IMPTAM: Including self-consistent magnetic field in ring current modeling
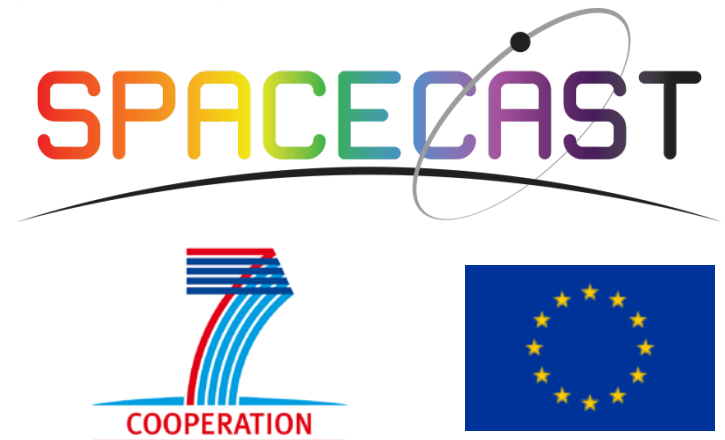
N. Yu. Ganushkina (1, 2)

(1) University of Michigan, Ann Arbor MI, USA/
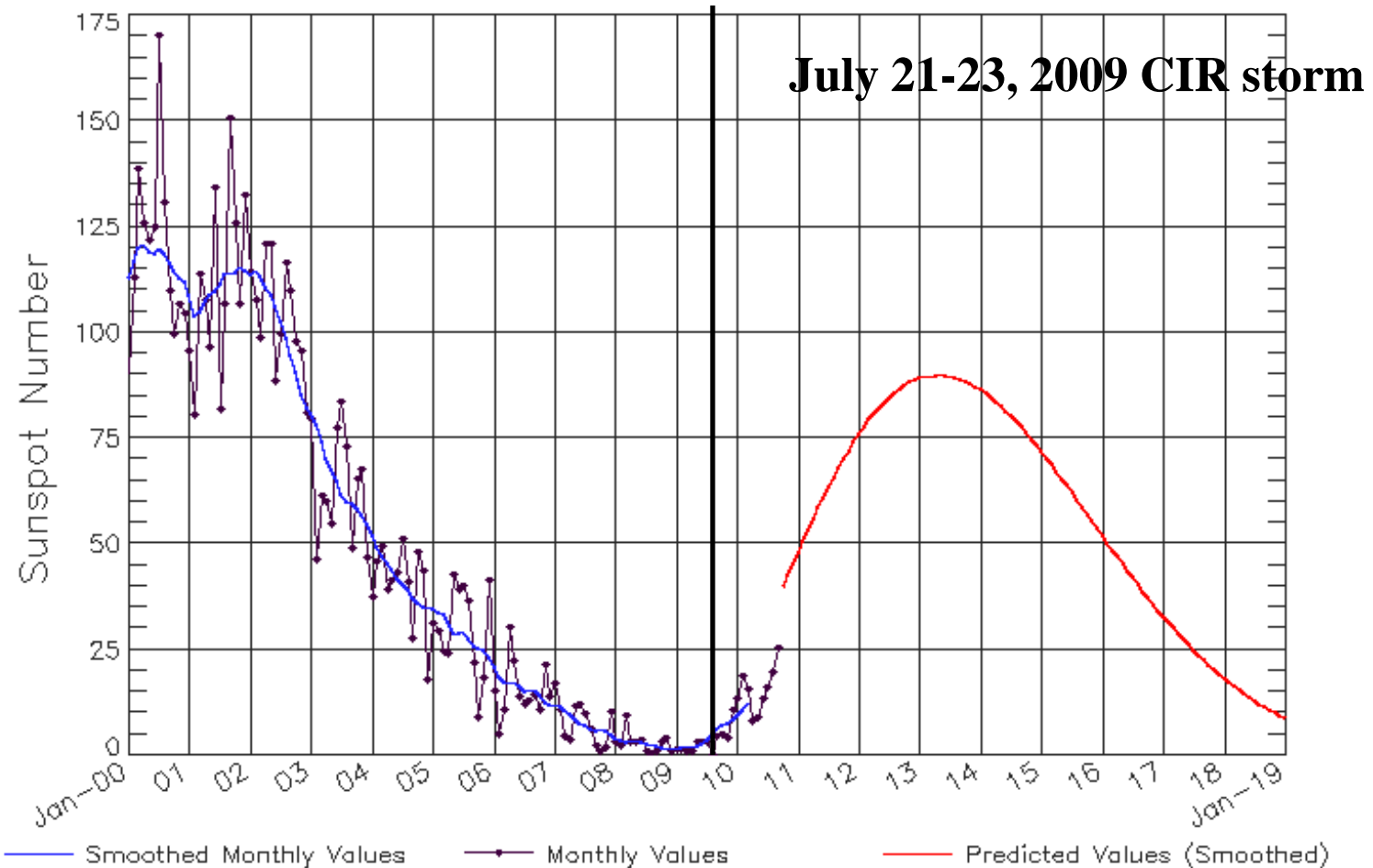*(2) Finnish Meteorological Institute, Helsinki, Finland*

2011 Joint CEDAR-GEM Workshop,26 June - 01 July 2011, Santa Fe, NM, USA

CIR-storm at the beginning of rising phases of solar cycle 24

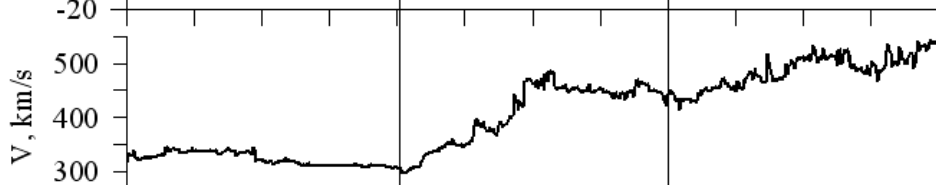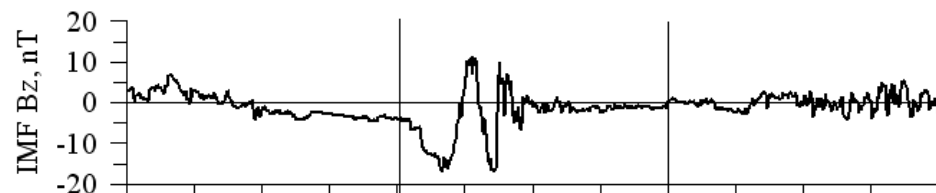ISES Solar Cycle Sunspot Number Progression
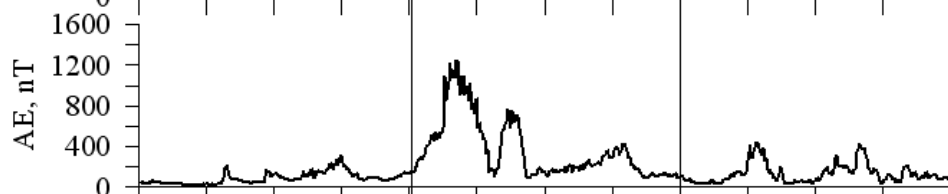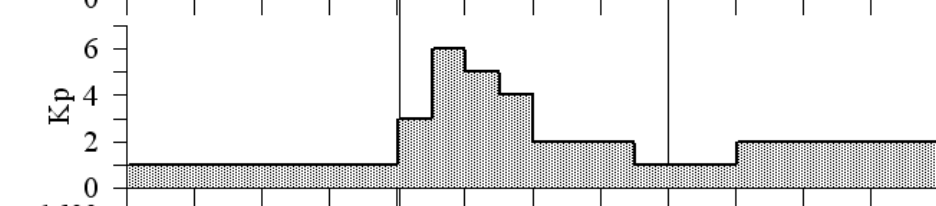Observed data through Sep 2010

July 21-23, 2009 CIR storm

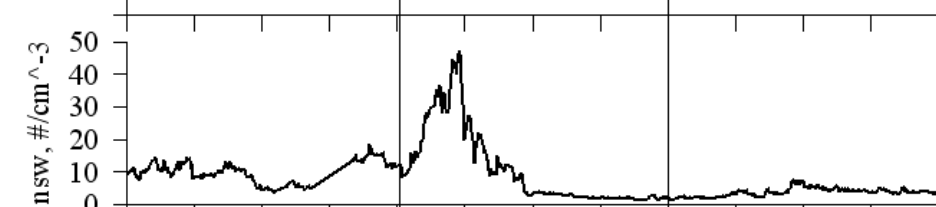Updated 2010 Oct 5

NOAA/SWPC Boulder,CO USA

Magnetic storm on July 21-23, 2009
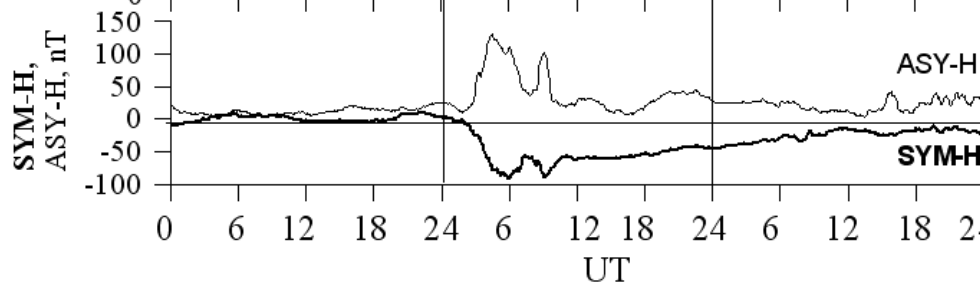

Smooth southward turning of IMF Bz

Density peak in front of High Speed stream

Small storm

High speed stream

Substorm activity

Long recovery

Inner Magnetosphere Particle Transport and Acceleration Model (1)
(*Ganushkina et al., AnnGeo, 2005, JGR, 2006*)

- Changes in distribution function f and flux calculations for ions and electrons **with arbitrary pitch angles** using *Liouville's theorem* taking into account **loss processes**.

$$\frac{df}{dt} = \frac{\partial f}{\partial \phi} \cdot V_\phi + \frac{\partial f}{\partial r} \cdot V_r + sources - losses$$

- **Boundary distribution**: at any location from 6.6 to 10 Re
- **Transport of particles**:
  - Drifts with velocities, radial and longitudinal, as sum of **ExB and magnetic drifts, 1**st and 2nd inv = const in **time-dependent magnetic and electric fields** with self-consistent magnetic field

$$\text{Vdrift} = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{mv_\perp^2}{2qB^3}\left(\vec{B} \times \nabla B\right) + \frac{mv_{II}^2}{q}\frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}$$

$$\langle v_0 \rangle = \frac{\mathbf{E}_0 \times \mathbf{B}_0}{B_0^2} + \frac{2p}{q\tau_b B_0}\nabla I \times e_0,$$

$$I = \int_{S_m}^{S_m'}\left[1 - B(s)/B_m\right]^{1/2} ds,$$

Inner Magnetosphere Particle Transport and Acceleration Model (2)
(*Ganushkina et al., AnnGeo, 2005, JGR, 2006*)

Losses for ions:

- **charge exchange** with Hydrogen from geocorona;
- **Coulomb interaction** in dense thermal plasmas (plasmasphere);
- **convection outflow**, particle intersects the magnetopause and flows away along magnetosheath magnetic field lines.

Including self-consistent magnetic field

- Obtain parallel pressure and perpendicular pressure from IMPTAM

$$P_\parallel = \int mv^2 f \cos^2 \alpha\, dp, \quad P_\perp = \int \frac{1}{2} mv^2 f \sin^2 \alpha\, dp, \quad dp = m^3 v^2 d\Omega dv$$

- Calculate the current perpendicular to magnetic field

$$\vec{j}_\perp = \frac{\vec{B}}{B^2} \times \left(\nabla P_\perp + \frac{P_{II} - P_\perp}{B^2} \left(\vec{B} \cdot \nabla \right) \vec{B} \right)$$

- Calculate the magnetic field induced by the ring and near-Earth tail currents using the Biot-Savart law

$$B(\vec{r}) = \frac{\mu_0}{4\pi} \int \int \int \frac{\vec{J}_\perp(\vec{r}\,') \times (\vec{r} - \vec{r}\,')}{\left| \vec{r} - \vec{r}\,' \right|^3} d^3 r'$$

- Calculated magnetic field is then used in IMPTAM to update the particle trajectories

- The procedure repeated 2 or 3 times, dependent on when the following calculations do not differ from the previous ones

Model-dependent Dst calculations during storms

1. Using **Dessler-Parker-Sckopke relationship**:

The energy in the ring current can be expressed by $\boxed{\dfrac{\Delta \vec{B}}{B_E} = -\dfrac{2}{3}\dfrac{W_{RC}}{W_{mag}}\hat{k}}$, where

$W_{mag} = \dfrac{4\pi}{3\mu_0} B_E^2 R_E^3$ is the total energy in the Earth's dipole magnetic field above the surface, B_E is the magnetic field at the Earth's surface, R_E is one Earth radii (6371 km).

$\Delta \vec{B}$ is the change in B measured at the surface of the Earth (Dst).

2. Calculating from the model ring current by **Biot-Savart law**:

The magnetic disturbance parallel to the earth's dipole at the center of the earth ΔB induced by the azimuthal component of $J_\perp$, is given by

$$\boxed{\Delta B = \frac{\mu_0}{4\pi}\int_r \int_\lambda \int_\phi \cos^2 \lambda J_\phi(r,\lambda,\phi)\,dr\,d\lambda\,d\phi}$$

$$\vec{j}_\perp = \frac{\vec{B}}{B^2}\times\left(\nabla P_\perp + \frac{P_{II}-P_\perp}{B^2}(\vec{B}\cdot\nabla)\vec{B}\right)$$

Combinations of models for IMPTAM for July 21-23, 1997 storm

	Electric Field	Boundary conditions
dipole	Volland-Stern	Tsyganenko and Mukai, 2003
T89	Volland-Stern	Tsyganenko and Mukai, 2003
T96	Volland-Stern	Tsyganenko and Mukai, 2003
TS04	Volland-Stern	Tsyganenko and Mukai, 2003
dipole	Boyle et al., 1997	Tsyganenko and Mukai, 2003
T89	Boyle et al., 1997	Tsyganenko and Mukai, 2003
T96	Boyle et al., 1997	Tsyganenko and Mukai, 2003
TS04	Boyle et al., 1997	Tsyganenko and Mukai, 2003

With no self-consistency best fit with observed Dst for
dipole + **T96** + **VS** model combination

Modeled Dst for July 21-23, 2009 storm
Dip + VS + Tsyganenko and Mukai, 2003 at 10 Re
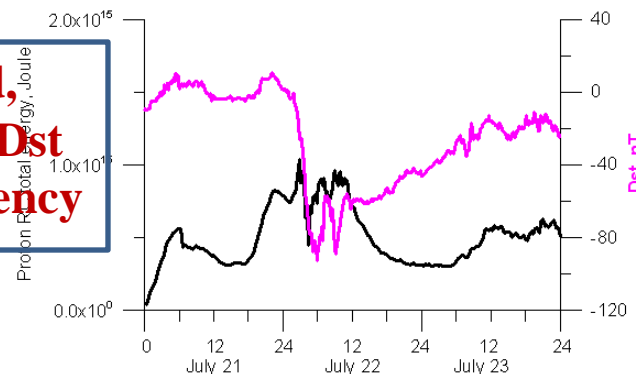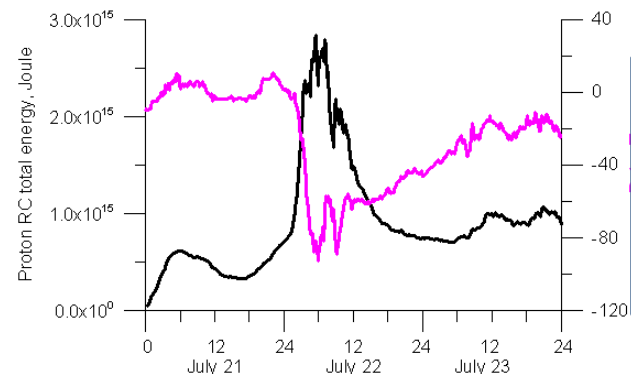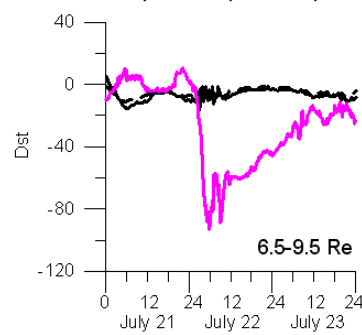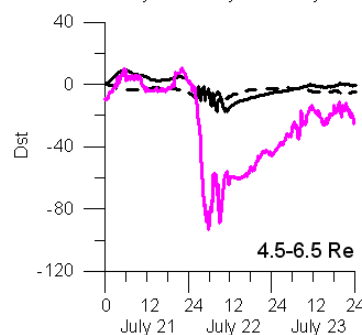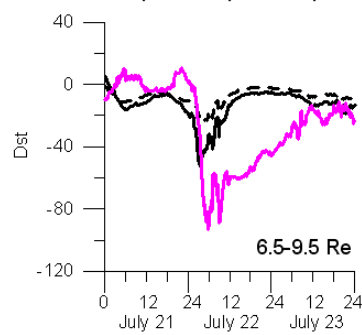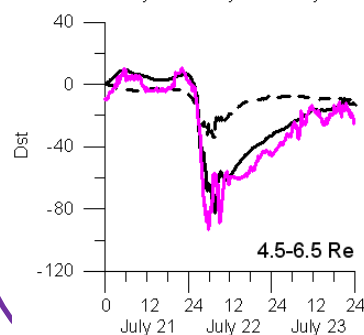### without self-consistent mag. field   with self-consistent mag. field
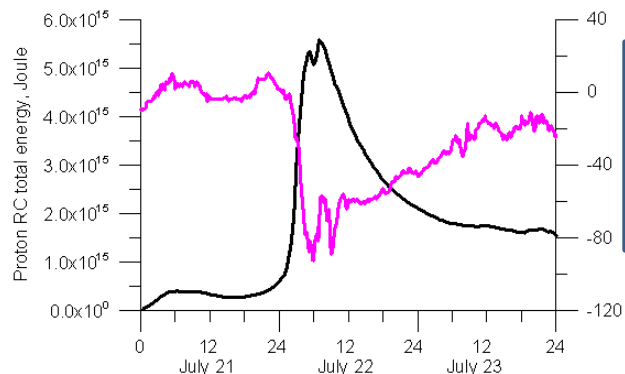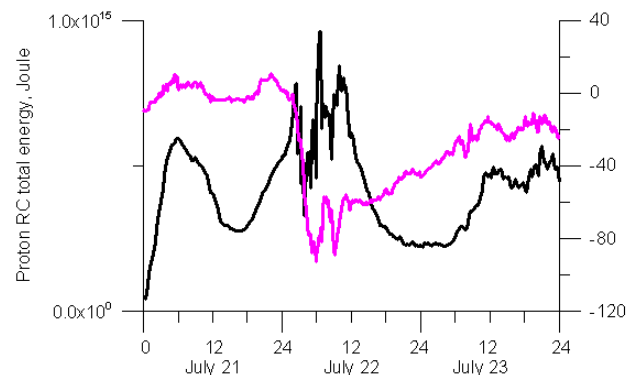

Only dipole, improved Dst fit with self-consistency
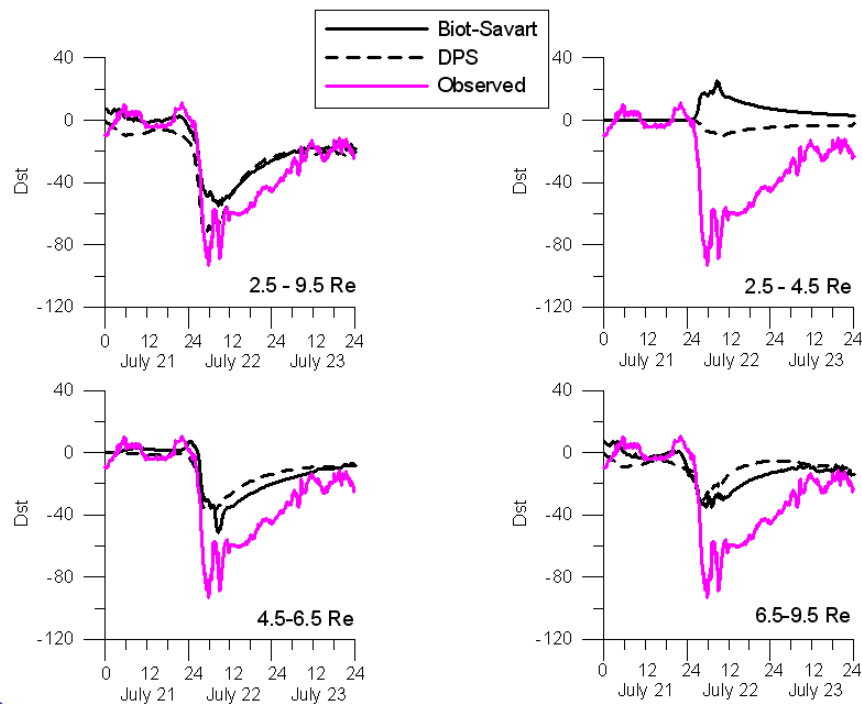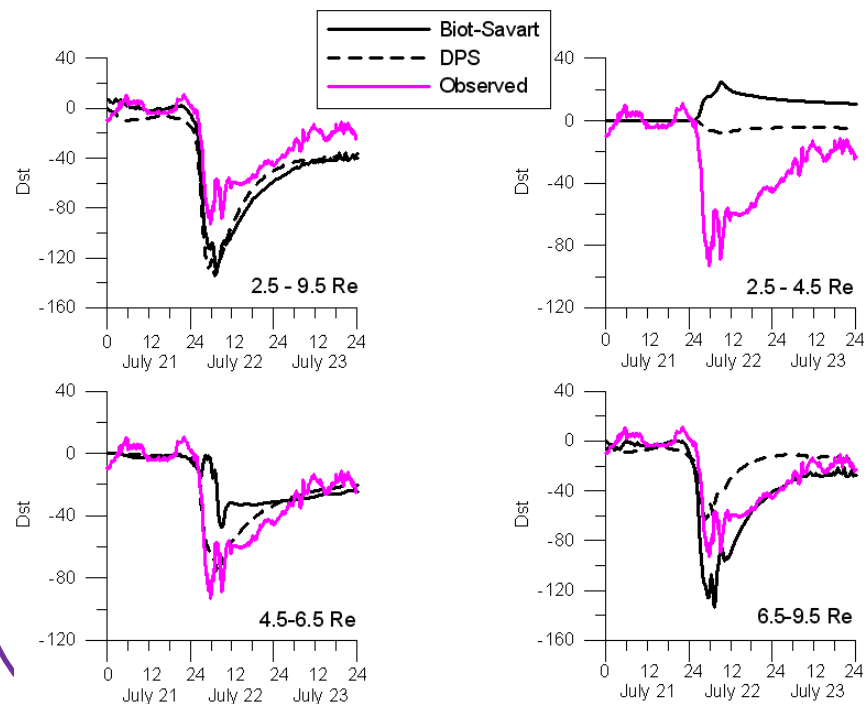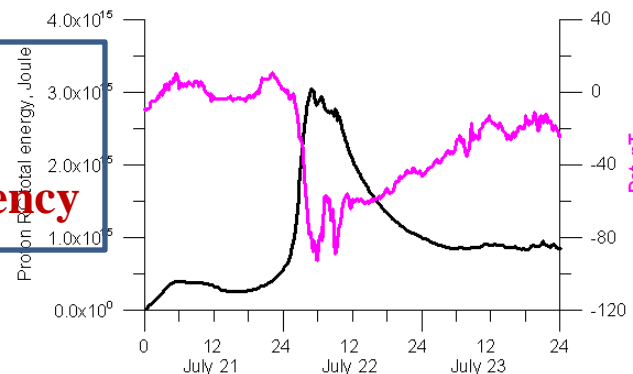
Modeled Dst for July 21-23, 2009 storm
Dip + Boyle + Tsyganenko and Mukai, 2003 at 10 Re
without self-consistent mag. field   with self-consistent mag. field

Only dipole, improved Dst fit with self-consistency
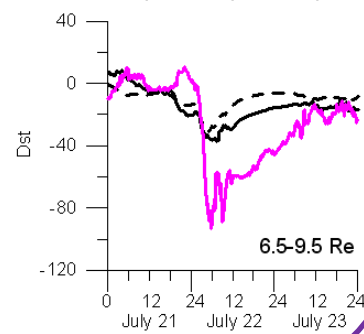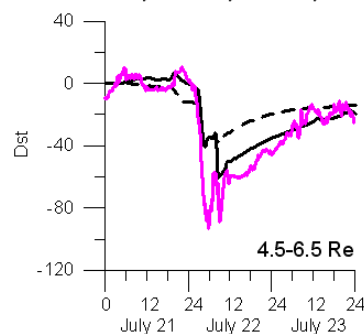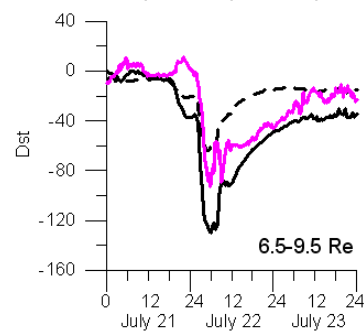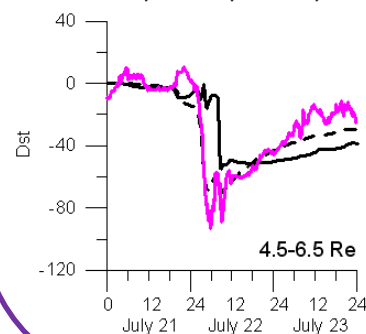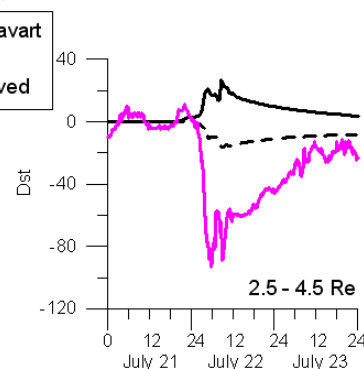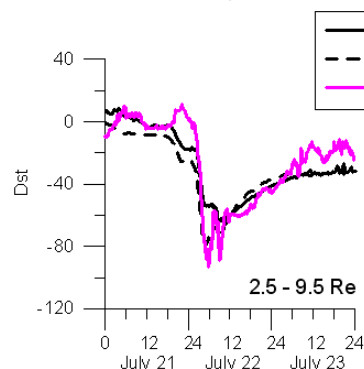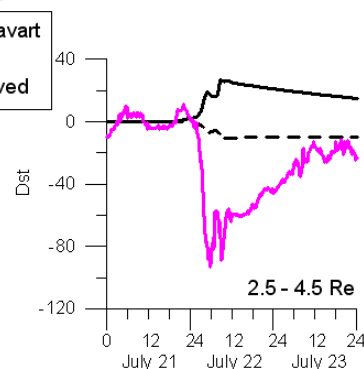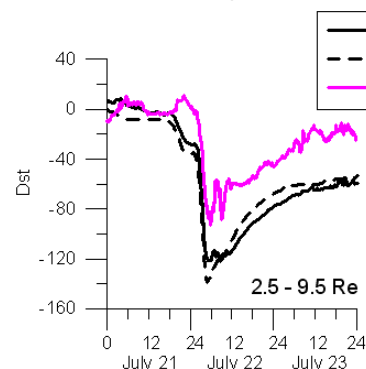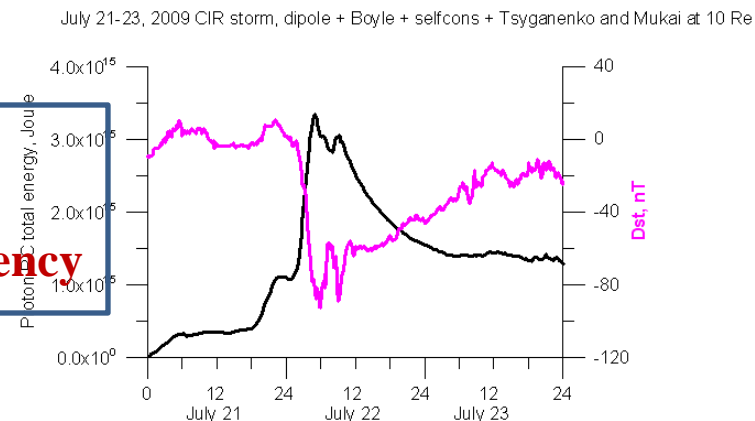
Modeled Dst for July 21-23, 2009 storm
Dip + T89 + Boyle + Tsyganenko and Mukai, 2003 at 10 Re
without self-consistent mag. field   with self-consistent mag. field
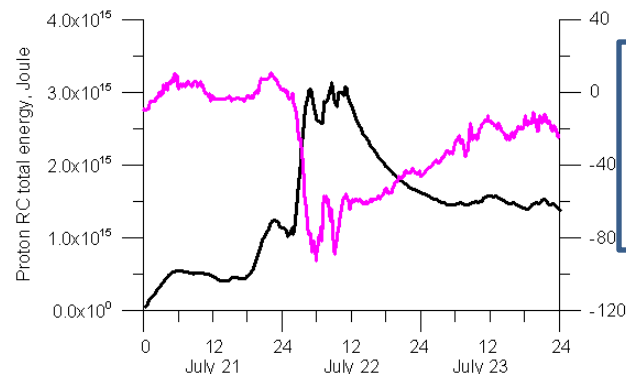
Realistic m. field, underestimated Dst with self-consistency
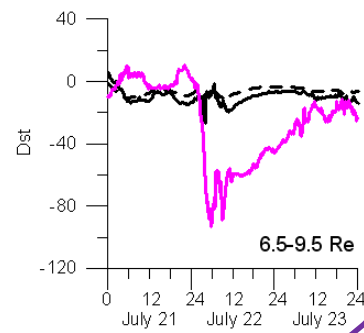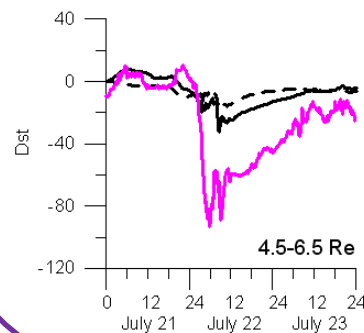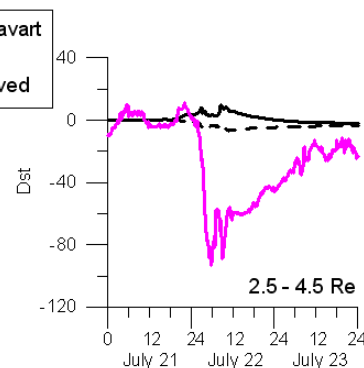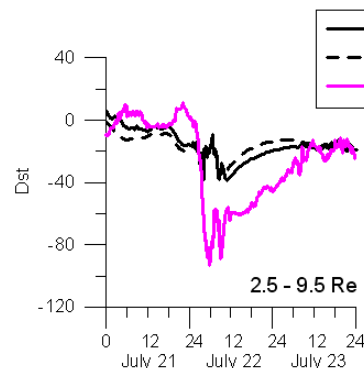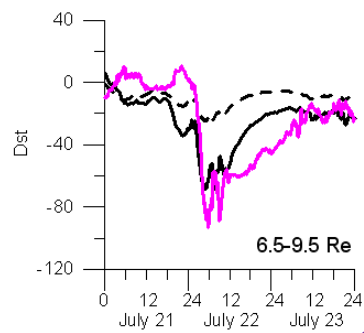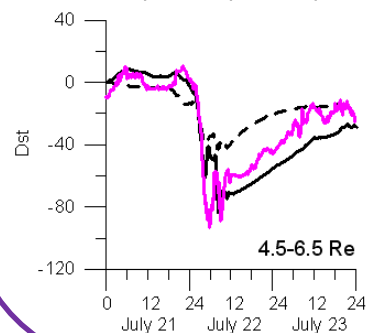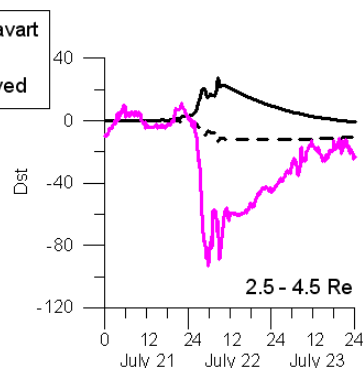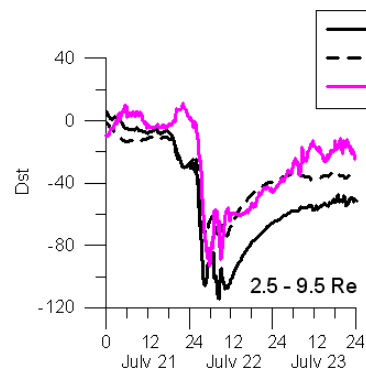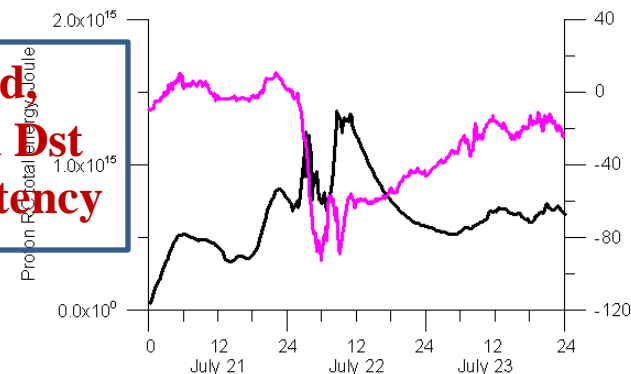
Modeled Dst for July 21-23, 2009 storm
Dip + T96 + Boyle + Tsyganenko and Mukai, 2003 at 10 Re
without self-consistent mag. field   with self-consistent mag. field
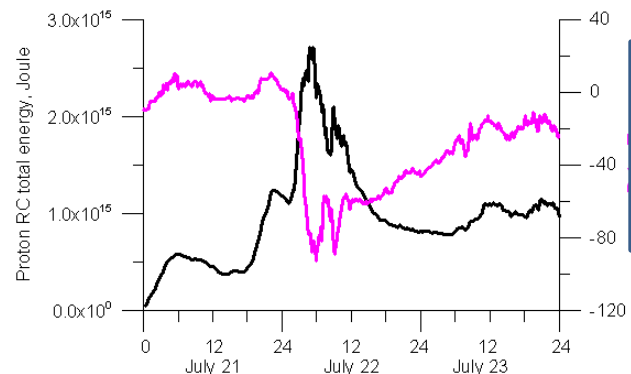
Realistic m. field, underestimated Dst with self-consistency
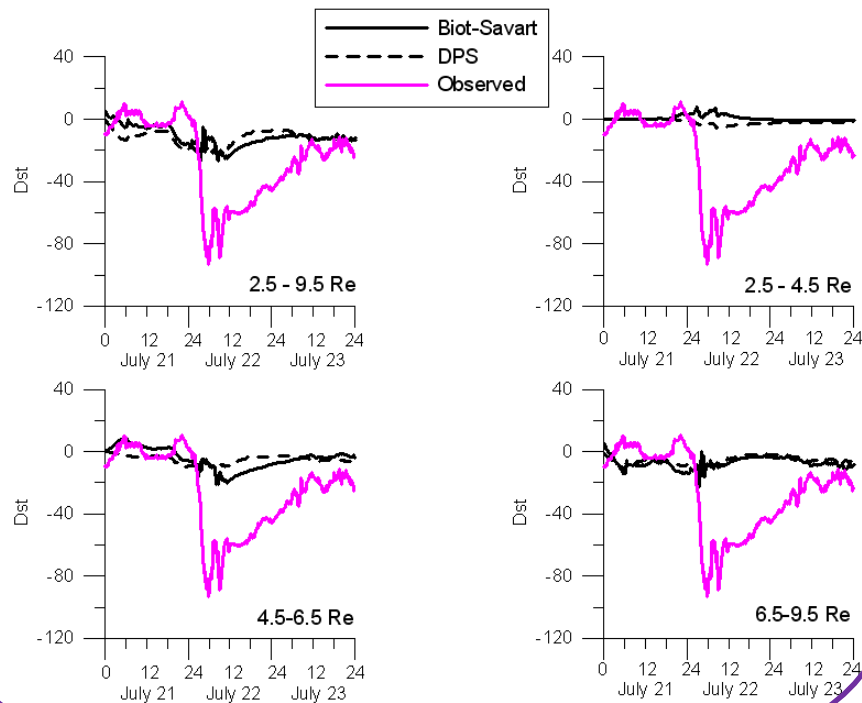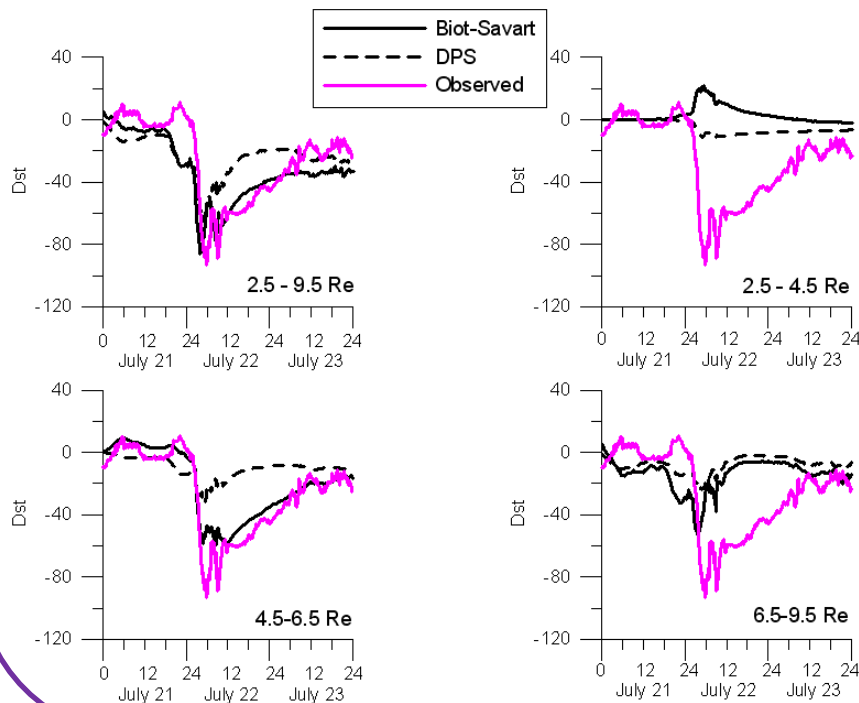
Modeled Dst for July 21-23, 2009 storm

Dip + T96 + VS + Tsyganenko and Mukai, 2003 at 10 Re
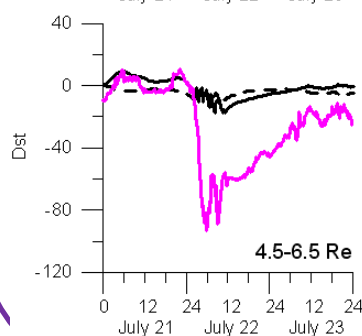
without self-consistent mag. field   with self-consistent mag. field

Realistic m. field, simple el. field, underestimated Dst with self-consistency
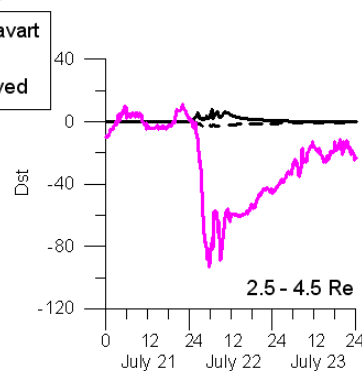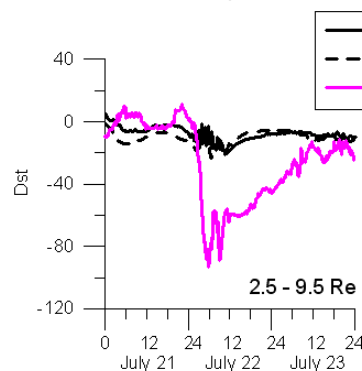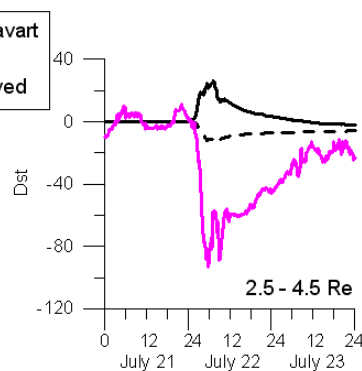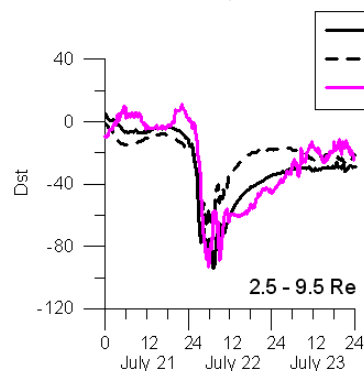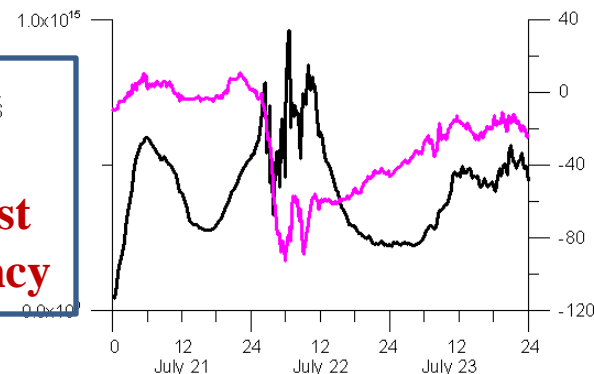
Modeled Dst for July 21-23, 2009 storm
Dip + T96 + VS + Tsyganenko and Mukai, 2003 at 10 Re
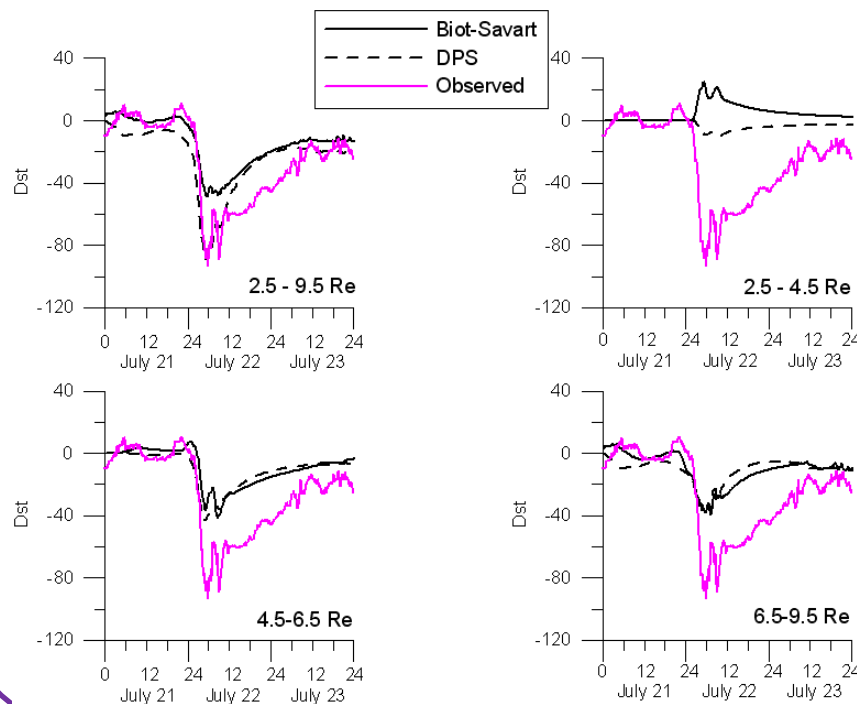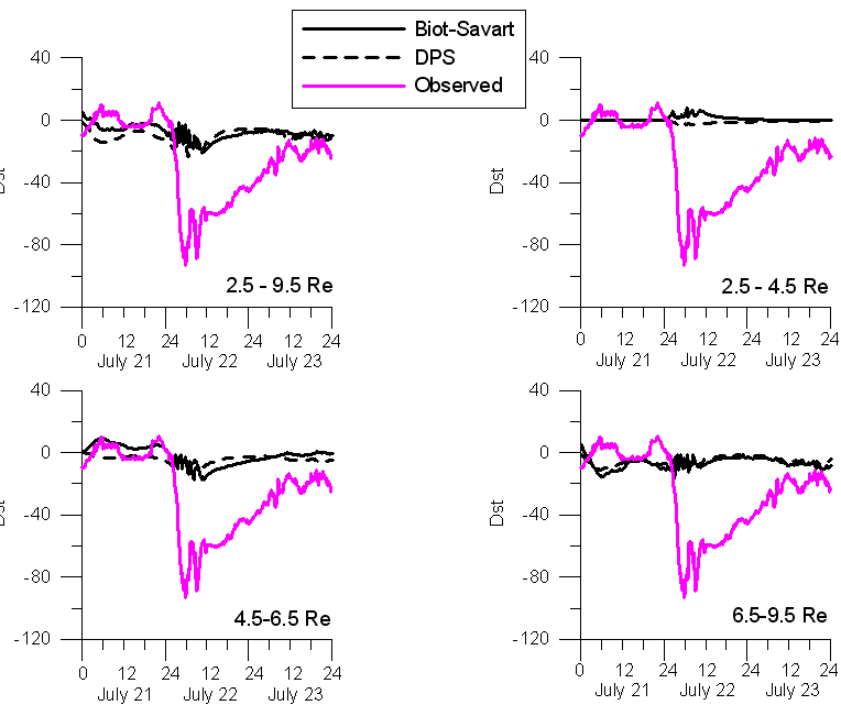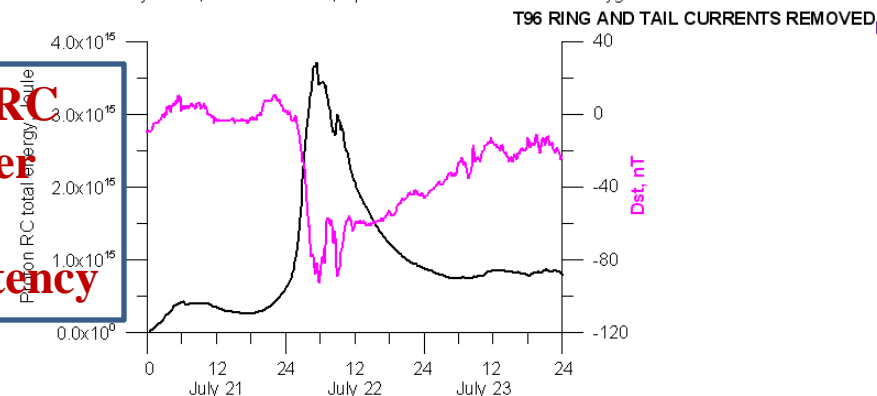### with self-consistent mag. field   T96 RC removed

Removing T96 RC gives better Dst fit with self-consistency
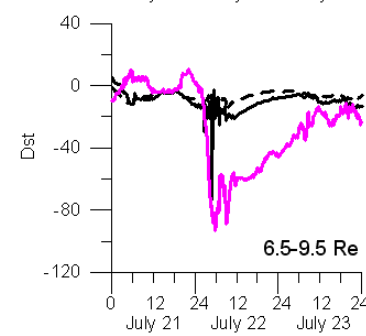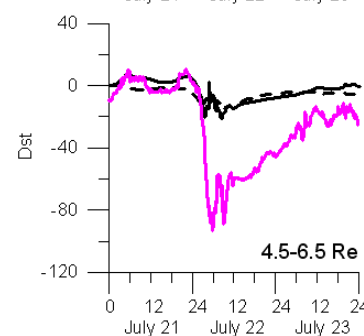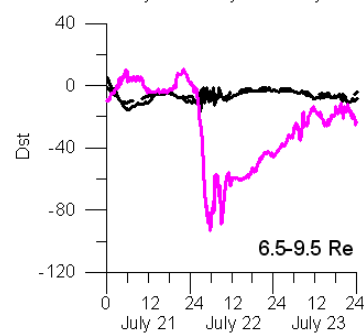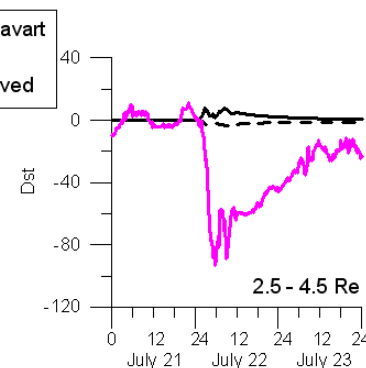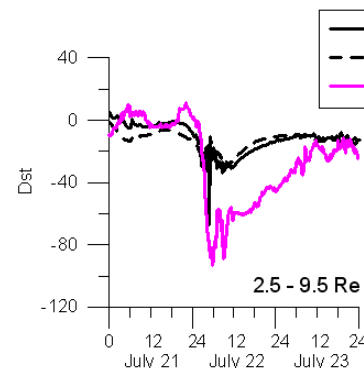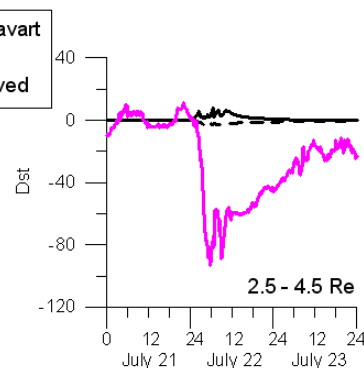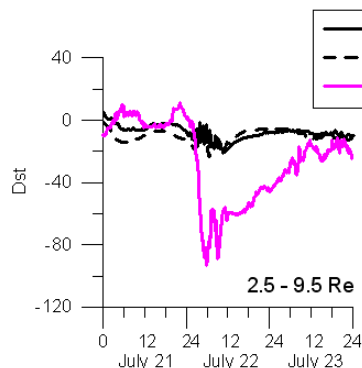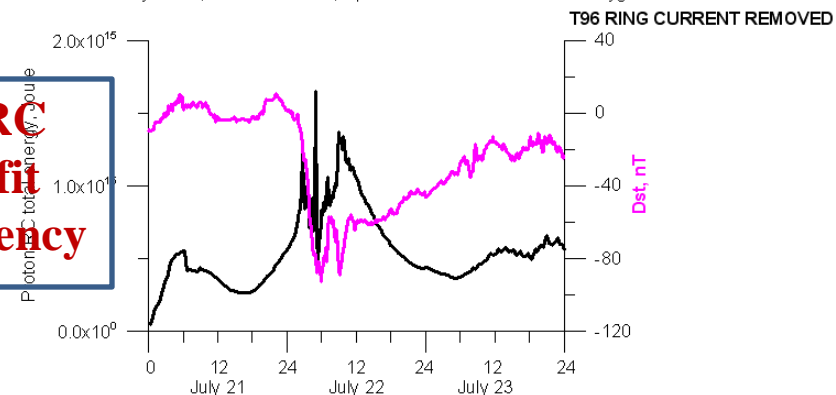
Modeled Dst for July 21-23, 2009 storm
Dip + T96 + VS + Tsyganenko and Mukai, 2003 at 10 Re
with self-consistent mag. field
T96 RC and TC removed
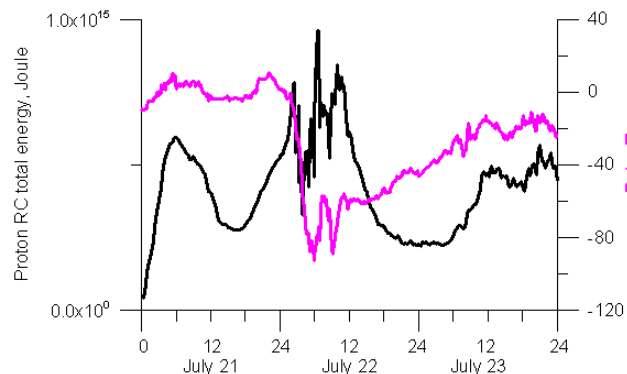
Removing T96 RC gives event better Dst fit with self-consistency

Time moments for current density maps for July 21-23, 2009 storm
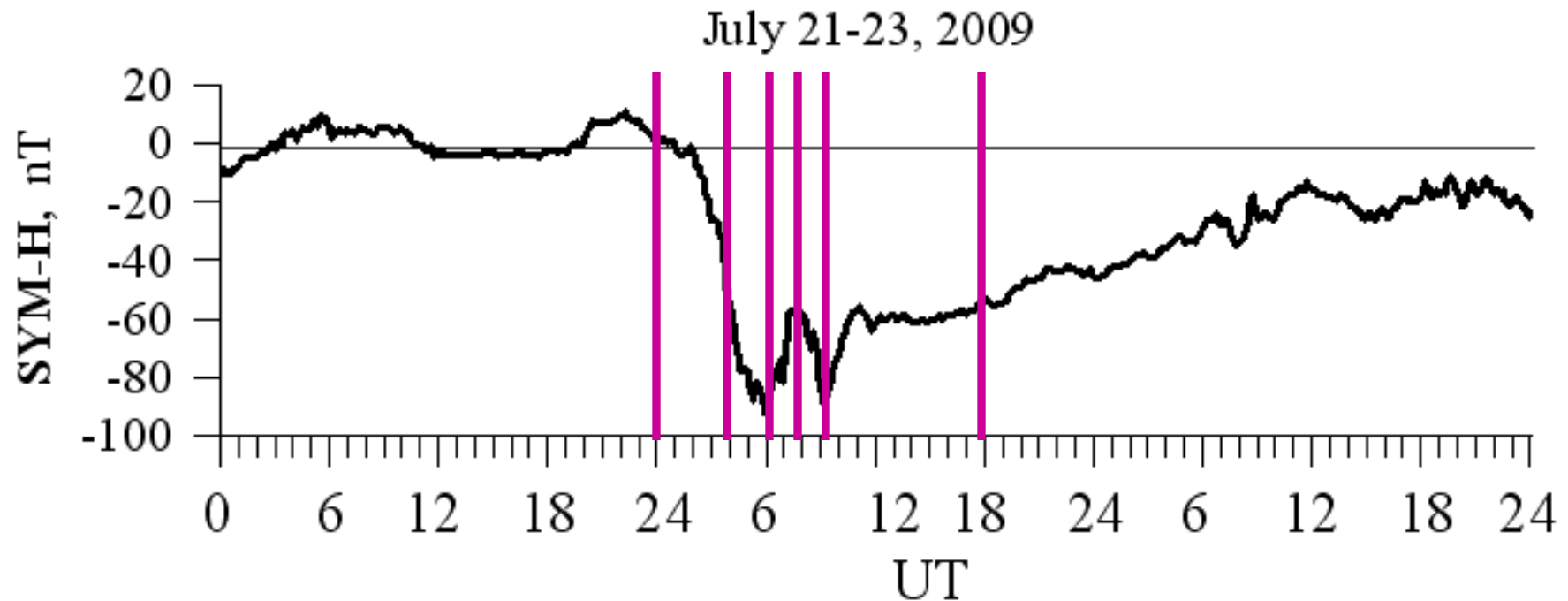
July 21-23, 2009

July 22, 2009
0000 UT, SYM-H = 2nT
0400 UT, SYM-H = -59nT
0555 UT, SYM-H = -92nT
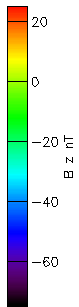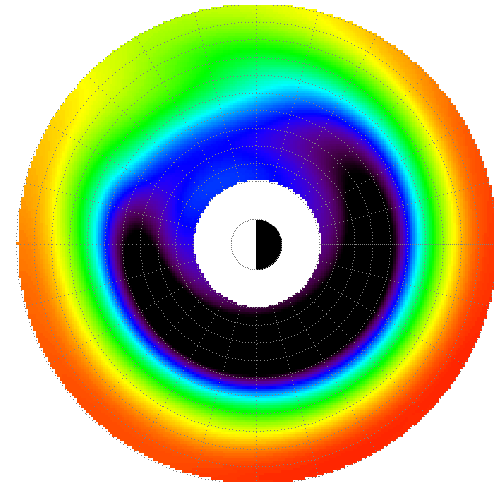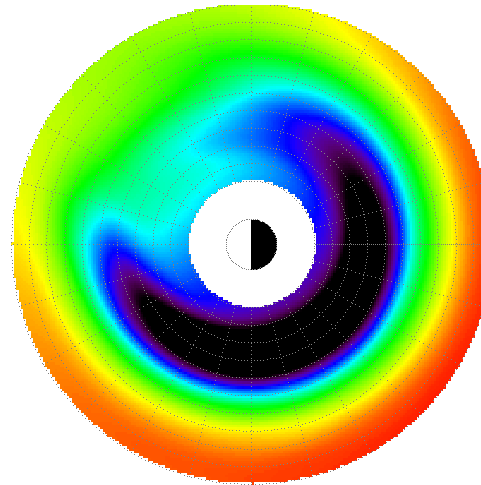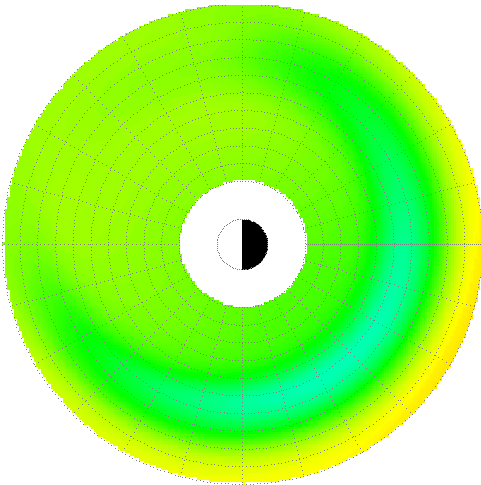0730 UT, SYM-H = -57nT
0905 UT, SYM-H = -89nT
1800 UT, SYM-H = -53nT

Induced magnetic field for July 21-23, 2009 storm, Dip + Boyle + Tsyganenko and Mukai, 2003 at 10 Re, best Dst fit with self-consistency
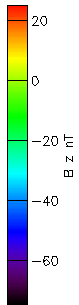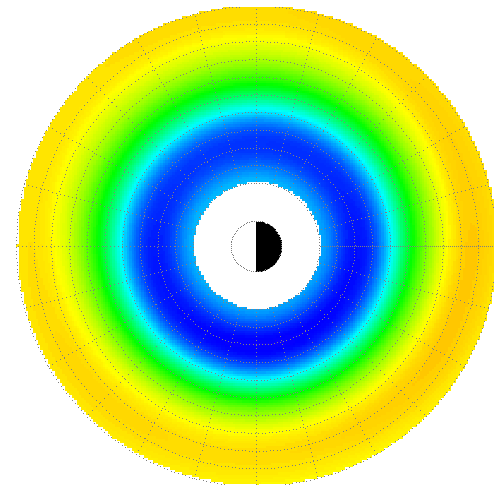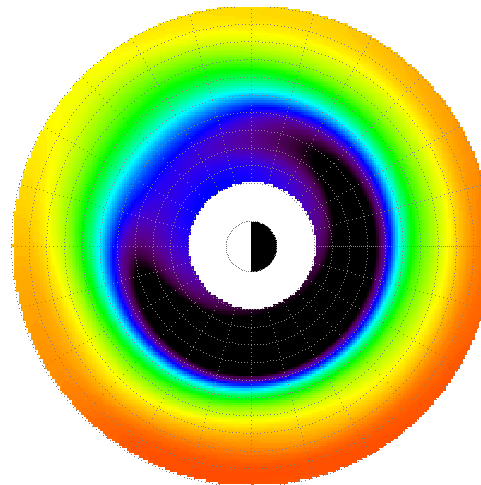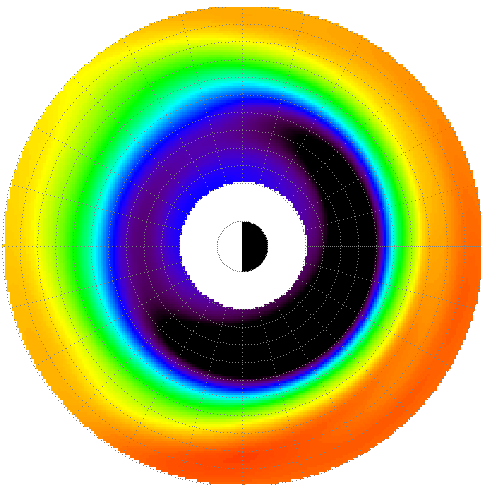
July 22, 00 UT

July 22, 04 UT

July 22, 06 UT, storm max

July 22, 08 UT

July 22, 0915 UT
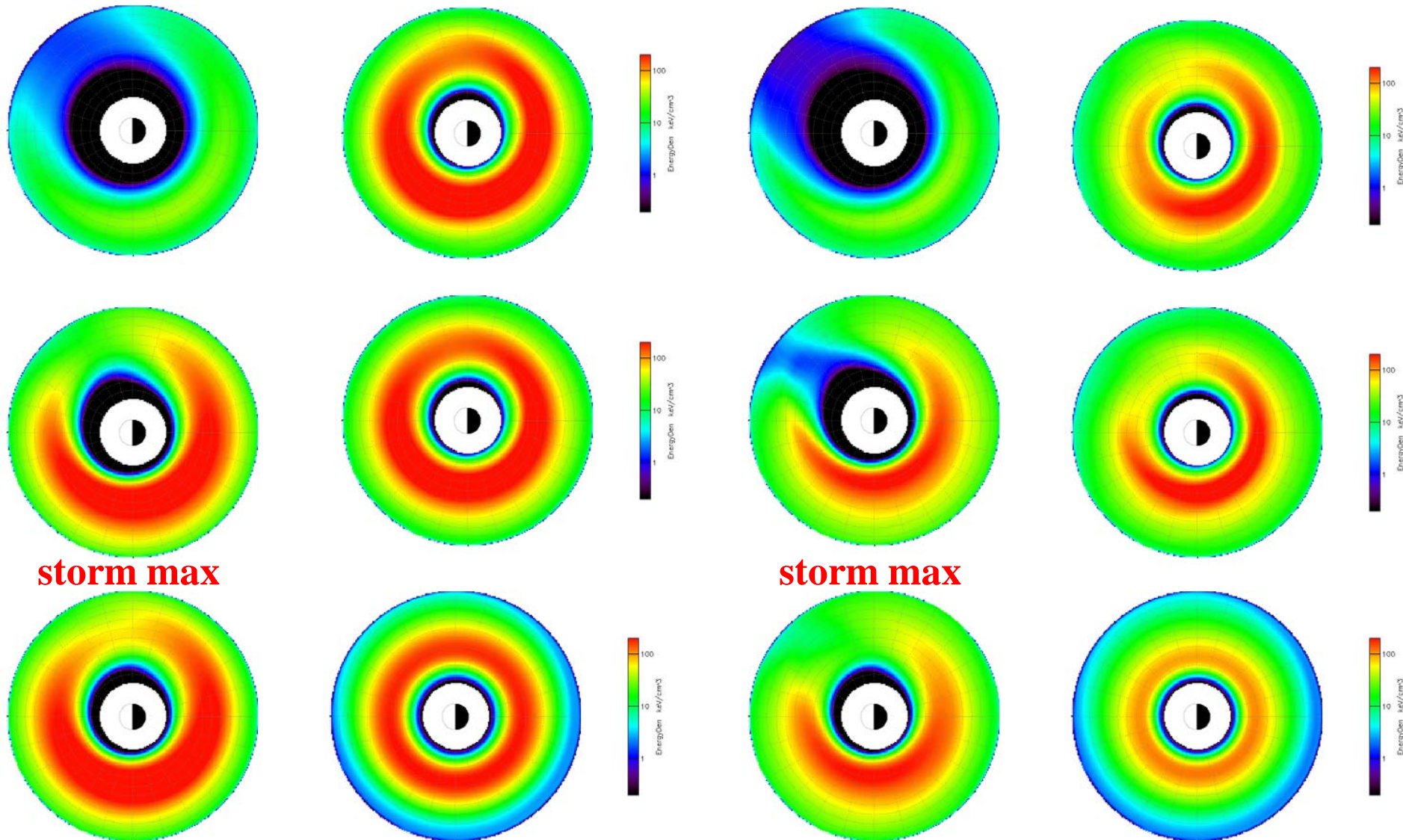
July 22, 18 UT

Equatorial energy density maps for July 21-23, 2009 storm

Dip + Boyle + Tsyganenko and Mukai, 2003 at 10 Re

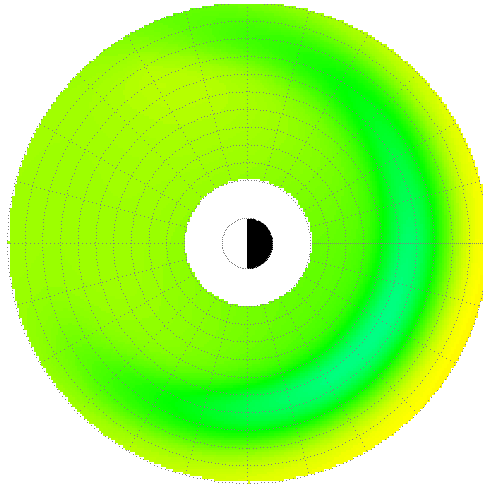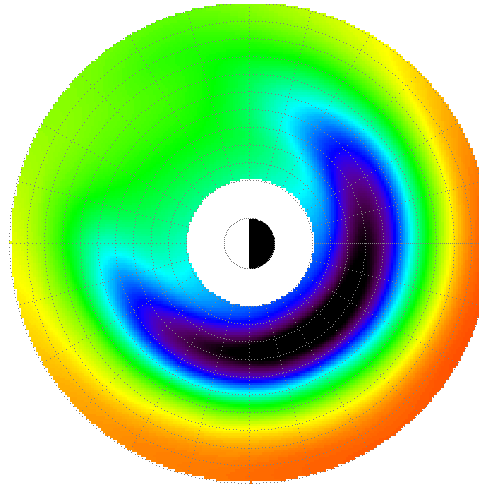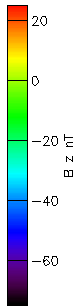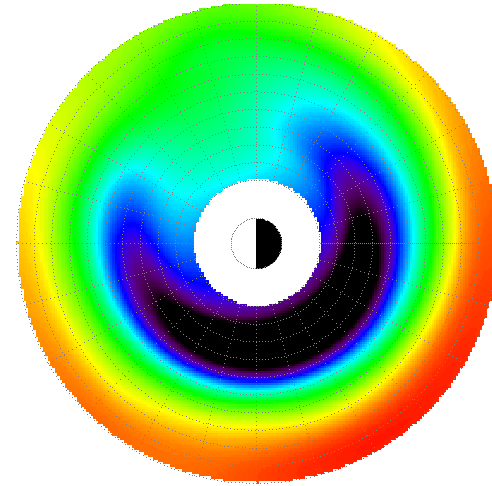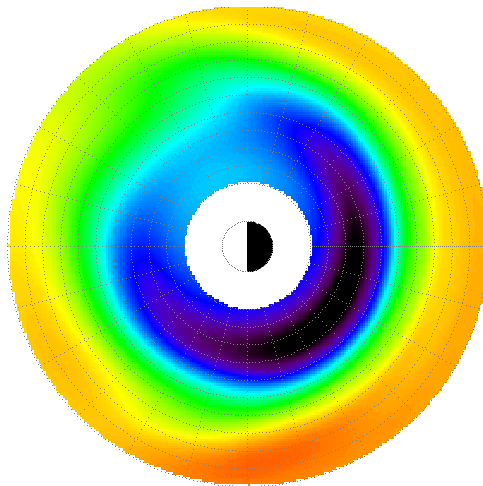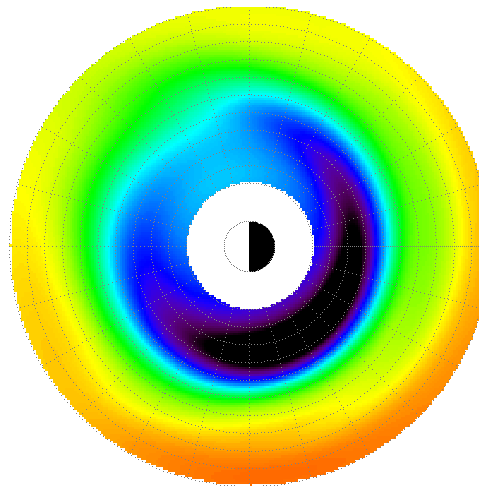without self-consistent mag. field   with self-consistent mag. field

storm max   storm max

Induced magnetic field for July 21-23, 2009 storm
Dip + T96 – RC, TC removed + VS + Tsyganenko and Mukai, 2003 at 10 Re
best Dst fit without self-consistency (with T96 RC and TC)

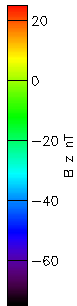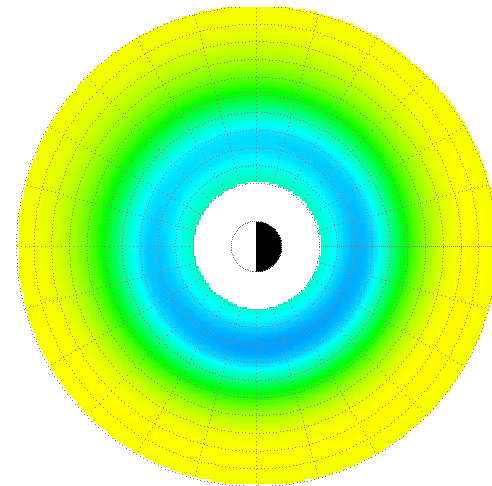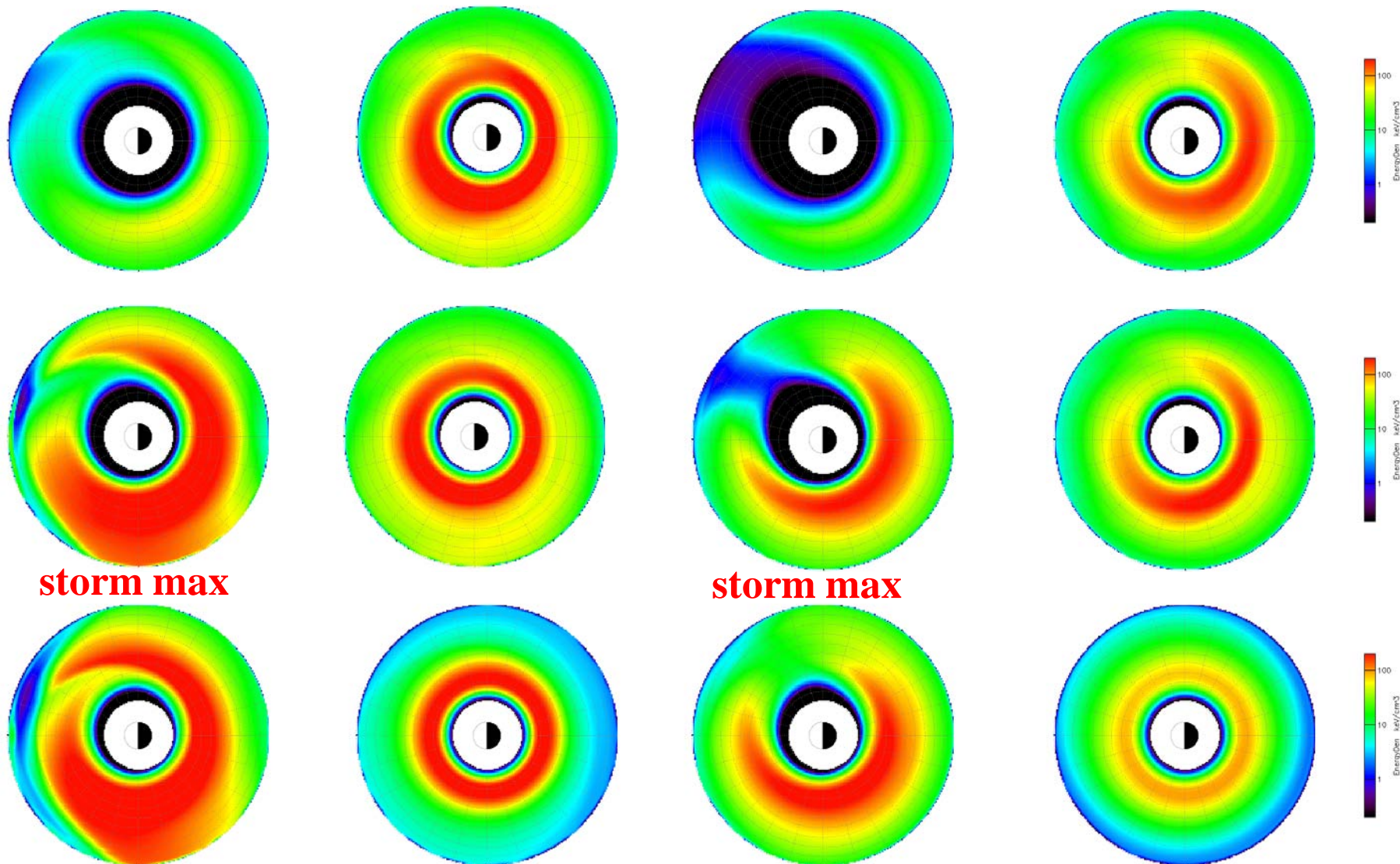**July 22, 00 UT** **July 22, 04 UT** **July 22, 06 UT, storm max**

July 22, 08 UT **July 22, 0915 UT** **July 22, 18 UT**

Equatorial energy density maps for July 21-23, 2009 storm
Dip + T96 + VS + Tsyganenko and Mukai, 2003 at 10 Re
without self-consistent mag. field   with self-cons. mag. f.
T96 RC and TC removed
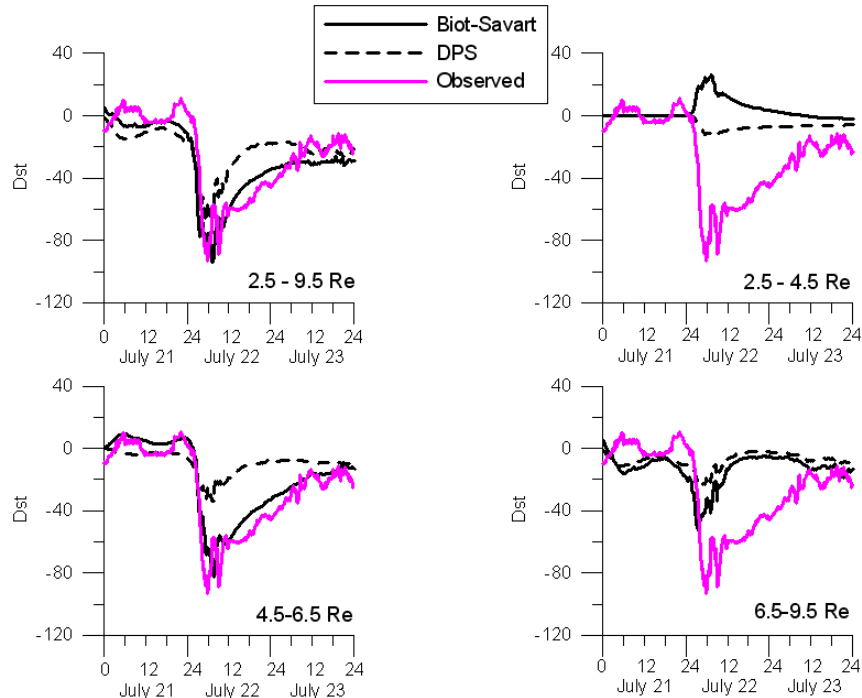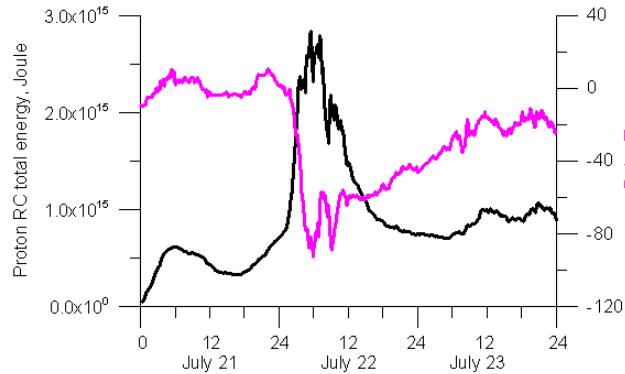

storm max   storm max

Contribution from electrons for July 21-23, 2009 storm without self-consistency

Dip + T96 + VS + Tsyganenko and Mukai, 2003 at 10 Re

Protons

Electrons
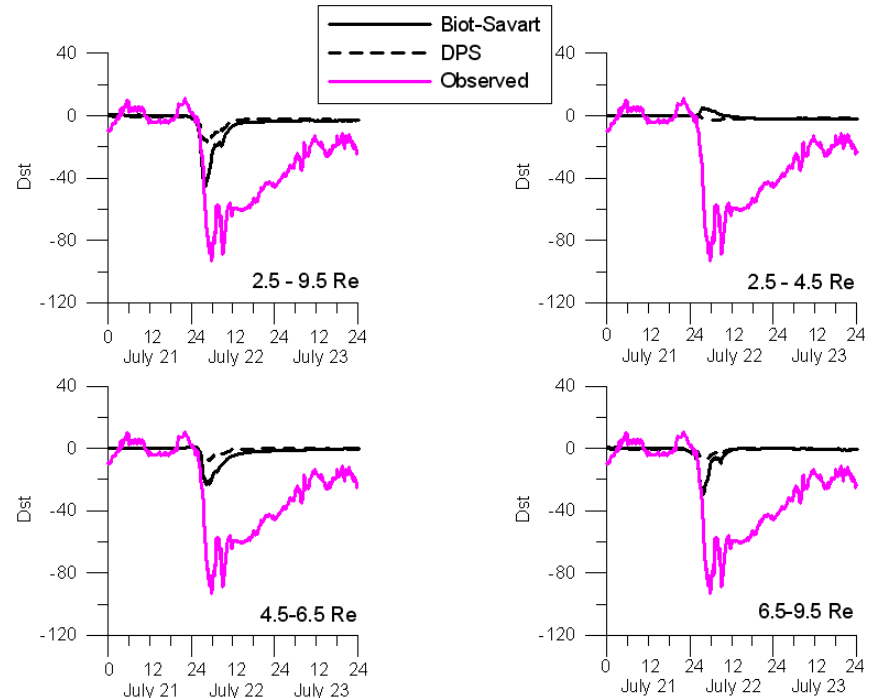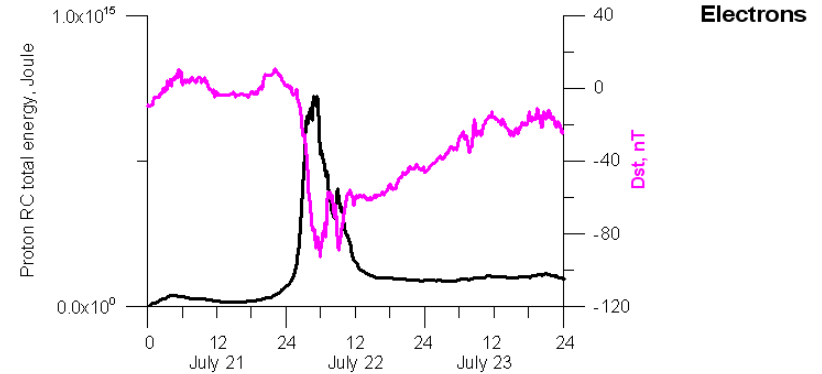

July 21-23, 2009 CIR storm, dipole + T96 + VS + Tsyganenko and Mukai at 10 Re

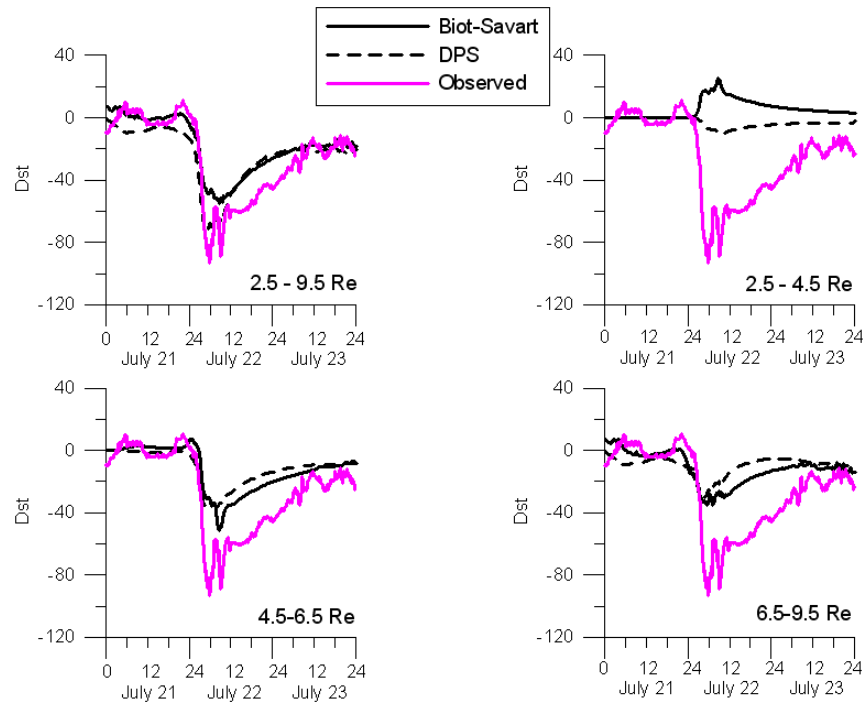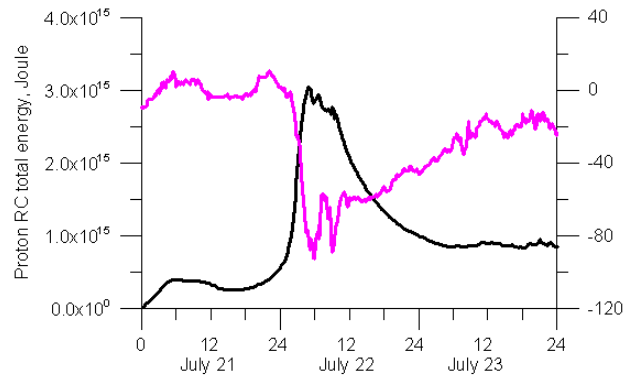July 21-23, 2009 CIR storm, dipole + T96 + Boyle + Tsyganenko and Mukai at 10 Re

Contribution from electrons for July 21-23, 2009 storm with self-consistency

Dip + VS + Tsyganenko and Mukai, 2003 at 10 Re