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Effect of sudden stratospheric warming on lunar tidal modulation of the equatorial electrojet

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[1] Using the equatorial electrojet (EEJ) peak current intensity as deduced from CHAMP magnetic observations from the years 2001 through 2009, we investigated the relationship between sudden stratospheric warming (SSW) and lunitidal signatures in the tropical ionosphere. There is a practically one-to-one correspondence between midwinter SSW periods and the strongest 13 day modulation of the EEJ strength as observed by CHAMP. That is, all the midwinter SSW periods from December 2001 to August 2009 were accompanied by an enhanced 13 day modulation of the EEJ strength. No other geophysical phenomenon brought about as strong a 13 day modulation as those of the midwinter SSW periods. During each midwinter SSW period the amplified 13 day modulation of the EEJ strengths starts roughly within ± 1 week around the first peak in stratospheric temperature difference. An oscillation with a period of 13.26 days is predicted by the lunitidal equation when considering the precession of the CHAMP orbit. When fitting the lunitidal equation to the EEJ modulations during the midwinter SSW periods, consistent phase delays of 4.4 ± 0.3 days of the tidal signal emerge for all the cases. The results suggest that the pronounced 13 day modulation of the EEJ strength is related to an enhancement of the lunar tide in the ionosphere by the SSW effect.

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1. Introduction

[2] Tides of the moon can easily be seen on Earth and have been an important part of our daily lives. However, how strong can we feel tides high up in the sky, e.g., at 100 km altitude? The lunitidal imprints in the low-latitude and midlatitude ionosphere have been investigated since the early years of ionospheric observations [see *Sharma and Rastogi*, 1971, and references therein]. However, it is not the lunitidal wind which in general dominates the low-latitude and midlatitude ionospheric dynamo. The dominant driver is the wind associated with the diurnally varying solar heating, which results in the so-called solar quiet (*Sq*) variation of the ionosphere. The *Sq* dynamo is driven primarily by diurnal ($T = 24$ h) tides [e.g., *Pedatella et al.*, 2011] while the lunitidal dynamo is mainly quasi-semidiurnal ($T \sim 12$ h; similar to that of the ocean tide) [e.g., *Pedatella and Forbes*, 2010]. The lunitidal effect is only $\sim 10\%$ of the *Sq* variation [e.g., *Hall*, 1966; *Yamazaki et al.*, 2011]. Moreover, the extreme ultraviolet (EUV) radiation of the Sun (a major controlling factor for the *Sq* variation of the ionosphere)

changes with a 27 day period, the solar rotation. As the period is similar to the lunar revolution period (29.5 days), it further complicates lunitidal observations in the ionosphere even when the data are averaged over a certain period [e.g., *Pedatella and Forbes*, 2010]. On occasions the lunitidal effect becomes greatly amplified (“big L days”), where it becomes 5–6 times the expected value and can establish dominance over the *Sq* variation [*Bartels and Johnston*, 1940]. In a climatological sense, the lunitidal effect on the low-latitude and midlatitude ionosphere is larger during northern winter [e.g., *Rastogi et al.*, 1985; *Stening and Fejer*, 2001; *Pedatella and Forbes*, 2010; *Yamazaki et al.*, 2011; H. Lühr et al., Global characteristics of the lunar tidal modulation of the equatorial electrojet derived from CHAMP observations, submitted to *Annales Geophysicae*, 2012].

[3] Sudden stratospheric warming (SSW) is a phenomenon characterized by a sudden temperature increase in the winter polar stratosphere. The phenomenon was first observed in 1950s [*Scherhag*, 1952, 1960], and the first dynamical model to explain it was given by *Matsuno* [1971]. SSW is caused by a rapid growth of quasi-stationary planetary waves (PWs), and accompanied by changes in stratospheric zonal mean flow [see *Liu et al.*, 2010; *Fuller-Rowell et al.*, 2011a, and references therein]. Though SSWs can occur in both the northern (NH) and southern hemisphere (SH) during respective local winters, major SSWs (characterized by a reversal of stratospheric zonal mean zonal wind) have been observed mainly in the NH [e.g., *McHall*, 1992]; that is, stronger SSWs are expected during months around December solstice. During SSW periods, upward propagation of

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tides through the mesosphere and thermosphere experiences global changes [see *Liu et al.*, 2010; *Fuller-Rowell et al.*, 2011a, and references therein]. As a result, the low-latitude and midlatitude ionosphere is modulated through the dynamo action of the tidal wind. The coupling between the stratosphere and the ionospheric dynamo was observed early in the 1960s [e.g., *Brown and Williams*, 1971, and references therein], but the interest in this subject has been revived lately [e.g., *Chau et al.*, 2009; *Sridharan et al.*, 2009; *Anderson and Araujo-Pradere*, 2010; *Fejer et al.*, 2010; *Goncharenko et al.*, 2010a; *Liu et al.*, 2011]. Also, *Liu et al.* [2010] and *Fuller-Rowell et al.* [2011b] conducted extensive numerical simulations on the ionospheric response to SSW. Recent theoretical and observational papers on the subject generally agree that strong PW during SSW amplifies “semidiurnal” tides at ionospheric heights, where dynamo action subsequently modulates the low-latitude ionosphere with semidiurnal behavior. For more details, readers are referred to the review by *Chau et al.* [2012].

[4] With the semidiurnal behavior and the seasonal variation (i.e., high activity during northern winter), it is attractive to surmise a certain relationship between the SSW and tides of the moon. *Stening et al.* [1997] conducted numerical simulations to show that lunar tides undergo a large change during SSW. *Fejer et al.* [2010] noted, during four SSW periods, that phase values of the semidiurnal component of the equatorial electrojet (EEJ) variation follow the lunar phase. They concluded that it is the “lunar” semidiurnal tide that is amplified by SSW and modulates the low-latitude and midlatitude ionosphere. *Fejer et al.* [2011] constructed statistical average patterns of vertical plasma drift (an ionospheric parameter closely related to EEJ [e.g., *Stolle et al.*, 2008]) during SSW, and showed that the patterns follow those of semidiurnal lunar tides. According to *Fejer et al.* [2011], (1) enhanced lunar semidiurnal effects start at about the onset of the SSW, and (2) the largest semidiurnal perturbation occur in the early morning sector. On the other hand, *Yamazaki et al.* [2011] and *Lühr et al.* (submitted manuscript, 2012) reported larger lunitidal amplitudes in the ionospheric current systems during December solstice (than in the other seasons) and speculated that it originates from SSW effects during that season. Although the studies mentioned above (and references therein) shed light on the interrelation between SSW and lunitidal signatures of the tropical ionosphere, they could not give a definitive answer as to whether there is a one-to-one correspondence between SSW and lunitidal enhancement at ionospheric heights. In other words, it is yet to be shown (1) whether every SSW is accompanied by notable amplification of ionospheric lunitidal signatures and (2) whether other geophysical phenomena can also generate lunitidal effects as strong as SSW can. These issues should be investigated with a long-term observation of the ionosphere. In this work we will investigate some 10 year long observations of the Challenging Mini-satellite Payloads (CHAMP) to show that there is practically a one-to-one correspondence between midwinter SSW periods and largest amplifications of ionospheric lunitidal signatures.

2. Observation

[5] The CHAMP satellite was launched in mid-2000 into a circular polar orbit (inclination: 87.2°) at ~450 km altitude.

It orbits the Earth approximately 15 times a day. A prime purpose of the satellite was the precise measurement of the geomagnetic field, accomplished by a flux gate magnetometer and an Overhauser scalar magnetometer. The nominal data rate of the magnetic observations is 1 Hz, corresponding to a spatial resolution of ~7.5 km. CHAMP operated successfully for more than 10 years until it reentered the atmosphere in September 2010. The orbit precession causes a change of the local time (LT) of the orbital plane at a rate of 12 h per ~131 days.

[6] As noted in section 1, the low-latitude and midlatitude ionosphere is mainly controlled by wind-induced dynamo electric fields. One of the most prominent manifestations of the low-latitude electric field is the EEJ. The EEJ is a strong eastward electric current flowing along the magnetic equator in the daytime ionospheric *E* region (~108 km altitude). The EEJ is an important ionospheric indicator because the strength is closely tied to that of the eastward electric field [*Stolle et al.*, 2008], which controls the equatorial and low-latitude ionospheric dynamics [*Chau et al.*, 2012]. As a strong current system, the EEJ manifests itself in the geomagnetic field which has been observed by CHAMP. Here we investigate the peak current intensity of the EEJ (hereafter, EEJ strength) as derived from the geomagnetic field data of CHAMP; see *Lühr et al.* [2004] for details of the method. For our spectral analysis we first calculate daily averaged EEJ strength over the 3400 days since 28 July 2000. If there is no EEJ data for a given day, the corresponding daily averaged EEJ strength is set to zero. As we conduct a spectral analysis of the EEJ time series, we do not discuss the results from the commissioning phase of the satellite (before May 2001), where occasional data gaps occurred that may compromise the spectral information.

[7] Figure 1 shows the midwinter SSW period of December 2001. The first panel shows daily averages of solar wind speed, which is known as an important driver of multiday variations in the ionosphere [e.g., *Lei et al.*, 2008; *Pedatella and Forbes*, 2011, and references therein]. The data are available at NASA-OMNI Web page (<http://omniweb.gsfc.nasa.gov/>). In the second panel the blue curve shows the orbit-by-orbit EEJ peak current intensity (~15 values per day), and the solid red curve corresponds to a fitted theoretical semidiurnal lunar tide at CHAMP positions (discussed in section 3). The vertical red dashed line marks the time when the precessing CHAMP orbit was at local noon, around which the EEJ strength generally reaches its maximum [*Lühr et al.*, 2004]. To the left and right thereof, CHAMP sampled the EEJ strength at postnoon and prenoon LTs, respectively. Solid and open circles correspond to new and full moons, respectively. The third panel presents a wavelet power spectrum of the standard score ($z_{EEJ_{daily}}$) of the daily-averaged EEJ strength:

$$z_{EEJ_{daily}} = \frac{EEJ_{daily} - \overline{EEJ_{daily}}}{\sigma_{EEJ_{daily}}},$$

where EEJ_{daily} is the daily averaged EEJ strength, $\overline{EEJ_{daily}}$ and $\sigma_{EEJ_{daily}}$ correspond to the mean (32.2 mA/m) and standard deviation (36.4 mA/m) of EEJ_{daily} over the whole 3400 days since 28 July 2000. The wavelet power increases logarithmically (base 2) from blue to red, and the color bar shows

Figure 1. Daily averages of solar wind speed (first panel), orbit-by-orbit equatorial electrojet (EEJ) strength (blue curve) and the theoretical semidiurnal lunar tide (solid red curve) as observed by a precessing platform like CHAMP (second panel), a wavelet transform of the daily averaged EEJ strength (third panel), the difference between the temperature at the North Pole (90°N) and the zonal mean temperature at 60°N, both at 10 hPa level (fourth panel), and zonal mean zonal wind at 60°N and 10 hPa level (black curve) and the average zonal wind (solid red curve) from 1979 to 2010 (fifth panel).

the exponents. We used the Morlet function (wave number of 6) as a mother wavelet.

[8] The fourth panel in Figure 1 shows the difference between the temperature at the North Pole (90°N) and the zonal mean temperature at 60°N, both at 10 hPa level. It is hereafter called stratospheric temperature difference. The black line in the fifth panel presents the zonal mean zonal wind at 60°N and 10 hPa level (positive eastward), and the red line is the average zonal wind from 1979 to 2010. The temperature and wind values are conventionally used to judge the occurrence of an SSW. For the temperature and wind we use the ERA-Interim reanalyses data of the European Centre for Medium-Range Weather Forecasts (ECMWF) [Dee *et al.*, 2011].

[9] Around 23 December 2001 the stratospheric temperature difference (black curve in the fourth panel in Figure 1) begins a steep upturn above the zero level, which marks the beginning of an SSW. Around 1 January 2002 the zonal wind (black curve in the fifth panel in Figure 1) reverses its sign, making the event a “major” SSW. Significant EEJ amplitude modulations with a period of ~ 13 days (second and third panels) begin around the start of the SSW (near 26 December 2001; see the second panel) and last for several weeks. Note in the second panel in Figure 1 that the EEJ amplitude oscillation period (~ 13 days) is actually shorter than the separation of new and full moon (~ 15 days). Note

also that neither the new moon nor the full moon coincides with the onset of enhanced EEJ oscillation (near 26 December 2001). Phases of the EEJ modulation (blue curve in the second panel) generally agree with those of the theoretical semidiurnal lunar tide (solid red curve). Peaks of the solar wind speed (first panel) sometimes exhibit weak correspondence to the EEJ strength minimum (second panel), but the overall correlation between the two is insignificant.

[10] Figure 2a shows the midwinter SSW period of January 2006 in the same format as that of Figure 1. The vertical red dashed line again marks the time when the CHAMP orbit was at local noon. Around 03 January 2006 a midwinter SSW begins (fourth panel), and modulations with a period of ~ 13 days (second and third panels) start to amplify (near 8 January 2006; see the second panel), and last for several weeks in the prenoon sector. Neither the new moon nor full moon coincide with the onset of enhanced EEJ modulation (near 8 January 2006). Note the theoretical semidiurnal lunar tide (solid red curve) in the second panel generated in the same way as for Figure 1. Phases of the EEJ modulation in the second panel (blue curve) exhibit good correspondence to those of the solid red curve, but the correlation to the solar wind speed (first panel) is again poor. Figure 2b presents a midwinter SSW period in January 2009, also in the same format. Around 21 January 2009 a midwinter SSW began, and modulations with a period of ~ 13 days (second and

Figure 2. The same as Figure 1, but for the midwinter sudden stratospheric warming (SSW) periods (a) in January 2006 and (b) January–February 2009.

third panels) begin to grow (near 26 January 2009; see the second panel), and last for several weeks. Also here the above mentioned facts about the theoretical semidiurnal lunar tide and solar wind are valid.

[11] To isolate lunital signatures from the EEJ dependence on LT and solar activity, we apply the following normalization which has been derived from a statistical analysis (Lühr et al., submitted manuscript, 2012):

$$EEJ' = \frac{EEJ}{\sqrt{\frac{\overline{F_{10.7}}}{200} \times |\cos(\frac{\pi}{12}(LT - 12[hour]))|}}, \quad (1)$$

where EEJ' and EEJ represent the normalized and original EEJ peak current densities, respectively, and $\overline{F_{10.7}}$ is the $F_{10.7}$ index averaged over 81 days. We average the EEJ' values of each day and detrend them using a 1-D median filter with a window size of 39 days (about 3 cycles of the 13 day oscillation). Let us call the result $\widetilde{EEJ}'$. Figure 3 shows all the observations from December 2001 to August 2009. From top to bottom the panels show $\widetilde{EEJ}'$, the wavelet power spectrum, wave power at the 13 day period, stratospheric temperature difference, and wind. Red dashed vertical grids correspond to noon LT of the CHAMP orbit. The white horizontal line in the second panel marks a frequency

Figure 3. SSW observations from December 2001 to August 2009. From top to bottom the panels show detrended daily averages of normalized EEJ strength, the wavelet power spectrum, wave power at the 13 day period, stratospheric temperature difference, and zonal wind. Red vertical lines correspond to noon LT of the CHAMP orbit. The white horizontal line in the second panel represents the 13 day period, and the blue horizontal line in the third panel is intended to guide the eye.

level at the 13 day period, along which wavelet power values are sampled and shown in the third panel. The blue dashed line in the third panel is a reference power level, plotted to guide the eye. In order to avoid singular behavior of the normalization near the terminator (see equation (1)), wave power is masked out when the CHAMP orbit was within 1.5 h from dawn/dusk (second and third panels). Year is (month and day are) given along the x axis of the first (fifth) panel. “Midwinter” periods, defined as a period extending from 15 December to 15 February, are marked by blue horizontal bars in the fourth panel. Note that the wavelet power spectrum (third panel) was obtained with the standard score of $\widetilde{EEJ}'$ (not EEJ_{daily}). That is, for the spectral analysis we used the standard score calculated with the mean (-2.0 mA/m) and standard deviation (31.8 mA/m) of $\widetilde{EEJ}'$ over the whole 3400 days since 28 July 2000. From the fourth panel we can identify midwinter SSW periods in every northern winter, except for a period between December 2004 and February 2005. In each midwinter period with SSW (in total, seven cases) 13 day oscillations of $\widetilde{EEJ}'$ are notably enhanced around the first SSW peak (the first positive peak of stratospheric temperature

difference). For subsequent SSW peaks within a given mid-winter period (e.g., in February 2002) the 13 day oscillation strength stays at an elevated level or exhibits a secondary peak. The 13 day oscillations are generally stronger for the first midwinter SSW peak than for the subsequent SSW peaks, as pointed out by *Chau et al.* [2012]. On average, the 13 day wave activity in $\widetilde{EEJ}'$ is stronger in lower solar flux years (2006–2009) than in higher flux years (2002–2005), which is consistent with the results of *Fejer et al.* [2011]. Late winter SSW periods (e.g., end of February 2005 and end of February 2007) do not exhibit as conspicuous enhancements of the 13 day oscillation.

[12] Wave power at 13 day period (third panel in Figure 3) shows occasional enhancements in the absence of major SSW. However, some of them should be interpreted with caution: e.g., during the so-called Halloween superstorm in October–November 2003 (marked by H in the third panel). Such large geomagnetic storms cause stand-alone EEJ spikes. The corresponding wavelet power spectrum (second panel) also shows wide-band enhancements. The overall EEJ behavior during the storms shows little signature of the

enhanced quasiperiodic oscillation with a period of 13 days as observed around the midwinter SSW periods.

[13] To summarize, all the midwinter SSW periods from December 2001 to August 2009 (7 cases) were accompanied by enhanced 13 day oscillations of the EEJ strength, as observed by CHAMP. No other geophysical event caused such 13 day modulations as strong as the seven SSW periods. Hence, we obtain a one-to-one correspondence between strongest lunitidal signals and midwinter SSW periods.

[14] In wavelet analysis there is a trade-off between the temporal and frequency resolution. Therefore, it is not easy to identify the exact onset time of 13 day oscillations from the wavelet power spectra. As an example, we applied the wavelet software used here to an ideal input consisting of a constant time series which after a while changes abruptly (<1 day) to a monochromatic 13 day oscillation. The resultant wave power spectrum at 13 day period shows an increase that ramps up from 10% to 90% in about 30 days centered around the onset time. Because of this slow response, we rather estimate the onset of the 13 day oscillations visually from the original time series (e.g., the second panels of Figures 1 and 2). For the seven midwinter SSW periods, onsets of the enhanced 13 day oscillations of the EEJ strength occur roughly within ± 1 week around the first peak of the stratospheric temperature difference.

3. Discussion

[15] How is the 13 day EEJ modulation related to the lunar tide? We know that the lunitidal period on ground is about 15 days. Let us discuss the origin of the 13 day oscillation. The new and full moon cycle repeats itself with a 29.53 day period. In scientific terms, the revolution period of the moon in the LT frame (period of the moon coming back to the Sun-Earth line segment) is approximately 29.53 days (T_{moon}). As the moon revolves around the Earth counterclockwise when viewed from the North Pole, the moon gains LT at a speed of $24/T_{moon}$ h/d. The CHAMP orbit precesses through LT at a speed so that it returns to the same LT after 261 days (T_{CHAMP}). Contrary to the moon, CHAMP loses LT everyday (i.e., the precession direction is clockwise when viewed from the North Pole) at a speed of $24/T_{CHAMP}$ h/d. The prime lunitidal effect on the tropical ionosphere is semidiurnal [Pedatella and Forbes, 2010]. Then, the lunitidal wave in the tropical ionosphere can be expressed as:

$$L = A \cos \left(2\pi \frac{d - d_0}{0.5 \times T_{moon}} - 2\pi \frac{h}{0.5 \times 24[\text{hour}]} \right), \quad (2)$$

where L is the lunitidal wave, A is the amplitude, d is day (or lunar age for this equation), h is LT, and d_0 is an arbitrary phase delay (delay of maximum positive noon time EEJ from the new-full moon day). For CHAMP observations, d and h are not independent but are interrelated by the precession condition.

$$h = -\frac{d - d_1}{T_{CHAMP}} \times 24[\text{hour}], \quad (3)$$

where d_1 is an arbitrary phase. Then, the lunitidal wave as observed by CHAMP is

$$\begin{aligned} L_{CHAMP} &= A \cos \left[2\pi \frac{d - d_0}{0.5 \times T_{moon}} + \frac{2\pi}{12} \frac{24(d - d_1)}{T_{CHAMP}} \right] \\ &= A \cos \left[4\pi d \left(\frac{1}{T_{moon}} + \frac{1}{T_{CHAMP}} \right) - 4\pi \left(\frac{d_0}{T_{moon}} + \frac{d_1}{T_{CHAMP}} \right) \right] \\ &\approx A \cos \left[2\pi \frac{d}{13.26[\text{days}]} + \phi_0 \right], \end{aligned} \quad (4)$$

where the combined phase ϕ_0 is given by

$$\phi_0 = -4\pi \left(\frac{d_0}{T_{moon}} + \frac{d_1}{T_{CHAMP}} \right),$$

Hence, the lunitidal period as observed by CHAMP should be 13.26 days: that is, CHAMP should observe faster oscillation than a ground observer would measure. This theoretical period agrees with that of the EEJ strength oscillations as observed by CHAMP.

[16] Next, let us evaluate the phase delay (d_0) of the lunitidal equation (equation (2)). We perform a discrete Fourier transform using 106 day ($= 13.25 \times 8$) segments of the $\widetilde{EEJ}$ data shown in Figure 3 (first panel) around the seven midwinter SSW periods. The eighth harmonic of the spectrum corresponds to the 13.25 day period (close to the lunitidal period as seen by CHAMP), and the phase angle corresponds to ϕ_0 in equation (4). As we know the lunar age (d) and the CHAMP LT (h) in equation (2), we can calculate d_0 from the equivalence of equations (2) and (4). For all seven SSW periods we have independently computed the phase delays. From all the cases we obtain similar d_0 with respect to the lunar phase. On average $d_0 = 4.4 \pm 0.3$ days was obtained. This mean value was used to create the theoretical semidiurnal lunar tide (solid red curve) in the second panels in Figures 1, 2a, and 2b. For all the midwinter SSW periods (including those in Figures 1 and 2), the 13 day modulation of the EEJ strength can be fitted reasonably well to equation (2) using a common phase delay of $d_0 = 4.4$ days. This result also supports a lunitidal origin of the 13 day oscillation.

[17] The phase delay (d_0) determined for the lunitidal modulation merits further discussion. The obtained phase delay of 4.4 days is consistent with the findings of Fejer *et al.* [2010] during SSW events. In Figures 7 and 8 of Fejer *et al.* [2010] the noon time ($h = 12$ h in equation (2)) EEJ strengths during SSW exhibit maximum positive excursions about 4 days after the new/full moon. Lühr *et al.* (submitted manuscript, 2012) investigated seasonal variations of the average lunitidal phase delay (d_0). During December solstice the average d_0 is 3.8 h in moon age (moon age (h) = $24 \text{ h} \times \text{moon age (days)} / T_{moon}$) (see Lühr *et al.*, submitted manuscript, 2012, Tables 1 and 2). This is also consistent with the d_0 of 4.4 days (3.6 h in moon age) obtained in our study. During equinox and June solstice months, Lühr *et al.* (submitted manuscript, 2012) reported smaller average d_0 of about 1.7 and 2.3 h in moon age, respectively. Note that Bartels and Johnston [1940] also mentioned the larger d_0 during northern winter. We cannot attribute the seasonal variation of the average d_0 entirely to

the midwinter SSW; it may also be a feature of the December solstice itself. As an example, also the 13 day EEJ modulation around 20 February 2004 (weak enhancement of lunitidal amplitude long after the midwinter SSW on 19 December 2003; see Figure 3) can be fit reasonably well to the lunitidal equation with $d_0 = 4.4$ days (figure not shown). Similar arguments are valid (figure not shown) for the 13 day EEJ modulations around 10 January 2005 (weak enhancement of lunitidal amplitude during the non-SSW northern winter; see Figure 3). Presently, we cannot offer a suitable process that is responsible for the seasonal variation of the average lunitidal phase (d_0). More work is necessary to elucidate the origin of the seasonal variation.

[18] Now we discuss the amplitudes of the lunitidal EEJ modulations. The wave power of the lunitidal EEJ modulation increases during midwinter SSW periods. As discussed above, the maximum power enhancement is generally an order of magnitude (see Figure 3), and the power stays above the normal level for several weeks (Figure 2) to months (Figure 1). For that reason the midwinter SSWs contribute to larger average lunitidal amplitudes in ionospheric currents during northern winter (than in the other seasons), as reported by Yamazaki *et al.* [2011] and Lühr *et al.* (submitted manuscript, 2012). The lunitidal modulation of the EEJ strength during midwinter SSW periods may have an LT dependence, just as that of the zonal E field [e.g., Fejer *et al.* 2011]. From CHAMP data we cannot investigate the LT dependence of the lunitidal signature so well because the CHAMP orbit precesses slowly through LT. Hence, we cannot exactly separate relative strength variations of the diurnal S_q to those of the semidiurnal lunitidal components during midwinter SSW periods. As a first approximation we neglect the LT dependence of the semidiurnal lunitidal amplitude, and compare the amplitude to that of the diurnal S_q variation. In the second panel of Figures 1, 2a, and 2b the amplitudes of semidiurnal lunar tides (13 day oscillation) reach ~ 60 mA/m; this value was used for the theoretical semidiurnal lunar tide (solid red curve). Generally, diurnal S_q variation of the EEJ strength has an average amplitude of ~ 100 mA/m during December solstice [see Lühr *et al.*, 2008, also submitted manuscript, 2012]. Then, the semidiurnal lunitidal component during midwinter SSW periods reaches about 60% of that of the diurnal S_q . As a result, the combination of lunitidal and S_q components exhibits significant deviation from the diurnal S_q pattern which is expected under normal conditions. In particular, it tends to cause counter-electrojets in the afternoon at certain moon phases.

[19] Let us discuss implications of all the above mentioned findings. Our results show that (1) 13 day oscillations of $\widetilde{EEJ}$ can be enhanced without SSW, (2) the oscillation is strongest during midwinter SSW periods (at least during the 8 years considered here), (3) a northern midwinter without SSW (e.g., December 2004 to February 2005) exhibits weaker 13 day oscillations than SSW-associated midwinters, and (4) during each midwinter SSW period amplification of the 13 day modulation starts roughly within ± 1 week around the first peak in stratospheric temperature difference. Points 2–4 suggest that strongest 13 day oscillations and midwinter SSW periods do not occur coincidentally, but have a causal relationship or share a common origin. The period and stable

phase ($d_0 = 4.4 \pm 0.3$ days) of the 13 day oscillations are consistent with the theoretical semidiurnal lunitidal equation (equation (2)), suggesting lunar origin of the oscillations. Hence, our results support the idea that midwinter SSW events improve the conditions for stronger EEJ modulation of semidiurnal lunar tides.

[20] Goncharenko *et al.* [2010b] and Fejer *et al.* [2010] showed that SSW-related variations of the tropical ionosphere are semidiurnal with its phase moving to later LT at a speed of $\sim 12/15$ h/d. The results were presented in the two-dimensional LT versus day plane [e.g., see Fejer *et al.*, 2010, Figure 3; Goncharenko *et al.*, 2010b, Figure 4]. As the CHAMP samples make a slant one-dimensional cut through the plane [see Fejer *et al.*, 2010, Figure 3], our observations should bear consistency with those of Goncharenko *et al.* [2010b] and Fejer *et al.* [2010]. Actually, our 13 day oscillation component of the EEJ strength variation can be represented by our equation (2), which is also semidiurnal with its phase shifting to later LT with a speed of $\sim 12/15$ h/d. Moreover, the amplitude of the 13 day oscillation component is comparable to that of the average S_q variation, explaining why during midwinter SSW periods the LT variation of the EEJ strength deviates significantly from the normal diurnal pattern. All these facts support consistency between our observations and those of Fejer *et al.* [2010] and Goncharenko *et al.* [2010b]. As discussed above we regard the 13 day oscillations as originating from the lunar semidiurnal tide, which tide may also explain the results of Goncharenko *et al.* [2010b] and Fejer *et al.* [2010].

[21] Stening [2011] questioned the lunar origin of the EEJ behavior during SSW. His argument was based on the fact that (1) large lunitidal signatures occur also during non-SSW periods and (2) there are different phase delays, d_0 , at different locations. In general, we cannot confirm his conclusions. Let us first discuss point 1. As mentioned in point 1 in two paragraphs above, our results show that 13 day oscillations of $\widetilde{EEJ}$ can indeed be enhanced in the absence of SSW (e.g., around 1 October 2007 in Figure 3), which is consistent with the results of Stening [2011]. Nevertheless, points 2–4 in that same paragraph support the claim that strongest lunitidal signatures and SSW have a causal relationship or share a common origin. As we used daily averages of the EEJ (averages over longitudes), we cannot give a decisive answer to point 2 in this paragraph. On a global average (irrespective of longitude) lunitidal signatures of the EEJ, during all midwinter SSW periods shown here, can be fitted reasonably well by a fixed phase delay of $d_0 = 4.4 \pm 0.3$ days. Lühr *et al.* (submitted manuscript, 2012) statistically investigated the longitude dependences of lunitidal signals in the EEJ. From their 5 year averages they could not find significant differences in phase delays between the three 120° sectors. Our Figures 1 and 2 show nonnegligible orbit-to-orbit variations of the EEJ strength within a day (see the blue curve in the second panel). These longitudinal variations of the EEJ strength can be attributed to solar nonmigrating tides, as shown by Lühr *et al.* [2008, 2011]. The nonmigrating tidal effects may explain the difference between our results (global average) and Stening [2011].

[22] With the Whole Atmosphere Model (WAM), Fuller-Rowell *et al.* [2011b] could reproduce the vertical plasma

drift observed at Jicamarca during the 2009 SSW event. Reasonable model-to-observation agreement was obtained in terms of the semidiurnal variation as well as its phase shift toward later LT sectors (see their Figure 4). As Fuller-Rowell *et al.* [2011b] did not include lunar tides as an input [Chau *et al.*, 2012], the result challenges our suggestion, i.e., the lunital origin of the semidiurnal variation. Nevertheless, our results show that phases of the semidiurnal variations are well aligned with the moon age for all the seven midwinter SSW events: that is, $d_0 = 4.4 \pm 0.3$ days. We regard this as a strong argument in favor of the lunital origin of the semidiurnal variation of the EEJ strength. Fuller-Rowell *et al.* [2011b] provided the model-to-observation agreement for only one case (the SSW event in January 2009). More numerical simulations may be needed to clarify the relation between SSW and enhanced modulation of ionospheric phenomena by lunar tides. We may speculate that the major reconfiguration of the middle atmosphere by SSW events improves the upward propagation conditions for the low-latitude lunital signal.

4. Summary

[23] Using the equatorial electrojet (EEJ) peak current intensity as deduced from CHAMP magnetic observations from the years 2001 through 2009, we investigated the relationship between sudden stratospheric warming (SSW) and lunital signatures in the tropical ionosphere. The main results of the paper can be summarized as follows:

[24] 1. There is practically one-to-one correspondence between midwinter SSW periods and strongest 13 day modulation of the EEJ strength, as observed by CHAMP. That is, all the midwinter SSW periods from December 2001 to August 2009 were accompanied by an enhanced 13 day modulation of the EEJ strength. No other geophysical phenomenon brought about as strong 13 day modulation as those of the midwinter SSW periods.

[25] 2. During each midwinter SSW period the amplified 13 day modulation of the EEJ strengths starts roughly within ± 1 week around the first peak in stratospheric temperature difference, independent of the prevailing lunar phase.

[26] 3. An oscillation with a period of 13.26 days is predicted by the lunital equation when considering the precession of the CHAMP orbit. The observed EEJ modulations are not correlated with variations of solar wind speed.

[27] 4. When fitting the lunital equation to the EEJ modulations during the midwinter SSW periods, consistent phase delays of the tidal signals emerge for all the cases. On average we obtain $d_0 = 4.4 \pm 0.3$ days from the seven cases.

[28] 5. On the basis of the observations we can conclude that midwinter SSWs seem to have a direct influence on the amplitude of the lunital signal in the ionosphere.

[29] 6. More research is needed for identifying the process that favors the amplification of the lunital wave at ionospheric altitudes.

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