator due to a storm is a function of kp. Therefore, only relative delays need to be examined. The average densities computed at 60°S and 60°N are used for that purpose. The time lag between those high latitudes and the equator depends on the speed of the disturbance and wind perturbations, which are generated at auroral latitudes and then travel equatorward. The absolute delay is measured with respect to the storm commencement as measured in the geomagnetic field, for example, using the planetary geomagnetic index kp or ap. However, these indices have the disadvantage of a low time resolution of 3 h. The orbital period of CHAMP is approximately 93 min, about half the time between two consecutive kp values and so effectively doubling the temporal resolution. Although this is not entirely correct, we can compute the average speed of the disturbance as follows: if the equatorial delay with respect to 60°S/60°N is one revolution, then the average speed is $6600\ \mathrm{km}/93\ \mathrm{min} = 1180\ \mathrm{ms}^{-1}$, for two revolutions it is $590\ \mathrm{ms}^{-1}$, and for three revolutions it is $393\ \mathrm{ms}^{-1}$. The speed computed for a delay of two or three revolutions agrees with theoretical estimations ($500–1000\ \mathrm{ms}^{-1}$) for large-scale waves [10]. Very high speeds are observed for the extreme storms for which kp exceeds 8: a delay of one revolution is detected in five cases on the nightside, and for the Halloween storm ($kp = 9$) both on the day *and* nightside. Table 3 lists the average equatorial delays with respect to 60°S/60°N. The delay is systematically shorter in the night sector, and its reduction as a function of storm intensity is ascertained. However, the number of storms is not sufficient for a robust regression relating kp to wave speed.

V. Conclusions

The equatorial enhancements observed with CHAMP and GRACE become larger than 100% when kp is larger than 7, and the NRLMSIS-00 predictions are in agreement with this. The largest effect, measuring 800%, was detected for a storm with a kp of 8^+ with GRACE. In case of very severe storms, NRLMSIS-00 underestimates the enhancements. The enhancements are larger on the nightside than on the dayside, and also larger for GRACE, due to its higher altitude, than for CHAMP. The day-to-night density ratios become smaller during storm periods; they are closest to unity for a local time of 0800/2000, also during the storm, and this was confirmed at 60°S and 60°N. The relative delay of the equatorial enhancement with respect to the ones observed at 60°S and 60°N decreases as a function of increasing kp; it is on average 10% shorter in the night sector than in the daylight sector. The large-scale disturbance speeds that are derived from the delay are of the order $400–1200\ \mathrm{ms}^{-1}$. The disturbances traveling fastest arise under extreme storm conditions with kp exceeding 8. The number of events considered in this study is still not sufficient to clearly delineate the perturbations as a function of local time and solar flux, in particular. However, both CHAMP and GRACE will operate until 2009 excepting incident, which will allow us to significantly increase the density database and thus the number of storms that may be evaluated.

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