The August 2011 URSI World Day Campaign: Initial Results

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Abstract

During a 10-day URSI World Day observational campaign beginning on August 1, 2011, an isolated, major geomagnetic storm occurred. On August 5, Kp reached values of 8⁻ and Dst dropped to -113 nT. The occurrence of this isolated storm in the middle of a 10-day URSI World Day campaign provides an unprecedented opportunity to observe the coupling of solar wind energy into the magnetosphere and to evaluate the varied effects that occur in the coupled magnetosphere-ionosphere-thermosphere system. Dramatic changes in the ionosphere are seen at every one of the active radar stations, extending from Greenland down to equatorial Peru in the American sector and

1 at middle latitudes in Ukraine. Data from TIMED and THEMIS are shown to support initial
2 interpretations of the observations, where we focus on processes in the middle latitude afternoon
3 sector during main phase, and the formation of a dense equatorial ionosphere during storm recovery.
4 The combined measurements strongly suggest that the changes in ionospheric conditions observed
5 after the main storm phase can be attributed in large part to changes in the stormtime thermosphere.
6 This is through the generation of disturbance dynamo winds and also global neutral composition
7 changes that either reduce or enhance plasma densities in a manner that depends mainly upon
8 latitude. Unlike larger storms with possibly more sustained forcing, this storm exhibits minimal
9 effects of persistent meridional stormtime wind drag, and little penetration of solar wind electric
10 potentials to low latitudes. It is, therefore, an outstanding example of an impulsive event that
11 exhibits longer-term effects through modification of the background atmosphere.

12

1. Introduction

The incoherent scatter radars (ISRs) at Sondrestrom (SON:67°N, 51°W; 73°N geomagnetic latitude), Millstone Hill (MLH:42.6°N, 71.5°W; 53°N geomagnetic latitude), Arecibo (ARO:18.3°N, 66.7°W; 32°N geomagnetic latitude), and Jicamarca (JRO:11.95° S, 76.87°W; 0.6°N geomagnetic latitude), and Kharkov (KHA: 49.6°N, 36.3°E; 45.7°N geomagnetic latitude) operated continuously during August 1-10, 2011 as part of the URSI World Day campaign (<http://www.eiscat.se>). Three of these radars are located at different latitudes close to the 70°W meridian (see Figure 1). Sondrestrom is at high latitude in the auroral zone/polar cap boundary. Millstone Hill is at middle latitude, but it could be considered in the subauroral zone especially during geomagnetic storm conditions (e.g. Buonsanto et al., 1999a, 1999b). Arecibo is at low latitude, and it lies well north the equatorial anomaly. Jicamarca is at the magnetic equator, though south of the geographic equator. Kharkov is located at about 100° east of this chain of radars, ~7 hours later in local time. Thus, this campaign provided a extensive, coordinated set of observations of the ionosphere, extending from the auroral zone to the equator during the geomagnetic storm that occurred during the 10-day period.

Drs. England and Liu requested the August 2011 World Day campaign for investigations of atmospheric planetary wave activities and interaction with the ionosphere. For the intended science goal, the participation of MLH, JRO, and ARO ISRs was specifically requested, and was successfully provided. SON and KHA ISRs offered their participation and joined the observation campaign voluntarily. The study period coincides with the onset of a major geomagnetic storm occurring on August 5. Starting at 0619 UT on August 2, the first of three M-class solar flares erupted from the sunspot region 1263. The third and largest of the flares (M9-class) peaked in X-ray

1 flux at 0357 UT on August 4, launching an associated coronal mass ejection that arrived around
2 1900 UT on August 5. The solar wind conditions are captured upstream by NASA's ACE satellite,
3 showing the arrival of a remarkable disturbance with high density (up to $40 \text{ H}^+/\text{cc}$) and magnetic
4 field strength ($>25 \text{ nT}$ for 6 hours). Furthermore, B_z was southward (in GSM coordinates) for
5 approximately half the time during the passage of the CME, reaching at one point -20 nT . This
6 combination of parameters indicates a strong coupling of the solar wind and magnetosphere, with
7 the expected resultant increase in activity in geospace. See Newell et al. (2008) for a detailed review
8 of energy coupling functions.

9 The World Day ISRs provides the capability to study the changes of the ionosphere that occur in
10 response to this energy input (e.g. Buonsanto 1999; Buonsanto et al., 1999a, 1999b; Goncharenko et
11 al., 2005). Observations of ionospheric parameters, including electron density (N_e), electron
12 temperature (T_e), ion temperature (T_i), and ion drift velocity (V_o), are provided, supporting a
13 characterization of the ionospheric response to the storm. Dramatic variations during this storm
14 times are observed in the ionosphere on a large-scale.

15 These ISR observations are supplemented by space-based observations. The GUVI instrument on
16 TIMED (Christensen et al., 2003) captures the variable condition of thermospheric composition that
17 strongly influences ionospheric production and loss. The NASA THEMIS spacecraft, as well as the
18 ground-based observations of the North American THEMIS GBO network, observe conditions in
19 the inner magnetosphere and auroral ionosphere. This comprehensive set of observations provides
20 insight into the coupling of solar wind energy into the ionosphere and the subsequent response. The
21 goal of this report is to provide a full initial description of the collected observations, highlighting
22 some of the outstanding system behaviors evident in the course of this storm.

2. Observations and data analysis

2.1. Observations of the geomagnetic conditions and their drivers.

The geomagnetic indices of Kp and Dst are displayed in Figure 2 for August 1-11, 2011 during the URSI World Day campaign. The Kp values are very low at only 0-2 during the early period of the campaign from August 1-4. On August 5, the value increases at the interval of 1500-1800 UT and reaches the largest value of 8⁻ at 2100-2400 UT, following the arrival of the CME at the magnetopause. The following day, Kp decreases and gradually reaches lower values in the range of 1-2 at the end of the day. The change in Dst features a sharp increase (onset) followed by a rapid decrease during 1800-2400 UT on August 5 (main phase). Main phase continues for several hours on August 6 and Dst reaches the lowest value of -113 nT at 0300 UT on August 6. After that, Dst starts to recover and gradually approaches 0 nT by the end of the campaign on August 11. This time series of Dst indicates the occurrence of a major geomagnetic storm.

The z-component (GSM) of the solar wind magnetic field component and the solar wind dynamic pressure are shown in Figure 3. Observed near the Earth-Sun L1 point by the Advanced Composition Explorer (ACE) satellite, these data are time-shifted to represent arrival time of the conditions at Earth. This is done in a simple manner, where B_z and pressure are delayed according to the 5-minute mean of the observed solar wind velocity throughout the storm period. These two parameters effectively predict important solar wind inputs at the boundary of Earth's magnetosphere that lead to the geomagnetic event.

A sharp increase in solar wind pressure just after 1800 UT marks the start of the event, with peaks in pressure occurring over the next 2 hours and a final spike above 20 nPa (and, not shown, 40 protons/cc) ending at 21 UT. Thereafter the pressure varies around 3-5 nPa, well above the pre-CME

1 level of approximately 1 nPa. In the IMF measurements, the features to note are the doubling of $|\mathbf{B}|$
2 to 10 nT after 1800 UT (coincident with the first density increase), and another major increase to
3 ~ 30 nT at 1900 UT. B_z is quite variable until ~ 2100 UT, at which time it turns to -20 nT for almost
4 2 hours. The rest of the period is marked by significant polarity reversals of B_z , with frequent
5 periods of southward B_z through to 1600 UT on August 6, as $|\mathbf{B}|$ drops below 10 nT again.

6
7 Magnetic field observations by the Time History of Events and Macroscale Interactions During
8 Substorms (THEMIS; Angelopoulos et al., 2008) are shown in Figure 4. The THEMIS-A spacecraft
9 data are shown, whose ~ 12 -Re apogee elliptical orbit of 12 Re extends into the dusk sector (+y GSE
10 sense) during this time period. The THEMIS satellite is in an outstanding position to support this
11 storm study, for its 24-hour orbit period and apogee place it in the afternoon sector along with the
12 radars at onset. Figure 1 shows the THEMIS orbit footpoint along with the ISR locations, mapped
13 with the T89 magnetospheric magnetic field model set to quiet times to illustrate the general
14 mapping (Tsyanenko, 1989). At 1902 UT on August 5, all three components of the THEMIS
15 magnetic field measurement show sharp departures from their normal trends, and B_z then suddenly
16 drops southward before 20 UT, followed by rapid fluctuations with both positive (northward) and
17 negative (southward) values. The outstanding observations serve as an accurate time marker for the
18 commencement of storm effects that are matched by the sudden increase in hourly Dst, an
19 occurrence that is also indicative of a sudden compression of the magnetopause.

20 21 22 2.2. Observations of the ionospheric response

1 The response of the terrestrial plasma environment to the storm input is extensive. Global maps of
2 assimilated vertical total electron content (TEC) measurements, derived from ground-based
3 receivers of global navigation satellite system (GNSS) radio signals, provide a summary of the
4 changes [Rideout and Coster, 2006]. Two 20-minute intervals of global measurements are shown
5 from 0600-0620 UT on August 5 and 6 in the two panels of Figure 5. The first panel shows TEC in
6 pre-storm undisturbed conditions and the second shows the same approximately 10 hours after
7 storm onset. The differences are noticeable almost everywhere, with major reductions (-30 to -60%)
8 of plasma density over the Americas, and similarly large enhancements over South Asia and Africa.
9 Note that this snapshot in time captures nighttime conditions over the Americas, and daytime
10 conditions over Asia. At all of the ISR sites shown in this work, a storm-time reduction in TEC is
11 evident at 6 UT on August 6. This is corroborated by each of the data sets shown here.

12 The ISR measurements for August 1-11 of 2011 during the URSI World Day campaign provide
13 observations of ionospheric parameters, including electron density (N_e), electron temperature (T_e),
14 ion temperature (T_i), and ion drift velocity (V_o). Observations at Sondrestrom, Millstone Hill,
15 Arecibo, Jicamarca, and Kharkov are presented and discussed. A “quicklook” summary of the
16 variations observed at all of the stations is provided in Table 1. Though grossly simplified, it
17 provides a picture of the changes observed. For example, ISR measurements at Kharkov showed
18 minimal changes until more than 6 hours into the storm, whereafter reductions in NmF2 and plasma
19 temperature enhancements were observed. Measurements at Sondrestrom showed immediate
20 density reduction and opposing changes in ion and electron temperatures.

21 First, Figure 6 shows the ISR observations at Sondrestrom for N_e , T_e , T_i , and northward component
22 of ion drift velocity (V_{pn}) at 100-600 km altitude during August 1-11, 2011. Coinciding with the
23 onset of the geomagnetic storm (see Figure 2), the observations feature a sharp decrease in N_e and T_e

1 in the F-region ionosphere at ~2000 UT on August 5. These changes appear to correspond to rapid
2 changes in the horizontal transport of plasma, with enhanced southward flow beginning at storm
3 onset on August 5th in the dusk and nighttime sectors, and then enhanced northward flow in the
4 daytime of the 6th. They have associated effects in T_i as large values occupy a broad altitude range,
5 extending from 600 km down into 300 km. N_e does not recover to pre-storm levels for four days.
6 This is likely due to the major thermospheric composition disturbance that reduces plasma densities
7 at high latitudes (Prölss and Roemer, 1987, Immel et al., 2000). Overall, dramatic changes of the
8 ionosphere in response to the geomagnetic storm disturbance are observed in each of the derived
9 ionospheric parameters.

10 Ionospheric effects of the storm observed over the Millstone Hill ISR are shown in Figure 7. The
11 observations feature a sharp increase in N_e at 200-600 km altitude for a few hours before 0 UT on
12 August 6, following the commencement of the geomagnetic storm. This effect is mid-latitude storm
13 enhanced density (SED; Foster, 1993), with characteristic high electron densities observed up to 600
14 km during a major uplift of the F-layer in the main phase of this storm. Separate GNSS TEC maps
15 (not shown; Rideout and Coster, 2006) confirm a strong SED plume during this period in the
16 American longitude sector. As shown in a number of studies, (e.g. Foster et al., 2014; Foster and
17 Vo, 2002), storm-time enhancements of this type are accompanied by strong westward and
18 northward transport of the F-layer plasma in the subauroral polarization stream (SAPS), as
19 ionosphere and magnetosphere are together entrained in enhanced sunward convective flow of
20 plasma through geospace, energized ultimately by the solar wind and enhanced ring current effects.
21 Although Millstone Hill velocity measurements are vertical only, observations by the ~840 km
22 altitude DMSP F16 satellite (Strom and Iwanaga, 2005) during a pass traversing Millstone Hill's
23 longitude near 2300 UTC show a clear and strong SAPS feature, with ~1500 m/s westward/cross-

1 track velocity just north of the observatory at 55 degrees magnetic invariant latitude. Fast SAPS
2 driven mid-latitude cross-B fluxes are characteristic of storm periods with dynamic equatorward
3 motion of the plasmasphere boundary layer (Carpenter and Lemaire, 2004) as the plasmopause
4 moves inward and the Region 2 ring current footprint changes.

5 Enhanced Millstone Hill local electron density is highly structured and dynamic during the
6 immediate post-storm period, and is accompanied by upward plasma transport at altitudes below
7 250 km and periods of downward transport at altitudes above ~300km. This complex behavior in
8 mid-latitude plasma transport and resulting features in electron density are similar to positive storm
9 effects reported by Goncharenko et al. [2007], and most likely are associated with enhanced
10 meridional neutral wind as concluded by Lu et al. [2008]. Observation of rapid variations in plasma
11 drift and density are characteristic of surges in equatorward meridional wind, related to traveling
12 atmospheric disturbances launched at higher latitudes.

13 Soon after the largest values are observed in N_e during the storm's main phase, the F-layer density
14 drops rapidly to very low values. This is likely a transition in Millstone Hill local conditions to a
15 region where enhanced magnetospheric convection leads to an elevated ion-neutral recombination
16 rate and creates a middle-latitude ionospheric recombination "trough" (Lee et al., 2011; Rodger et
17 al, 1992). In effect, as the storm proceeds and the planet rotates, the origin of parcels of plasma
18 over Millstone Hill switches from the daytime middle latitude to evening sub-auroral regions.
19 Plasma densities in these regions are greatly enhanced and reduced, respectively. The greatly
20 reduced electron density effect may also be the first indication of a mid-latitude neutral composition
21 disturbance. Inspection of North American GNSS TEC maps (Figure 4) confirms the formation of a
22 trough at mid-to-high latitudes (40-60 N geodetic latitude) in the early UT hours of Aug 6, 2011
23 along with a general decrease in TEC at lower latitudes. When the SED effect is present at mid-

latitudes, T_e shows a sharp decrease. This effect has been observed previously (*cf.* Goncharenko et al., 2007; Huang et al., 2005), and is caused by the enhancement in electron cooling rates that are proportional to N_e^2 (Roble, 1975). At the same time, T_i shows a marked increase, reflecting the fact that the ion population is strongly coupled to the neutral gas through collisions, and the enhanced ion velocities and frictional heating of the thermospheric gas raises the bulk ion temperature in concert with the gas temperature (Burke et al., 2009). Following this period, though, a significant nighttime increase is evident in both T_e and T_i and is especially prominent from 200 to 600 km altitude as the expanded convection zone moves MLH's position into regions nearer the ionospheric trough.

At lower latitudes, the observations by the ISR at Arecibo in Figure 8 show a significant variability in N_e in response to the storm. The increasing N_e covers a broad altitude range, with enhancements from 600 km down into 300 km. A deep depletion occurs thereafter, beginning soon after nightfall at the station (2 UT) that is also seen across the ionosphere from top to bottom. The recovery of nighttime plasma densities is rapid and possibly indicative of transport effect, though the observed trends are quite like the MLH radar observations. Also like the MLH radar observations, daytime ionospheric conditions on August 6 show a greatly reduced abundance of electrons at all altitudes. The ion drift at Arecibo exhibited very large fluctuation during the storm period which caused unusual change in the ion composition. Gong et al. [2013] present a detailed analysis of the response of the ionosphere at Arecibo to these storm-time drivers. The extreme variation in vertical velocities (not shown) have concomitant effects in ionospheric densities and heights, which the bottom panel of Figure 8 shows. One can identify 3 main enhancements in topside plasma density. At 500 km, the enhancements occur at approximately 2130, 2315 and 0130 UT. Gong et al. discuss the relation between vertical velocity, NmF2 and hmF2 extensively and the role of winds,

composition, and downward proton transport in affecting them.

Figure 9 shows the ISR observations of N_e , T_e , T_i , and V_o from Jicamarca. The observations around 0500-1200 UT on August 6 are contaminated due to the presence of equatorial spread F (ESF), so they are not included in the plot. The variations at the storm onset are subtle, but include a small increase in F-region N_e following the storm. Following the data gap caused by the occurrence of ESF, increased T_e is observed extending from 600 km to 200 km altitude. A small increase in T_i is also observed. The larger changes are in N_e and V_o , with the latter showing practically no upwelling of the ionospheric plasma during the day of the 6th, a condition not observed on any other day during the study period. One might then expect low electron densities on this day, as this fountain effect is the normal means of lifting and enhancing the daytime equatorial ionospheric density. However, the peak F2-layer density (Figure 9a) evidently increases to much greater values than any other day of the period throughout the daytime of the 7th. The height and density of the layer observed at JRO is summarized later in this report.

Figure 10 shows the ISR observations during this geomagnetic storm from Kharkov, located $\sim 100^\circ$ east of Millstone. As opposed to the American sector, this locale is in darkness for most of the storm main phase. Of the evident storm effects, there is a trend toward reduced N_e beginning before 0000 UT on August 6, compared to pre-storm levels. There is also a significant increase in T_e and T_i prior to sunrise (~ 0200 UT), continuing into daytime and a reversal of the usually observed trend of upward ion velocities post midnight (noted on the 4th, 5th and 7th), showing downward flows prior to sunrise on the 6th. These interrelated changes are possibly the result of several phenomena including 1) development of a middle latitude disturbance wind dynamo and 2) reduction of electron and ion cooling rates due to reduction in either the electron densities themselves, or atomic oxygen densities. These processes develop naturally from the storm-time heating occurring at high latitudes,

1 and subsequent advection of plasma temperature and neutral composition disturbances to middle
2 latitudes by enhanced neutral winds. The resulting effects may be seen in the enhanced T_e and T_i
3 after sunrise [Schunk and Nagy, 1978; Chernogor et al., 2007], and in the strong downward ion
4 velocities in the 2300-0200 UT period [Blanc and Richmond, 1980]. Specifically, the Blanc and
5 Richmond model of the disturbance electric field predicts eastward electric fields of ~ 1 -2 mV/m in
6 this time period, thus imparting a significant downward velocity to the F-layer. Given that the storm
7 is in recovery phase by 0200 UT, it is not likely that magnetospheric electric potentials extend to the
8 latitude of KHA, and are unlikely to be the cause of effects observed after 0200 UT.

9 From each of the previously presented ISR data at low and middle latitudes, the storm effects can be
10 summarized by deriving the F-layer height and density parameters, h_mF2 and N_mF2 . These are
11 shown in Figure 11, where the departure from prior trends can be observed at every station. Notably,
12 middle latitude stations all show F-layer height increases, followed by significant F-layer density
13 reductions. JRO (Figure 11d) stands out from this trend, showing a remarkable enhancement in the
14 F-layer density with lower heights (by 20-50 km) during storm recovery on August 6, between ~ 15
15 and 24 UT.

16 This could strictly be related to changes in the plasma density profile, with little change in the total
17 plasma content over JRO. To address this, another key parameter of storm effects, the total electron
18 content (TEC), is derived from each of the N_e data shown in the previous figures, and shown in
19 Figure 12. It is clear from this that an enhancement in TEC over JRO is observed in the same period
20 as . An overall ~ 20 -30% greater abundance of plasma is observed overhead at any time in the day of
21 storm recovery relative to prior days.

22 One possible explanation is that the relative abundance of atomic oxygen neutral gas is enhanced

after the storm. TIMED GUVI can provide some indication of whether this is supported by thermospheric observations. TIMED determines the O/N_2 ratio globally once per day when orbiting away from the solar terminators. In this case, the local time of the GUVI observations is $\sim 07:00$ LT, and airglow brightnesses are sufficient for determination of O/N_2 from the single track spectrographic mode measurements that the instrument now obtains continuously. Figure 13 shows the O/N_2 on August 6 compared to conditions on the previous day, when activity was very low. The first tracks come from the Asian sector, where the O/N_2 perturbation is not very large, but it grows in magnitude as the tracks continue to the West. The O/N_2 is not interpretable over Jicamarca due to the fact of contamination of the GUVI detector by radiation belt particles in the South Atlantic Anomaly. However, the regions around South America show small increases in O/N_2 with increases of $\sim 20\%$ in the ratio over Ecuador. It is possible that the region in the vicinity of JRO experienced an increase in O/N_2 on the order of 20% and a corresponding change in net ionospheric production rates driven by solar EUV. If this is the case, it would account for the corresponding factor of 1.2-1.3 increase in TEC over Jicamarca after the geomagnetic storm. In fact, the dynamical variations in the Chapman parameters suggest strong downward winds as the expanded and enhanced regions of auroral heating drive a global Hadley-type circulation with resultant downwelling gas and enhanced O/N_2 throughout the vertical column of air in the thermosphere near the equator.

3. Discussion

The August 2011 geomagnetic storm was observed to have major effects on the density and dynamics of the ionospheric plasma from the auroral zone to the equator. A major effect is to modify ionospheric densities globally. Reductions generally occur through either enhanced ion recombination driven by bulk convective motion of the plasma, or by enhancement of the molecular neutral species. The radars themselves can provide a measure of the bulk motion and drift-enhanced

1 recombination, but the change in the neutral gas that comes with storms is necessarily observed by
2 other means, in this case by TIMED GUVI. The temporal cadence of the TIMED measurements is
3 24 hours, but the “memory” of the composition effect is also on the order of hours, regulated by the
4 diffusion of the various species throughout the atmospheric column.

5 The most remarkable reduction in plasma density is observed at Arecibo (ARO Figure 8), with
6 similar strong nighttime reduction also seen at SON (Figure 6) and MLH (Figure 7), followed by
7 significant suppression of the growth of electron densities through the following day. This
8 suppression is clearly related to the composition disturbance, and the continued negative storm
9 effects that remain, imprinted on the thermosphere following a ~6 h period of high latitude heating,
10 and slowly wane to seasonal levels over the 24-36 hours that follow. Different behavior is observed
11 for more longer lasting geomagnetic storms, where equatorward-directed winds from high latitudes
12 provide a more continuous drag on the F-region plasma, lifting the plasma along the magnetic field
13 lines and maintaining enhanced F-layer densities for longer durations. Pincheira et al. (2002) give
14 several examples of the occurrence of this process for historical storm events.

15 An observation that ties much of the observations together are the TIMED GUVI measurements,
16 where it is evident that thermospheric O/N_2 is significantly enhanced at low and equatorial latitudes.
17 Conversely, it is reduced at middle and high latitudes, predominantly in the Northern Hemisphere
18 (NH), this latter point due to the fact that it is Northern Summer and the additional insolation and
19 conductivity in the auroral zone leads to greater high latitude heating in the NH and greater
20 equatorward inner-hemispheric winds [Fuller-Rowell et al., 1996]. In the convergence of winds
21 originating in the polar regions during a geomagnetic storm in August, the northern hemisphere
22 winds are larger and the band of maximum subsidence is therefore found generally south of the
23 equator. This is borne out in the global GUVI observations and may explain the extreme post-storm

enhancement of JRO densities. Furthermore, the images show a major reduction in thermospheric O/N_2 in the vicinity of ARO and up to MLH and SON. It is clear that the reduction in densities at these stations may be attributed in large part to the composition disturbance, with the additional strong effect of disturbance winds being largest at Arecibo. Unfortunately, the vertical drift measurements at Arecibo were difficult to derive during the World Day period, given the large composition changes observed there [Gong et al., 2013].

The generation of a strong disturbance dynamo by this storm is evidenced by the ionospheric measurements at JRO (Figure 9), where the ionospheric peak height is lower than quiet days during the storm recovery on August 6 and upward plasma drifts are near zero much of the day. This is likely due in part to disturbed zonal winds that produce dynamo fields counter to the normally generated Sq fields. The surprising observation is the counter intuitive finding that the ionospheric peak is also denser than any other time during the World Day period. The presence of a oxygen-rich composition environment, discussed above, is therefore deemed a likely component of the physical processes that contribute to the stormtime variability at JRO.

4. Summary

This study presents the coordinated observations of the ionosphere by ISRs at Sondrestrom (67°N), Millstone Hill (42.6°N), Arecibo (18.3°N), and Jicamarca (11.95° S) along the ~70°W meridian, and Kharkov (36.3°E) for August 1-11, 2011 during the URSI World Day campaign. These observations coincide with a major geomagnetic storm occurring on August 5, with Kp index increases to 8 and Dst decreases to -100 nT. These campaign observations allow the study of the ionospheric variations in response to the geomagnetic storm at various latitudes.

1 In summary, we find the following effects:

2 1) Major enhancements in ionospheric density at 400-600 km altitude in the afternoon sector at
3 storm onset at MLH and ARO, indicative of the expansion of magnetospheric convection fields well
4 into middle latitudes.

5 2) The nearly complete elimination of the F-layer at nighttime at SON, MLH, and ARO,
6 accompanied by strong spread-F at JRO, at the peak of the magnetic storm.

7 3) Major reductions (~50%) in ionospheric density at middle and high latitudes during the storm
8 recovery in daytime, as compared to pre-storm values.

9 4) Major enhancement (100%) in equatorial F-layer peak density at the equator during storm
10 recovery in daytime, as compared to pre-storm values.

11 These data show the remarkable behavior of the coupled inner magnetospheric-ionospheric system,
12 and evidence for strong control of the ionospheric state by the thermospheric composition, which is
13 in turn modified by magnetospheric inputs and joule heating variability, preconditioned by the
14 seasonal trends of solar EUV production of ionospheric conductivities and driven by the strong solar
15 wind drivers. The resultant remarkable enhancement in the equatorial ionosphere shows the
16 importance of global scale studies with both global and regional measurements to capture the
17 behavior in order to understand the physical behavior of geospace. Further studies should invoke
18 numerical modeling efforts to confirm the findings elicited from direct observations. Also, this study
19 points to the need for O/N_2 measurements in the South American region uncontaminated by the
20 harsh regional environment of the measurement in LEO orbits. This could come from global UV
21 imagers in geosynchronous orbits that are not susceptible to the contamination of in-situ sensors, or
22 from new UV sensors in LEO orbits that either through shielding or operational techniques provide

O/N_2 measurements unaffected by SAA radiation. Two new NASA missions, ICON and GOLD, will though their unique implementations provide the O/N_2 measurements in these adverse conditions. Without these measurements, a key parameter of the environment that supports the growth of these large plasma densities is basically unknown.

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19 **13 Figures and Captions Follow**
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Figure 1: Map of the American Sector with ISR locations and THEMIS orbit footpoint noted. The red dots give the locations of the ISRs at Sondrestrom, Millstone Hill, Arecibo, Jicamarca and Kharkov.

Figure 2: Geomagnetic indices of a) 3-hourly K_p index and b) Dst index for August 1-11, 2011 during the URSI World Day campaign. Note: the day number on the x-axis marks midday.

Figure 3: Combined solar wind observations of ACE MFI and SWEPAM instruments for August 5-6, 2011 a) solar wind bulk pressure, b) IMF Bz in GSM coordinates and c) IMF $|\mathbf{B}|$. Data are time-shifted for arrival time at the magnetopause, based upon the 5-minute mean GSM-x velocity at the time of each individual observation.

Figure 4: a) Distances of the THEMIS-A satellite to the Earth's center given in units of Earth Radius (Re) for August 5-6, 2011. b) X, Y, and Z components of the magnetic field $\mathbf{B}$ as observed by THEMIS-A satellite.

Figure 5: Ionospheric vertical total electron content determined from ground based GNSS receivers. Top panel shows pre-storm values, bottom panel shows storm recovery conditions.

Figure 6: The ISR measurements over Sondrestrom (67°N, 51°W) for a) electron density (N_e), b): electron temperature (T_e), c) ion temperature (T_i), and d) ion velocity perpendicular northward (V_{pn}) for August 1-11, 2011 during the World Day campaign.

Figure 7: The ISR measurements at Millstone Hill (42.6°N, 71.5°W) for a): electron density (N_e), b): electron temperature (T_e), and c): ion temperature (T_i) for August 1-11, 2011.

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Figure 8: The ISR measurements of electron density (N_e) over Arecibo (18.3°N, 66.7°W) during August 1-11, 2011. The bottom panel provides detail of August 5-7.

Figure 9: The Jicamarca ISR measurements for a): electron density (N_e), b): electron temperature (T_e), c): ion temperature (T_i), and d): vertical ion velocity (V_o) during August 1-11, 2011. Bottom panel is the same set of data, focusing on the three day period including the geomagnetic storm.

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3 Figure 10: The ISR measurements at Kharkov (49.6°N, 36.3°E) for a): electron density (N_e), b):
4 electron temperature (T_e), c): ion temperature (T_i), and d): vertical ion velocity (V_o) for August 3-7,
5 2011.

Figure 11. $h_m F_2$ (blue) and $N_m F_2$ (red) from the low and middle latitude ISR stations from the World Day period. A two-component Chapman layer is fitted to the N_e values from the 4 stations shown earlier in this report.

Figure 12. Total electron content (TEC) of the ionospheric layer at the low and middle latitude ISR stations from the World Day period. TEC is determined from the sum of each station's Ne values shown earlier in this report.

Figure 13: TIMED GUVI thermospheric O/N_2 determined from 1356/N₂ LBH ratios, interpolated from the ~15 daily tracks obtained in spectrograph mode. Data come from the 0700 LT sector and are collected over 24 hours to produce a global average.

Station	0-3h	3-6 h	6-12 h	12-24 h	24-48 h	Altitude/Time Res shown
SON	↓ ↓ ↑	↓ ↓ ↑	↓ ↑ ↑	↓ ↑ ↑	↓ ↑ ↑	25-60 km/1 h avg
MLH	↑ → ↑	↓ ↓ ↑	↓ ↑ ↑	↓ → →	→ → →	5 km / 1 h avg
ARO	↑	↑	↓	↓	↓	.2-4 km / 1 m
JRO	→ →	→ →	No data	↑ ↑	↑ →	15 km / 1 h avg
KHA	→ → →	→ → →	↓ ↑ ↑	↓ ↑ →	→ → →	55 km / 15 m
Legend : → NmF2 / → <i>Te</i> / → <i>Ti</i>						

Table 1: Basic changes in F-layer conditions $NmF2$, T_e , and T_i at each ISR for discrete intervals of geomagnetic storm main phase and recovery. Values of the parameter above or below quiet-time conditions for the local time sector are indicated with vertical arrows. Horizontal arrows indicate conditions similar to undisturbed periods. Also indicated are the key sampling parameters for the data shown in the following figures. 1-h averages are determined from higher resolution measurements.