

An empirical model of the global distribution of plasmaspheric hiss based on Van Allen Probes EMFISIS measurements

JingZhi Wang¹, Qi Zhu¹, XuDong Gu^{1*}, Song Fu^{1*}, JianGuang Guo², XiaoXin Zhang², Juan Yi¹, YingJie Guo¹, BinBin Ni¹, and Zheng Xiang¹

¹Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430079, China;

²Key Laboratory of Space Weather, National Center for Space Weather, China Meteorological Administration, Beijing 100081, China

Key Points:

- The empirical model is a third-order polynomial function of L -shell, magnetic local time (MLT), magnetic latitude (MLAT), and AE^*
- The model can perform the hiss amplitude distribution by L /MLT and L /MLAT
- All data are based on Van Allen Probes EMFISIS measurements

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Abstract: Using wave measurements from the EMFISIS instrument onboard Van Allen Probes, we investigate statistically the spatial distributions of the intensity of plasmaspheric hiss waves. To reproduce these empirical results, we establish a fitting model that is a third-order polynomial function of L -shell, magnetic local time (MLT), magnetic latitude (MLAT), and AE^* . Quantitative comparisons indicate that the model's fitting functions can reflect favorably the major empirical features of the global distribution of hiss wave intensity, including substorm dependence and the MLT asymmetry. Our results therefore provide a useful analytic model that can be readily employed in future simulations of global radiation belt electron dynamics under the impact of plasmaspheric hiss waves in geospace.

Keywords: hiss; Van Allen Probes; global model

1. Introduction

Plasmaspheric hiss is a broadband incoherent whistler mode emission with frequencies ranging from ~ 20 Hz to ~ 2 kHz that is observed predominantly inside the plasmasphere or high density plumes (Thorne et al., 1973, 1979; Meredith et al., 2004; Li W et al., 2013, 2015a, b; Ni BB et al., 2014; Shi R et al., 2017). It can persist under quiet conditions; its fluctuations are positively correlated with the level of solar activity (Smith et al., 1974; Thorne et al., 1973, 1974). Broadband amplitudes of plasmaspheric hiss range from a few pT to as high as 100 pT (Thorne et al., 1973; Smith et al., 1974; Meredith et al., 2004). Plasmaspheric hiss is mainly observed at a broad range of wave normal angle, e.g., its propagation near the geomagnetic equator is predominantly field-aligned, but oblique at higher latitudes (Santolík et al., 2001; Bortnik et al., 2008).

It has been well recognized that electron scattering by plasmaspheric hiss acts as a dominant contributor to formation of the slot region, which separates the radiation belts into inner ($1.2 < L < 2$) and outer ($3 < L < 7$) parts (Lyons et al., 1972; Lyons

and Thorne, 1973; Albert, 1994; Abel and Thorne, 1998a, b; Meredith et al., 2004, 2006a, b). Resonant interactions with plasmaspheric hiss result in electron scattering losses with decay time scales varying from less than 1 hour to tens or hundreds of days. Decay times are closely dependent on electron energy, ambient magnetic field, and plasma density, as well as on wave amplitude, spectral intensity, and wave normal angle (WNA) distribution of the hiss waves as a function of spatial location and geomagnetic activity level (Meredith et al., 2007; Ni BB et al., 2014; Yu J et al., 2017). As reported in Summers et al. (2007a, b), the pitch angle diffusion coefficient of resonant electrons in quasi-linear formalisms is proportional to the wave amplitude. Thus, the development of a reliable global model of hiss wave amplitude is essential to facilitate quantification of hiss-induced electron scattering rates and resultant global variations of radiation belt electron distribution.

A number of empirical models of hiss wave global distribution have been constructed in previous studies (Meredith et al., 2004; Kim et al., 2015; Li et al., 2015b). Data from the Combined Release and Radiation Effect Satellite (CRRES) are utilized to investigate the features of plasma waves. Meredith et al. (2004) presented elaborate global maps of hiss wave intensity and described its distribution features. Orlova et al. (2014) produced empirical quadratic fittings of B_w^2 as a function of Kp , L , and geomagnetic latitude (λ) for the daytime and nighttime sectors respectively. However,

Correspondence to: X. D. Gu, guxudong@whu.edu.cn

S. Fu, fusion@whu.edu.cn

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the CRRES wave instrument has limitations in space and frequency band, in particular it records only electric field data; accordingly, some important wave information such as magnetic field spectral intensity was estimated, based on theoretical assumptions. Characteristics of whistler mode waves have also been analyzed by Agapitov et al. (2013) with Cluster data, which separate chorus from hiss merely by f_{ce} (the electron cyclotron frequency), i.e., chorus frequency above $0.1f_{ce}$ and hiss below $0.1f_{ce}$, though their frequencies may actually overlap. Subsequently Agapitov et al. (2014) parameterized the hiss wave activity at $L < 2$ based on Akebono spacecraft observations. In addition, combined observations of Cluster (Agapitov et al., 2013) and Polar (Tsurutani et al., 2015) showed that hiss can be widely distributed over the magnetic latitude, extending to $\lambda > 45^\circ$.

Recently, using data from Van Allen Probes, Spasojevic et al. (2015) and Yu J et al. (2017) constructed one-dimensional fitting models of hiss wave amplitude as a function of AE , L , MLT , and Kp , L , MLT , respectively. Highlighting the dependence of hiss amplitude on single variables, those studies focus on the fluctuations of the fitting curves associated with each variable in their hypothetical formulae and do not reproduce the observed latitudinal variations of hiss wave amplitude. Since the dependence on $MLAT$ cannot be neglected in accurate predictions of hiss amplitude, as previous studies have done, the present investigation considers the combined effects of L , MLT , $MLAT$, and AE^* , and intends to establish a more comprehensive empirical model of plasmaspheric hiss amplitude as a function of these four input parameters.

2. Data and Methodology

Van Allen Probes were launched on September 8, 2012 with perigee of $\sim 1.1R_E$ (radius of the Earth), apogee of $\sim 5.8R_E$, inclination of 10° , and an orbital period of ~ 9 hours. Equipped with identical electromagnetic detectors, the EMFISIS instruments onboard Van Allen Probes can acquire high quality measurement of whistler-mode waves in the inner magnetosphere (Kletzing et al., 2013). The waveform receiver (WFR) on EMFISIS provides wave power spectral densities ranging from 10 Hz–12 kHz with a temporal resolution of 6 s. The high frequency receiver (HFR) records electric spectral information between 10 and 400 kHz, in which the traces of upper hybrid resonance (UHR) frequency can be used to estimate the ambient plasma density (Mosier et al., 1973) and identify the location of the plasmopause that separates the regions outside and inside the plasmasphere (e.g., He F et al., 2011, 2013, 2016, 2017; Katus et al., 2015; Verbanac et al., 2015; Zhang XX et al., 2017a, b).

According to the wave characteristics of hiss emissions, in this study we identify a hiss event with the ellipticity > 0.7 (i.e., right-hand polarized) and the frequency band within 10–2000 Hz in the

plasmasphere. By doing so, we distinguish the hiss waves from chorus waves outside the plasmasphere and from magnetosonic waves with nearly linear polarization. Subsequently, we integrate the wave spectral intensity in the determined frequency band to calculate the wave amplitude (B_w). In our following analysis we concentrate on the hiss emissions with $B_w \geq 5$ pT.

The adopted database consists of observations made during the period from September 8, 2012 to June 30, 2017: L -shell (L), magnetic local time (MLT), magnetic latitude ($MLAT$), AE^* (averaged value of the AE index in the previous hour), and hiss wave amplitude (B_w) with temporal resolution of 6 s. We then implement two methods to construct our empirical global model of hiss wave amplitude. In each method, we divide the entire database data into two groups, i.e., the training group and the test group. The training group is used as the baseline to obtain the fitting coefficients in the regression, while the test group is regarded as a comparison to examine the model's performance and verify its reliability.

As tabulated in Table 1, for Method #1, data in first three years are selected as the training group (Database 1) and the remaining datasets are reserved as the test group (Database 2). For Method #2, we divide them in another way: data collected during odd-number days are set as the training group (Database 3), and the others are the test group (Database 4). Furthermore, we divide each Database (1–4) into 12 sub-groups in terms of AE^* and MLT , to take into account the geomagnetic effect and MLT variation. Hence, we rank the AE^* values into three geomagnetic levels (quiet, $AE^* < 100$ nT; moderate, $100 \text{ nT} \leq AE^* \leq 300$ nT; active, $AE^* > 300$ nT) and classify all the $MLTs$ into four sectors (dayside, 09–15; duskside, 15–21; nightside, 21–03; dawnside, 03–09). Correspondingly, twelve groups of fitted parameters need to be derived from regression of these training groups, and we then examine the feasibility of the resulting fitting functions through self-consistency and verification with the test groups. To check differences between the model and observations, we define the variable, R_d , given as $\frac{|w_{obs} - w_{mod}|}{w_{obs}}$, where w_{obs} is the observed hiss wave amplitude and w_{mod} is the model result, as a criterion to evaluate our empirical model. Clearly, lower values of R_d represent higher similarity between observations and the model.

Taking L , MLT , $MLAT$, AE^* , and B_w as known quantities and $F(i, j, k, l)$ as unknown, we implement the fits of a third-order polynomial function as follows:

$$\log_{10}(B_w) = \sum_{i=0}^3 \sum_{j=0}^2 \sum_{k=0}^2 \sum_{l=0}^2 F(i, j, k, l) A^i B^j C^k D^l, \quad (1)$$

where the parameters A , B , C , and D are quantified as $L/10$, $MLT/24$, $MLAT/20$, and $AE^*/500$, respectively. Following previous studies of Spasojevic et al. (2015) and Yu et al., (2017), we set the

Table 1. Classification of each adopted database.

Type	Method #1	Method #2
Training group	Every day during the period of 2012/9/8–2015/9/8 (Database 1)	Odd-number days during the period of 2012/9/8–2017/6/30 (Database 3)
Test group	Every day during the period of 2015/9/9–2017/6/30 (Database 2)	Even-number days during the period of 2012/9/8–2017/6/30 (Database 4)

maximum values of i , j , k , and l as 3, 2, 2, and 2, respectively; consequently we have 108 coefficients for the fit to each training group.

3. Analysis Results

Based on the two methods described above, we do the fits for the training groups, compute the model results with the obtained polynomial fitting functions, and perform quantitative comparisons with the statistical observations of the test groups.

First, we follow Method #1 to establish the empirically analytic model of plasmaspheric hiss intensity, the results of which are shown in Figures 1–4. Figures 1 and 2 show the global distributions of time-averaged root-mean-square (RMS) hiss wave am-

plitudes in the equatorial plane and the meridian plane, at resolution of $0.5L \times 1\text{MLT}$ and $1^\circ \times 0.1L$, respectively, obtained using Database 1 (the period from 2012/9/8–2015/9/8), and comparisons between these statistical observations and results of the empirical model.

The first-row subplots in Figure 1 reveal that the hiss wave amplitude strengthens significantly when AE^* increases and that the waves on the dayside are much stronger than those at the nightside. Overall, hiss wave activity shows a strong dependence on L -shell, MLT, and geomagnetic level. Correspondingly, the second-row panels illustrate model results of hiss wave amplitude for the same time period as in Figures 1a–1c, obtained using the fitted three-order polynomial function (i.e., Equation (1)). It is evident

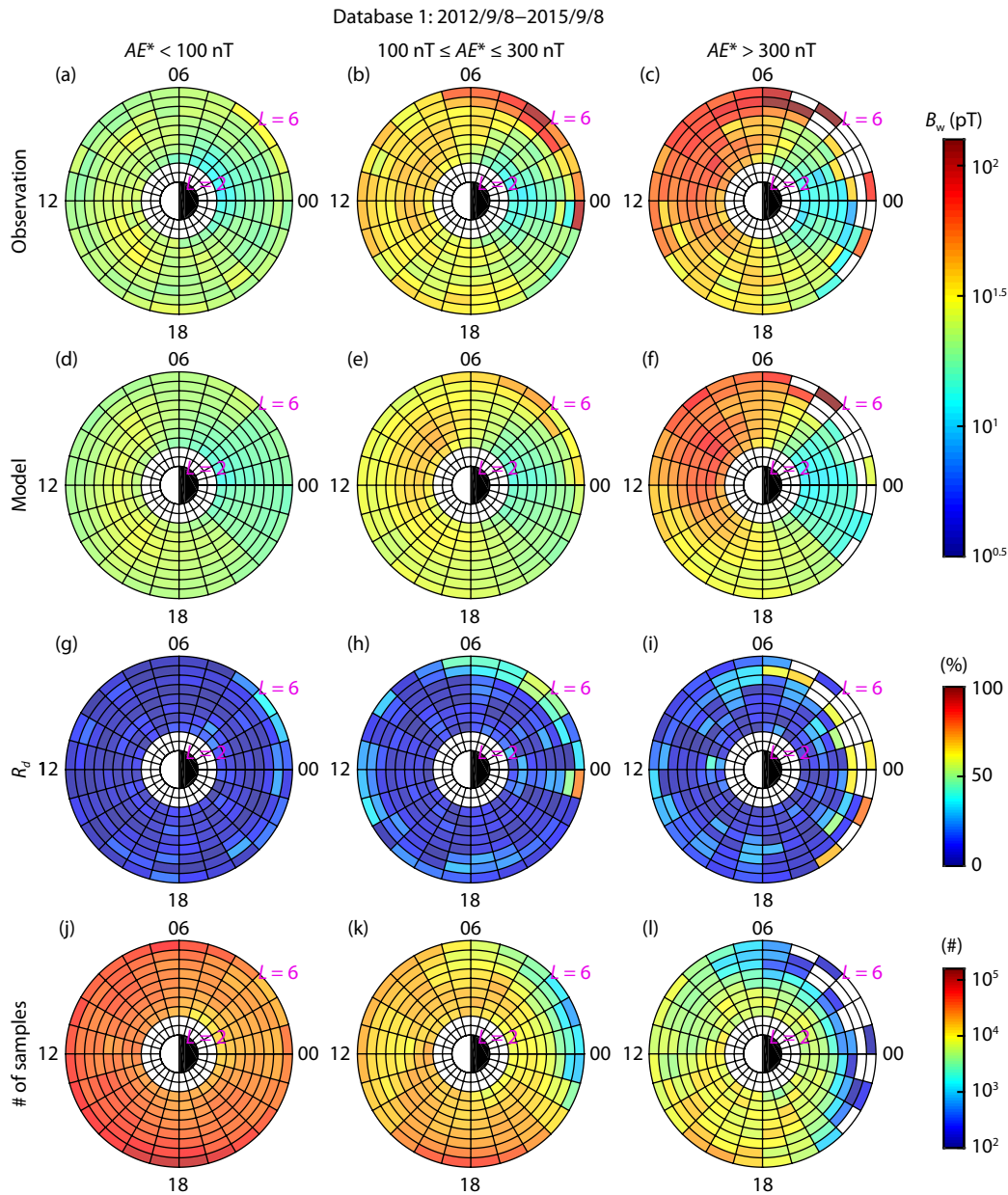


Figure 1. (a–c) Global L -MLT distribution of hiss wave amplitude from Van Allen Probe observations of Database 1; (d–f) self-consistent model results of Database 1; (g–i) relative differences (R_d) between them; (j–l) corresponding numbers of samples collected during quiet, moderate, and active times (left to right).

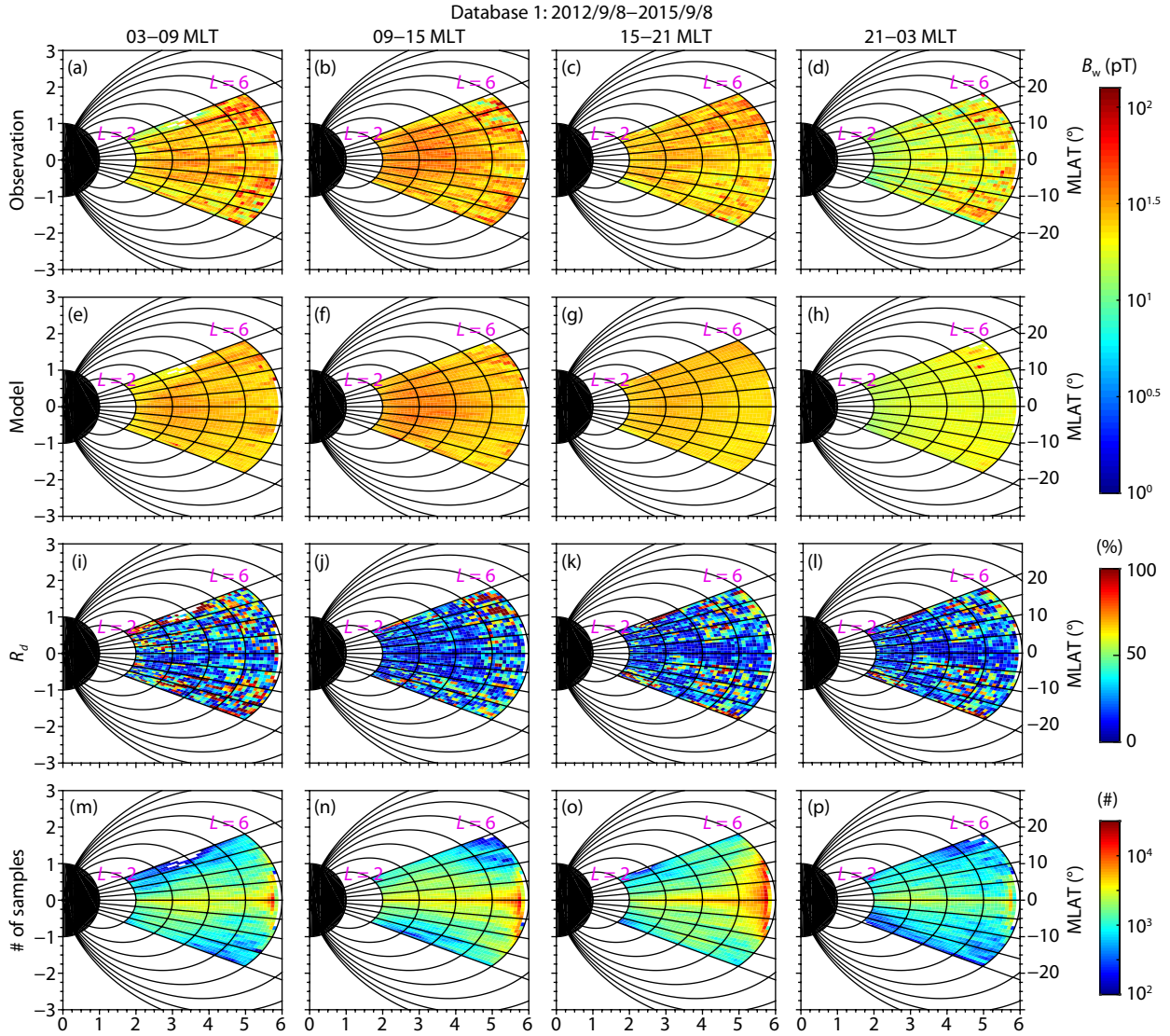


Figure 2. (a–d) Latitudinal L -MLAT distribution of hiss wave amplitude from observations in Database 1; (e–h) self-consistent model results of Database 1; (i–l) relative differences (R_d) between them; (m–p) corresponding numbers of samples during different MLT sectors (left to right).

that the fitted function reflects the major features of the observed global dynamics of plasmaspheric hiss. The relative differences (R_d) between the observations and model results are shown in Figures 1g–1i. It is clearly seen that during most bins the relative differences are less than 15%, though the differences are larger in some limited regions of $L = 4.5$ – 6 and MLT ~ 23 – 06 .

Figure 2 results are similar to those in Figure 1 but as a function of L and MLAT in the indicated four MLT sectors. It can be seen clearly that, besides its L -shell and MLT dependence, the hiss wave amplitude also depends on MLAT but in a less significant manner. Figures 2i–2l confirm that during most bins the relative differences between the observations and model results are less than 20%, showing good agreement between model and empirical data.

Figures 3–4 present Database 2 (the test data) results in the same format as Figures 1–2, to verify consistent model performance during periods exclusive to the training group.

While the wave observations are slightly different from those in

Database 1, the dominant trends are favorably similar. In order to validate the feasibility of the fitting function, we compare the observations from Database 2 (Figures 3a–3c) with the model results for the same period that are obtained using the empirically analytic function model as a function of L , MLT, MLAT, and AE^* derived using Database 1 (Figures 3d–3f). Apparently, large differences between the observational and model results occur especially during geomagnetically moderate and active times, showing that the value of R_d can be well above 1 in association with large deviation of the model results from the observations. In addition, it is distinct in Figure 4 that the model results become much less reliable compared to the observations, especially for the interval of MLT = 03–09. These discrepancies between model results and observations during the time period exclusive to the test group tell that the empirical model obtained using Method #1 has limitations that make it unsuited to the task of obtaining a global hiss wave distribution.

Accordingly, we adopt Method #2 to establish an empirical model of the global distributions of hiss intensity; that is, the data during

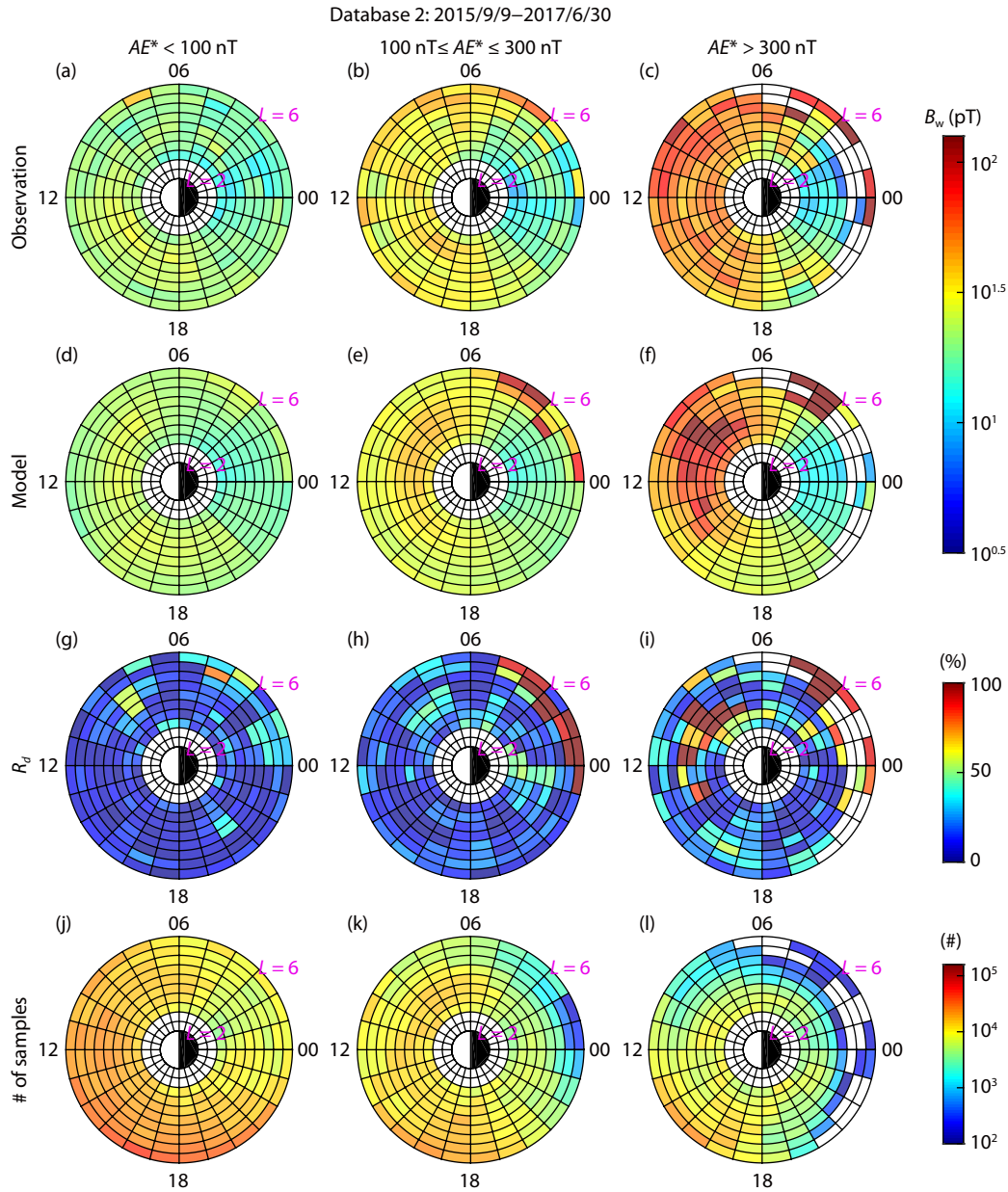


Figure 3. (a–c) Global L -MLT distribution of hiss wave amplitude from observations of Database 2; (d–f) model results calculated by Method #1 of Database 2; (g–i) relative differences (R_d) between them; (j–l) corresponding numbers of samples during quiet, moderate, and active times (left to right).

the odd-number days are set as the training group (Database 3) and used to acquire the fitting function $F(i, j, k, l)$, and the data during the even-number days are set as the test group to verify the model's performance.

First, we use Database 3 for the fits and self-consistency comparisons, the results of which are shown in Figures 5 and 6. Evidently, the fitting model results and the observations exhibit favorable agreement in most L -MLT bins (Figure 5), justifying the feasibility of the empirical model. While the differences between the observations and the model become relatively larger in the L -MLAT bins at high L shell, the majority of R_d -values are below $\sim 20\%$ (Figure 6), thereby confirming good performance of the model.

Again, to validate the performance of the fitting model obtained using Database 3 as the training group, we use Database 4 to apply the model and compare the model results with the observations, the results of which are shown in Figures 7 and 8.

Compared with the statistical observations (Figures 7a–7c), the model can reproduce well the global distribution of hiss wave amplitude including the MLT asymmetry and geomagnetic activity dependence (Figures 7d–7f). As shown in Figures 7g–7i, the relative differences (R_d) are $< 15\%$ for over 80% of L -MLT bins, justifying good performance of the fitting model, while the model becomes less feasible at high L -shells on the nightside, especially for active conditions with $AE^* > 300$ nT. In addition, the empirical model can reproduce well the major features of hiss wave amp-

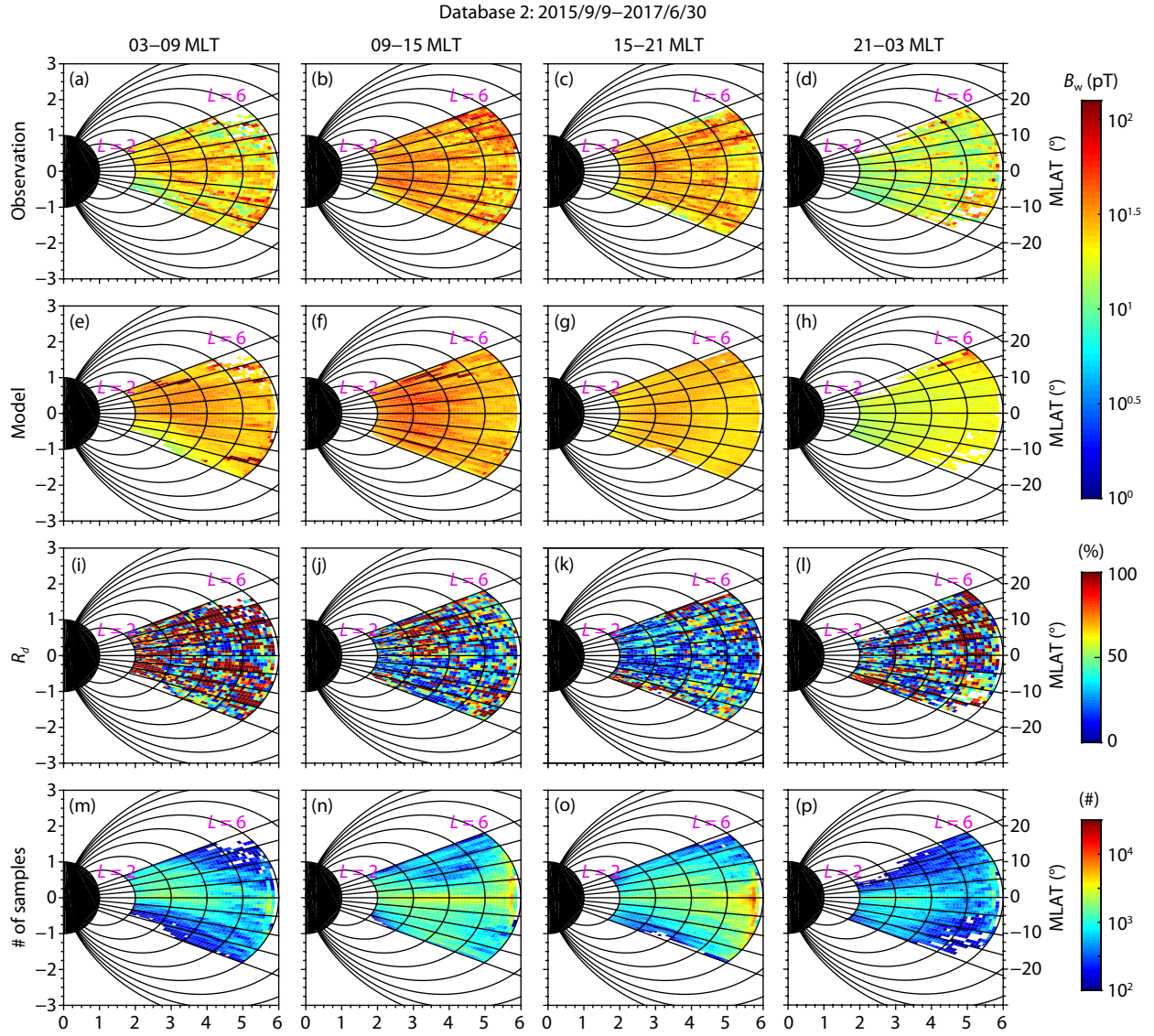


Figure 4. (a–d) Latitudinal L -MLAT distribution of hiss wave amplitude from observations in Database 2; (e–h) model results calculated by Method #1 of Database 2; (i–l) relative differences (R_d) between them; (m–p) corresponding numbers of samples during different MLT sectors (left to right).

litute distribution in the L -MLAT bins for different MLT intervals, as shown by the R_d -values < 20% in general (Figures 8i–8l).

Some discrepancies at higher latitudes may be attributed to hiss wave amplitude enhancements during geomagnetically disturbed periods, which, however, are difficult to be captured by the fits possible with third-order polynomial functions.

Overall, this study establishes an empirical model of the global distribution of hiss wave intensity by implementing third-order polynomial function fits to the long-term Van Allen Probes EMFISIS wave data, which is determined by Equation (1) and the polynomial coefficients tabulated in Tables S1–S12 in the Appendix for the four considered MLT sectors (i.e., 03–09, 09–15, 15–21, and 21–03) under three geomagnetic conditions (i.e., quiet-time: $AE^* < 100$ nT; moderate-time: $100 \text{ nT} \leq AE^* \leq 300$ nT; active-time: $AE^* > 300$ nT).

4. Concluding Remarks

In the present study, we have used approximately five years of Van Allen Probes EMFISIS wave data to analyze statistically the global distribution of plasmaspheric hiss intensity at $L = 2$ –6 under various conditions of geomagnetic activity. During quiet times or times of weak substorm activity ($AE^* < 100$ nT), the hiss wave amplitude distribution is not dependent on MLT. However, when substorm activity intensifies, the hiss wave amplitude distribution is more dependent on MLT and the intense hiss events are concentrated at high L ($L > 5$) on the morning side and the nightside (MLT \sim 00:00–06:00). Furthermore, the observation results (the first row of our Figures 2, 4, 6, and 8) suggest that the hiss amplitude distribution is slightly dependent on MLAT in the data on which the present study is based, which means the distribution is mainly controlled by L and MLT. The hiss wave amplitude is very intense inside the dayside plasmasphere (the first row of Figures

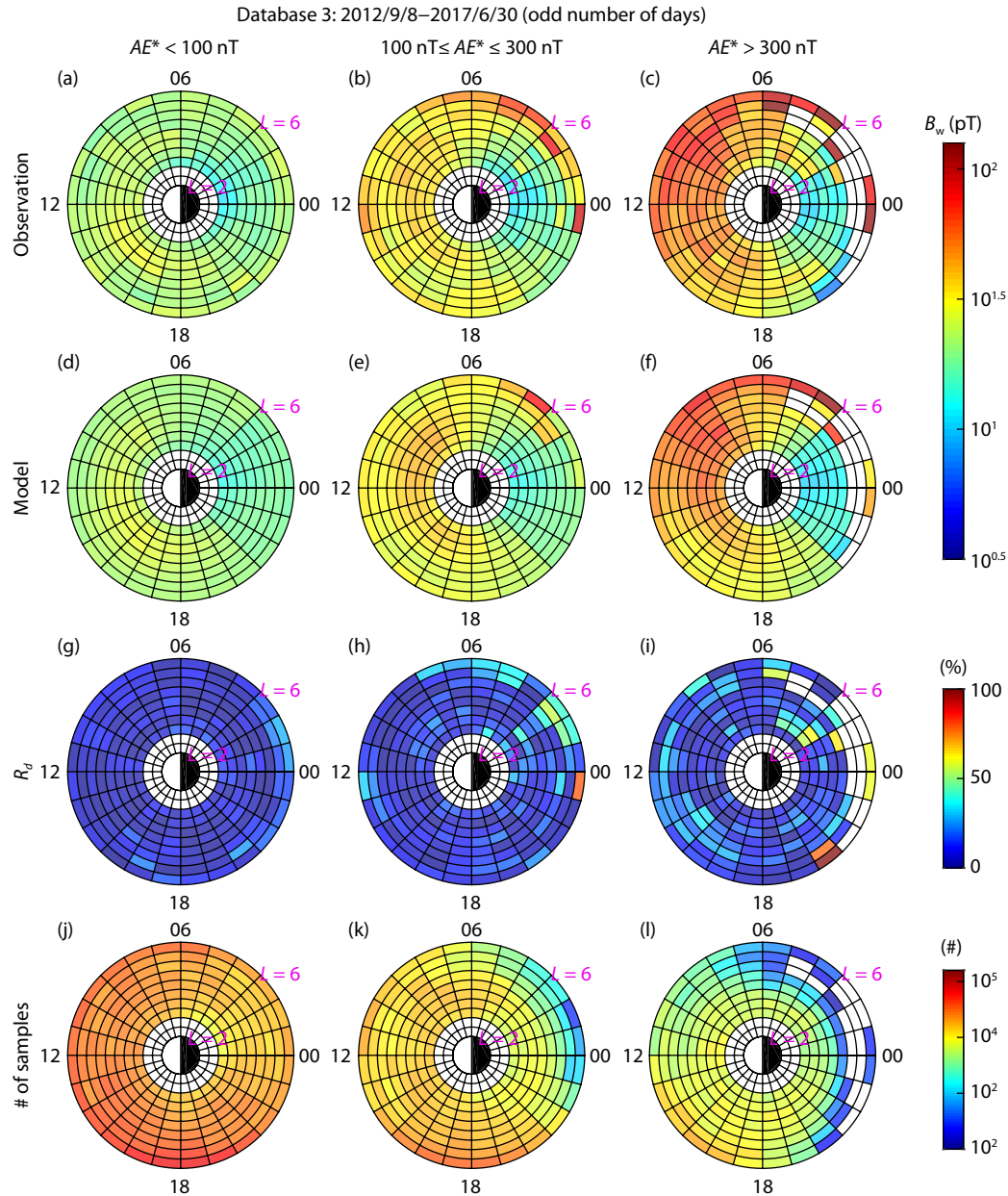


Figure 5. (a–c) Global L -MLT distribution of hiss wave amplitude from observations of Database 3; (d–f) self-consistent model results of Database 3; (g–i) relative differences (R_d) between them; (j–l) corresponding numbers of samples collected during quiet, moderate, and active times (left to right).

1, 3, 5, and 7). Inspired by observations that hiss wave amplitudes vary sensitively with spatial location and AE^* , we have then performed numerical fits to the statistical observations in terms of a third-order polynomial as a function of L , MLT, MLAT, and AE^* . By doing so, we have constructed an empirically analytic model of the global distribution of plasmaspheric hiss amplitude. The significance mainly lies in the treatment of fluctuation. The hiss amplitude can be obtained through the model simply by using AE^* and position information. The results of previous studies (Spasojevic et al., 2015, Yu J et al., 2017) show good agreement with hiss amplitude observations when for single variables (L or MLT) are considered. Since the 2D model including L /MLT or L /MLAT is of greater importance, in this study we present the fitting model to investigate the relationship between B_w and L /MLT, and also B_w

and L /MLAT. Our 2D model can perform the hiss amplitude distribution by L /MLT and L /MLAT simultaneously. Beyond this, our model can be simplified for 1D usage; the results show good consistency with Spasojevic et al. (2015) and Yu J et al. (2017).

Two different methods have been implemented to separate the training group and the test group, as shown in Table 1. Our analysis indicates that Method #2, which uses the odd-number days as the training group and the even-number days as the test group, is superior in deriving well-performing fitting functions for the global hiss wave model. One possible reason can be that the training and test groups in Method #2 may reflect the phases of a solar cycle more reasonably. Several other factors that may affect the modeling results should also be considered: first, the latitudin-

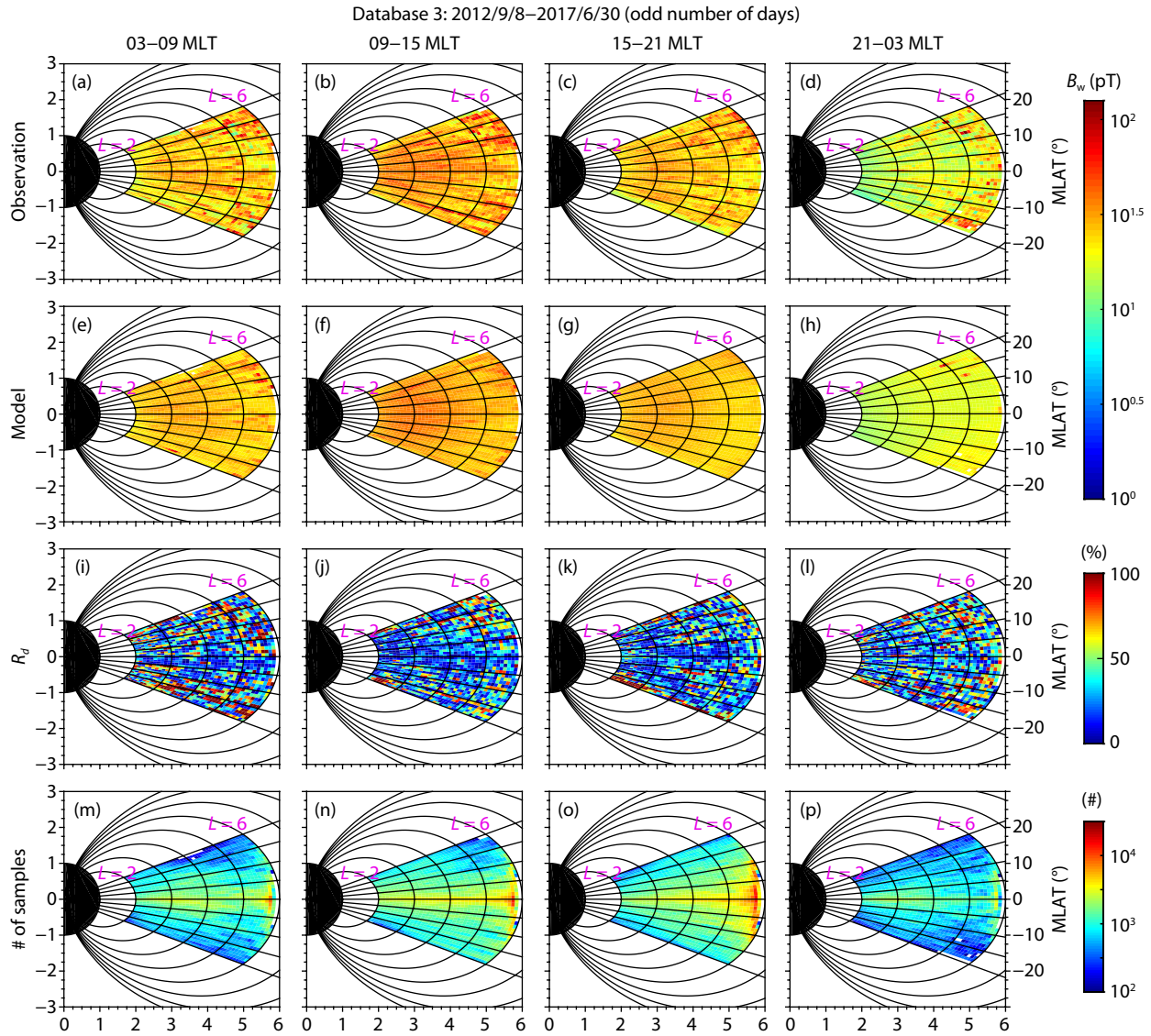


Figure 6. (a–d) Latitudinal L -MLAT distribution of hiss wave amplitude from observations in Database 3; (e–h) self-consistent model results of Database 3; (i–l) relative differences (R_d) between them; (m–p) corresponding numbers of samples during different MLT sectors (left to right).

al distribution of the number of samples is dependent on the MLAT, which could be another reason why Method #1 is worse than Method #2; second, Databases 1 and 2 have more differences in the MLAT distribution, which may also be the cause of differences between the observations and model results. These unsolved questions require further investigation in future studies.

In summary, it is well demonstrated, by quantitative comparisons between the statistical observations and model results, that the empirical model in terms of fitted functions can reflect favorably the major features of the global distribution of hiss wave intensity, including the MLT asymmetry, substorm dependence, and latitudinal variations (Xiang Z et al., 2017). Because both the energy spectra and pitch angle distributions of radiation belt electrons are critically affected by hiss wave scattering (e.g., Ni BB et al., 2013, 2014, 2017, 2019; Zhao H et al., 2019; Li LY et al., 2008; Hua M et al., 2019), and because the scattering rates increase proportionally to the square of hiss amplitude for the near-resonance

cases, our results therefore provide an empirically useful analytic model to be readily used for numerical quantification of hiss-driven electron diffusion coefficients and global simulations of resultant modulation of radiation belt electron dynamics in response to varying conditions of solar wind and geomagnetic activities.

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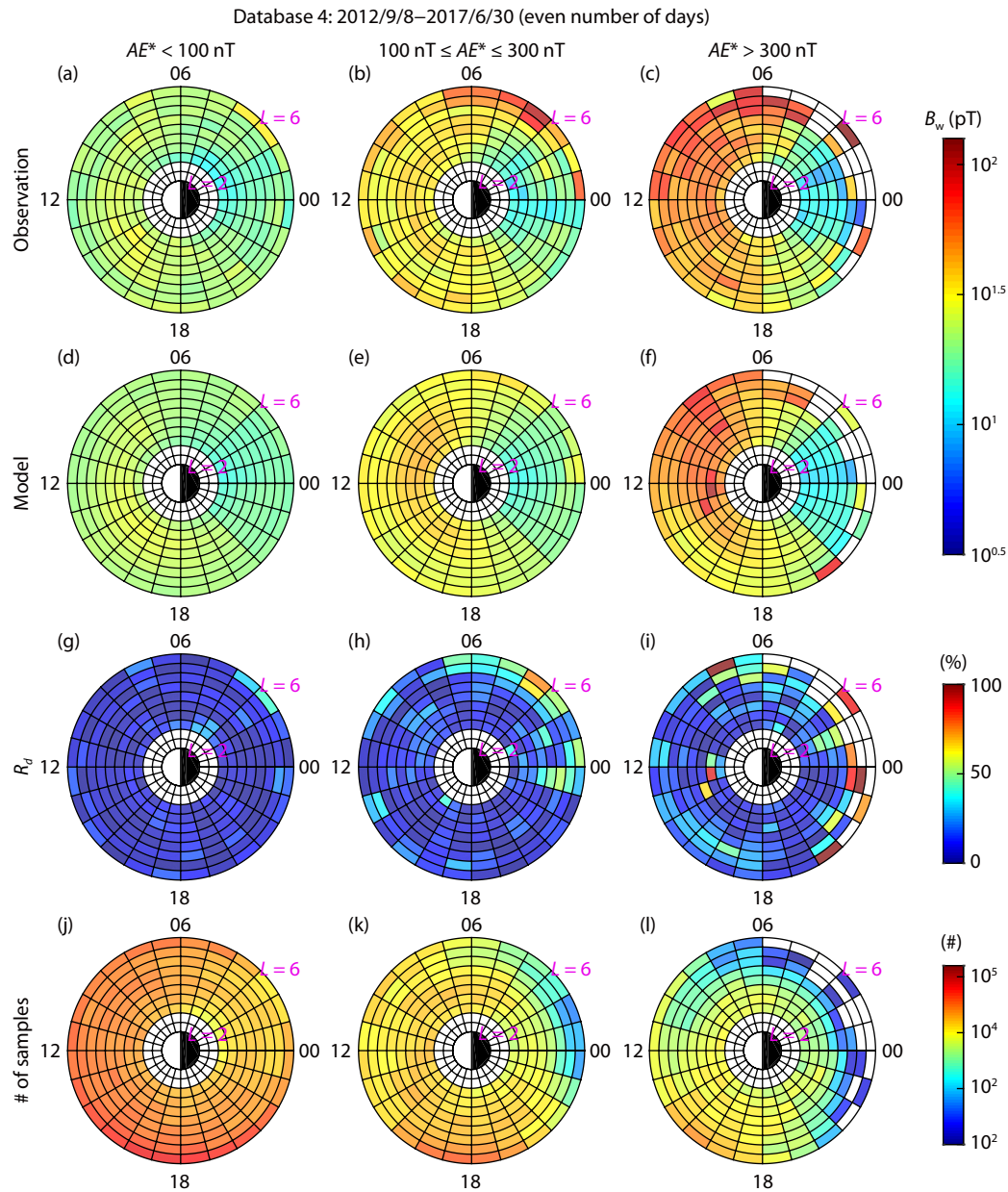


Figure 7. (a–c) Global L-MLT distribution of hiss wave amplitude from observations of Database 4; (d–f) model results calculated by Method #2 of Database 4; (g–i) relative differences (R_d) between them; (j–l) Corresponding numbers of samples during quiet, moderate, and active times (left to right).

Supplementary Materials

Fitting coefficients of global hiss wave amplitudes described by Equation (1), with A , B , C , and D standing for $L/10$, $MLT/24$, $MLAT/20$, and $AE^*/500$ respectively in the tables below.

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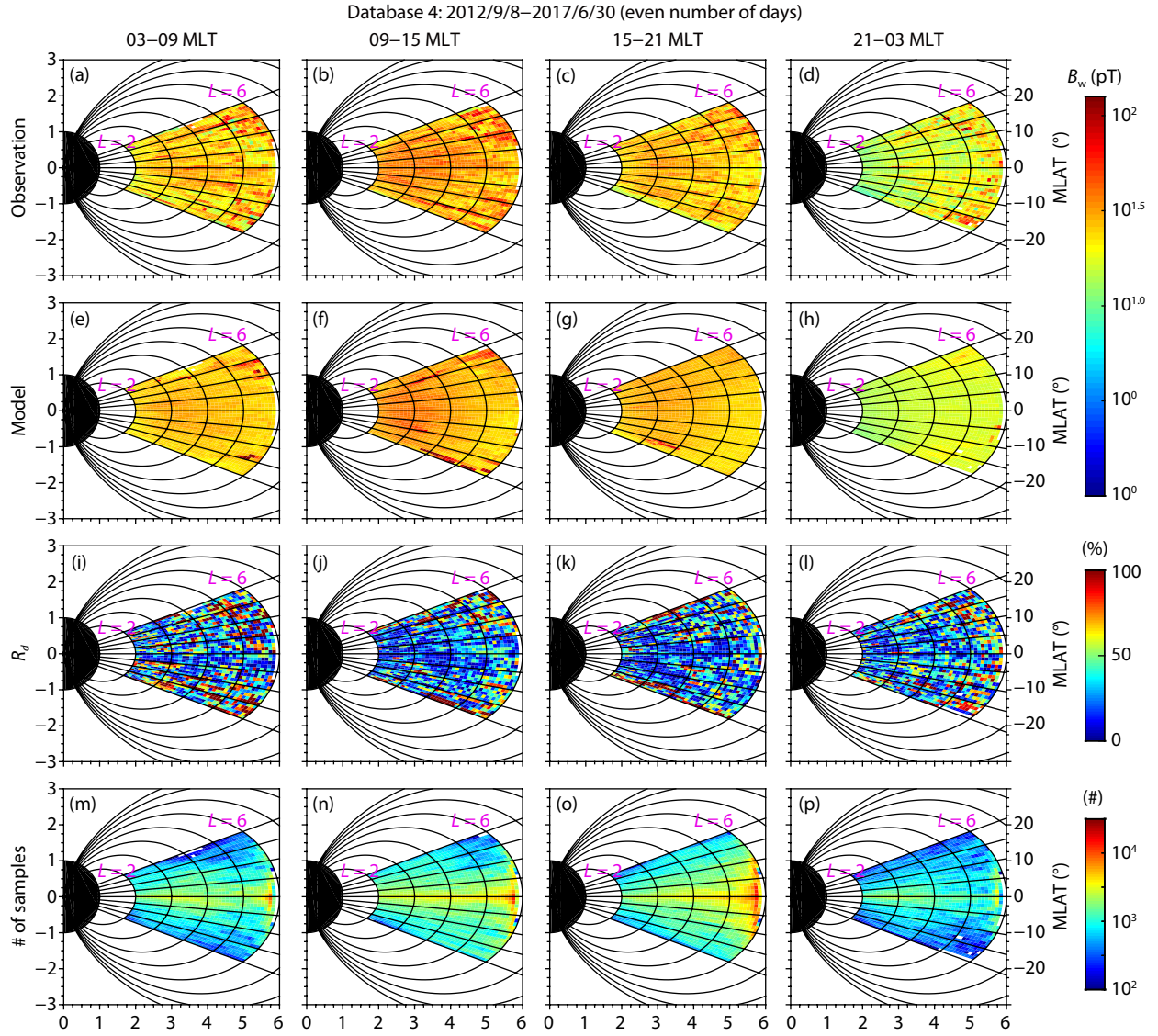


Figure 8. (a–d) Latitudinal L -MLAT distribution of hiss wave amplitude from observations in Database 4; (e–h) model results calculated by Method #2 of Database 4; (i–l) relative differences (R_d) between them; (m–p) corresponding numbers of samples during different MLT sectors (left to right).

Table S1. For the case of $3 \leq \text{MLT} < 9$ when $AE^* < 100$ nT.

	A^3	A^2	A	1
$B^2 C^2 D^2$	−266514.9971	396133.7612	−184520.1083	22417.0169
$B^2 C^2 D$	54078.0900	−73746.8387	34075.0324	−4159.9805
$B^2 C^2$	−5621.4548	6523.7330	−2538.6389	289.3744
$B^2 C D^2$	711003.3528	−869701.6097	336135.7473	−36131.3944
$B^2 C D$	−162514.4515	198471.9394	−77133.7749	8403.3444
$B^2 C$	5460.4956	−7038.6107	2935.1354	−339.9128
$B^2 D^2$	12383.3494	36038.8107	−26108.7679	4090.9090
$B^2 D$	−5046.8114	−11409.0749	8713.9449	−1313.8818
B^2	1167.8761	−144.9262	−286.1891	57.2291
$B C^2 D^2$	109462.4900	−189592.8830	95759.0780	−12030.0396

Continued from Table S1

	A^3	A^2	A	1
BC^2D	-22770.5610	35900.9413	-17996.1522	2267.7925
BC^2	2614.9908	-3200.3276	1298.0470	-150.7319
BCD^2	-399735.7029	486461.0926	-185965.6797	19759.4410
BCD	89648.4882	-108883.2325	41859.1725	-4512.8917
BC	-3072.1548	3905.0191	-1596.3226	181.6559
BD^2	13119.3847	-34517.3428	17091.5814	-2350.3062
BD	-3057.1654	10660.3297	-5661.1607	768.2433
B	-133.1410	-385.0074	285.6188	-41.8407
C^2D^2	-8925.5333	19872.9552	-11002.8916	1400.9854
C^2D	1961.5531	-3790.8888	2059.6952	-260.8511
C^2	-260.5572	337.9240	-141.9811	16.4166
CD^2	49165.7159	-59712.5852	22671.5047	-2376.0183
CD	-10827.3537	13107.7268	-4999.7083	531.5406
C	374.1982	-471.3872	189.8032	-21.1261
D^2	-3683.7443	5466.8612	-2190.9823	278.3865
D	1167.1453	-1918.8436	821.3382	-101.4842
1	-47.9098	104.0285	-49.1017	7.6187

Table S2. For $3 \leq \text{MLT} < 9$ when $100 \text{ nT} \leq AE^* \leq 300 \text{ nT}$.

	A^3	A^2	A	1
$B^2C^2D^2$	331653.7991	-308724.7892	85439.2375	-6834.3308
B^2C^2D	-241950.8713	225856.0542	-63900.4468	5298.6881
B^2C^2	42092.5539	-39622.5307	11528.0842	-989.3248
B^2CD^2	-30330.8124	36914.0125	-16526.4601	2262.0703
B^2CD	-813.0019	-3918.5268	6060.2020	-1315.9209
B^2C	2057.5584	-824.1222	-811.5823	243.6292
B^2D^2	-137886.6057	142068.7276	-42807.3836	3577.8427
B^2D	106875.8033	-110329.2476	33724.7500	-2866.8768
B^2	-19767.3055	20493.2503	-6391.3540	555.4488
BC^2D^2	-186784.8467	173025.2772	-47277.7337	3707.6257
BC^2D	137389.8139	-127709.9661	35625.4506	-2887.3134
BC^2	-23877.6413	22387.1216	-6417.5656	537.2465
BCD^2	17663.7459	-20102.7491	8714.8459	-1168.0038
BCD	-1797.5484	3467.5402	-3431.5976	692.6035
BC	-792.7300	316.6578	415.8051	-123.0988
BD^2	70177.6085	-71475.3936	21189.5131	-1740.4780
BD	-54224.0265	55197.0739	-16574.8150	1386.2145
B	10003.5159	-10274.1115	3168.2252	-271.3915
C^2D^2	23356.0741	-21140.9820	5549.2345	-406.8674

Continued from Table S2

	A^3	A^2	A	1
C^2D	-17446.3873	15895.2195	-4271.5491	324.4526
C^2	3086.8747	-2847.3167	790.1641	-62.5019
CD^2	-1941.2948	2015.7225	-843.7662	110.3938
CD	311.1382	-340.1256	319.5751	-65.1887
C	74.4323	-51.4628	-31.4615	11.3554
D^2	-7709.1922	7698.6539	-2219.8704	175.7890
D	6041.5387	-6004.5814	1750.7038	-141.2786
1	-1111.2043	1114.1224	-333.5586	29.1836

Table S3. For $3 \leq \text{MLT} < 9$ when $AE^* > 300$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	6132.7613	-27930.8705	11651.5562	-1113.2363
B^2C^2D	-42815.7524	82673.4313	-30777.2382	2865.2209
B^2C^2	37990.7017	-55785.8343	19486.3362	-1779.3551
B^2CD^2	-64036.0325	51549.2193	-12378.0540	847.4860
B^2CD	114298.9448	-90899.8767	21070.5138	-1340.9157
B^2C	-45958.2849	35709.9717	-7758.8220	413.6833
B^2D^2	16006.5829	-7613.0548	801.5318	6.6229
B^2D	-28049.8313	11604.8521	-500.9973	-103.9934
B^2	7399.3240	132.7468	-1469.2754	195.2219
BC^2D^2	7989.1234	7255.6867	-4462.3906	465.6041
BC^2D	3203.5654	-30890.6393	13397.9060	-1306.4381
BC^2	-12601.4592	24661.2024	-9224.4162	861.4047
BCD^2	34438.2147	-26848.3917	6264.1346	-419.9600
BCD	-59565.2802	45655.6805	-10175.6042	623.2360
BC	22997.2083	-16977.2613	3429.1713	-161.0901
BD^2	-11028.8682	5649.5698	-775.4366	22.5878
BD	19404.6519	-8840.1046	820.2465	14.5789
B	-5664.8571	820.0595	630.4501	-92.2497
C^2D^2	-3547.9859	880.4892	148.3611	-28.8548
C^2D	4192.7312	584.0480	-909.5064	107.4561
C^2	-350.2315	-1663.0556	808.4976	-81.9262
CD^2	-4156.7722	3070.2755	-688.0119	44.8482
CD	6954.1099	-5030.6860	1065.6385	-62.0595
C	-2606.0522	1792.1408	-330.7502	12.9542
D^2	1830.1727	-989.6628	157.7775	-7.3790
D	-3320.6072	1671.6640	-226.6916	7.6697
1	1146.7147	-400.4969	-6.6888	7.2731

Table S4. For $9 \leq \text{MLT} < 15$ when $AE^* < 100$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	629884.9981	-704561.3756	236123.6731	-24458.1348
B^2C^2D	-186449.5938	214143.2284	-73522.9196	7600.7679
B^2C^2	9859.9713	-12173.5796	4461.3441	-472.1497
B^2CD^2	40426.9278	-74824.5923	27475.3091	-1057.7387
B^2CD	26081.4585	-22956.4169	7566.3318	-1206.4892
B^2C	-3150.9226	3150.7331	-1054.2248	130.7475
B^2D^2	-425735.9035	445985.9123	-137474.9455	12161.9005
B^2D	102505.6268	-109727.0210	34662.5765	-3156.3718
B^2	-4963.7051	5566.8348	-1842.3759	172.6923
BC^2D^2	-578928.5758	643869.6617	-215185.3916	22565.6035
BC^2D	171190.6501	-197223.3796	68048.7862	-7118.7784
BC^2	-9095.0724	11370.7693	-4215.4383	450.4360
BCD^2	-53180.7345	88403.4235	-32210.0716	1505.6013
BCD	-25102.6522	21531.6270	-6873.9905	1130.0184
BC	3372.6792	-3349.1747	1098.5430	-133.1092
BD^2	445754.0520	-469938.1203	146202.9813	-13142.2304
BD	-105703.5663	114052.7380	-36428.4483	3371.1101
B	5136.6792	-5815.8431	1949.8871	-185.6119
C^2D^2	128119.2472	-140783.7539	46586.5678	-4936.3869
C^2D	-37662.4911	43430.8074	-15013.9783	1586.4379
C^2	1998.3167	-2533.6223	950.2927	-102.4939
CD^2	16734.6294	-25521.5664	9214.2985	-499.8170
CD	5836.5497	-4845.1243	1480.8104	-252.5459
C	-883.7282	870.9973	-279.6956	32.9784
D^2	-114081.9787	120791.1982	-37827.7391	3439.3908
D	26693.0495	-28982.9744	9339.3403	-873.6237
1	-1282.2221	1458.1511	-491.7567	48.6827

Table S5. For $9 \leq \text{MLT} < 15$ when $100 \text{ nT} \leq AE^* \leq 300 \text{ nT}$.

	A^3	A^2	A	1
$B^2C^2D^2$	-169864.1685	147455.0384	-32886.8818	1505.1670
B^2C^2D	130383.1144	-112560.8228	24526.2227	-962.8418
B^2C^2	-22365.0240	19117.4984	-3981.7294	114.3034
B^2CD^2	-139011.8288	145722.3046	-48273.5030	4794.3010
B^2CD	115734.3602	-122340.2537	40873.8247	-4056.8831
B^2C	-21231.0770	22556.7890	-7555.3091	740.8990
B^2D^2	-37444.2493	48027.6866	-18563.9424	1952.8074
B^2D	26352.4851	-34065.8492	13311.0788	-1439.8912
B^2	-4917.4746	6152.4054	-2368.9573	257.3706

Continued from Table S5

	A^3	A^2	A	1
BC^2D^2	193321.4523	-174237.8943	42071.8227	-2420.7938
BC^2D	-148952.9454	133411.3280	-31560.3969	1655.2613
BC^2	25620.7880	-22754.5790	5203.0059	-233.4869
BCD^2	143821.9669	-149879.9036	49306.6154	-4866.6454
BCD	-119807.0605	125903.8889	-41793.2646	4125.1234
BC	22021.6420	-23271.2594	7751.7619	-756.4568
BD^2	35237.0632	-45609.4155	17734.8507	-1864.9925
BD	-24541.1752	32148.4689	-12680.9205	1373.0821
B	4612.8304	-5824.8700	2259.7143	-245.7838
C^2D^2	-53549.9666	49738.0385	-12707.6404	829.3473
C^2D	41574.0809	-38362.6236	9630.8017	-590.3443
C^2	-7201.5844	6603.9642	-1618.0443	90.3080
CD^2	-36699.1157	37931.4620	-12344.1107	1204.9972
CD	30593.7282	-31889.1734	10479.5269	-1023.9428
C	-5641.7512	5917.5459	-1953.9292	188.9122
D^2	-7846.7149	10377.5080	-4099.8631	433.1066
D	5360.0358	-7230.9882	2914.8373	-317.1766
1	-980.3300	1267.2780	-501.2689	56.7315

Table S6. For $9 \leq \text{MLT} < 15$ when $AE^* > 300$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	-31993.8136	36350.2045	-12567.1004	1153.6804
B^2C^2D	65046.8285	-76045.8471	26740.9094	-2483.7590
B^2C^2	-29375.6610	35116.2003	-12477.5683	1147.1708
B^2CD^2	-150.4137	-931.4761	888.6293	-135.8866
B^2CD	17481.1852	-15612.7851	3539.6859	-188.5353
B^2C	-15577.0949	14709.2991	-3816.5509	263.8378
B^2D^2	1501.7008	-2734.6008	1196.6681	-122.1471
B^2D	-5178.1268	8533.7132	-3533.0662	353.4630
B^2	3170.0384	-5116.3017	2086.0565	-209.4092
BC^2D^2	32561.2017	-37073.5770	12812.5938	-1176.8440
BC^2D	-65390.7075	76840.6779	-27080.6938	2522.4960
BC^2	28769.8107	-34819.4777	12474.0677	-1155.9478
BCD^2	-775.3958	2061.5781	-1276.5211	171.4736
BCD	-15580.0601	13246.3806	-2720.2183	111.5433
BC	14743.2103	-13635.5241	3438.1251	-227.0693
BD^2	-1534.6187	2744.9817	-1183.0081	119.6319
BD	5378.4352	-8676.4002	3526.4529	-348.9818
B	-3102.6496	5018.5670	-2032.9596	202.7243
C^2D^2	-8149.1462	9285.7846	-3200.7904	293.8390

Continued from Table S6

	A^3	A^2	A	1
C^2D	16073.3979	-18981.3168	6694.7619	-624.9779
C^2	-6818.1265	8377.6824	-3026.2587	282.4056
CD^2	472.4027	-830.8122	420.3314	-51.8246
CD	3289.2412	-2608.3565	448.6455	-6.4834
C	-3397.5641	3064.5458	-743.7383	45.6803
D^2	411.2663	-703.0306	293.8160	-29.3386
D	-1452.1749	2246.5070	-885.0933	86.5118
1	830.0756	-1301.6374	516.5562	-49.1952

Table S7. For $15 \leq \text{MLT} < 21$ when $AE^* < 100$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	502956.9265	-539128.3919	162997.4350	-11347.8250
B^2C^2D	-113445.6282	119077.1007	-34329.3681	2265.3844
B^2C^2	3276.0336	-3230.7921	770.7469	-29.5738
B^2CD^2	157210.5677	-213224.4394	81353.1972	-9973.3017
B^2CD	-74359.6575	94332.0713	-34624.8291	3840.0784
B^2C	4960.6349	-6373.8833	2359.7361	-255.2794
B^2D^2	-325638.9011	359494.1791	-115501.3005	9258.6430
B^2D	51615.4180	-56416.3949	17634.4180	-1328.2824
B^2	-573.9870	603.2576	-145.7251	-1.0749
BC^2D^2	-718212.2574	771041.5231	-233097.7411	16232.2811
BC^2D	159873.2797	-168175.6795	48398.1224	-3172.3739
BC^2	-4424.4420	4377.1854	-1025.1029	35.5277
BCD^2	-164889.3781	237262.1277	-93580.3798	12233.4214
BCD	97030.0976	-124752.9570	46246.4867	-5224.7885
BC	-6799.8377	8825.3793	-3292.1941	359.7621
BD^2	494266.5954	-545293.6129	175472.2080	-14174.7311
BD	-79249.9878	86620.8634	-27190.6987	2080.3337
B	971.3968	-1018.7705	257.5490	-3.1859
C^2D^2	262395.7950	-282540.0548	85653.9028	-6033.4447
C^2D	-57857.2535	61113.1883	-17628.2573	1163.2656
C^2	1576.1757	-1571.5676	367.7632	-12.7950
CD^2	36477.0645	-59567.5142	24948.3281	-3593.2854
CD	-30929.8153	40537.0913	-15224.6182	1756.3501
C	2308.0058	-3034.7736	1142.4299	-126.1022
D^2	-189357.3284	208806.6558	-67321.9007	5486.7131
D	31157.3121	-34050.0090	10738.0056	-835.8921
1	-441.6704	456.7027	-118.3040	4.9437

Table S8. For $15 \leq \text{MLT} < 21$ when $100 \text{ nT} \leq AE^* \leq 300 \text{ nT}$.

	A^3	A^2	A	1
$B^2C^2D^2$	93608.8811	-99129.7690	34001.2091	-4022.7276
B^2C^2D	-76919.5127	83277.6117	-28706.9010	3299.9839
B^2C^2	12047.6256	-13441.2021	4741.1544	-554.2596
B^2CD^2	-101043.1854	108320.6616	-34647.3669	3143.5469
B^2CD	88592.0627	-95344.3339	30571.9557	-2754.5159
B^2C	-15301.5783	16315.5162	-5164.9895	448.3235
B^2D^2	-90468.5901	102938.6861	-35797.5100	3751.9817
B^2D	72443.6599	-81900.6731	28201.0568	-2915.3123
B^2	-12884.7832	14594.5450	-5019.4980	512.0447
BC^2D^2	-131111.6890	138410.6585	-47580.7641	5719.2727
BC^2D	107716.9153	-116697.5797	40429.3929	-4720.5602
BC^2	-16725.0565	18755.6724	-6678.4186	796.3718
BCD^2	160921.7848	-173343.3489	55671.2223	-5053.0726
BCD	-140460.4094	151887.3397	-48922.0289	4420.9577
BC	24425.4249	-26222.1361	8360.2948	-732.0562
BD^2	134092.0390	-153291.3326	53557.2123	-5635.3154
BD	-108035.3083	122651.0370	-42407.2877	4399.2731
B	19075.0580	-21693.7179	7491.9321	-768.7761
C^2D^2	45135.6942	-47371.0058	16302.6130	-1992.7369
C^2D	-37088.5944	40149.0026	-13979.0482	1659.5441
C^2	5691.3770	-6414.5665	2309.8626	-281.7614
CD^2	-62815.8241	67885.5183	-21856.3421	1983.0585
CD	54705.6403	-59355.6320	19176.0729	-1736.4545
C	-9583.8709	10341.7678	-3314.4556	292.2754
D^2	-49409.4172	56695.8478	-19880.8569	2097.0375
D	40032.1588	-45603.7988	15819.2237	-1644.4106
1	-6979.0670	7962.5121	-2758.1727	286.2224

Table S9. For $15 \leq \text{MLT} < 21$ when $AE^* > 300 \text{ nT}$.

	A^3	A^2	A	1
$B^2C^2D^2$	-1829.3591	-587.4156	1164.1513	-259.9248
B^2C^2D	-1757.2425	4277.4628	-3162.8914	686.3738
B^2C^2	-3003.5657	3324.1760	-371.8121	-184.5379
B^2CD^2	-12211.0051	10877.9200	-2708.4724	203.9189
B^2CD	34058.6401	-32021.0297	8632.3466	-686.0533
B^2C	-15231.1783	14413.9471	-3857.5838	297.3967
B^2D^2	4236.7924	-3758.4586	941.0589	-45.7887
B^2D	-6926.4342	6521.6285	-1678.5517	61.2233
B^2	2985.1491	-3203.8975	910.2741	-37.0109

Continued from Table S9

	A^3	A^2	A	1
BC^2D^2	700.9561	2672.3186	-2260.9915	430.0345
BC^2D	5060.9111	-8754.0784	5522.8809	-1092.7459
BC^2	3854.3675	-4227.9542	245.1139	304.1879
BCD^2	17249.2805	-15189.3713	3705.5840	-272.1701
BCD	-48633.6842	45430.6074	-12127.1988	952.8634
BC	21845.9720	-20534.2901	5436.1308	-413.5728
BD^2	-5921.7142	5368.5874	-1374.5254	69.1577
BD	10043.8037	-9731.4713	2574.3572	-104.3332
B	-4786.1755	5257.6537	-1535.5133	73.1924
C^2D^2	224.8326	-1408.1570	963.8340	-169.6245
C^2D	-2273.1720	3649.4858	-2214.6980	420.1827
C^2	-1467.1437	1555.0067	-47.5418	-117.9417
CD^2	-6012.4862	5221.5247	-1241.6993	88.5275
CD	17125.1575	-15871.8048	4184.9588	-324.8277
C	-7718.2414	7195.9406	-1879.5879	141.0361
D^2	2083.5260	-1928.0878	503.1514	-26.1625
D	-3685.4162	3651.8279	-984.5011	43.4187
1	1962.9860	-2184.9943	650.9175	-33.2332

Table S10. For $21 \leq \text{MLT} < 3$ when $AE^* < 100$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	78763.3201	-70953.4215	17898.7742	-1439.3581
B^2C^2D	-21308.5777	19385.5327	-4916.1973	371.5218
B^2C^2	1355.2223	-1248.0642	324.4378	-24.3469
B^2CD^2	-81512.5192	86332.2005	-26434.5405	2334.6949
B^2CD	20283.1122	-21191.7675	6459.3212	-575.1379
B^2C	-1352.0203	1402.9724	-429.5032	38.8220
B^2D^2	-44623.4589	53791.7013	-20025.8662	2291.6462
B^2D	14313.1686	-16487.0934	5830.2838	-636.0968
B^2	-1096.0362	1209.4196	-405.8388	41.1090
BC^2D^2	-77283.1734	68446.0694	-16839.1821	1364.0079
BC^2D	21090.8216	-18943.0997	4712.5379	-358.0203
BC^2	-1362.0066	1246.7419	-321.9076	24.5684
BCD^2	91013.8294	-97245.0751	30272.9614	-2722.3949
BCD	-22484.0807	23802.3541	-7400.8736	671.8152
BC	1478.9923	-1556.7355	485.3099	-44.5170
BD^2	46269.0705	-55171.8689	20368.9337	-2334.2277
BD	-14739.9411	16875.8488	-5941.3381	649.9034
B	1126.6437	-1242.7771	417.5811	-42.5079
C^2D^2	3222.2702	-2493.1073	584.5990	-79.1772

Continued from Table S10

	A^3	A^2	A	1
C^2D	-1104.8296	964.6767	-251.1849	27.5374
C^2	75.8759	-68.7066	18.7087	-1.9568
CD^2	-10859.7647	12081.3927	-4078.3578	401.0778
CD	2518.3306	-2831.8652	970.0610	-97.1894
C	-147.7759	165.3412	-56.4296	5.6820
D^2	-1896.6714	2283.9892	-893.5652	119.4325
D	677.7034	-764.1779	272.3790	-33.1051
1	-51.6867	54.9470	-17.4602	3.2163

Table S11. For $21 \leq \text{MLT} < 3$ when $100 \text{ nT} \leq AE^* \leq 300 \text{ nT}$.

	A^3	A^2	A	1
$B^2C^2D^2$	-57019.3361	43046.7962	-10082.0642	734.2537
B^2C^2D	26850.9381	-18283.2664	3771.4534	-233.2010
B^2C^2	-2572.1777	1423.4839	-204.7980	4.6060
B^2CD^2	-28576.4602	23138.1742	-5344.0995	331.6583
B^2CD	23254.2636	-19765.9681	4821.6157	-324.0250
B^2C	-4627.3395	4144.7511	-1084.7928	81.1160
B^2D^2	-3724.8879	5266.9111	-1561.2734	101.8974
B^2D	6397.9463	-7117.0772	1984.8604	-136.5674
B^2	-1655.9537	1735.3889	-481.9074	33.9444
BC^2D^2	54049.7630	-40590.7766	9461.8151	-686.6623
BC^2D	-25582.3355	17266.6460	-3531.5461	216.7897
BC^2	2466.9510	-1341.9042	187.9051	-3.8626
BCD^2	29740.3530	-24332.8418	5690.6267	-357.2131
BCD	-24353.1457	20852.1989	-5133.2978	347.5365
BC	4808.6367	-4323.6752	1136.2007	-85.0516
BD^2	4602.6476	-6209.6000	1885.5551	-136.1870
BD	-6905.4185	7690.0970	-2191.3714	159.2823
B	1729.1972	-1824.6403	515.9028	-37.7617
C^2D^2	-3648.1521	3017.1415	-795.8842	67.5684
C^2D	2072.6618	-1645.7120	424.8206	-36.4804
C^2	-268.1996	209.5025	-54.8183	4.9326
CD^2	-4172.9902	3801.8255	-1057.3326	87.1069
CD	3148.4384	-2908.2295	818.6345	-68.2110
C	-521.9749	489.1567	-139.7461	11.8942
D^2	140.1179	-8.3992	-14.1078	1.1023
D	54.9715	-134.5670	46.2524	-3.3622
1	-39.8132	51.6017	-15.2822	2.5156

Table S12. For $21 \leq \text{MLT} < 3$ when $AE^* > 300$ nT.

	A^3	A^2	A	1
$B^2C^2D^2$	-4767.3972	2391.6324	-186.9034	-13.7966
B^2C^2D	8849.6518	-3612.6320	-73.7785	71.8434
B^2C^2	-3941.6253	1194.0994	218.7614	-49.3895
B^2CD^2	-237.0725	120.0989	-38.6316	2.3034
B^2CD	-1389.1577	1306.8915	-298.5480	21.8833
B^2C	1803.1691	-1589.1820	386.2908	-28.9243
B^2D^2	-2120.6692	1732.8122	-434.2252	33.8314
B^2D	4825.2319	-4080.9516	1061.9505	-85.3927
B^2	-2359.9272	2116.9879	-582.8724	47.8042
BC^2D^2	4009.2050	-1790.6478	39.7558	24.5674
BC^2D	-7322.6675	2447.2619	347.6579	-91.0338
BC^2	3323.3825	-761.7557	-309.4931	54.8654
BCD^2	29.1433	-12.5949	30.9978	-3.0094
BCD	1803.2254	-1493.6573	299.5264	-18.8906
BC	-2002.5882	1667.8647	-381.6669	26.9726
BD^2	2285.5556	-1890.1988	478.2440	-37.4343
BD	-5197.1076	4430.9076	-1158.6021	93.2198
B	2535.1290	-2279.0977	627.2383	-51.3663
C^2D^2	76.2616	-136.5977	51.8708	-4.7539
C^2D	-163.8528	276.4589	-101.8775	9.0071
C^2	-25.5844	-36.2580	19.3630	-1.5412
CD^2	-117.7559	131.5090	-44.7731	4.1161
CD	248.3031	-299.9492	106.9029	-10.2377
C	-57.1891	106.1994	-45.2434	4.7107
D^2	-192.7063	172.2809	-44.3984	3.3900
D	475.4294	-421.9168	108.1886	-8.2028
1	-241.3631	214.4019	-54.5530	5.2218

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