Dayside Field Aligned Current and Energy Deposition (FED)—Final report

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The Dayside Field Aligned Current and Energy Deposition (FED) Focus Group (FG) commenced in 2010 to explain the relation between enhanced dayside field-aligned currents, their sources in the solar wind and their impacts in the ionosphere-thermosphere system. The FG's primary objective was to develop an understanding of the magnetospheric source of localized heating that produces unanticipated regions of dayside thermospheric expansion at high latitudes. A secondary objective was providing data-model comparison for events exhibiting this behavior. A tertiary objective was to improve GGCM specification of dayside energy input possibly associated with bowshock, dipole tilt (seasonal effects), and IMF B_X modulations. When the Focus Group was approved for a 2.5-year run instead of the requested 5-year run, the tertiary objective was dropped and the remaining research tasks were addressed with the following priority:

Priority 1 Strong IMF B_Y and precipitating particle effects
Dayside energy sources and transport for events with large IMF B_Y (with B_Z +/-)
Dayside field-aligned current systems for large in-the-ecliptic IMF (B_Y)
The location and nature of Poynting and particle energy deposition for IMF B_Z>0
The relation of such events to cusp region thermospheric neutral density anomalies
Overall magnetospheric structure during large IMF B_Y disturbances
Particle and conductivity influences on high-latitude heating events
Priority 2 Measurements and model-data comparison
Methods for detecting such disturbances; indices vs. space-based monitors
MHD modeling of such disturbances and model-data comparisons
Priority 3 Solar wind drivers, magnetospheric structure, asymmetry, seasonality
The role of enhanced solar wind density and speed during such events
Overall energy contributions to the coupled magnetosphere-ionosphere-thermosphere

Activities and Research Topics: **The Dayside FED FG inspired 16 peer-reviewed publications.** See list at the end**.** Researchers affiliated with the FED FG investigated magnetospheric disturbances that appeared to provide direct energy into the dayside thermosphere with little energy input to the magnetotail. The implication of such events is that the Dst index could remain unperturbed or even show storm recovery while the coupled dayside high-latitude region is greatly disturbed. This possibility was explored during the Joint GEM-CEDAR meeting in 2011. Results from the FED effort also linked to the M-I Coupling Ion Outflow FG and the GGCM Metrics FG. Additionally:

- At the first FED FG meeting a list of storms was proposed and posted on the GEM Wiki page. This list guided many of the subsequent model-data comparison studies.
- In addition to the summer and fall 2010, fall 2011 and summer 2012 GEM FED ses-

sions at the GEM and Mini GEM meetings, the FED FG hosted a Joint GEM-CEDAR session during the 2011 joint meeting.

SUMMARY: Carlson et al. [2012] list four factors that cause the high-latitude cusp region to be sensitive to external energy input. 1) Strong velocity shears and flow channels near the cusp; 2) Strong vertical expansion over flow channels; Thermospheric density response to altitude dependent Joule heating; and 4) Thermospheric density response to altitude dependent electron density profile. FG activities investigated deeply items 1 and 4. Work on item 3 was underway as the FG ended.

Advances for Priority 1: Strong IMF B_Y and precipitating particle effects. The origin and influence of dayside strong, confined velocity shears and sunward flow channels during intervals of large IMF B_Y were amply demonstrated by: *Crowley et al.* [2010], *Knipp et al*. [2011], *Li et al*. [2011], *Eriksson and Rastätter* [2013] and *Wilder et al*. [2012a, 2012b and 2013]. Several of these studies showed IMF B_Z+ was also important in creating localized flow channels. The solar wind mechanical force and the **J** x **B** force act on the newly opened field high-latitude field lines created by cusp reconnection to produce a Pedersen current, which consequently generates an intense Joule heating region, and a pair of adjacent and opposite field-aligned currents (FACs) connecting to the magnetopause currents, forming a closed circuit. The intense Joule heating region is also the region with strong downward Poynting flux. The distribution, scale, and magnitude of this Joule heating region and corresponding FACs in the polar regions are mainly controlled by IMF clock angle, IMF magnitude, and solar wind dynamic pressure. A northward IMF condition with a large B_Y component will result in an extended region with intense Joule heating and FAC, thus making a spacecraft transiting the dayside region more likely to observe a strong downward Poynting flux. Convection in the flow channels and localized convection under northward IMF can lead to intense localized neutral upwelling, as well as large-scale gravity waves.

The role of soft particle precipitation in dayside energy deposition also came under scrutiny and debate. Both *Zhang et al*. [2012] and *Deng et al*. [2013] concluded that while soft electron precipitation have relatively minor effects on the interaction between the magnetosphere and ionosphere, they can significantly modify the plasma distribution of the F-region ionosphere and the neutral density of the thermosphere. Both papers attempted to quantify the interaction.

Advances for Priorities 2 and 3: Measurements, model-data comparison, solar wind drivers, magnetospheric structure and asymmetry, and seasonality. Easy access to CCMC runs-on-request was crucial to the success of the Dayside FED FG. The importance and necessity of satellite constellations (AMPERE and DMSP) for providing measurements and promoting model-data comparison cannot be overstated.

Outstanding Issues for Priority 1: The single most important aspect of unfinished FG business is the relative roles of Poynting flux and particle precipitation in the cusp region.

Outstanding Issues for Priorities 2 and 3: Even with the expanded data coverage provided by AMPERE and DMSP, several studies showed that the cusp region with confined regions of reverse convection were not covered with sufficient resolution to reveal important dynamics (see entries below). Further, numerous issues such as dynamic pressure effects; northern-southern hemisphere and day-night asymmetries and seasonal influences were not investigated adequately during the short FG lifetime.

DETAILS: Below are detailed outcomes from Priority 1, 2 and 3 tasks, as well as the Joint GEM-CEDAR discussions.

Outcomes from Priority 1 tasks: Strong IMF B_Y and precipitating particle effects.
In all meetings of the FED FG there were active discussions of energy deposition and field aligned current structures related to events associated with large IMF B_Y and or strong positive IMF B_Z

Climatology:
To provide a background of FAC structure and orientation **Simon Wing** discussed source regions of dayside FAC based on statistical analysis of many years of DMSP data. *Wing et al*. [2011] found that each FAC sheet originates from more than one region in the magnetosphere, depending on the latitude and the magnetic local time. Region 0 FAC are located mostly on open field lines. Region1 FAC mostly map to closed field lines, in morning and afternoon, but near noon, they map mostly to the low latitude boundary layer. Region 2 FAC originate mostly from the central plasma sheet and boundary plasma sheet and and inner magnetosphere, all of which are on closed field lines. Near noon, some R2 may originate from the low-latitude boundary layer and can be on open or closed field lines.

Art Richmond showed statistical Poynting flux patterns from DE -2 derived from 18 months of data. The derived patterns show net Earth-directed Poynting flux. He showed that dayside energy deposition dominates for all IMF clock angles

Delores Knipp presented patterns of extreme Poynting flux deposition associated with a large east-west interplanetary magnetic field component, based on DMSP data. *Knipp et al*. [2011] demonstrated that high-latitude Poynting flux was sometimes in excess of 100 mW/m^2—an order of magnitude above typical values. During intervals of large IMF B_Y the Poynting flux deposition peaks in the dayside with the pre/post noon maximum in Poynting flux depending on IMF B_Y sign. A significant fraction of these events occur with high-speed solar wind. The locations of these extreme events are consistent with the dayside flows channels discussed in *Li et al*. [2011].

Case and Event Studies:
Wenhui Li showed results from an OPENGGCM study of dayside energy deposition during northward IMF during the 21 Jan 2005 storm event. He was able to trace the field lines from the flank-merging region to the location of strong Poynting flux deposition shown in the DMSP data by *Knipp et al*. [2011]. *Li et al*. [2011] showed OPENGCM simulations for several events in late 2004 and in 2005. They conclude that flank merging is a source of FACs, dayside E x B flow channels and intense Poynting flux to the cusp.

Geoff Crowley provided an overview of thermospheric response from select events. *Crowley et al*. [2010] presented evidence of large thermospheric density effects associated with localized Poynting flux deposition based on CHAMP satellite data and simulations using the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIMEGCM). The TIMEGCM was driven by high-fidelity high-latitude inputs specified by the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) algorithm, and reproduced the main features of the density enhancements observed by CHAMP. This first detailed explanation of a high latitude density enhancement observed by CHAMP focused on the August 24, 2005 interval.

Stefan Eriksson reviewed Poynting flux observations for the 15 May 2005 storm: He showed the relation between high-latitude reconnection driven convection and NBZ currents and further illustrated FACs adjacent to well-defined flow channels. Subsequently he used DMSP and AMPERE magnetic perturbations for the 5 April 2010 storm to show IMF B_Y effects and dawnside FAC evolution during the early storm phase. This material is partially reported in a recent submission by *Wilder et al*. [2013]. Subsequently **Stefan Eriksson** described Alfvén Mach number and IMF clock angle dependencies of sunward directed ExB flow channels and their embedded Joule heating rates in the ionosphere. He showed a BATSRUS run from CCMC for 15 May 2005, highlighting field aligned currents and flow channels. A BATSRUS simulation on the effects of Alfven Mach number and IMF clock angle on the location and flow speed magnitude within the magnetospheric counterparts of such flow channels is reported in *Eriksson and Rastätter* [2013].

Rick Wilder investigated intense Joule heating, thermospheric upwelling, and large-scale gravity waves and their association with reverse convection under northward IMF for April 5 2010. *Wilder et al*. [2012a] used AMPERE and AMIE data to show that reverse convection under northward IMF could also lead to intense localized upwelling, as well as large-scale gravity waves. During intervals of strong northward IMF there can be intense reverse convection that produces vertical winds and enhanced thermospheric density. Large-scale gravity waves with 700 m/s wave speed and 1000 km wavelength can arise from the density perturbations. The challenge for this event is separating solar wind dynamic pressure effects from IMF change effects. Subsequently *Wilder et al*. [**2012b]** used DMSP particle data and the AMIE convection patterns to show that the most intense cusp-region Joule heating occurred on streamlines which crossed the open-closed boundary. This confirmed the prediction by *Li et al*. [2011] that the intense energy deposition in the cusp on Aug 24, 2005 was driven by reconnection between the IMF and magnetosphere at high latitudes. Additionally, *Wilder et al*. showed that asymmetric reconnection theory [e.g. Birn et al, 2008 and references therein] could be used to predict average ionospheric flow conditions in the channels where Joule heating was at its most intense.

Aaron Ridley: Investigated effects of concentrated dayside energy deposition on the global and regional thermosphere using a BATSRUS idealized simulation for 15 May 2005. He also reported neutral density enhancements associated with IMF B_Y and appropriately placed particle deposition.

Modeling:

Yue Deng showed the significance of different heating mechanisms to the cusp neutral density enhancement using the Global Ionosphere Thermosphere Model (GITM) non-hydrostatic model. She compared effectiveness of Poynting flux and soft particle precipitation in producing neutral density enhancements near the cusp. Using a specified input of Poynting flux of and soft electrons for a GITM simulation, *Deng et al*. [2013] showed that the Poynting flux increases the neutral density 34%. While the direct heating from soft electron precipitation (100 eV) produces only a 5% neutral density enhancement at 400 km, the associated enhanced ionization in the F-region from the electron precipitation leads to a neutral density enhancement of 24% through increased Joule heating. Thus, the net effect of the soft electron is close to 29% and the combined influence of Poynting flux and soft particle precipitation causes a more 50% increase in neutral density at 400 km, which is consistent with than CHAMP observations in extreme cases. The effect of electron precipitation on the neutral density at 400 km decreases sharply with increasing characteristic energy such that 900 eV electrons have little effect on neutral density. *Deng et al.,* [2013] conclude that the altitudinal distribution of energy input is important to neutral upwelling and TEC distribution and that soft particle deposition into the upper F region cusp is a very efficient heat source.

Brent Sadler (presented by M. Lessard): *Sadler et al.,* [2012] investigated soft electron precipitation effects at higher altitude using the Otto model. In the model auroral precipitation and Joule heating heat ambient electrons. The electron gas expands upward and the ions are pulled upward by the electric field. Ion momentum drags the neutrals upward. The estimated "cooking time" for this effect is 10-30 min: Electron temperatures rise in 1-3 min and upward ion velocity increases in 3-5 min. This should drive ion outflow and possibly enhanced neutral density structures in the F-region

Binzheng Zhang discussed the roles of particles in heating the dayside near-cusp region. He used the coupled magnetosphere-ionosphere thermosphere model (LFM+TIEGCM = CMIT) to investigate the effects of precipitating soft electrons. *Zhang et al*. [2012] included two types of soft electron precipitation - direct-entry cusp precipitation and Alfven-wave induced, broadband electron precipitation - the effects of which were self-consistently included in a coupled global simulation model. Simulations show that while both types of soft electron precipitation have relatively minor effects on the interaction between the magnetosphere and ionosphere, they can significantly modify the plasma distribution of the F-region ionosphere and the neutral density of the thermosphere. Enhancements in F-region electron density and temperature and bottomside Pedersen conductivity caused by soft electron precipitation are shown to enhance the Joule heating per unit mass and the mass density of the thermosphere at F-region altitudes. The simulations provide a causal explanation of CHAMP satellite measurements of statistical enhancements in thermospheric mass density at 400 km altitudes in the cusp and pre-midnight auroral region.

Ramon Lopez suggested that some of the FAC associated with the large dayside energy deposition events originate at the bowshock during intervals of low Mach number [*Lopez et al.,* 2011].

Bob Strangeway discussed earlier work that related cusp-region FACs to IMF B_Y control and ion outflow using FAST data and. **Paul Song** discussed heating in the cusp region during northward IMF. **Betsy Mitchell** showed evidence from her Ph D dissertation that IMF B_Y decouples energy input into the ionosphere from energy input into the inner magnetosphere. This is the subject of a soon-to-be-submitted manuscript.

<u>Outcomes from Priority 2 and 3 tasks: Measurements and model-data comparison and Solar wind drivers, magnetospheric structure and asymmetry, seasonality</u>

In addition to the model data comparisons associated with task 1, the following investigations shed light on the relation between enhanced dayside field-aligned currents, their sources in the solar wind and their impacts in the ionosphere-thermosphere system.

Crowley et al. [2010] used TIMEGCM and AMIE to provide a global framework for interpretation of the CHAMP densities. These simulations revealed that the observed density enhancement in the dayside cusp region results from unexpectedly large amounts of energy entering the Ionosphere-Thermosphere system at cusp latitudes during an interval of strong (+20 nT) B_Y. The key data input in the AMIE runs was the DMSP data. When only magnetometers were ingested, the corresponding potential patterns were much smoother and the cross-cap potential was underestimated, and a thermospheric model driven by such AMIE patterns was unable to reproduce the Joule heating peak in the noon sector, and as a result failed to produce the observed density enhancement.

Gang Lu showed distributions of FACs and Poynting Flux under northward and southward IMF. She compared the individual satellite measurements with the global maps of Poynting flux derived from AMIE for November 2004 storm, and showed that even with 2 concurrent DMSP satellites (DMSP F-15 and F16), their coverage was not adequate to describe the full global energy storm deposition. She also showed dayside energy deposition during northward IMF and large east-west IMF. These results were reported in Deng et al. [2009].

Eric Lund presented sounding rocket measurements of electron heating in association with field-aligned currents and soft precipitation measured by the SCIFER rocket launch on 18 Jan 2008 over Svalbard. The rocket had an apogee of 1468 km. The rocket payload included a sensor that is designed to measure the temperature of thermal electrons. *Lund et al*. [2012] show that elevated electron temperatures measured in situ are correlated with electron precipitation as inferred from auroral emissions (poleward moving forms) during the 60–120 s preceding the passage of the rocket. This integrated "cooking time" is an important factor in determining the origin and resulting flux of outflowing ions.

Lasse Clausen showed global Poynting flux derived from SuperDARN and AMPERE measurements. He used SuperDARN and AMPERE to get 2-min average Poynting flux. He showed example from 20 Dec 2010. He concluded that the AMPERE coverage may miss confined reverse-convection at high latitudes.

Slava Merkin used AMPERE, SuperDARN, and a Lyon-Fedder-Mobarry (LFM) global MHD simulation to deduce ionospheric electrodynamics. He reconstructed the potential distribution from AMPERE and compared this with SuperDARN. AMPERE and SuperDARN can help confirm conductances by rotations of flow vectors. The AMPERE data show NBZ system during August 3-4 2010 in the sunlit hemisphere. Using LFM, he mapped a Poynting flux patch in northern hemisphere to reconnection site in opposite hemisphere. Subsequently he compared (AMPERE) data and an ultra-high resolution (~60 km in the ionosphere) LFM simulation for an interval during the August 3-4 2010 storm, wherein there was a solar wind dynamic pressure jump and a south to north rotation of the IMF B_Z component with $B_Y < 0$. The LFM and AMPERE current patterns showed remarkable agreement during this period. The dayside peak of the upward current moved from post-noon to pre-noon in response to the IMF B_Z rotation. He showed that the magnetic perturbations underlying AMPERE patterns were consistent with the simulated response. He also noted that, particularly during northward IMF conditions, if the orbit crossing point is far from the locus of the NBZ current system, the AMPERE fit may not capture the true geometry of the currents because the pole of the inversion basis functions is at the orbit crossing point rather than the magnetic pole. The new generation of AMPERE inversions fixes this problem by putting the basis function pole at the magnetic pole.

Delores Knipp showed dayside DMSP Poynting flux and soft particle asymmetries and compared those to CHAMP neutral enhancements. For all years and most conditions the enhancements were stronger in northern hemisphere cusp than in southern hemisphere cusp. As suggested by Art Richmond's climatology study in many instances the cusp energy deposition overwhelms the nightside energy deposition. Temporal variability of this effect is under investigation. She also showed dayside energy deposition for slow flow, high-speed streams and solar ejecta. High- speed streams compete with ejecta as the dominant dayside energy driver.

Outcomes from the Joint GEM-CEDAR 2011 Session

The joint GEM-CEDAR session supported a number of cross-disciplinary discussions that extended into investigations reported at the summer 2012 GEM meeting

Herb Carlson showed 2-min resolution data from the EISCAT radar that likely contained Flux Transfer Events. (FTEs). The FTE's should pull solar-produced plasma into polar cap and create patches that give rise to polar cap scintillation. He suggested that poleward moving forms with signatures of particle flash are indicators of FTEs. *Carlson et al*. [2012] addressed four key aspects of cusp upwelling: 1) Ubiquitous strong velocity shears and flow channels near the cusp; 2) Strong vertical expansion over flow channels; Joule heating is a strong function of altitude; and 4) Thermospheric density response is strongly dependent on the electron density profile. Together these factors help explain the 10-50% cusp neutral density enhancements reported by *Luhr et al*. [2004].

Juan Rodriguez: Discussed auroral forms that extend equatorward from the persistent midday aurora during geomagnetically quiet periods. He showed data from a 630 nm all-sky imager near the cusp. The auroral forms appeared equatorward of cusp near noon with east-west extent of 1000 km. These are possible flux transfer events. He also showed additional events called "crewcut" events. These are quiet-time auroral features extending equatorward from the dayside oval during negative B_x and B_Y-dominated conditions.

Chin Lin: Showed polar cap neutral density enhancements observed by the CHAMP accelerometer. He surveyed CHAMP neutral density data and searched for density perturbations that were two sigma or more above the previous 24-hour orbit average. He found a tendency for long lasting perturbations on dayside and near dawn. The tendency appears to have strong IMF B_Y modulation. Further the high-latitude density peaks occur in summer hemisphere in 2001-2005

Dan Weimer reviewed measurements and predictions of thermospheric temperature changes based on work he has done with drag data provided by US Space Command. He reported good global agreement from the empirical model.

Yi-Jiun Su discussed the high-altitude energy input to the thermospheric dynamics: for the August 4-7 2011 storm event. She compared density from DMSP and GRACE sensors, the High Accuracy Satellite Drag Model (HASDM), and the JB2008 and JB2008-with-Weimer-2005 models. She reported that the thermosphere responded immediately as the solar wind energy began to deposit energy into the high-latitude region; however, it took 6 hours to reach the maximum of the thermospheric energy. The thermosphere did not return to pre-storm level for a very long time. She estimated that the high latitude system transferred 3 $x10^{16}$ J of energy to 2.5 $x10^{16}$ J of heat--very efficient heat transfer.

Jiannan Tu: Discussed the time scales of dynamic Magnetosphere-Ionosphere-Thermosphere coupling. He characterized:

- Short time scale= Alfven wave travel time
- Intermediate time scale = 10-20 min for quasi steady state
- Long time scale > 1 hr for steady state of entire M-I-T system

He reported most energy deposition is during intermediate time scales. *Tu et al*. [2011] investigated convection-driven ionosphere-thermosphere (I-T) heating using a three-fluid inductive approach. The M-I-T coupling was via a 1-D stratified atmosphere. They reported the heating to be essentially frictional in nature rather than Joule heating, as commonly assumed. The heating rate reaches a quasi-steady state after about 25 Alfvén travel times. Further, the dynamic heating rate can be more than twice greater than the quasi-steady state value. The heating is strongest in the E-layer but the heating rate per unit mass is concentrated around the F-layer peak height. This implies a potential mechanism of driving O^+ upflow from O^+ rich F-layer. They also reported that the I-T heating caused by the magnetosphere-ionosphere coupling can be simply evaluated through the relative velocity between the plasma and neutrals without invoking field-aligned currents, ionospheric conductance, and electric field.

Athanasios Boudouridis presented a case study of the effect of solar wind dynamic pressure fronts on dayside field-aligned currents and thermospheric density for April 5 2010 using CHAMP data and TIMEGCM simulations. The challenge is to separate pressure pulse effects from IMF effects and determine their relative importance, since often both happen at same time. The pressure and IMF front passed ACE at ~ 0830 UT. The first responses were in the post-noon/afternoon MLT sector; these appear to coincide with intense FACs and Joule heating as produced in the AMIE procedure. The CHAMP and TIMEGCM results show enhanced neutral density in the same general region, but the magnitudes of the perturbations are not yet in agreement. The associated traveling atmospheric disturbance traveled to the equator in ~ 3.5 hr. More effort will be devoted to determining how common the response is and to determining the relative roles of the changing IMF and dynamic pressure.

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