First in-situ observation of night-time F region currents with the CHAMP satellite

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[1] The CHAMP satellite in its polar, low-Earth orbit (450 km altitude) is a suitable platform for studying F region currents. High precision magnetic field measurements are used to detect and characterize these upper ionospheric currents on the Earth's nightside. A few examples are presented to illustrate the special features of the currents and a statistical study is performed on half a year of data revealing their global distribution. We find a spatial confinement of the currents to the near-equatorial region bounded by the Appleton anomaly and their appearance in the pre-midnight sector. The distribution with longitude exhibits high occurrence rates in the Atlantic sector and very few events in the Indian sector. The currents flow generally westward at a height-integrated current density of several mA/m. Small-scale fluctuations observed in current intensity are interpreted as an indication for plasma instabilities in the F region. Our analysis indicates that the appearance of F region currents is coupled with the presence of plasma bubbles. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2409 Current systems (2708); 2439 Ionospheric irregularities

1. Introduction

[2] The ability of the ionospheric F region to carry currents depends on a small ratio of the E to F region height-integrated Pedersen conductivity. Typically the boundary between these two regions is chosen to coincide with the conductivity minimum around 150 km (e.g., [*Rishbeth and Garriott*, 1969]). At night times when the E region conductivity is small, F layer currents can be important [*Rishbeth*, 1971a; 1971b]. This is in particular true for the equatorial and tropical ionosphere. Here the length of magnetic field lines within the F region is large and the Pedersen conductivity has to be integrated along the field lines. Above 400 km these field lines cross the Appleton anomaly where the conductivity is expected to be elevated. The Appleton or equatorial anomaly denotes regions of enhanced plasma density about 15° north and south of the dip equator occurring during the evening and pre-midnight hours. For further details concerning the equatorial electrodynamics causing this fountain effect and the instabilities, we refer readers to *Kelley* [1989].

[3] Studies of the F region dynamo have received considerable attention in recent years. Comprehensive modelling efforts have been undertaken to investigate the relationship between the F region dynamo and the complex plasma dynamics at lower latitudes around sunset (e.g., [*Crain et al.*, 1993; *Eccles*, 1998]). Of particular interest in this context is the development of plasma instabilities. The evolution of spread F and plasma bubbles is described by e.g., *Fejer et al.* [1999] and *Whalen* [2000]. Both studies are based on large observational data sets.

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[4] Observations reported on the F region dynamo concentrate primarily on electron density, plasma drift, as well as on wind fields and the derived electric fields. Overviews of recent findings have been given by *Titheridge* [1995] and *Fejer* [1997]. So far, little has been published about direct current measurements in the F region, probably because of the weak magnetic effect they cause, they can easily be masked by other variations.

[5] In this letter we report, to our knowledge for the first time, in-situ F region current observations from the nightside tropical zone. Signatures in the total magnetic field measurements obtained by the CHAMP satellite are interpreted in terms of F region currents. In the subsequent sections we present the observations and then offer our interpretation of the measurements. Finally we discuss possible causes for the currents and how they are related to other F region phenomena.

2. Observations

[6] The CHAMP satellite was launched on 15 July 2000 into an almost circular, near-polar (incl. = 87.3°) orbit with an initial altitude of about 450 km. The prime mission objectives are studies related to the gravity field, magnetic field and the atmosphere. Instruments supporting the magnetic field investigations are precision scalar and vector magnetometers, a dual-head star camera system and a digital ion driftmeter. Further details of the CHAMP satellite and mission can be found at the web site http://op.gfz-potsdam.de/champ/.

[7] Only magnetic field data from the scalar Overhauser magnetometer are used here. The measurements considered are from the first six months of the mission covering August 2000 through January 2001, during which time the orbital plane precessed through all local times.

[8] Magnetic field readings sampled along the track of a low-Earth orbiting satellite comprise the sum of contributions from various sources. Before studying a particular effect, all the other parts must be removed correctly. Since we are interested in nightside effects, we have limited our study to the hours 19 to 06 local time (LT), during which the influence of E region currents can be neglected. Furthermore, we took only data from periods of low activity ($Kp \leq 2$). The main field was removed from the scalar data by subtracting a recent field model (Ørsted-05b-01 [*Olsen*, 2002]). In addition, the ring current effect was eliminated on an orbit-by-orbit approach [*Maus et al.*, 2002].

[9] Single-point satellite measurements are known to suffer from spatial-temporal ambiguities. In order to overcome this problem we have taken advantage of the fact that — during the considered time period — the CHAMP spacecraft had an orbit repeat cycle of approximately three days. This means, the satellite sampled the same region on Earth every three days. When comparing readings from such repeat tracks, constant parts (with respect to a three day time-scale) will show up again, e.g. residuals of the main field, constant parts of magnetospheric currents and

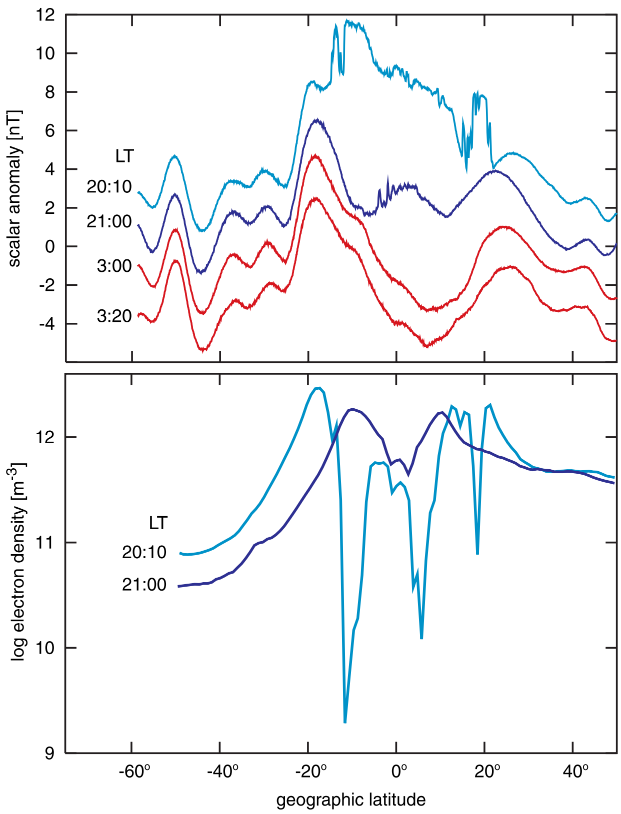

Figure 1. (Top panel) Residuals of the magnetic field magnitude from repeated sampling of the −38.5°E meridian at different local times. Each of the four curves has been offset by 2nT for better readability. (Bottom panel) Electron densities measured simultaneously with the top two magnetic field traces. The dip equator is located at 2.4°N.

lithospheric magnetization. Time varying parts, e.g. ionospheric and magnetospheric currents, may differ.

[10] As an example, the top panel of Figure 1 shows scalar magnetic field residuals at 1 Hz data rate from a longitude strip at $-38.5° \pm 0.5°$. The four curves are very similar outside the tropical zone although the dates of measurement are in some cases more than two months apart. (The measurement dates of the traces from top to bottom: 22. Sep., 13. Sep., 18. Nov, 15. Nov. 2000.) This figure also demonstrates the high reproducibility and low noise of the CHAMP magnetic field measurements. The lower two curves reflect just lithospheric magnetization, while the upper two curves show significant deviations of several nano Tesla inside a ±20° latitude band.

[11] Several points are worth noting. The top curves exhibiting the fluctuations are obtained at times before local midnight, while the lower ones are from post-midnight. The deflections are centered around the dip equator (here at 2.4°N) and they generally show an enhancement in the field strength. In contrast to the unperturbed traces, the disturbed signal contains a significant amount of small-scale fluctuation.

[12] The lower panel of Figure 1 shows electron density measurements obtained by the Langmuir probe on CHAMP. This instrument takes readings every 15 s. Each data point is plotted. The two density curves correspond to the two top field traces, respectively. Clearly visible in the density profiles are the Appleton anomalies on both sides of the equator. There are deep density depletions observed in the region of the anomaly during the earlier event. Fluctuations in field strength are well aligned with these depletions. The density at post-midnight hours (not shown) is much lower and shows no enhancements.

[13] After having detected these unexpected night-time field perturbations we were interested in their statistical properties, in particular the spatial and temporal distribution. It is rather difficult to design an algorithm that automatically identifies the deflections of interest in the large background signal. For our statistical analysis we therefore focussed on small-scale variation. We removed the crustal signal, still visible shown in Figure 1, with the help of a lithospheric anomaly model [*Maus et al.*, 2002] and subsequently high-pass filtered the data by subtracting a running mean over 40 sec, which corresponds to a cut-off scale length of 300 km. To emphasize the power in this small-scale range the signal was squared.

[14] Figure 2 shows the global distribution of the fluctuation power separately for local times before and after midnight. During the latter period no disturbances are detected. All remaining features on that map can be related to steep gradients in the crustal anomalies. A completely different picture is obtained for the pre-midnight hours. Here we find a lot of small-scale power within a band of ±20° latitude centered on the dip equator. The differences in longitude are rather striking. High occurrence rates of fluctuations are present in the Atlantic sector opposed to the rare events in the Indian sector and an intermediate density over the Pacific sector. This asymmetry cannot be attributed to the data coverage, as the tracks considered were densely spaced and evenly distributed.

[15] After having detected the large differences in longitude we wanted to see whether this holds only for the small-scale variation or is also valid for the DC part. Figure 3 shows scalar residuals in the same format as Figure 1. The data are taken from the same days, but four orbits earlier bringing us into the Indian sector. There are only small differences between any of the four tracks which could be attributed to ionospheric currents. The density curves corresponding again to the two top field traces, show, as expected, the equatorial anomalies. Obviously, a mechanism other than just the enhanced charge density is needed to control the presence or absence of the currents.

3. Interpretation in Terms of F Region Currents

[16] As stated in the Introduction we believe that the time-varying deflections in the pre-midnight local time sector are caused by F region currents. This is inferred from the significant small-scale signal content in the perturbed region. To first approximation, the wave length of a spatial variation, here of order 100 km, has to be equal or larger than the distance to the source. With CHAMP at 450 km altitude the E-region is too far away (340 km) as to be considered as the source region for the observed fluctuations.

[17] The deflections generally have a positive sign corresponding to a northward pointing magnetic field, indicative of westward flowing currents below the CHAMP orbit. This suggestion is supported by the absence of any such signatures in the Ørsted data at altitudes between 640 and 860 km (N. Olsen, private communication, 2001). The "silence" in Ørsted scalar data is also consistent with our statement that the short period fluctuations reflect spatial features rather than being caused by temporal variations e.g., compressional waves [*Jadhav et al.*, 2001].

[18] The top curve in Figure 1 exhibits positive deflections over a latitude range bounded by the Appleton anomaly. The second curve shows a deflection close to the dip equator only. While the small-scale fluctuations peak along the latitudes of the Appleton anomaly, as is obvious from Figure 2, the DC part is also present at the equator.

[19] For a crude estimate of the current density we may use the infinite current sheet approximation

$$\Delta B = \frac{\mu_0}{2} J, \qquad (1)$$

where J is the sheet current density and ΔB the magnetic field effect of the current. Reading 3nT as a typical magnetic deflection

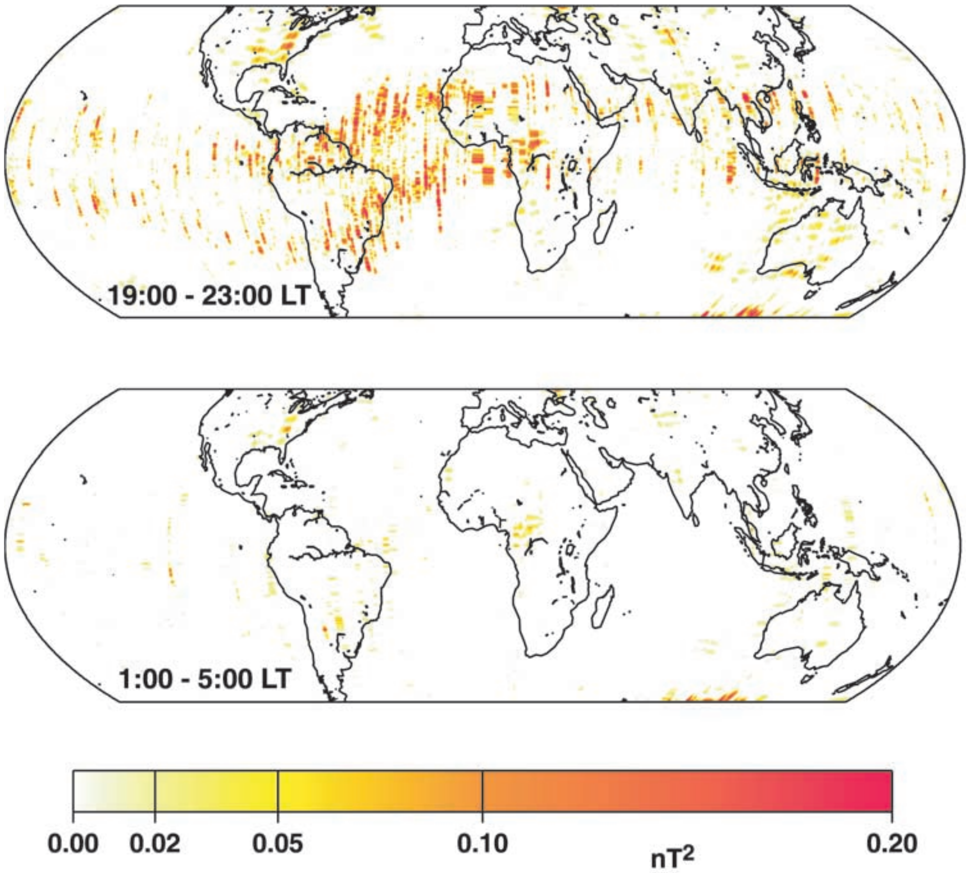

Figure 2. Distribution of small-scale current fluctuation with longitude and local time. Magnetic field readings, after subtraction of main field and lithospheric field models, have been high-pass filtered (wavelength < 300 km) and squared. Signal power is confined to bands north and south of the dip equator (top map). After midnight no such fluctuations are observed (bottom map).

from our observation we may conclude that the actual height-integrated current density has to be equal to or larger than 5mA.

4. Discussion

[20] We have interpreted the observed magnetic field deflections in the pre-midnight tropical zone as an indication for westward flowing F region currents. Let us now address possible causes of these currents. Relevant terms contributing to the current density, **j**, are [*Kelley*, 1989, Sect. 4.2.]

$$\mathbf{j} = \sigma_\mathbf{p}\mathbf{E} + [\mathbf{n m_i g} \times \mathbf{B} - \mathbf{k}(\mathbf{T_i} + \mathbf{T_e})\nabla_\mathbf{n} \times \mathbf{B}] \cdot \frac{\mathbf{1}}{\mathbf{B^2}}, \qquad (2)$$

where σ_P is the Pedersen conductivity in the F region and **E** the electric field; n is the electron density, m_i the mass of the dominant ion species (O^+), **g** the acceleration due to gravity, k the Boltzmann constant, T_e and T_i the electron and ion temperature, ∇n the vertical electron density gradient and **B** the magnetic field with magnitude B.

[21] The two terms in brackets reflect the contributions of the gravity and the charge density gradient to the horizontal current. Both terms are independent of the prevailing conductivity and thus also contribute in collisionless plasmas. It is known that steep vertical electron density gradients build up at the bottom side of the F region in the post-sunset sector. This is caused by the rapid recombination process in the dark lower ionosphere. Inserting numbers for the F region at equatorial latitudes in favor of currents in the pre-midnight sector, $n = 3 \times 10^{12}$ m^{-3}, vertical component of gradient, $(\nabla n)_z = 5 \times 10^7$ m^{-4}, $(T_e + T_i) = 2000$ K, $m_i = 16 \times 1.67 \times 10^{-27}$ kg, $B = 25 \times 10^{-6}$ T, we obtain a contribution to the current density j [. . .] = 7×10^{-8} Am^{-2} from the terms in brackets. Although of reasonable strength, the derived current direction is eastward, opposite to our observation.

[22] The background electric field on the nightside points westward and has an amplitude of about 1 mV/m [*Fejer*, 1997]. *Crain et al.* [1993] show in their Figure 2 an altitude profile of the nightside Pedersen conductivity at 15° dip latitude, derived from the MSIS and IRIS models. Estimating a height-integrated Pedersen conductivity over the full F region from that graph reveals $\Sigma_{PF} = 0.15$ S. For the electric field driven current we thus obtain a height-integrated density, $J = \Sigma_{PF}E = 0.15$ mA/m which is more than an order of magnitude less than the observed strength according to equation 1. Hence, the driving mechanism for the observed currents is not clear to us at this point.

[23] An interesting further observation is that the currents are always accompanied by small-scale fluctuations. The occurrence of the westward currents appears to be related to the presence of F region instabilities which we believe are the cause of the fluctuations. In the Indian sector we find the same density profiles (Appleton anomaly) as in the Atlantic sector but no density depletions and no F region currents. The occurrence distribution with longitude (cf. Figure 2) is almost identical to the one resulting from an extensive survey of equatorial plasma bubbles by *Huang et al.*, [2001] using several years of DMSP data. We may speculate that the instability itself modifies the plasma conditions and causes the effective conductivity enhancement in the upper F region. More

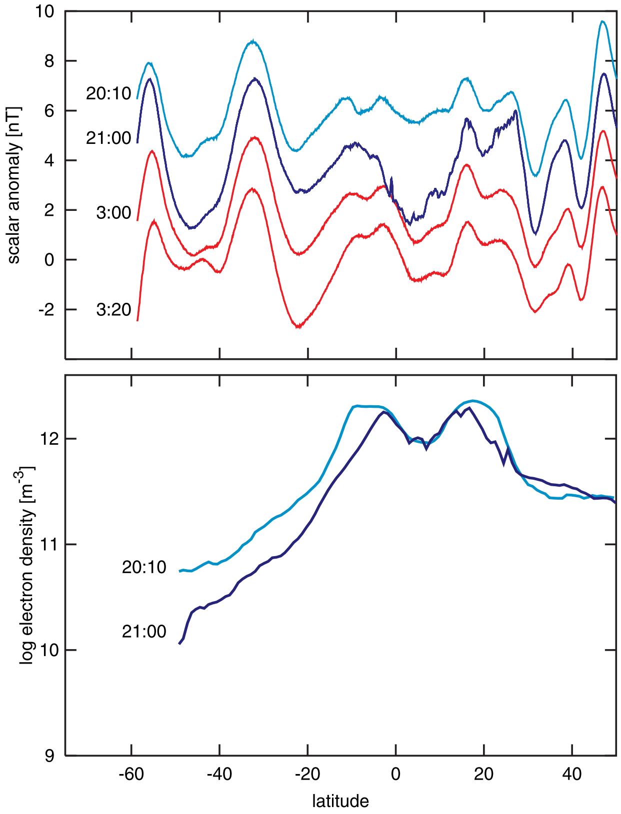

Figure 3. Same as Figure 1, but for the 55.2°E meridian. The dip equator is located at 7.4°N.

detailed observations and studies are required in order to identify the processes involved in the current generation.

5. Conclusions

[24] We have presented CHAMP magnetic field data providing for the first time in-situ evidence of westward currents in the tropical ionospheric F region in the pre-midnight sector. The height-integrated current density is estimated to be of the order of 5 mA/m. Within the limited range considered (Kp = 0 . . .2) we could not find a relation between the current intensity and the magnetic activity.

[25] The current signatures are generally accompanied by small-scale (≈100 km) intensity fluctuations. We associate these fluctuations with spread F features.

[26] The occurrence distribution of the F region currents with longitude shows a clear peak in the Atlantic sector, a minimum in the Indian sector and intermediate rates over the Pacific. This pattern resembles very closely the distribution of F region instabilities, as reported by *Huang et al.* [2001].

[27] The identified currents, although small in amplitude, are of significance in several respects. Due to their distinct distribution in longitude and latitude, they cause spurious effects in high-resolution magnetic field modeling. For main field and lithospheric studies it is advisable to avoid using data from times before 22 LT.

[28] The suggested relation of the currents to F region instabilities imply that magnetic field observations in this height range contain valuable information for studies of equatorial spread F and ionospheric scintillation events.

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