

Satellite-based electron density background definition at mid-latitudes and comparison with IRI-2016 model under different solar conditions

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In these Supplementary Materials the complete results of the study for each different condition (i.e., year/satellite, season, night-time or noon hours) are presented, in terms of:

- the distribution of the relative deviations between IRI and satellite backgrounds $\delta N_{e,bkg}$ [%], along with the value of some statistical parameters such as Standard Deviation (SD), Mean Relative Deviation (MRD), and bias;
- the distribution of positive and negative anomalies (i.e., N_e variations from the background greater than 30%) with respect to each background and geomagnetic activity level.
- the number of positive and negative anomalies with respect to each background and geomagnetic activity level, along with their percentage with respect to the data in the corresponding condition.

Specifically, the conditions considered in the study are the following.

(i) Year/satellite: 2004 and 2009 for CHAMP, 2016 and 2017 for Swarm.

(ii) Season: Winter (January, February, November, December), Equinox (March, April, September, October), and Summer (May, June, July, August);

(iii) Noon hours (from 11 LT to 13 LT) and night-time (from 22 LT to 04 LT).

For more details on the data and the methodology used, please refer to the main content of the manuscript: <https://doi.org/10.1016/j.asr.2023.05.029>.

S1 Analysis of 2004 CHAMP data

S.1.1 Comparison between the IRI and CHAMP backgrounds for 2004

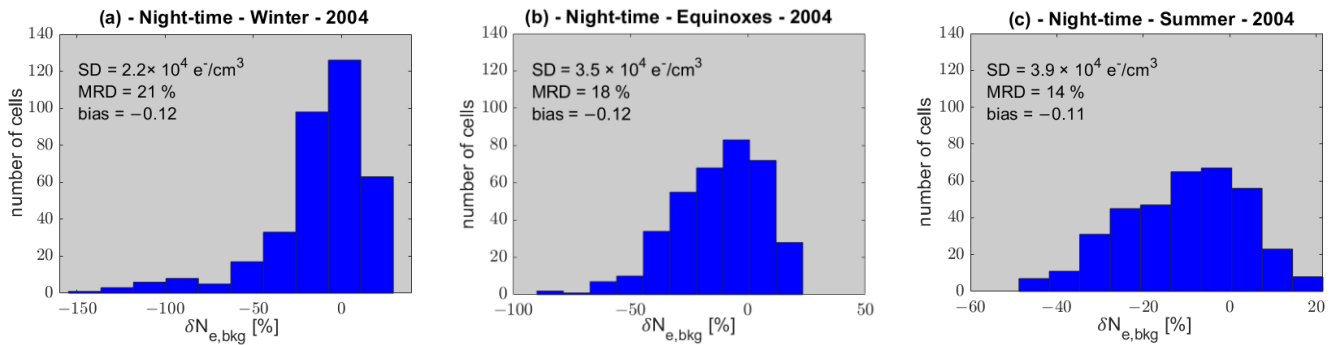


Figure S1. Distribution of the relative deviation $\delta N_{e,bkg}$ [%] between IRI and CHAMP backgrounds during night-time in 2004: (a) Winter, (b) Equinox, (c) Summer. The values of the Standard Deviation (SD), Mean Relative Deviation (MRD) and bias are also provided.

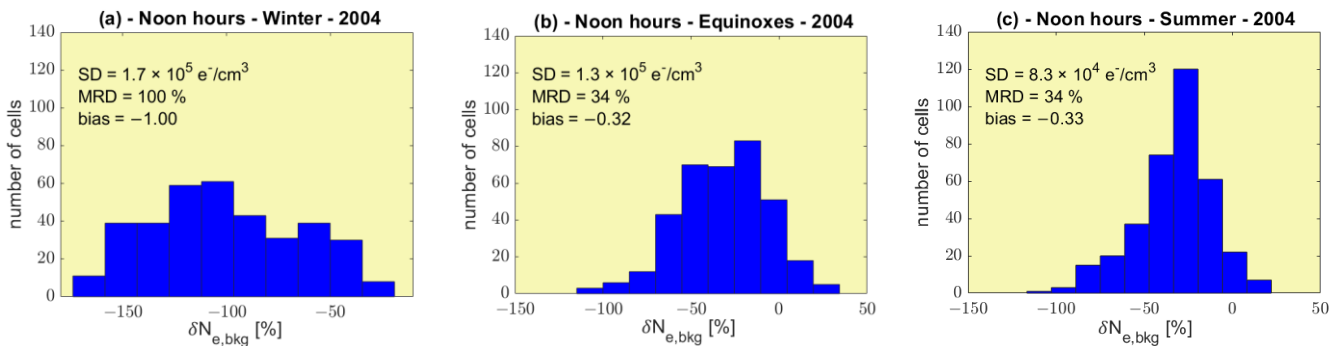


Figure S2. Same as Figure S1, for noon hours.

S.1.2 Anomalies with respect to the IRI background for 2004

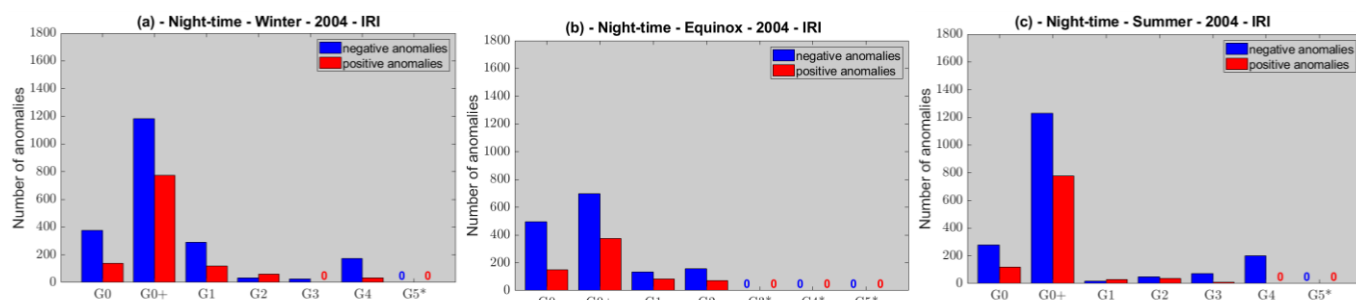


Figure S3. Distribution of the nocturnal positive (in red) and negative (in blue) anomalies with respect to the IRI background through the different geomagnetic activity levels in 2004: (a) Winter, (b) Equinox, (c) Summer. In case no negative or positive anomalies are identified, a blue or red “0” is reported respectively on the corresponding level. The asterisk “*” indicates that such a level was not reached during night-time hours of the specific season.

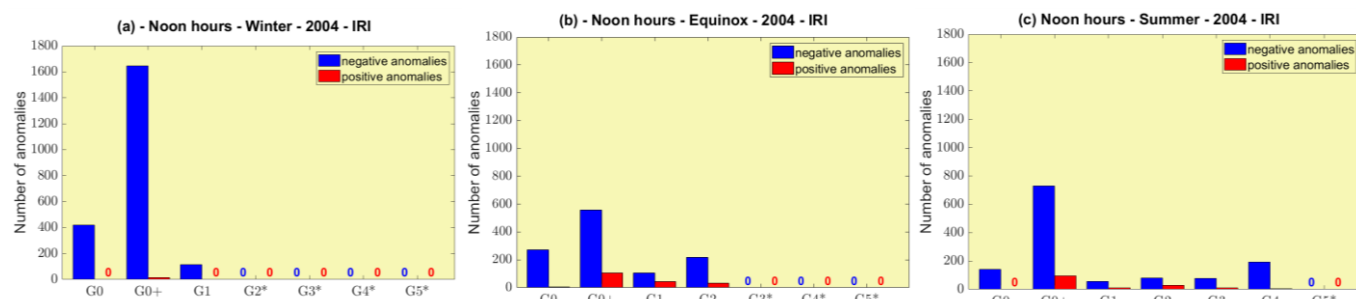


Figure S4. Same as Figure S3, for diurnal anomalies.

S.1.3 Anomalies with respect to the CHAMP background for 2004

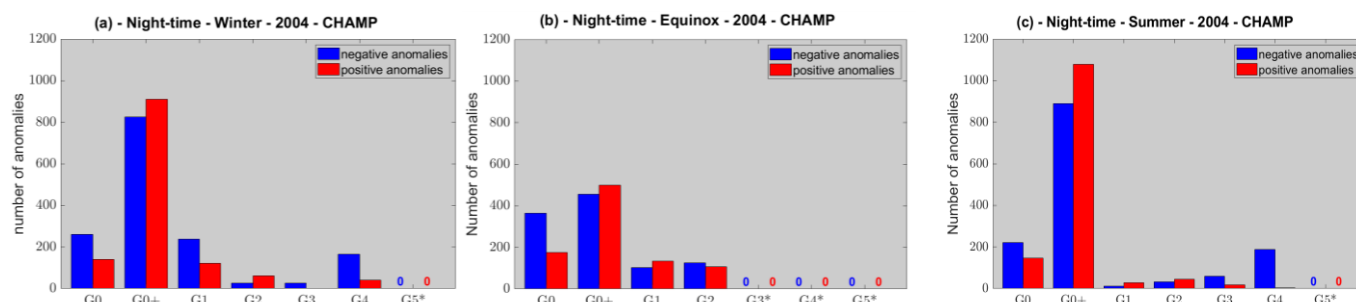


Figure S5. Same as Figure S3, for anomalies with respect to the CHAMP background.

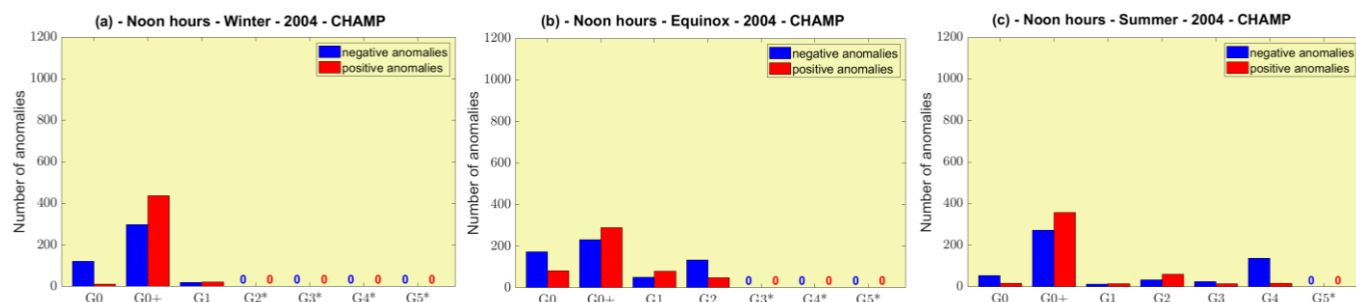


Figure S6. Same as Figure S5, for diurnal anomalies.

S.1.4 Statistical representation of the anomalies with respect to the IRI and CHAMP backgrounds for 2004

Table S1. Number of positive and negative anomalies with respect to the total windows that occurred in the different seasons and night-time or noon hours for CHAMP satellite in 2004. G5 geomagnetic activity level was never reached during this year.

Level	Backgr.	Anom.	Night-time			Noon hours		
			Winter	Equinox	Summer	Winter	Equinox	Summer
G0	IRI	Neg	377 (32.7%)	494 (41.8%)	277 (33.1%)	418 (95.9%)	274 (53%)	141 (61.3%)
		Pos	138 (12%)	150 (12.7%)	117 (14%)	0 (0%)	7 (1.4%)	0 (0%)
	Satellite	Neg	260 (22.5%)	365 (30.9%)	222 (26.6%)	122 (28%)	173 (33.5%)	54 (23.5%)
		Pos	141 (12.2%)	175 (14.8%)	146 (17.5%)	12 (2.8%)	81 (15.7%)	17 (7.4%)
	Total windows		1153	1183	836	436	517	230
G0+	IRI	Neg	1183 (23.9%)	698 (26.6%)	1228 (27%)	1646 (81.3%)	558 (40.2%)	731 (42.6%)
		Pos	775 (15.7%)	376 (14.3%)	778 (17.1%)	14 (0.7%)	107 (7.7%)	95 (5.5%)
	Satellite	Neg	825 (16.7%)	456 (17.4%)	890 (19.6%)	298 (14.7%)	231 (16.6%)	273 (15.9%)
		Pos	911 (18.4%)	499 (19%)	1079 (23.7%)	436 (21.5%)	289 (20.8%)	359 (20.9%)
	Total windows		4941	2625	4545	2025	1389	1715
G1	IRI	Neg	290 (36.4%)	136 (25.5%)	19 (20.9%)	116 (88.5%)	108 (36.4%)	55 (61.1%)
		Pos	117 (14.7%)	84 (15.8%)	28 (30.8%)	0 (0%)	45 (15.2%)	10 (11.1%)
	Satellite	Neg	237 (29.7%)	102 (19.1%)	12 (13.2%)	20 (15.3%)	51 (17.2%)	14 (15.6%)
		Pos	121 (15.2%)	133 (25%)	29 (31.9%)	22 (16.8%)	80 (26.9%)	15 (16.7%)
	Total windows		797	533	91	131	297	90
G2	IRI	Neg	33 (21.2%)	156 (38.5%)	47 (25.1%)	0 (0%)	218 (55.9%)	81 (43.8%)
		Pos	61 (39.1%)	73 (18%)	36 (19.3%)	0 (0%)	31 (7.9%)	28 (15.1%)
	Satellite	Neg	26 (16.7%)	125 (30.9%)	32 (17.1%)	0 (0%)	134 (34.4%)	35 (18.9%)
		Pos	61 (39.1%)	106 (26.2%)	45 (24.1%)	0 (0%)	49 (12.6%)	61 (33%)
	Total windows		156	405	187	0	390	185
G3	IRI	Neg	27 (67.5%)	0 (0%)	72 (50.7%)	0 (0%)	0 (0%)	77 (55.4%)
		Pos	0 (0%)	0 (0%)	8 (5.6%)	0 (0%)	0 (0%)	11 (7.9%)
	Satellite	Neg	26 (65%)	0 (0%)	60 (42.3%)	0 (0%)	0 (0%)	25 (18%)
		Pos	2 (5%)	0 (0%)	17 (12%)	0 (0%)	0 (0%)	16 (11.5%)
	Total windows		40	0	142	0	0	139
G4	IRI	Neg	173 (72.4%)	0 (0%)	200 (87.7%)	0 (0%)	0 (0%)	194 (83.6%)
		Pos	35 (14.6%)	0 (0%)	2 (0.9%)	0 (0%)	0 (0%)	4 (1.7%)
	Satellite	Neg	165 (69%)	0 (0%)	188 (82.5%)	0 (0%)	0 (0%)	138 (59.5%)
		Pos	40 (16.7%)	0 (0%)	4 (1.8%)	0 (0%)	0 (0%)	17 (7.3%)
	Total windows		239	0	228	0	0	232

S.2 Analysis of 2009 CHAMP data

S.2.1 Comparison between the IRI and CHAMP backgrounds for 2009

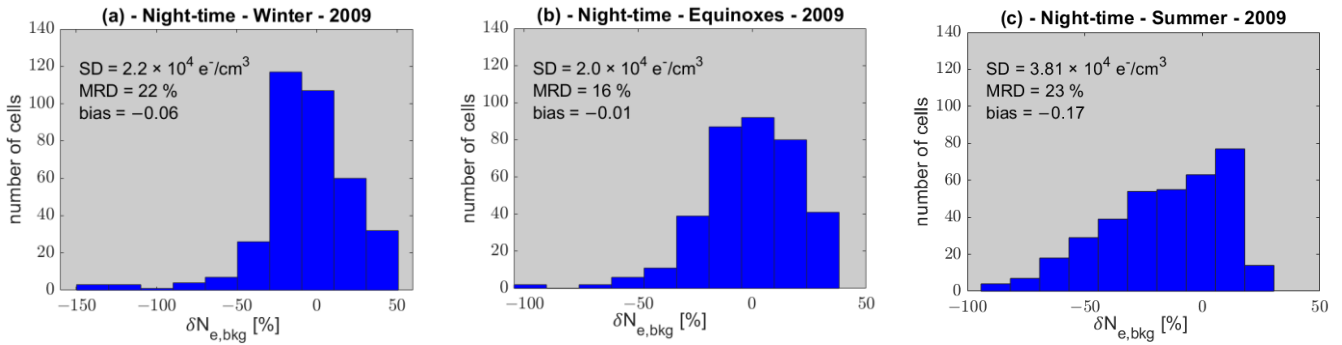


Figure S7. Distribution of the relative deviation $\delta N_{e,bkg}$ [%] between IRI and CHAMP backgrounds during night-time in 2009: (a) Winter, (b) Equinox, (c) Summer. The values of the Standard Deviation (SD), Mean Relative Deviation (MRD) and bias are also provided.

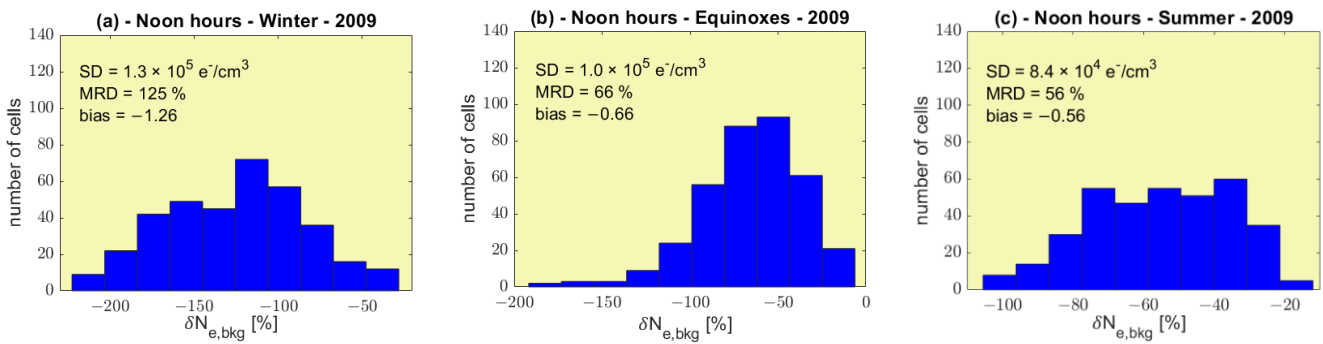


Figure S8. Same as Figure S7, for diurnal anomalies.

S.2.2 Anomalies with respect to the IRI background for 2009

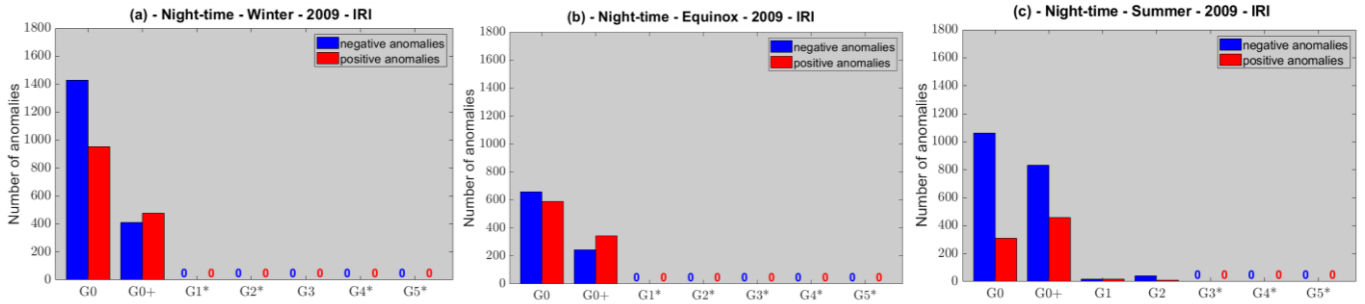


Figure S9. Distribution of the nocturnal positive (in red) and negative (in blue) anomalies with respect to the IRI background through the different geomagnetic activity levels in 2009: (a) Winter, (b) Equinox, (c) Summer. The “0” and “*” symbols mark the absence of anomalies or days in the corresponding level, respectively.

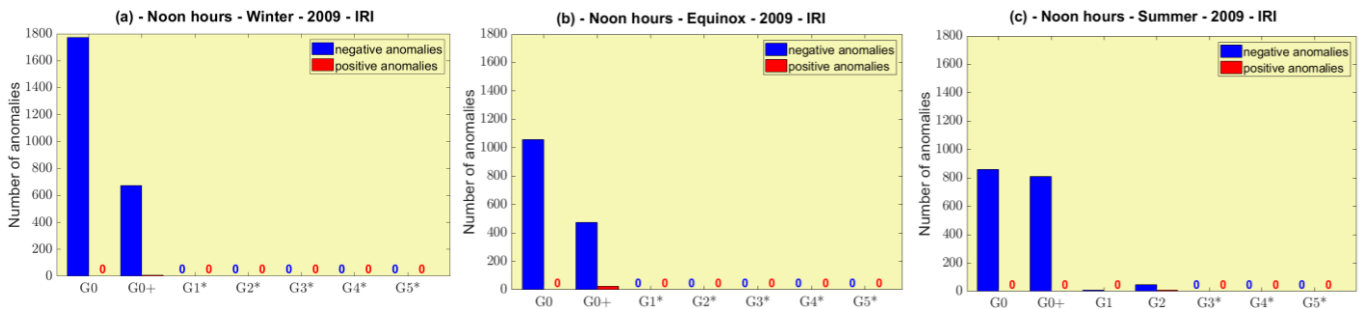


Figure S10. Same as Figure S9, for diurnal anomalies.

S.2.3 Anomalies with respect to the CHAMP background for 2009

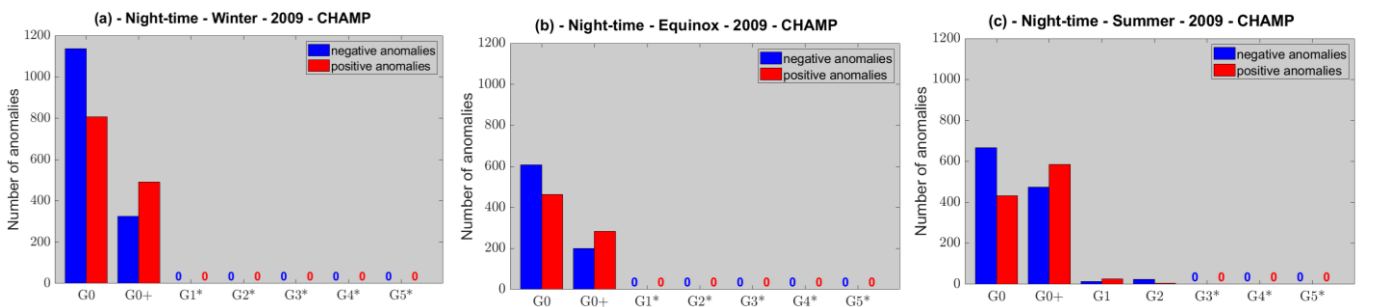


Figure S11. Same as Figure S9, for anomalies with respect to the CHAMP background.

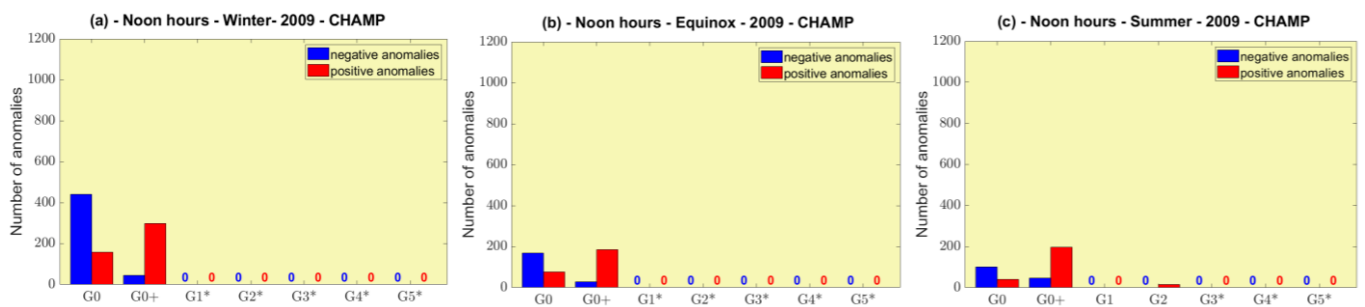


Figure S12. Same as Figure S11, for diurnal anomalies.

S.2.4 Statistical representation of the anomalies with respect to the IRI and CHAMP backgrounds for 2009

Table S2. Number of positive and negative anomalies with respect to the total windows that occurred in the different seasons and night-time or noon hours for CHAMP satellite in 2009. G3 or higher geomagnetic activity levels were never reached during this year.

Level	Backgr.	Anom.	Night-time			Noon hours		
			Winter	Equinox	Summer	Winter	Equinox	Summer
G0	IRI	Neg	1428 (28.3%)	658 (21.8%)	1063 (36.6%)	1773 (96.8%)	1059 (79.1%)	860 (78%)
		Pos	952 (18.9%)	590 (19.6%)	309 (10.6%)	0 (0%)	0 (0%)	1 (0.1%)
	Satellite	Neg	1136 (22.5%)	608 (20.2%)	668 (23%)	440 (24%)	169 (12.6%)	101 (9.2%)
		Pos	807 (16%)	463 (15.4%)	432 (14.9%)	159 (8.7%)	76 (5.7%)	40 (3.6%)
	Total windows		5049	3013	2904	1832	1338	1102
G0+	IRI	Neg	412 (19.7%)	244 (15.6%)	833 (29.7%)	675 (78.9%)	473 (60.6%)	811 (57.5%)
		Pos	478 (22.8%)	344 (22%)	457 (16.3%)	9 (1.1%)	24 (3.1%)	2 (0.1%)
	Satellite	Neg	325 (15.5%)	200 (12.8%)	474 (16.9%)	46 (5.4%)	28 (3.6%)	47 (3.3%)
		Pos	490 (23.4%)	283 (18.1%)	586 (20.9%)	299 (35%)	185 (23.7%)	198 (14%)
	Total windows		2095	1562	2805	855	781	1410
G1	IRI	Neg	0 (0%)	0 (0%)	17 (18.7%)	0 (0%)	0 (0%)	10 (100%)
		Pos	0 (0%)	0 (0%)	17 (18.7%)	0 (0%)	0 (0%)	0 (0%)
	Satellite	Neg	0 (0%)	0 (0%)	14 (15.4%)	0 (0%)	0 (0%)	1 (10%)
		Pos	0 (0%)	0 (0%)	26 (28.6%)	0 (0%)	0 (0%)	0 (0%)
	Total windows		0	0	91	0	0	10
G2	IRI	Neg	0 (0%)	0 (0%)	40 (48.8%)	0 (0%)	0 (0%)	47 (58%)
		Pos	0 (0%)	0 (0%)	8 (9.8%)	0 (0%)	0 (0%)	8 (9.9%)
	Satellite	Neg	0 (0%)	0 (0%)	24 (29.3%)	0 (0%)	0 (0%)	1 (1.2%)
		Pos	0 (0%)	0 (0%)	5 (6.1%)	0 (0%)	0 (0%)	16 (19.8%)
	Total windows		0	0	82	0	0	81

S.3 Analysis of 2016 Swarm data

S.3.1 Comparison between the IRI and Swarm backgrounds for 2016

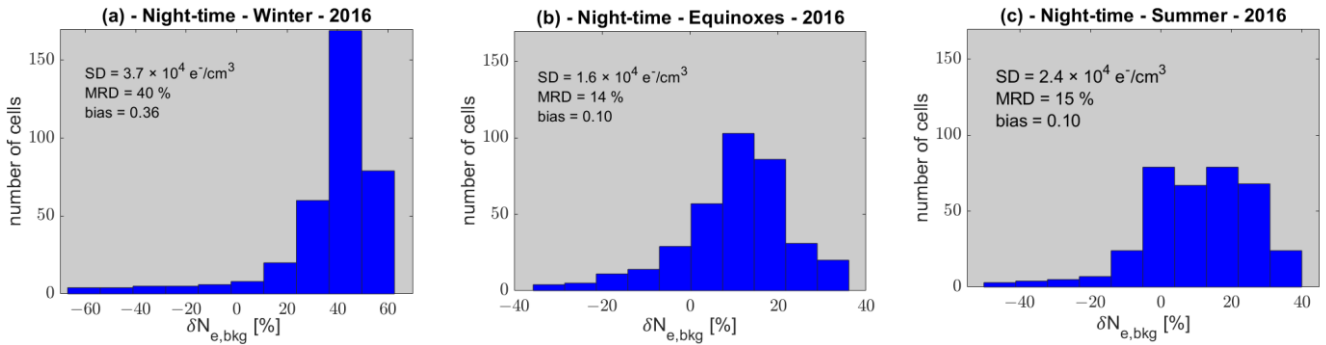


Figure S13. Distribution of the relative deviation $\delta N_{e,bkg}$ [%] between IRI and Swarm backgrounds during night-time in 2016: (a) Winter, (b) Equinox, (c) Summer. The values of the Standard Deviation (SD), Mean Relative Deviation (MRD) and bias are also provided.

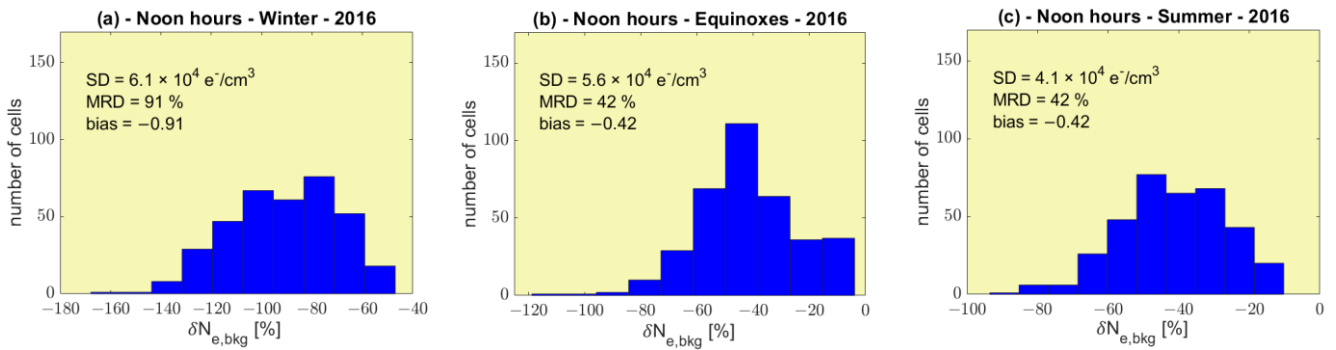


Figure S14. Same as Figure S13, for diurnal anomalies

S.3.2 Anomalies with respect to the IRI background for 2016

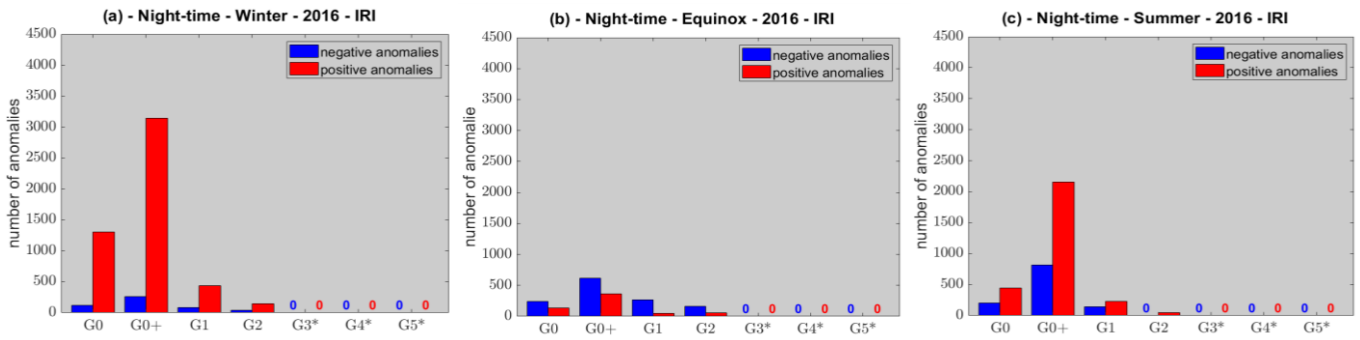


Figure S15. Distribution of the nocturnal positive (in red) and negative (in blue) anomalies with respect to the IRI background through the different geomagnetic activity levels in 2016: (a) Winter, (b) Equinox, (c) Summer. The “0” and “*” symbols mark the absence of anomalies or days in the corresponding level, respectively.

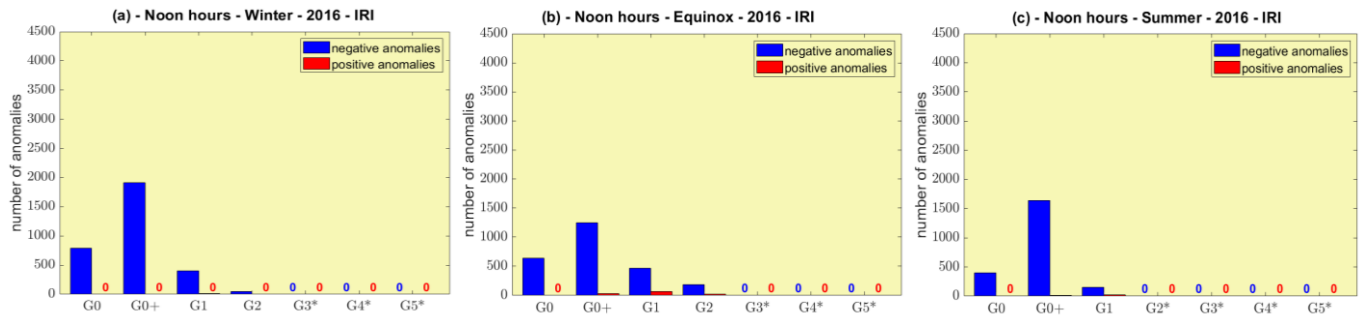


Figure S16. Same as Figure S15, for diurnal anomalies.

S.3.3 Anomalies with respect to the Swarm background for 2016

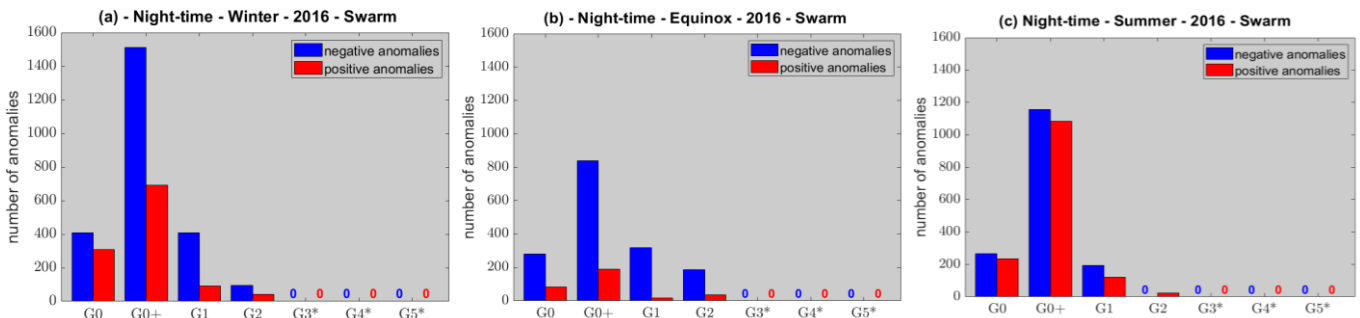


Figure S17. Same as Figure S9, for anomalies with respect to the Swarm background.

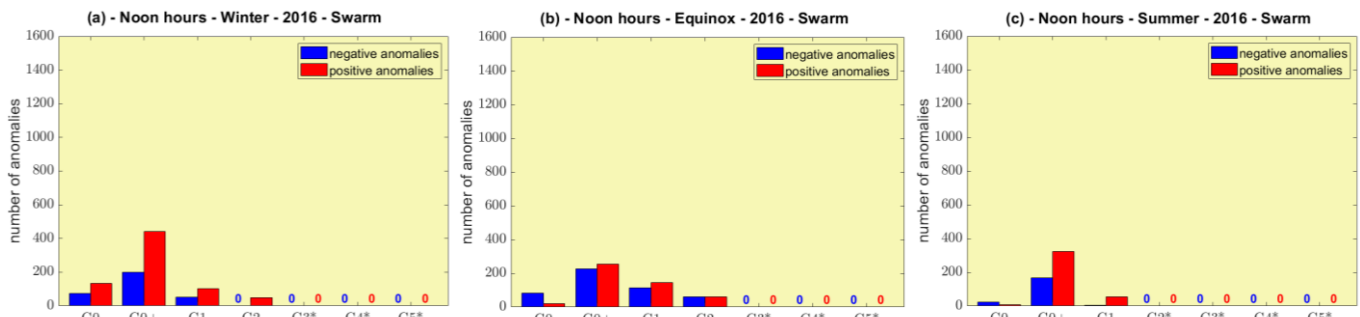


Figure S18. Same as Figure S17, for diurnal anomalies.

S.3.4 Statistical representation of the anomalies with respect to the IRI and Swarm backgrounds for 2016

Table S3. Number of positive and negative anomalies with respect to the total windows that occurred in the different seasons and night-time or noon hours for Swarm satellite in 2016. G3 or higher geomagnetic activity levels were never reached during this year.

Level	Backgr.	Anom.	Night-time			Noon hours		
			Winter	Equinox	Summer	Winter	Equinox	Summer
G0	IRI	Neg	109 (5.1%)	241 (26.9%)	206 (18.1%)	801 (86.3%)	641 (57.4%)	393 (64.9%)
		Pos	1329 (62.5%)	154 (17.2%)	432 (37.9%)	0 (0%)	0 (0%)	0 (0%)
	Satellite	Neg	460 (21.6%)	295 (32.9%)	252 (22.1%)	75 (8.1%)	40 (3.6%)	21 (3.5%)
		Pos	288 (13.5%)	69 (7.7%)	255 (22.3%)	133 (14.3%)	20 (1.8%)	8 (1.3%)
	Total windows		2126	896	1141	928	1116	606
G0+	IRI	Neg	238 (4.4%)	595 (24.4%)	813 (14%)	1898 (81.4%)	1307 (46.8%)	1654 (48.4%)
		Pos	3121 (57.2%)	368 (15.1%)	2101 (36.1%)	0 (0%)	27 (1%)	17 (0.5%)
	Satellite	Neg	1610 (29.5%)	852 (35%)	1092 (18.8%)	203 (8.7%)	186 (6.7%)	152 (4.4%)
		Pos	651 (11.9%)	163 (6.7%)	1168 (20.1%)	445 (19.1%)	279 (10%)	327 (9.6%)
	Total windows		5461	2436	5812	2333	2790	3418
G1	IRI	Neg	77 (8.1%)	257 (36.2%)	143 (20.1%)	394 (82.6%)	472 (51.3%)	154 (44.1%)
		Pos	425 (45%)	44 (6.2%)	225 (31.6%)	9 (1.9%)	46 (5%)	17 (4.9%)
	Satellite	Neg	418 (44.2%)	333 (46.9%)	184 (25.9%)	51 (10.7%)	92 (10%)	6 (1.7%)
		Pos	90 (9.5%)	17 (2.4%)	135 (19%)	103 (21.6%)	143 (15.5%)	49 (14%)
	Total windows		945	710	711	477	920	349
G2	IRI	Neg	32 (11.8%)	154 (44.3%)	3 (3.7%)	49 (57%)	185 (60.5%)	0 (0%)
		Pos	147 (54%)	45 (12.9%)	43 (53.1%)	3 (3.5%)	10 (3.3%)	0 (0%)
	Satellite	Neg	95 (34.9%)	183 (52.6%)	2 (2.5%)	0 (0%)	54 (17.6%)	0 (0%)
		Pos	43 (15.8%)	23 (6.6%)	28 (34.6%)	44 (51.2%)	46 (15%)	0 (0%)
	Total windows		272	348	81	86	306	0

S.4 Analysis of 2017 Swarm data

S.4.1 Comparison between the IRI and Swarm backgrounds for 2017

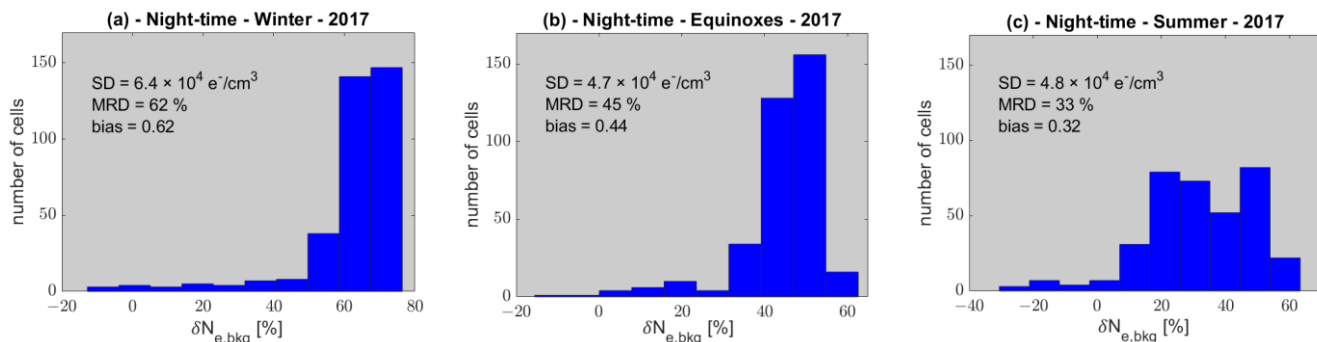


Figure S19. Distribution of the relative deviation $\delta N_{e,bkg}$ [%] between IRI and Swarm backgrounds during night-time in 2017: (a) Winter, (b) Equinox, (c) Summer. The values of the Standard Deviation (SD), Mean Relative Deviation (MRD) and bias are also provided.

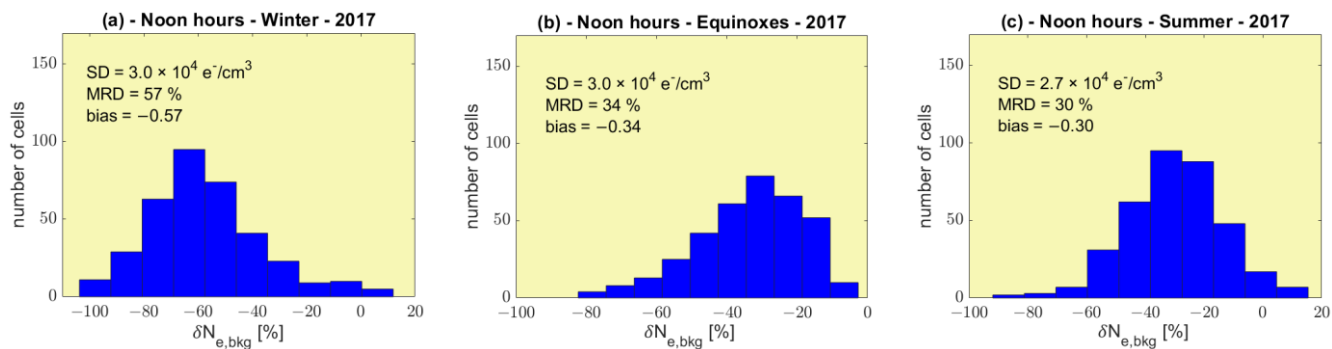


Figure S20. Same as Figure S19, for diurnal anomalies

S.4.2 Anomalies with respect to the IRI background for 2017

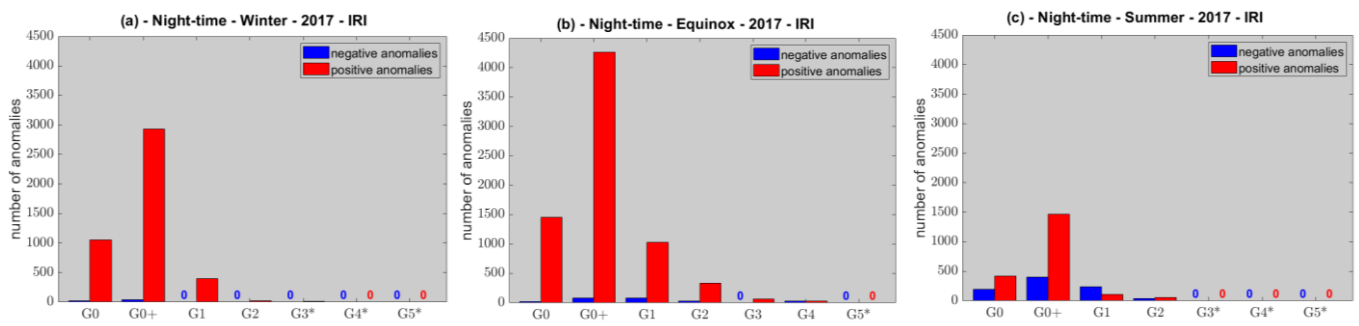


Figure S21. Distribution of the nocturnal positive (in red) and negative (in blue) anomalies with respect to the IRI background through the different geomagnetic activity levels in 2017: (a) Winter, (b) Equinox, (c) Summer. The "0" and "*" symbols mark the absence of anomalies or days in the corresponding level, respectively.

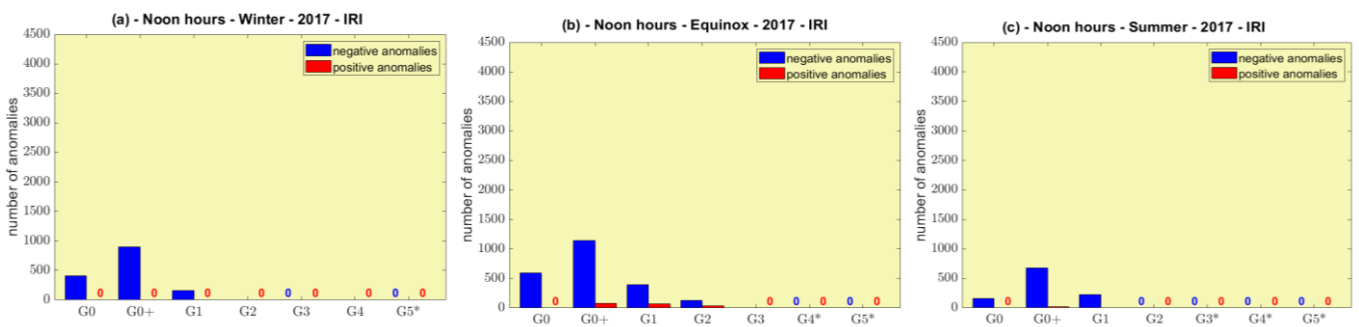


Figure S22. Same as Figure S21, for diurnal anomalies.

S.4.3 Anomalies with respect to the Swarm background for 2017

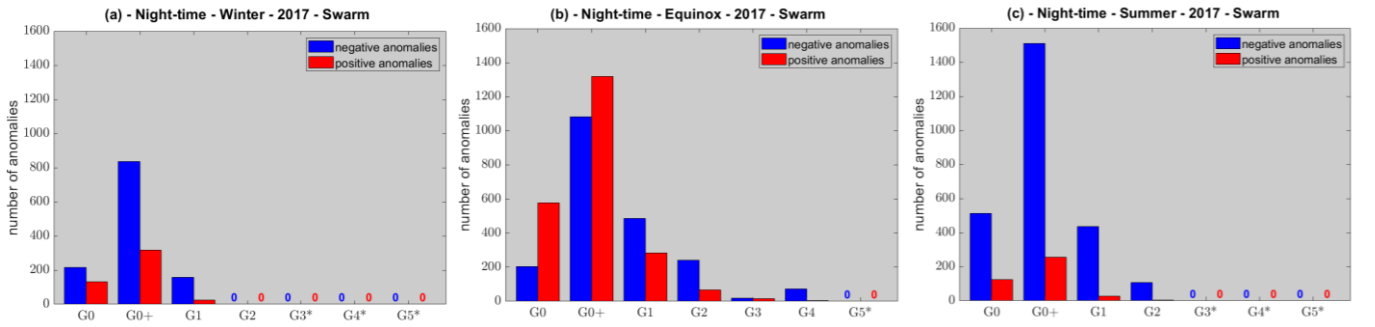


Figure S23. Same as Figure S21, for anomalies with respect to the Swarm background.

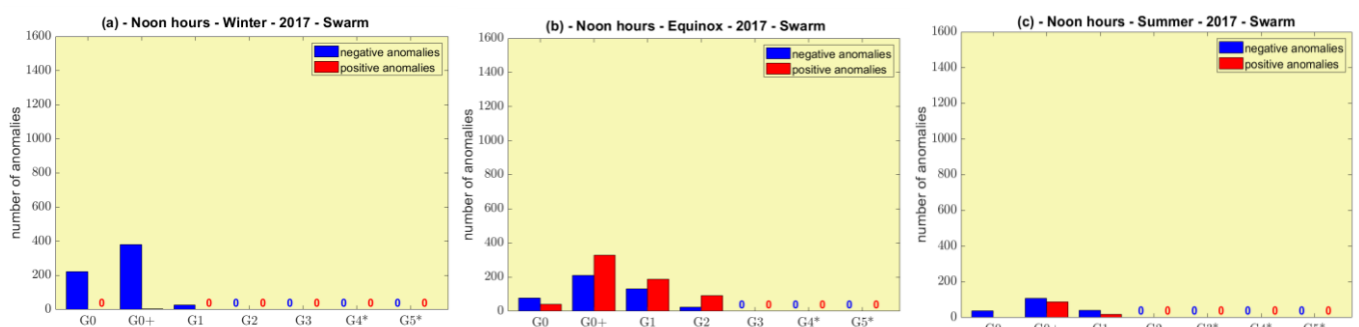


Figure S24. Same as Figure S23, for diurnal anomalies.

S.4.4 Statistical representation of the anomalies with respect to the IRI and Swarm backgrounds for 2017

Table S4. Number of positive and negative anomalies with respect to the total windows that occurred in the different seasons and night-time or noon hours for Swarm satellite in 2017. G5 geomagnetic activity level was never reached during this year.

Level	Backgr.	Anom.	Night-time			Noon hours		
			Winter	Equinox	Summer	Winter	Equinox	Summer
G0	IRI	Neg	26 (2.2%)	18 (1%)	191 (15.7%)	413 (90.8%)	592 (56.4%)	159 (52.1%)
		Pos	1083 (92.6%)	1453 (84.4%)	422 (34.8%)	0 (0%)	0 (0%)	0 (0%)
	Satellite	Neg	243 (20.8%)	205 (11.9%)	513 (42.3%)	268 (58.9%)	79 (7.5%)	38 (12.5%)
		Pos	115 (9.8%)	577 (33.5%)	123 (10.1%)	1 (0.2%)	42 (4%)	2 (0.7%)
	Total windows			1169	1721	1213	455	1049
G0+	IRI	Neg	42 (1.3%)	81 (1.5%)	403 (10.6%)	908 (88.1%)	1145 (42.3%)	681 (46.6%)
		Pos	2987 (94%)	4261 (77.4%)	1464 (38.5%)	0 (0%)	76 (2.8%)	22 (1.5%)
	Satellite	Neg	894 (28.1%)	1081 (19.6%)	1511 (39.7%)	416 (40.3%)	210 (7.7%)	108 (7.4%)
		Pos	278 (8.8%)	1320 (24%)	255 (6.7%)	1 (0.1%)	330 (12.2%)	89 (6.1%)
	Total windows			3177	5504	3802	1031	2710
G1	IRI	Neg	8 (2%)	81 (5.1%)	235 (39.6%)	120 (85.1%)	399 (40.2%)	223 (48%)
		Pos	337 (85.5%)	1028 (65.1%)	104 (17.5%)	0 (0%)	73 (7.4%)	8 (1.7%)
	Satellite	Neg	168 (42.6%)	485 (30.7%)	436 (73.4%)	29 (20.6%)	132 (13.3%)	41 (8.8%)
		Pos	21 (5.3%)	283 (17.9%)	28 (4.7%)	0 (0%)	189 (19.1%)	19 (4.1%)
	Total windows			394	1578	594	141	992
G2	IRI	Neg	0 (0%)	30 (5.2%)	43 (23%)	2 (66.7%)	125 (39.1%)	0 (0%)
		Pos	12 (100%)	335 (58.6%)	55 (29.4%)	0 (0%)	41 (12.8%)	0 (0%)
	Satellite	Neg	0 (0%)	241 (42.1%)	106 (56.7%)	0 (0%)	23 (7.2%)	0 (0%)
		Pos	0 (0%)	67 (11.7%)	5 (2.7%)	0 (0%)	91 (28.4%)	0 (0%)
	Total windows			12	572	187	3	320
G3	IRI	Neg	0 (0%)	3 (3.7%)	0 (0%)	5 (71.4%)	4 (25%)	0 (0%)
		Pos	0 (0%)	62 (75.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Satellite	Neg	0 (0%)	18 (22%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Pos	0 (0%)	17 (20.7%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Total windows			0	82	0	7	16
G4	IRI	Neg	0 (0%)	31 (29%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Pos	0 (0%)	28 (26.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Satellite	Neg	0 (0%)	73 (68.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Pos	0 (0%)	5 (4.7%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Total windows			0	107	0	0	0