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Comment on "Storming the Bastille: the effect of electric fields on the ionospheric F-layer" by Rishbeth et al. (2010)

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1 Introduction

In our estimation, Rishbeth et al. (2010) have made several fundamentally incorrect statements. We have great admiration for the past works of the now deceased first author, but we feel that corrections need to be made to set the scientific record straight. Rishbeth et al. have stated "Mannucci et al. (2005) have shown that, in response to these (meridional $\boldsymbol{E} \times \boldsymbol{B}$) drifts, storm TEC enhancements occur across the dayside ionosphere at low and middle latitudes." "The work of Mannucci et al. (2005) shows quiet-day TEC at the equator near 50 units with middle latitude values near 30 units of $10^{16}\,\mathrm{m}^{-2}$. Even if the entire plasma content at the equator were transported without loss to middle latitudes, it is not possible to account for TEC enhancements to 200 and sometimes 300 units." "Thus TEC enhancements at latitudes beyond 25 degrees cannot generally be attributed to transport from the equator". Later they say "Whenever plasma transport is invoked to explain an ionospheric phenomenon, one must ask: Can the plasma travel far enough in its lifetime to produce the observed effect? Detailed modeling is needed to settle this question, but in some cases the time required is so long that changes in local time and in the imposed electric field pattern become the dominant consideration. With these considerations, a longitudinally confined, latitudinally extended, TEC enhancement at middle latitudes, such as is observed during superstorm events, would require a similar configuration in the electric field. Evidence for this feature, how it is formed and how it evolves during a storm epoch also represent some key challenges to our understanding."

It is the purpose of this short note to explain (1) how the "TEC enhancements to 200 and sometimes 300 units" occurs by meridional $\boldsymbol{E} \times \boldsymbol{B}$ drifts and photoionization alone, (2) how "TEC enhancements beyond 25° can be caused by this same process" and (3) why "the time required is so long that changes in local time and the imposed electric field pattern becomes the dominant consideration" is not a real concern.

2 What is the source of the near-equatorial and mid-latitude TEC enhancement?

One fundamental question concerning the dayside TEC enhancement during superstorms is, is this due to a source mechanism that is located near the Equator (the prompt penetrating electric fields (PPEFs) and the superfountain effect) or near the auroral zones due to particle precipitation and atmospheric heating, or both? Precipitation in the auroral regions will create neutral winds which will come down from the auroral regions towards the Equator. This latter effect leads to what has been called the "disturbance dynamo" (Blanc and Richmond, 1980; Fuller-Rowell et al., 1997). To partially answer this question we first show Fig. 1, a result whose interpretation Rishbeth et al. questions. The figure is taken from Mannucci et al. (2005). The figure displays verticalized TEC data from the CHAMP spacecraft which was orbiting the Earth at an altitude of ∼400 km. CHAMP only detects the part of the ionosphere that is above the satellite. Three orbits from ±60° MLAT are shown. All of the orbits shown passed over the magnetic equator at ∼13:00 LT. The blue curve with the time designations of 18:40 and 19:00 UT shows a quiet time TEC distribution prior to the superstorm on 30 October 2003. The normal equatorial ionospheric anomalies

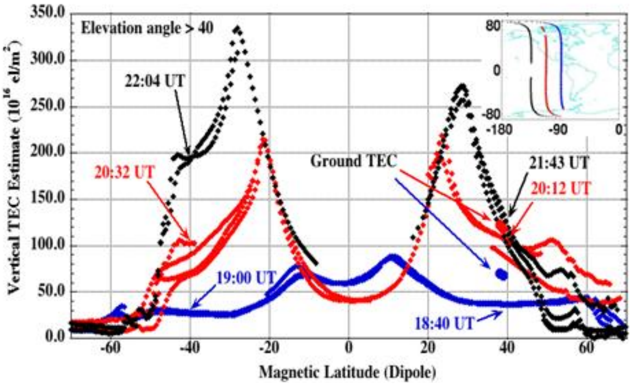

Fig. 1. Three passes of the CHAMP satellite through the dayside ionosphere at ∼12:30 to 13:30 MLT. CHAMP was at an altitude of ∼400 km. The blue curve was taken prior to the 30 October 2003 magnetic storm. The red curve was taken at the beginning of the storm, and the black near the end of the storm. The figure is taken from Mannucci et al. (2005), Fig. 3.

(EIAs: Namba and Maeda, 1939; Appleton, 1946) are present at $\sim\pm10°$. The next two curves in red and black correspond to the TEC above CHAMP after the magnetic storm had started and was in progression. In the 20:12 to 20:32 UT pass (in red), the EIAs are now located at $\sim\pm22°$ MLAT with peak TEC values of ∼210 units. It is also noted that the equatorial region, $|\mathrm{MLAT}| < 10°$, the TEC values are less than that noted during the quiet interval. Some of the plasma in this equatorial region has presumably been swept up and convected to higher altitudes and latitudes by the convection electric field.

The third pass is the most dramatic of all. The black curve with the 21:43 UT and 22:04 UT time indicators shows that the ionospheric anomalies have moved to higher magnetic latitudes and are even more intense. The peaks are now at $\sim\pm30°$ and have values of ∼270 TEC units in the Northern Hemisphere and ∼330 TEC units in the Southern Hemisphere. The southern hemispheric peak may be higher due to either the fact that the spacecraft passed through the south peak later in time or that this is possibly a seasonal effect.

Another feature present in Fig. 1, but not discussed in Mannucci et al. (2005), is that there are TEC enhancements above quiet time values at magnetic latitudes beyond the ionization peaks. In the two passes during the storm main phase (the red and black curves), there are enhancements up to $\sim\pm50°$ MLAT. In Tsurutani et al. (2004), ground-based TEC data were used to show similar enhancements at these high latitudes. The latter results were for an intense magnetic storm that occurred on 5–6 November 2001.

The main point we wish to make about this figure is that the CHAMP data show that the EIAs become displaced from their normal location ($\sim\pm10°$) *poleward* with increasing time. This can only be caused by the prompt penetrating electric field, not by the disturbance winds originating in the auroral zone regions. This figure indicates that a PPEF is important for the ionospheric storm, but could the disturbance winds also be contributing to the intensity of the ionization peaks? This question cannot be answered using spacecraft data alone, but could be answered by computer simulations.

3 Computer modeling of the 30 October 2003 superstorm: SAMI2

The NRL SAMI2 model is a low-latitude ionospheric model that describes the dynamics and chemical evolution of seven ion and seven neutral species (Huba et al., 2000, 2002). Collisions between electrons, ions and neutrals are taken into account. SAMI2 solves collisional two-fluid equations for electrons and ions along the Earth's dipole magnetic field lines, taking into account photoionization of neutrals, recombination of ions and electrons, and chemical reactions. Drift of magnetic flux tubes defines the ionospheric plasma transport in a perpendicular direction to the magnetic field lines. The $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift is caused by the eastward polarization electric field superimposed on the Earth's background magnetic field. Verkhoglyadova et al. (2006, 2008) have modified SAMI2 to insert a prompt penetration electric field (PPEF). The PPEF is specified along the Equator and mapped to higher latitudes along the magnetic field equipotentials. We do not consider a meridional electric field distribution that is not represented by this mapping.

The PPEF for 30 October 2003 was calculated following the Rostogi and Klobuchar technique. The Kyoto University ionospheric model was used to obtain the conductivity values. The equatorial electrojet was assumed to be centered at an altitude of ∼105 km, where a Cowling conductivity of $1.9 \times 10^{-2}\,\mathrm{S\,m^{-1}}$ was calculated for local noon. The magnetic perturbation at the CHAMP was measured, a ground reflectance of ∼11 % and an infinite line current assumed in order to derive the electric field intensity. A value of $\sim 4\,\mathrm{mV\,m^{-1}}$ was obtained. We direct the reader to the original articles (Verkhoglyadova et al., 2006, 2008) for further details.

The TEC modeling of the 30 October 2003 magnetic storm has been previously shown by Verkhoglyadova et al. (2006, 2008). In Fig. 2, we show the oxygen ions associated with the storm. The top left-hand panel shows the ionosphere prior to the magnetic storm. The northern hemispheric ionospheric anomaly is at the normal location, $\sim+10°$ MLAT. The Southern Hemisphere anomaly is more diffuse and the peak is located at $\sim-20°$ to $-25°$ MLAT. This hemispheric difference may be due to seasonal effects.

The upper right-hand panel shows the ionosphere after the PPEF has been on for ∼2 h, the length of the main phase of the storm. The PPEF is applied at 12:00 LT for the equatorial ionosphere and terminated at 14:00 LT. The ionosphere has essentially reached an equilibrium (not shown to conserve space). The EIA peaks are located between ∼450 and

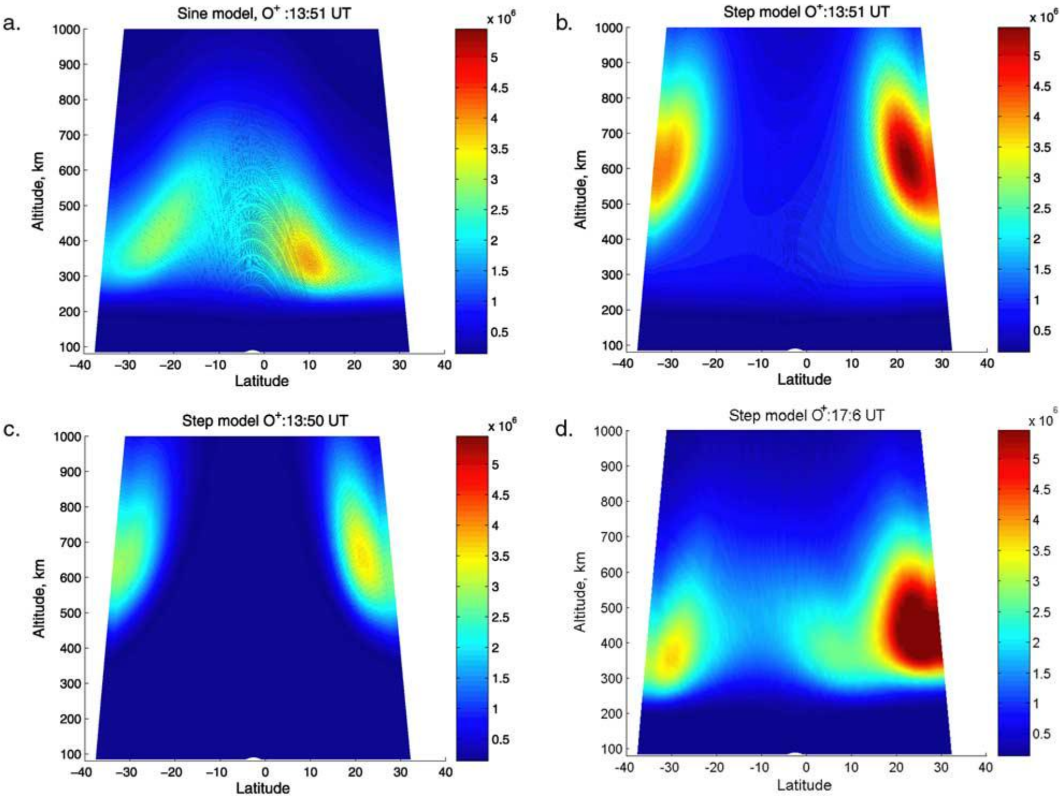

Fig. 2. Oxygen ion features of the 30 October 2003 magnetic storm modeled by SAMI2. The top-left panel shows the quiet time ionosphere, the top-right the ionosphere after the storm-time electric field has been applied for ∼2 h, the bottom-left with the electric field on for ∼2 h but with the sun turned off, and the bottom-right, after the magnetic storm had finished for ∼2 h. Taken from Tsurutani et al. (2008), Fig. 6.

800 km and at latitudes of ∼18° to 30° in the north and from $\sim -28°$ to $< -35°$ in the south. There are TEC enhancements at latitudes above the EIA peaks as well.

Ionospheric electrons were also examined for the same PPEF conditions. The peak locations of the EIAs and the electron densities closely match those of the oxygen ions. For interested readers, we refer them to Verkhoglyadova et al. (2006).

The lower left-hand panel is the same as for the upper right-hand panel, but with the solar photoionization turned off. There are two primary differences between the results of these two cases. With the sun off, the EIA peaks are essentially at the same height and latitude location. The peak TEC intensities are lower. The second important feature is that the ions (and electrons) are removed in the near-equatorial range, ±20° MLAT. There is a void there. This panel partially answers another question posed by Rishbeth et al. (2010) "… one must ask the question Can the plasma travel far enough in its lifetime to produce the observed effect?" It can be concluded from this modeling study that significant TEC enhancements at middle latitudes are possible due to transport, not solely by production. Plasma originally from latitudes lower than where the "displaced" TEC peaks are observed has been transported to the peaks and elsewhere. From the greater intensity of the displaced EIA peaks in the upper right-hand panel, it can be concluded that solar production of ionization leads to the enhanced densities of the displaced peaks (relative to the nonsolar case).

Finally, we look at the ionosphere ∼2 h after the storm has subsided. This is shown in the bottom right-hand panel. The EIA in the Northern Hemisphere is now more intense than that during the storm. The altitude is lower and the latitude is higher. The northern peak is now from ∼300 to 550 km at a latitude of $\sim +20°$ to $> 30°$ MLAT. The southern hemispheric peak is less intense, at an altitude of ∼300 to 400 km and a latitude of $\sim -30°$ MLAT.

How does the SAMI2 modeling compare with the Mannucci et al. (2005) TEC measurements? The TEC at altitudes above 400 km at ∼13:00 LT and at 25° MLAT have been calculated and are shown in Fig. 3. Two curves are displayed, a quiet time set of values shown in stars and the 30 October 2003 storm interval (with 2 h of $E = 4\,\mathrm{mV\,m^{-1}}$ applied) shown in open triangles. In the storm electric field case, the TEC increases until ∼15:15 LT when a peak value of ∼270 TEC units is reached. This closely matches the peak EIA observed by CHAMP during the third CHAMP pass shown in Fig. 2. This also suggests that the very large electric field values derived using the CHAMP magnetometer

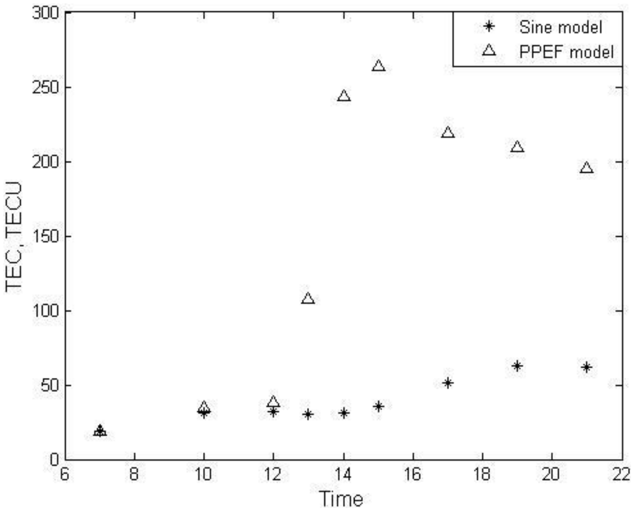

Fig. 3. The SAMI2-derived TEC at altitudes above 400 km at ~13:00 LT and at 25° MLAT. The starred values are for a quiet time interval with a peak diurnal electric field of 0.53 mV m^{-1} at 07:00 LT. The open triangles represent the TEC for the case of an electric field of 4 mV m^{-1} for a 2 h duration. In the storm case, the TEC increases until a peak value of ~270 TEC units is reached. This closely matches the peak EIA observed by CHAMP during the third CHAMP pass shown in Fig. 2.

measurements are quite plausible. The storm-time electric field magnitude is a factor of ~8 times the diurnal variation (assumed to be a peak value of 0.53 mV m^{-1} at 07:00 LT in the model).

From the use of the SAMI2 model, which has no disturbance winds included, it is shown that the features of the peaks in the anomalies can be explained by the PPEF (and photoionization) alone. Most if not all of the peak TEC intensities are caused by the PPEFs during the first 2 h of the intense magnetic storm.

4 Where do all the dayside TEC electrons come from?

One question that Rishbeth et al. (2010) posed is where can all these electrons in the Mannucci et al. (2005) observations come from? If one sweeps up all of the near-equatorial electrons (and ions), we agree, there is not enough to create peaks with 200 or 300 TEC units at middle latitudes. The answer can be shown graphically in Fig. 4.

Figure 4 shows a scenario for increasing the dayside TEC during a magnetic storm. The top panel shows a quiet time ionospheric density profile as a function of height. When the eastward directed PPEF impinges on the dayside near equatorial ionosphere, the ionosphere is convected upward, as indicated in the bottom panel. In actuality, the ionosphere is convected both upward and towards the magnetic poles, as was shown in Figs. 1 and 2. The ionospheric electron–ion recombination rate is much slower at higher altitudes (Tsurutani et al., 2005), so the "old" ionospheric densities are more or less stable. Meanwhile, the near-equatorial region has become out of equilibrium and is subjected to ionization increase/replenishment by solar photoionization. Thus, there is a net gain of dayside TEC due to this uplift (and convection to higher latitude) process. We call this overall process the "dayside ionospheric superfountain".

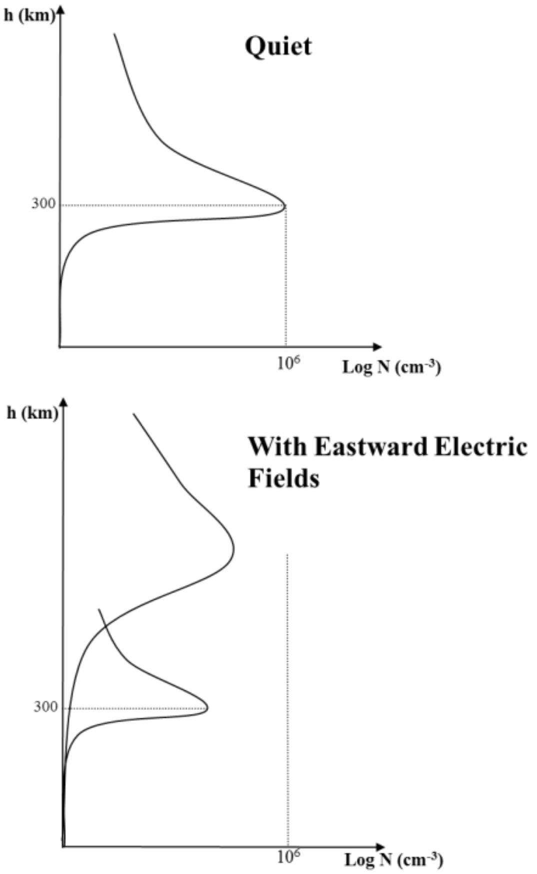

Fig. 4. A schematic showing the effect of uplifting the F-region ionosphere. The top panel shows the quiet time dayside configuration. The bottom panel shows how a new ionosphere is created after the old ionosphere is convected to higher heights during a storm-time PPEF event. Taken from Tsurutani et al. (2004), Fig. 12.

5 TEC peak locations

How can one get TEC peak locations beyond ±25° when the Rishbeth et al. (2010) calculations indicate that this is not physically possible "under normal circumstances"? "Superstorms" have been identified as those storm events with peak Dst or SYM-H values < -240 to -250 nT (Tsurutani et al., 1992; Echer et al., 2008). This intensity is of course an arbitrary cutoff, but it has been used by the magnetospheric storm community for communication purposes. The main point is not all superstorms are alike (Mannucci et al., 2008, 2009). Rishbeth et al. (2010) did their calculations for the Bastille Day storm. The peak Dst value for that storm was -301 nT. The peak Dst for the 30 October 2003 magnetic storm was -390 nT, a $\sim 25\,\%$ increase in intensity. Because the storm convection electric fields and the storm intensity are closely related (Gonzalez et al., 1994), one can assume that the 30 October 2003 storm had stronger PPEFs than did the Bastille Day event. A second, related feature is that with stronger PPEFs convecting the plasma to greater heights, the downfalling plasma will go to higher latitudes (shown in Fig. 2).

The 1–2 September 1859 Carrington storm has recently been modeled using the SAMI2 code (Tsurutani et al., 2012). The storm intensity was the highest in recorded history, Dst ~ -1760 nT. The storm-time electric field has been estimated at $\sim 20\,\mathrm{mV\,m^{-1}}$ (Tsurutani et al., 2003). Similar features to the 30 October 2003 storm were found, but all effects were even more severe. The EIAs were found to be located at ~ 500 to 900 km altitude with broad peaks located $\sim \pm 25°$ to 40° MLAT.

6 Final comments

We hope we have answered most of the Rishbeth et al. (2010) comments and questions pertaining to the daytime ionospheric super-fountain. It has been shown that the convection due to the dayside PPEF and photoionization can cause the displaced EIAs observed by Mannucci et al. (2005) without regard to disturbance dynamo effects. During superstorms, main phases often last only ~ 2 h (Gonzalez et al., 1994), and "the imposed electric field pattern" is not a major concern. What is still unclear is what is the contribution to enhanced TEC at magnetic latitudes beyond $\pm 30°$ during superstorms? It is possibly a combination of both PPEFs and the disturbance winds with expanded convection electric field (Heelis et al., 2009). However, it is clear from this comment paper that transport from lower latitudes and increased production at both middle and lower latitudes may be able to explain all of the Mannucci et al. (2005) observations.

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