Solar Wind Control of Plasma Sheet Thermal Electrons at r = 6-11Re: Empirical Model

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Motivation

Multiple simulations of the inner magnetosphere require the boundary condition set between GEO and R ~10 Re [Chen et al., 1994, Jordanova et al., 1996, Fok et al, 2001, Ebihara et al., 2005, Liemohn et al., 2006, Ganushkina at el., 2005, Wolf et al., 1991, Sazykin 2000, Toffoletto et al., 2003]

Multiple authors addressed the topic of the plasma parameters dependence on the solar wind conditions [Terasawa et al., 1997, Borovsky et al., 1998, Wing and Newell 2002, Wang et al., 2006, 2007, 2010]. One the other hand, there are few analytical equations which could be used as a boundary conditions [Tsyganenko and Mukai 2003, Sergeev et al., 2015]

We present the empirical model of the electron density and temperature in the near-Earth plasma sheet. The work is done using THEMIS plasma and magnetic field measurements

Data: THEMIS A, D, E probes

Plasma measurements:

ESA electrons: 30eV - 30 keV

ions: 30eV - 25 keV

SST > 25 keV - 300 keV

SST low energy limit increases with mission lifetime

Plasma moments are computed from
combined distribution functions E = 30 eV - 300 keV (ESA + SST)
ESA - SST Energy gap is interpolated

Magnetic field measurements:

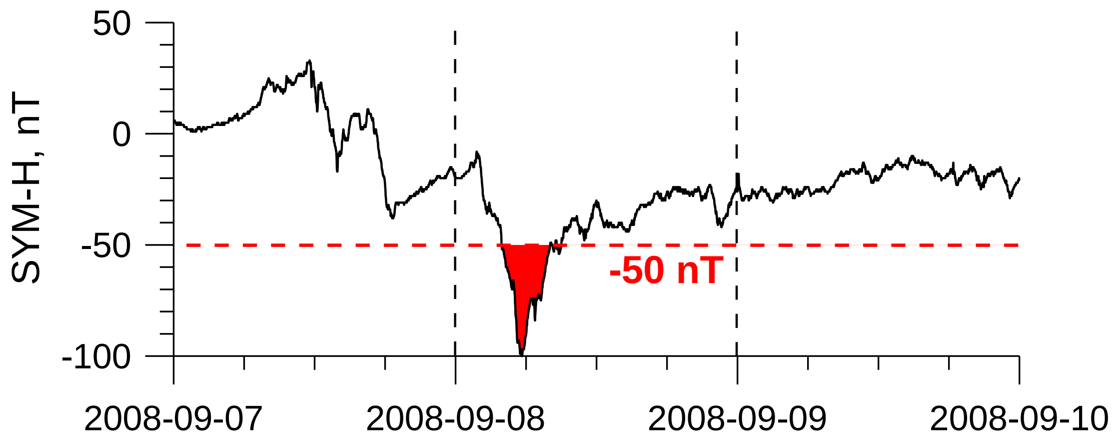
Flux Gate Magnetometer

Solar wind plasma parameters and IMF:

OMNI database, 1-min res.

Activity selection

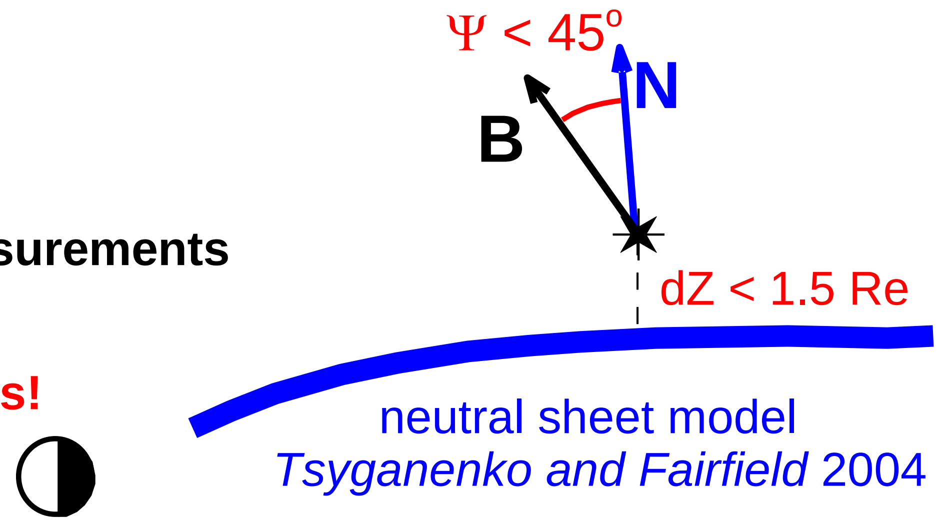
Storm-time intervals
2007-2013



Spatial selection

- **R = 6-11 Re, nightside**
- **The near-neutral sheet measurements**

Caution! This criterion tends to select thick current sheet events!

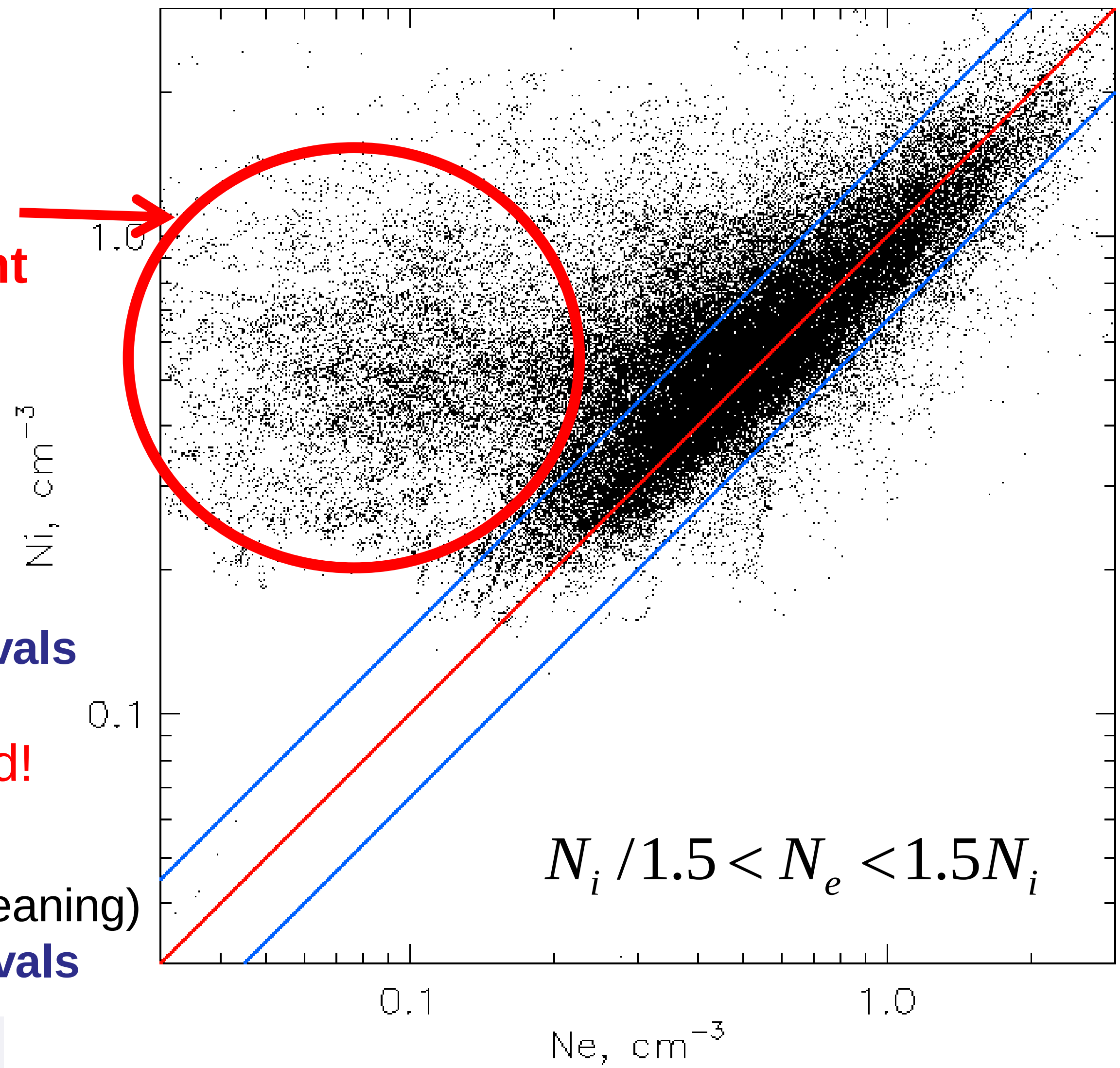


Depending on detectors modes the data are available:

~1.6 min resolution (accumulated during one spin period, 3 sec) **Auxiliary data set**

Spin resolution (3 sec), averaged over 1.6 min ; **Primary data set:**

Ni=Ne test



Primary data set
~63,000 records
After removal of bad points
~45,000 **1264 1h intervals**

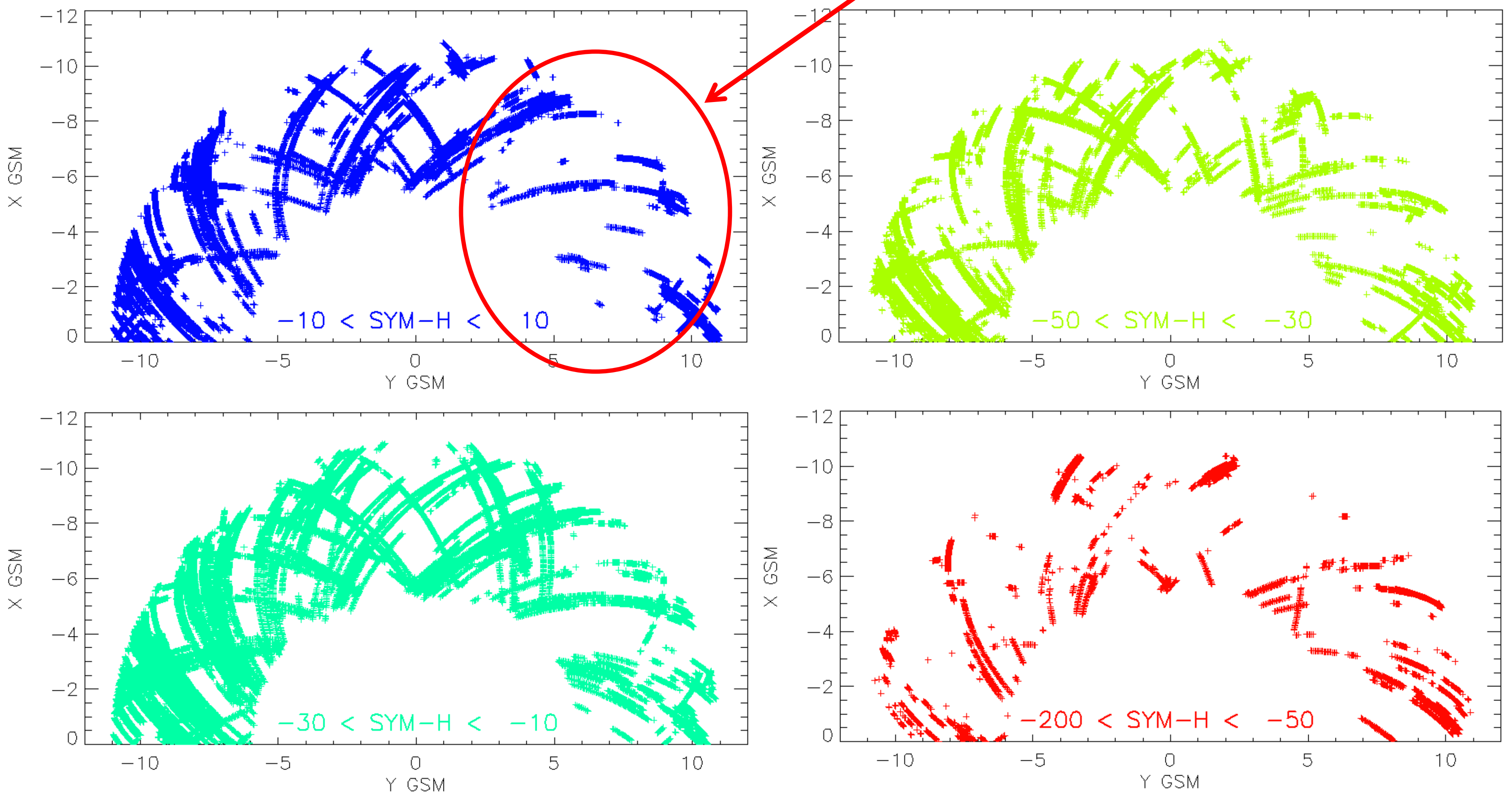
~1/3 of data was excluded!

Auxiliary data set (after cleaning)
~12,000 **1371 1h intervals**

years	2007	2008	2009	2010	2011	2012	2013
# Primary	0	0	0	7,475	11,347	12,693	13,486
# Auxiliary	1,992	583	38	1,688	2,033	2,520	3,317

Data coverage: Primary data set

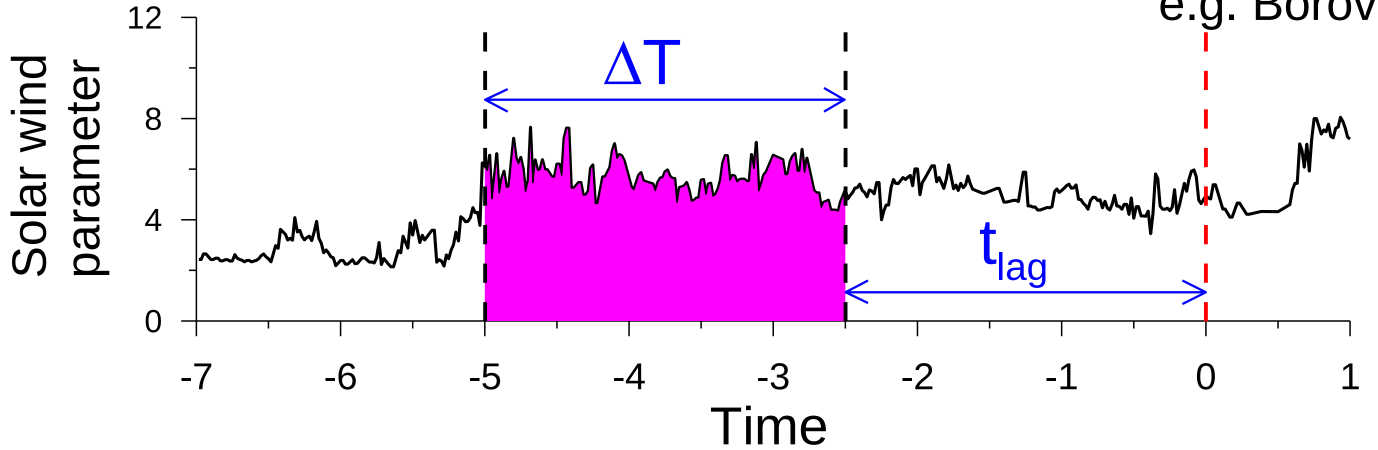
Underpopulated area
Ne≠Ni



Parameterization of Te, Ne dependence on solar wind parameters

Plasma sheet can respond to the solar wind changes with a delay of few hours

e.g. Borovsky et al., 1998



Density model

(1) N_{SW}, solar wind proton density

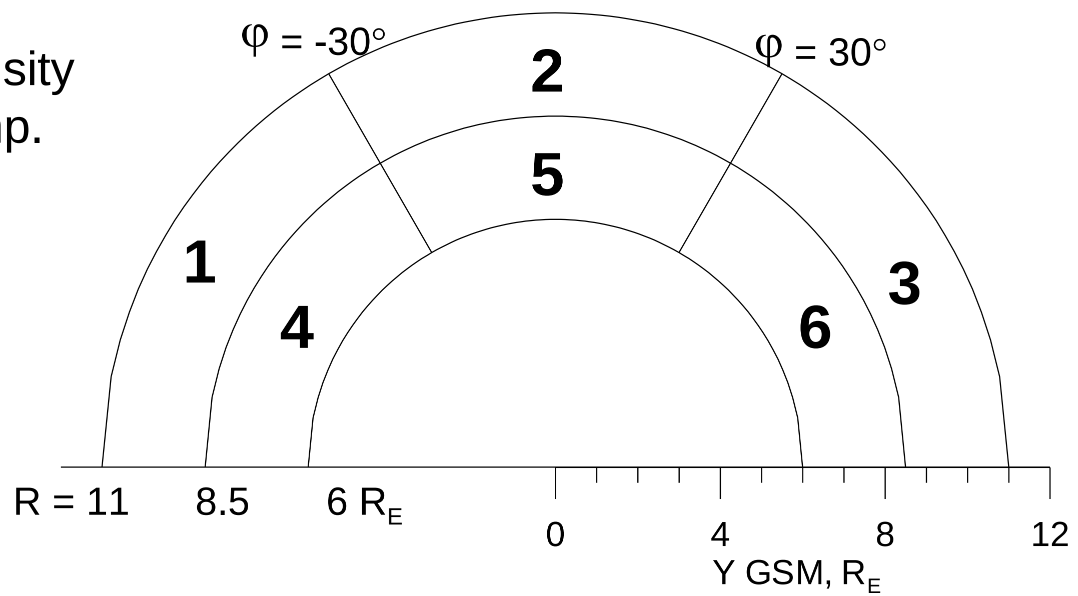
(2) IMF B_S, IMF southward comp.

Temperature model

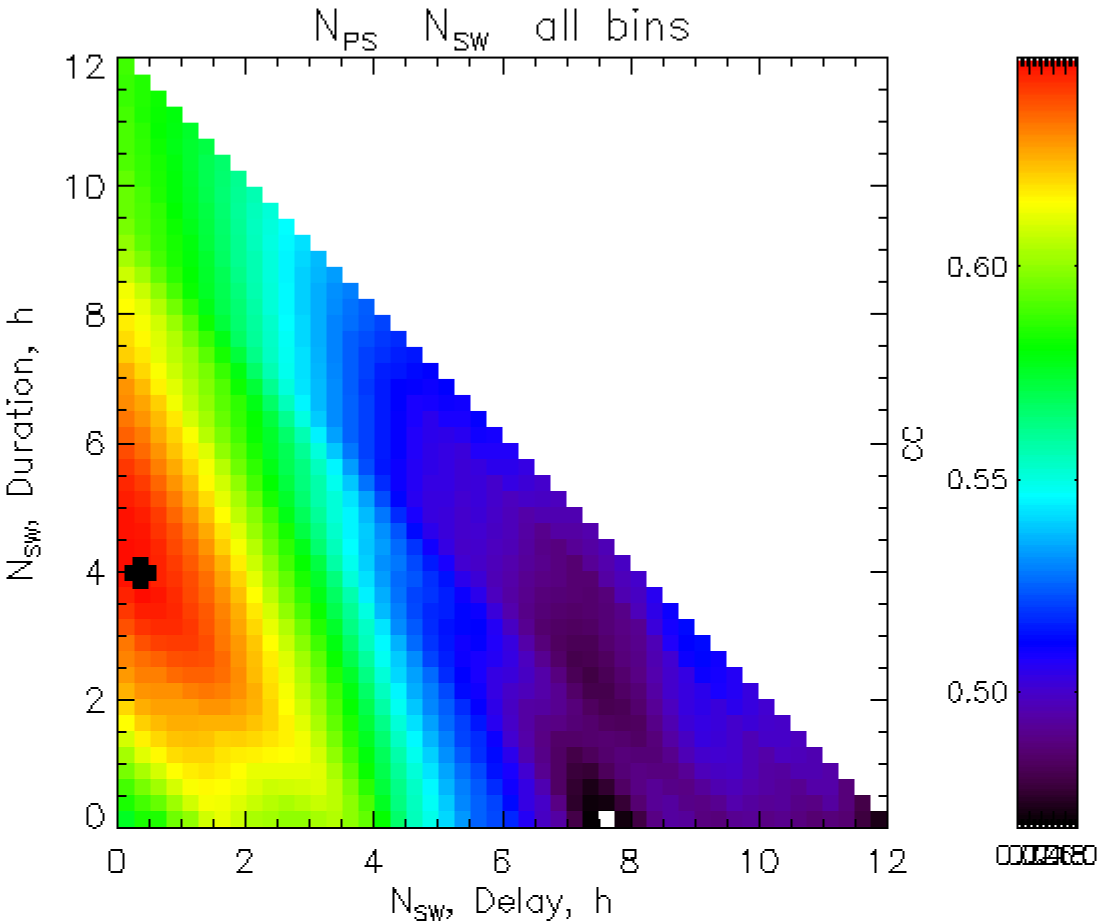
(1) V_{SW}, solar wind velocity

(2) IMF B_S, IMF southward comp.

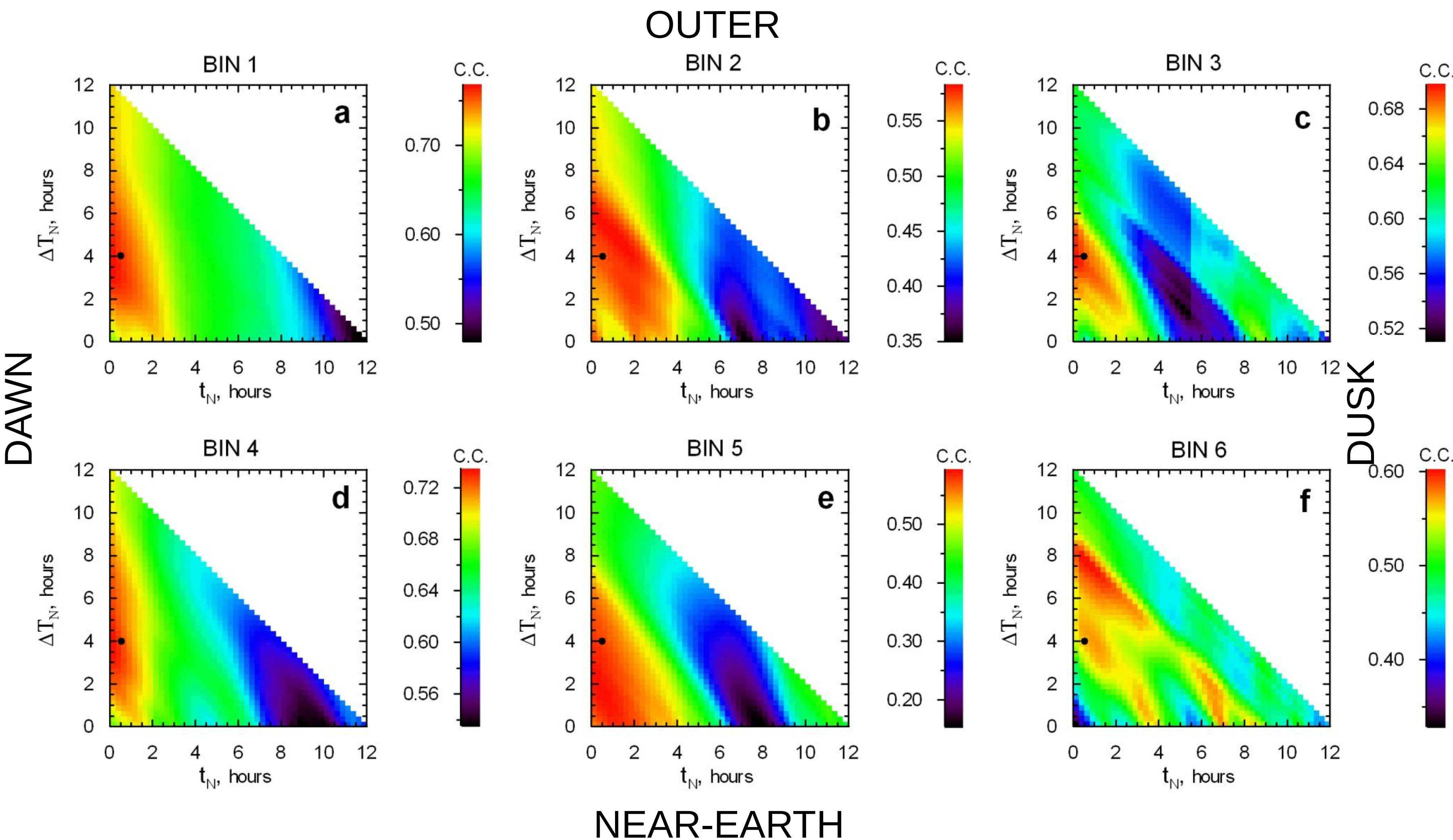
(3) IMF B_N, IMF northward comp.



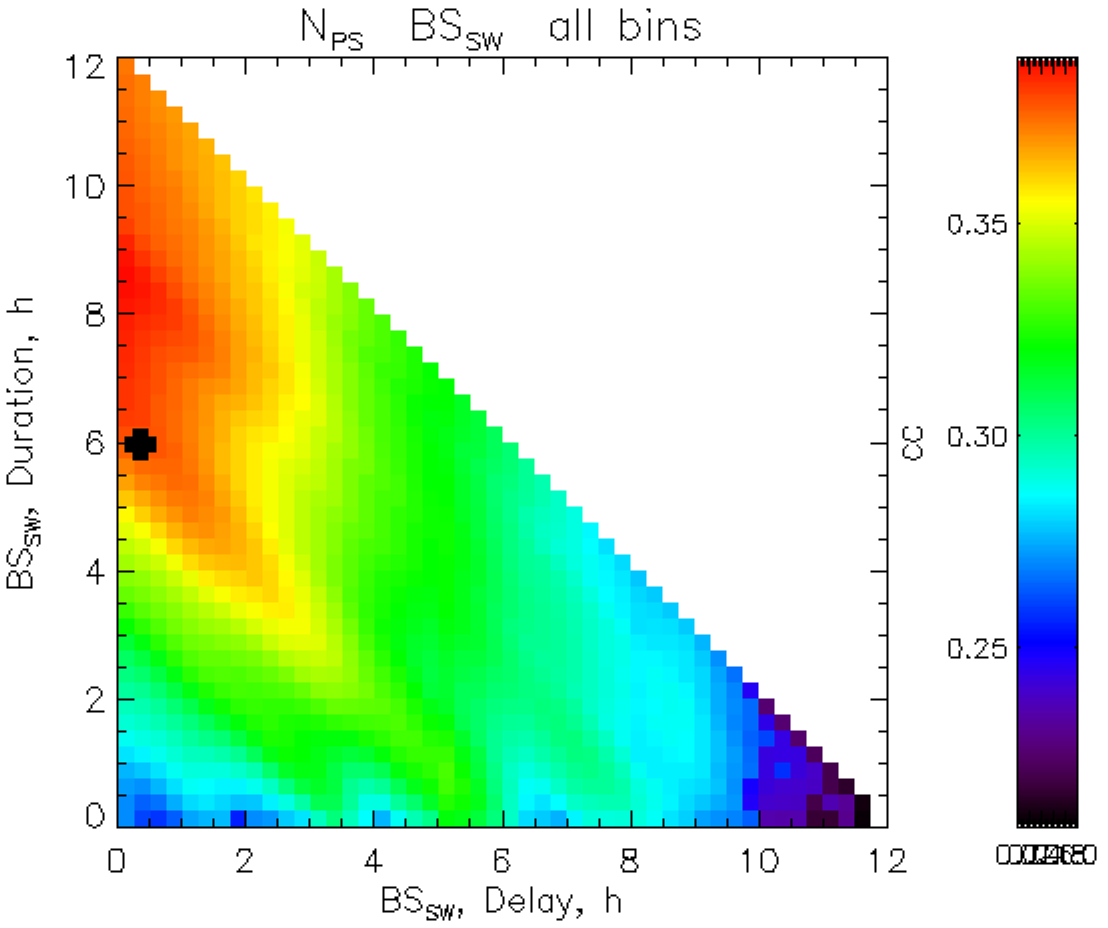
Correlation between plasma sheet **density** and **solar wind proton density**



Correlation between plasma sheet **density** and **solar wind proton density**



Correlation between plasma sheet **density** and **IMF southward component**



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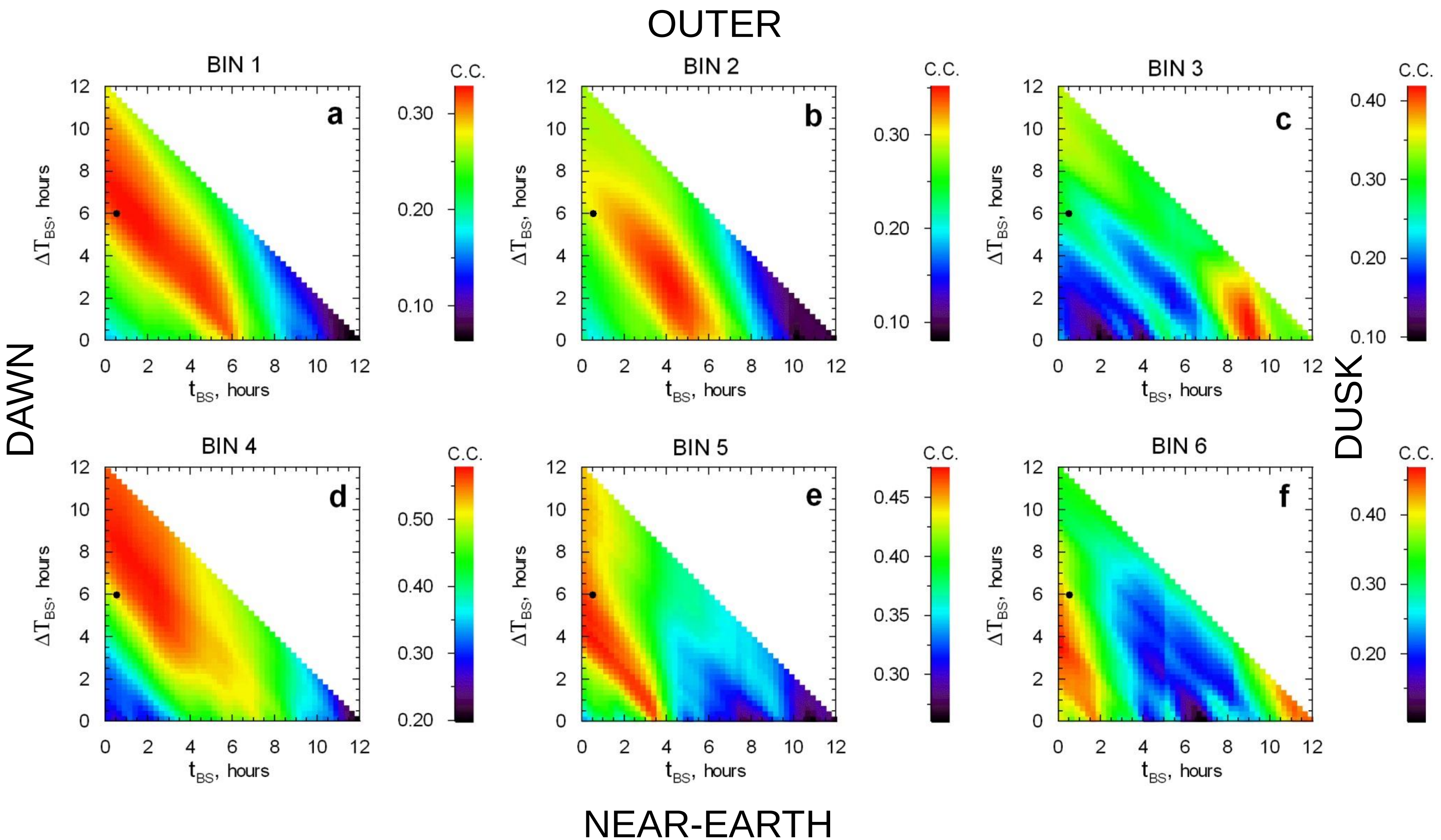
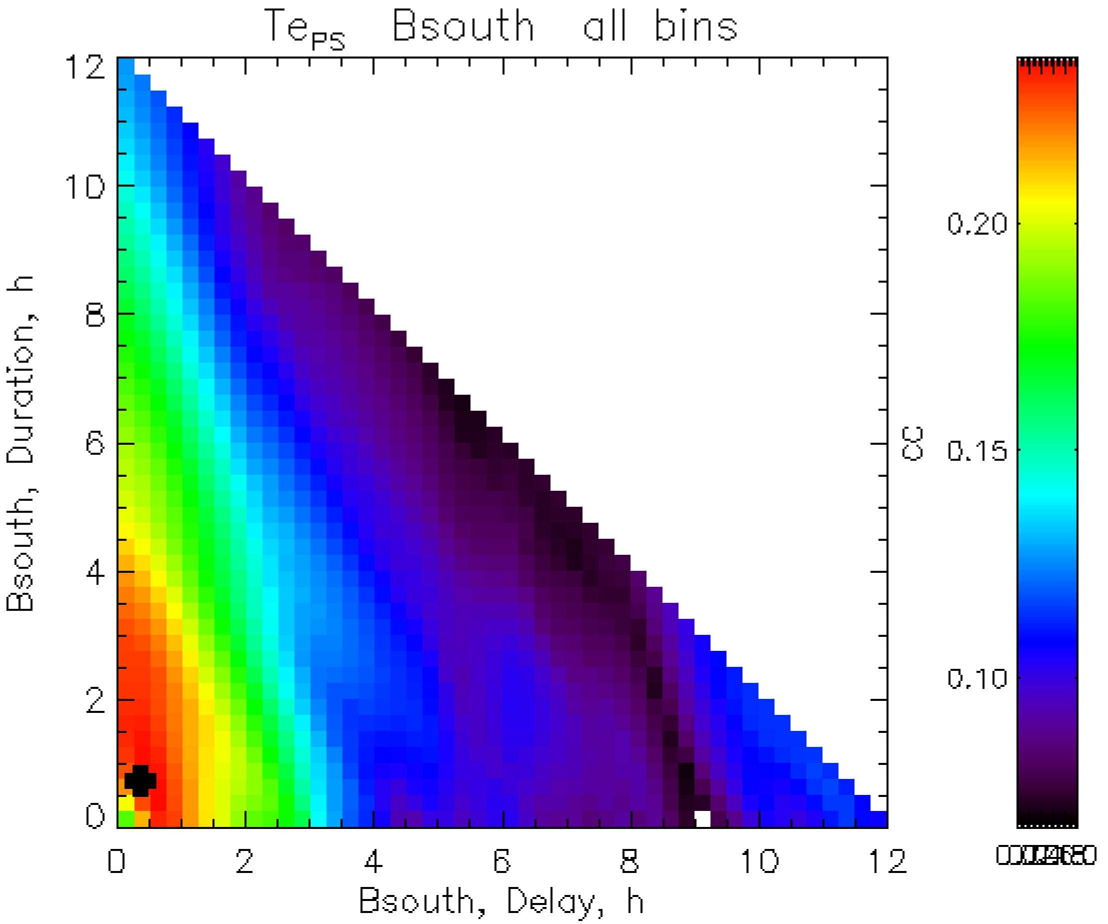
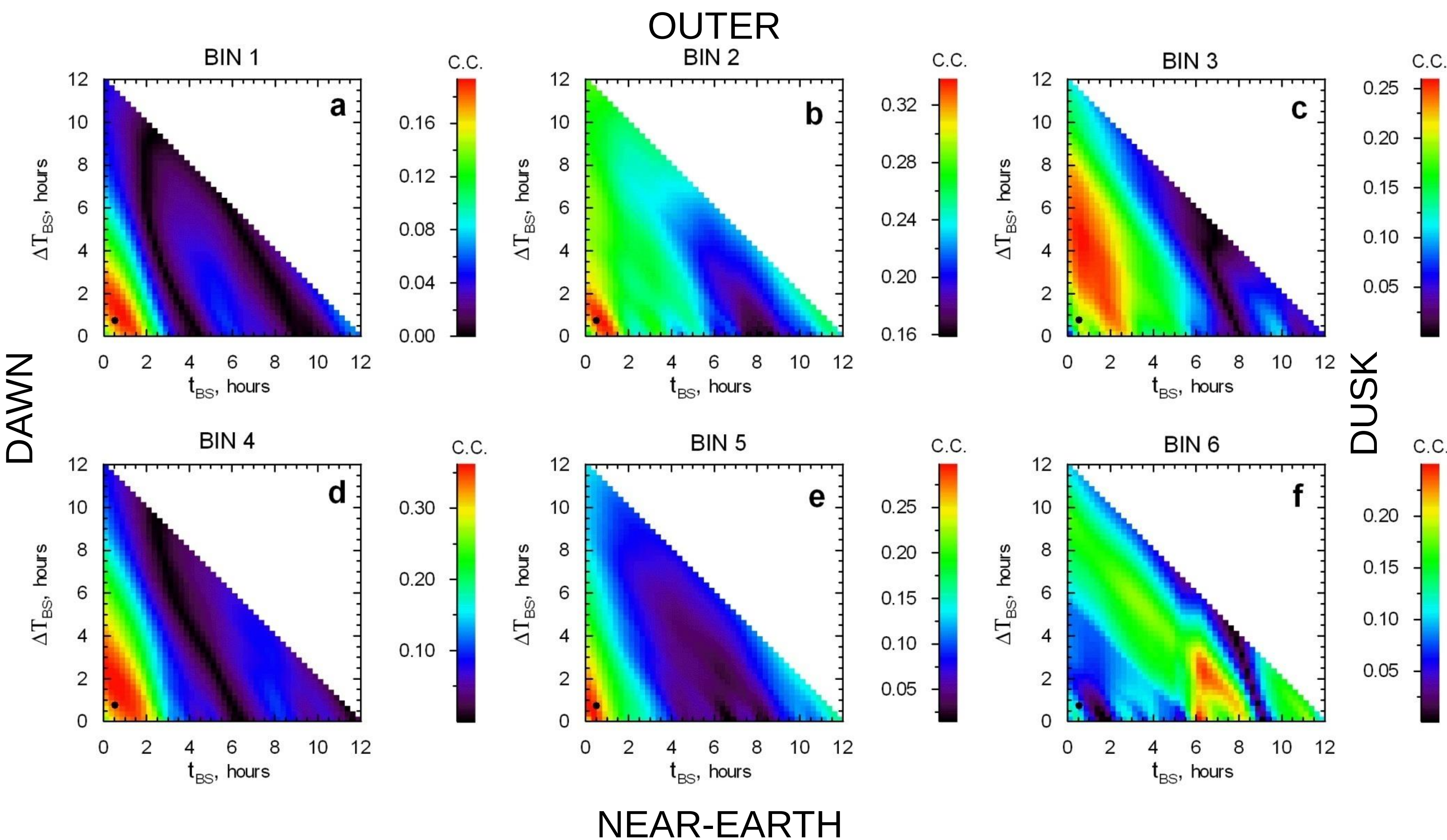


Correlation between plasma sheet **electron temperature** and **IMF southward component**



Correlation between plasma sheet **electron temperature** and **IMF southward component**



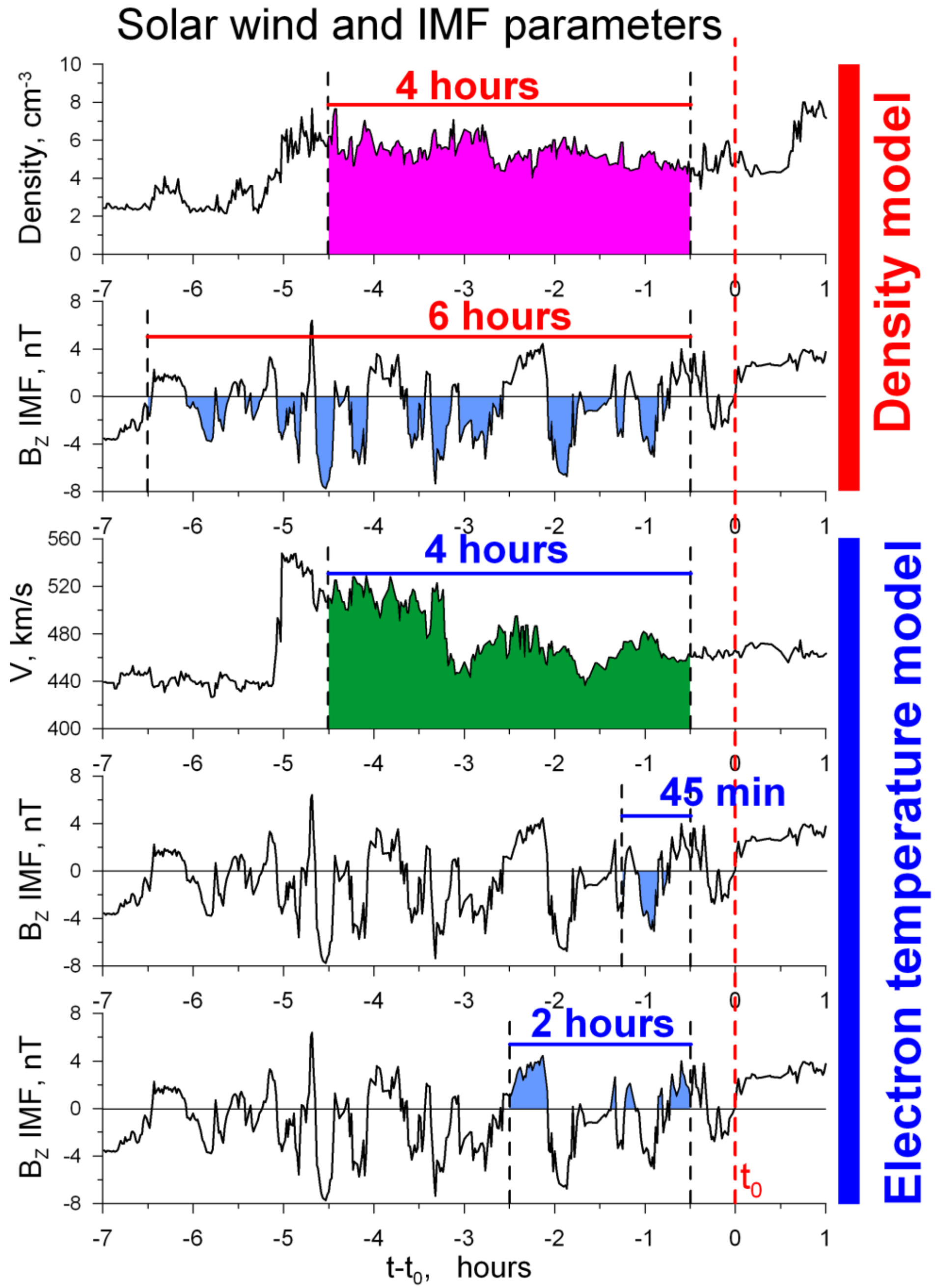
C.C.= 0.64

C.C.= 0.38

C.C.= 0.51

C.C.= 0.24

C.C.= 0.33



Analytical models:

$$P^{PS} = G_0(r,\phi) + \sum_j G_j(r,\phi) \cdot P_j^{SW}$$

$$G(r,\phi) = c_1 + c_2 r + c_3\phi + c_4\phi^2 + c_5 r\phi + c_6 r\phi^2$$

18 coefficients for N_e model, 24 coefficients for T_e model

Correlation coefficients between the data and model predictions

Density model: **0.83**

Temperature model: **0.73** **Reference coefficients**

Simplification

We seek for a minimal set of terms which still provide good model quality

After this set is found, we introduce non-linear dependence

Resulting correlation coefficients are:

Density model: **0.82** 7 coefficients

Temperature model: **0.75** 9 coefficients

Final model equations

Electron density model: 7 coefficients

$$N_e = 1.23 - 1.01 \cdot r + 0.874 \cdot r\phi^2 - 0.82 \cdot \phi^2$$

positive → $$+0.392 \cdot N_{SW}$$

positive → $$\boxed{+(0.521 - 0.474 \cdot r)} \cdot B_S$$

Electron temperature model: 9 coefficients

$$T_e = [-0.0215 - 0.426 \cdot \phi$$

positive → $$\boxed{+0.874} \cdot V_{SW}$$

positive → $$\boxed{+(0.587 - 0.538 \cdot r\phi^2)} \cdot B_S^{0.32}$$

negative → $$\boxed{-0.489 \cdot r} \cdot B_N^{0.36}]^{2.31}$$

$$r = R / 10\,\mathrm{Re}$$

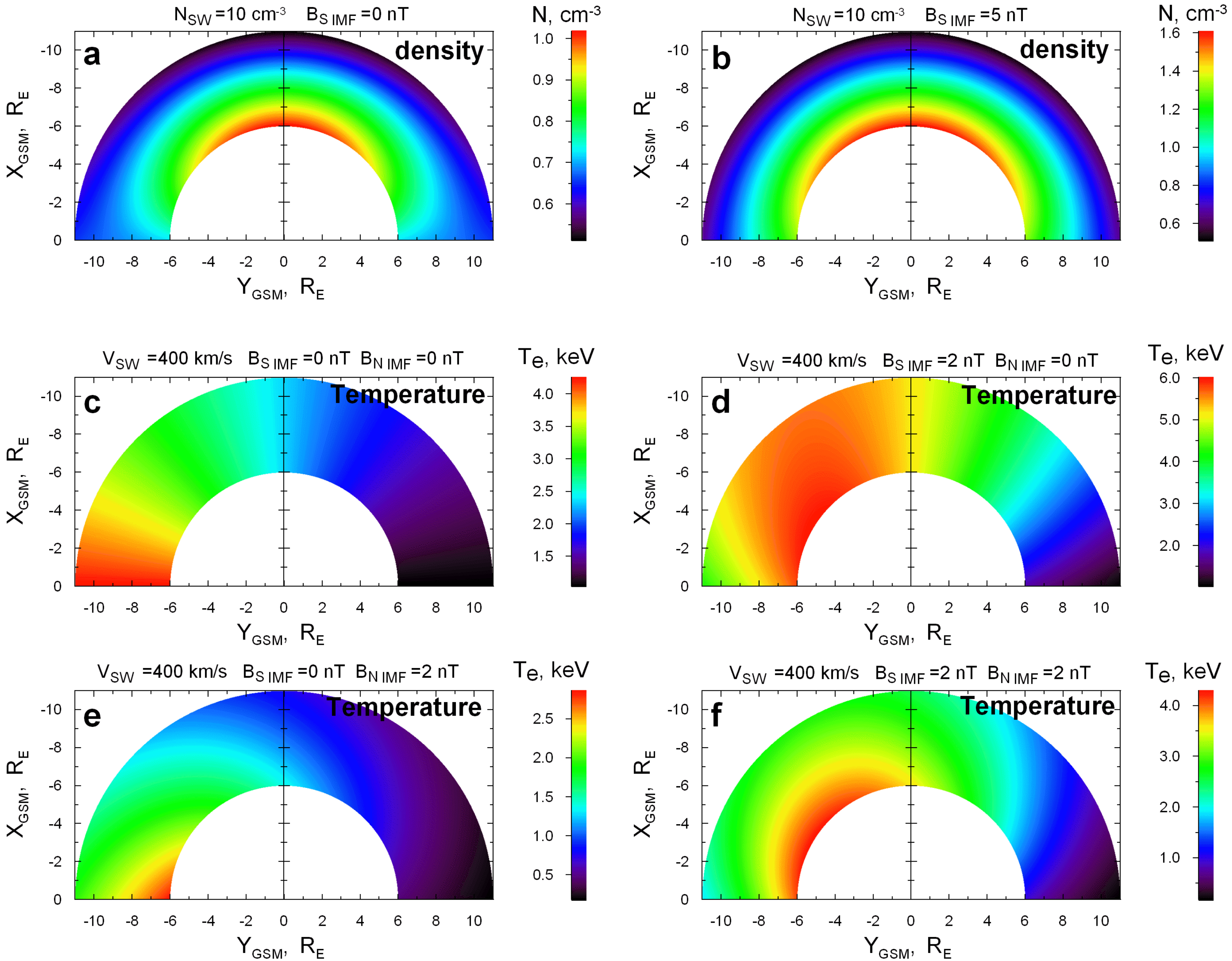
$$\phi = \arctan(-Y / X) / 90°$$

$$N_{SW} = \langle N_{SW} \rangle / 10cm^{-3}$$

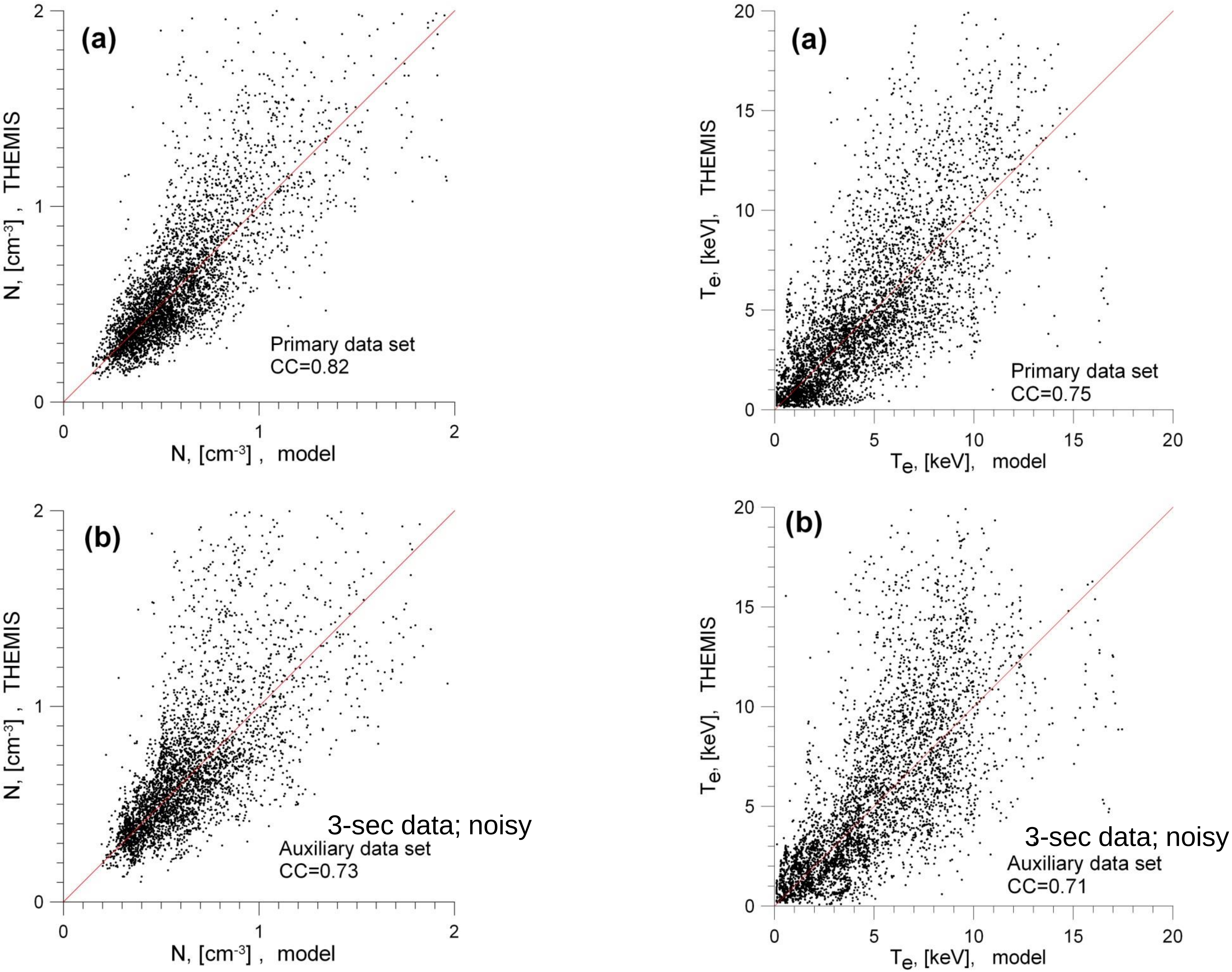
$$V_{SW} = \langle V_{SW} \rangle / 400km/s$$

$$B_S = \langle B_S^{IMF} \rangle / 2nT$$

$$B_N = \langle B_N^{IMF} \rangle / 2nT$$



N_SW =10 cm-3 B_S IMF =0 nT
density
a
N, cm-3
N_SW =10 cm-3 B_S IMF =5 nT
density
b
V_SW =400 km/s B_S IMF =0 nT B_N IMF =0 nT
Temperature
c
Te, keV
V_SW =400 km/s B_S IMF =2 nT B_N IMF =0 nT
Temperature
d
V_SW =400 km/s B_S IMF =0 nT B_N IMF =2 nT
Temperature
e
V_SW =400 km/s B_S IMF =2 nT B_N IMF =2 nT
Temperature
f
X_GSM, R_E
Y_GSM, R_E


(a)
N, [cm-3] , THEMIS
N, [cm-3] , model
Primary data set
CC=0.82
(a)
Te, [keV], THEMIS
Te, [keV], model
Primary data set
CC=0.75
(b)
N, [cm-3] , THEMIS
N, [cm-3] , model
3-sec data; noisy
Auxiliary data set
CC=0.73
(b)
Te, [keV], THEMIS
Te, [keV], model
3-sec data; noisy
Auxiliary data set
CC=0.71

Conclusions

- The empirical models of the plasma sheet T_e and N_e at r=6-11Re have been constructed.

- The models are based on ~ 400 hours of THEMIS measurements during geomagnetic storms

- For given location in the equatorial plane, the models output the plasma sheet T_e and N_e as a function of time-integrated solar wind and IMF parameters.

- The models show very good performance

Density:	C.C.=0.82;	RMS = 0.23 cm^{-3}
Temperature:	C.C.=0.75;	RMS = 2.6 keV

For the model description see *Dubyagin et al.*, JGR, 2016
The model codes and subroutines for the input parameter computation are given in supplemental materials.

Table 7. Characteristics of the Empirical Models' Quality

	Bin Index							
	All	1	2	3	4	5	6	
C.C.	0.82	0.77	0.73	0.70	0.84	0.73	0.72	
RMS (cm⁻3)	0.23	0.21	0.16	0.17	0.28	0.29	0.32	Ne
MAD (cm⁻3)	0.15	0.13	0.11	0.13	0.20	0.22	0.23	
C.C.	0.75	0.72	0.72	0.65	0.79	0.75	0.54	
RMS (keV)	2.6	2.5	3.1	2.0	2.4	2.9	2.3	Te
MAD (keV)	1.8	1.8	2.1	1.3	1.8	2.1	1.7	

[a]The first to third rows are for the electron density model, and the fourth to sixth rows are for the temperature model.

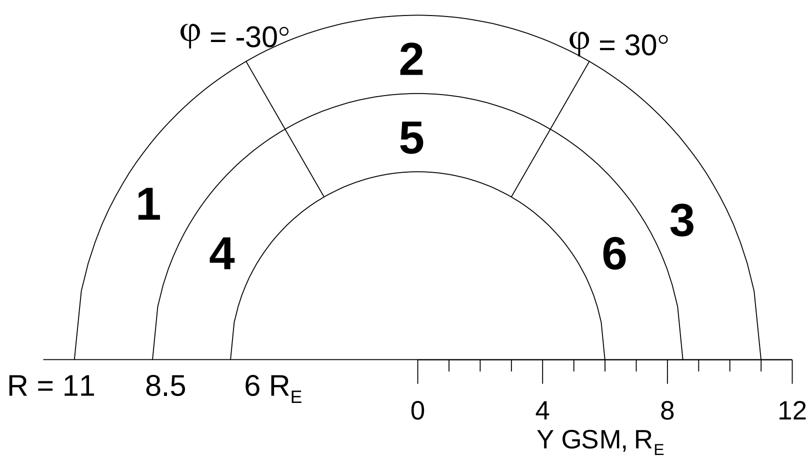


Table 8. The Same as Table 7 but for Comparison With Auxiliary Data Set

	Bin Index						
	All	1	2	3	4	5	6
#	12,171	5,220	1,211	1,069	2,922	1,014	689
C.C.	0.73	0.61	0.70	0.70	0.63	0.79	0.80
RMS (cm−3)	0.28	0.27	0.18	0.19	0.34	0.32	0.28
MAD (cm−3)	0.19	0.16	0.12	0.14	0.25	0.23	0.21
C.C.	0.71	0.75	0.65	0.82	0.72	0.67	0.57
RMS (keV)	3.1	2.4	3.6	3.7	2.9	4.3	4.2
MAD (keV)	2.2	1.8	2.5	2.2	2.2	3.0	3.0

[a]In addition, a number of data records for every bin is given in the first row.

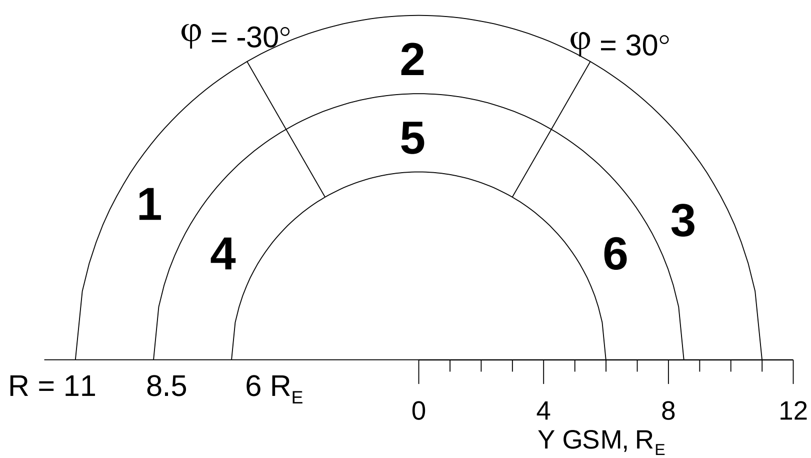


Table 3. Correlations of the Plasma Sheet Electron Density With the Solar Wind Parameters[a]

	Bin Index					
	1	2	3	4	5	6
N_{SW}	0.71	0.54	0.60	0.69	0.57	0.39
IMF B_S	0.18	0.20	0.16	0.28	0.38	0.36
IMF B_N	0.24	0.33	0.35	0.16	0.13	0.08
N_{SW}	0.77	0.58	0.70	0.73	0.59	0.60
IMF B_S	0.33	0.35	0.42	0.58	0.48	0.47
IMF B_N	0.28	0.35	0.46	0.18	0.20	0.22

[a]The first to third rows are for instant values $t_0 - 45$ min, and the fourth to sixth rows show best correlations found for all lags and durations of averaging.

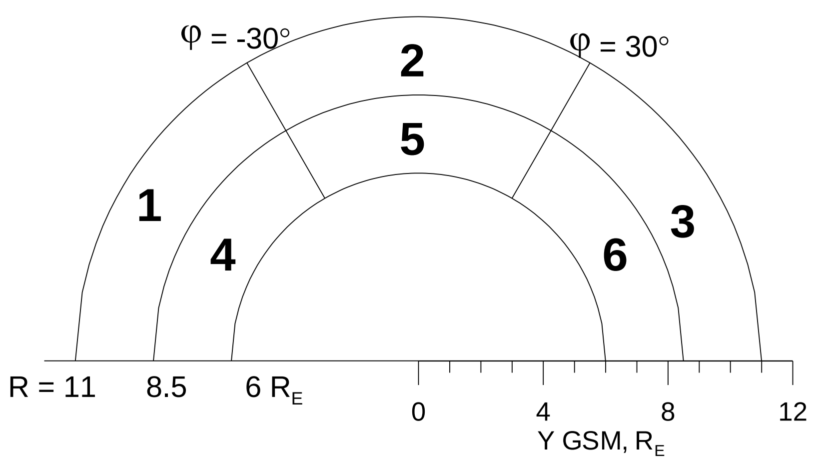


Table 4. Correlations of the Plasma Sheet Electron Temperature With the Solar Wind Parameters

	Bin Index					
	1	2	3	4	5	6
V_{SW}	0.59	0.63	0.28	0.59	0.59	0.31
IMF B_S	0.17	0.32	0.19	0.32	0.28	0.12
IMF B_N	−0.36	−0.29	−0.17	−0.42	−0.38	−0.23
V_{SW}	0.60	0.65	0.40	0.61	0.60	0.37
IMF B_S	0.19	0.34	0.26	0.36	0.30	0.25
IMF B_N	−0.42	−0.31	−0.25	−0.53	−0.39	−0.32

[a] The first to third rows are for instant values $t_0 - 45$ min, and the fourth to sixth rows show best correlations found for all lags and durations of averaging.

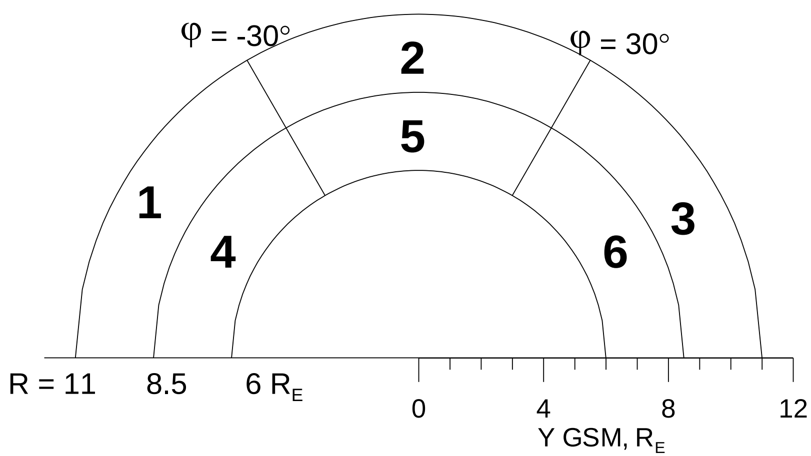


Table 6. Empirical Model Parameters

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
Density	1.23	−1.01	0.874	−0.820	0.392	0.521	−0.474		
Temperature	−0.0215	−0.426	1.47	0.587	−0.538	−0.489	0.32	0.36	2.31
Density[a]	1.01	−0.747	0.303	−0.248	0.362	0.498	−0.474		
Temperature[a]	−0.0922	−0.390	1.64	0.767	−1.02	−0.395	0.26	0.52	2.16

[a]Model coefficients obtained by fitting the model to the auxiliary data set.

$$N_{ps} = A_1 + A_2 R^* + A_3 \phi^{*2} R^* + A_4 \phi^{*2} + A_5 N^*_{sw} + (A_6 + A_7 R^*) B^*_S,$$

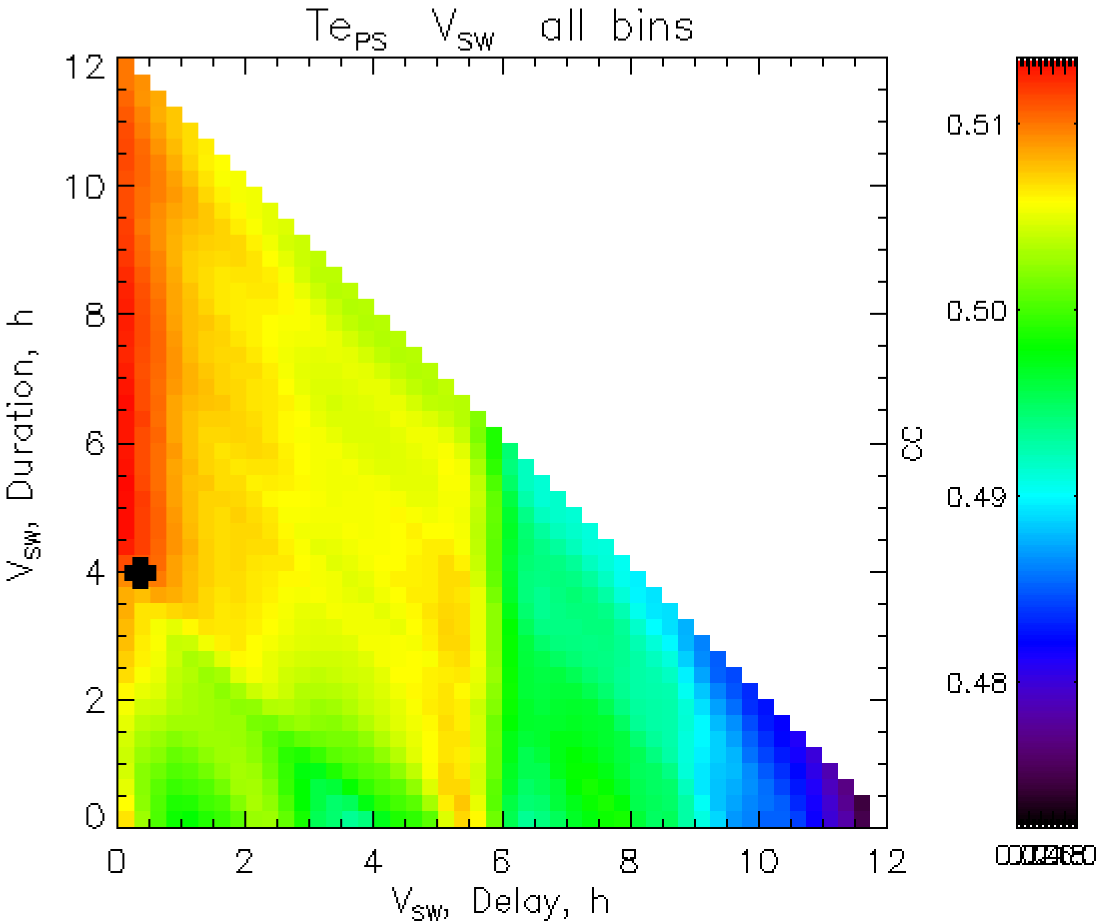
$$T_{ps} = \Big[A_1 + A_2 \phi^* + A_3 V^*_{sw} + (A_4 + A_5 \phi^{*2} R^*) B_S^{*A_7} + A_6 R^* B_N^{*A_8}\Big]^{A_9},$$

''

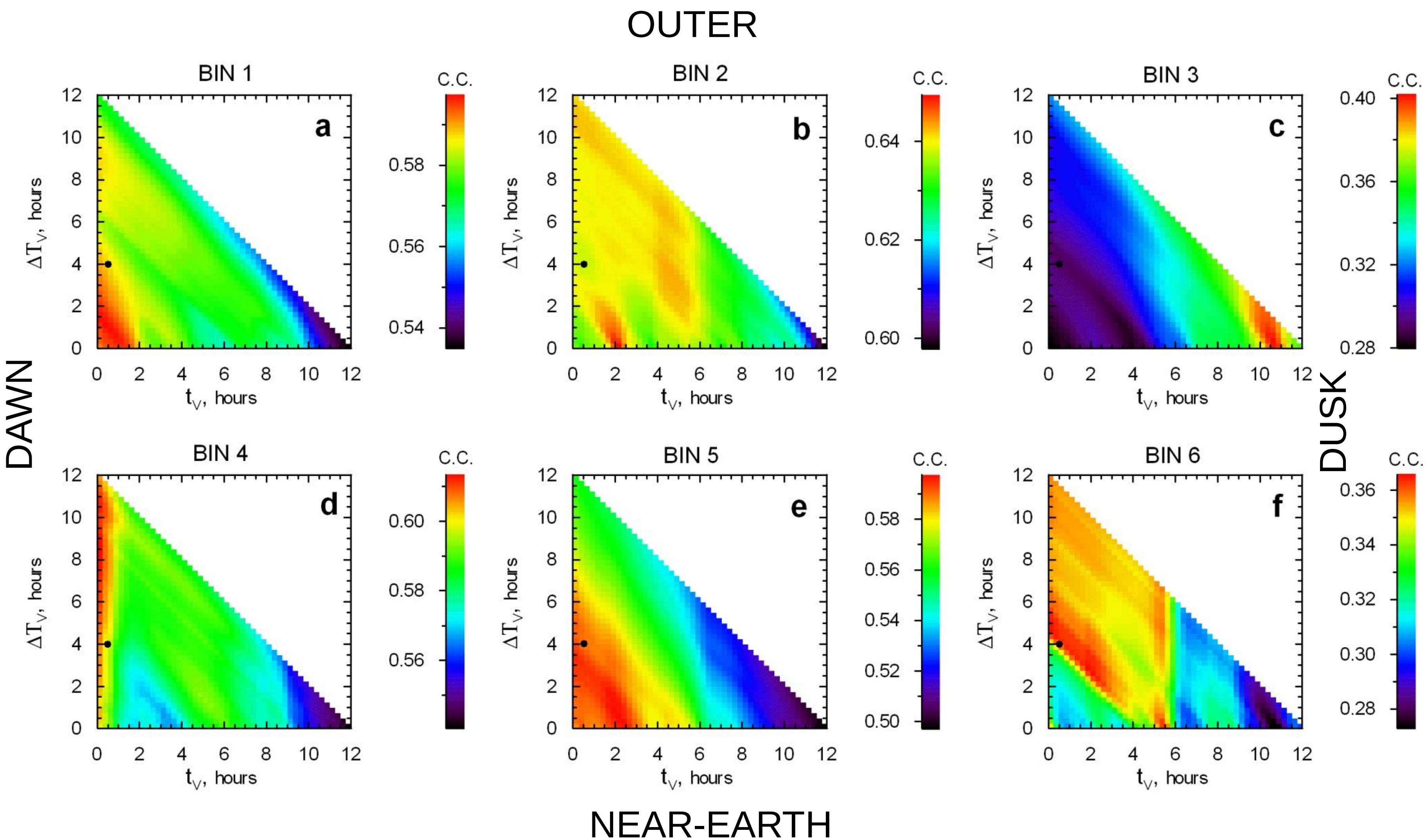
$$\mathrm{ERR} = \sum_j W \cdot |T_j^{\mathrm{THM}} - T_j^{\mathrm{model}}| \,.$$

: W is a linear function of T_j^{THM} changing from 1 at $T_j^{\mathrm{THM}} = 0$ to 1.5 at $T_j^{\mathrm{THM}} = 22$ keV.

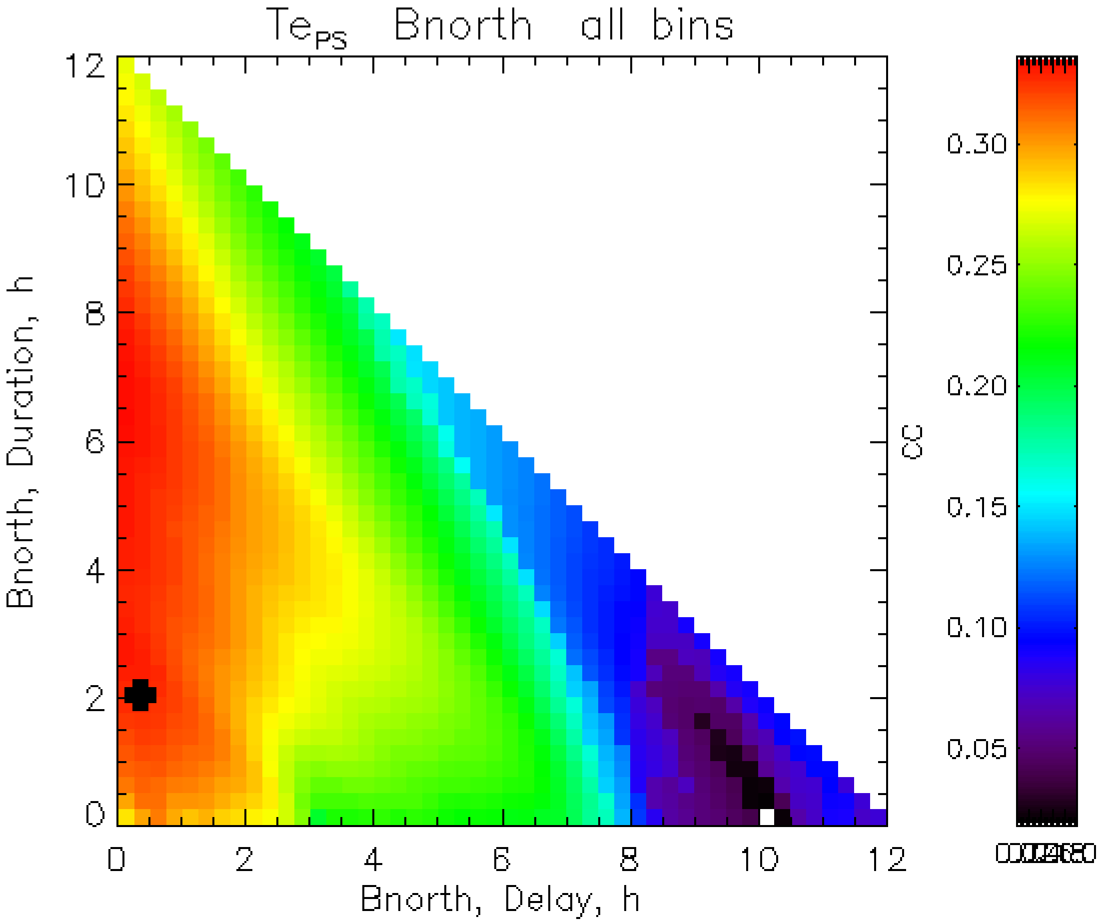
Correlation between plasma sheet **electron temperature** and **solar wind velocity**



Correlation between plasma sheet **electron temperature** and **solar wind velocity**



Correlation between plasma sheet **electron temperature** and **IMF northward component**



Correlation between plasma sheet **electron temperature** and **IMF northward component**