Investigating the main features of the correlation between electron density and temperature in the topside ionosphere through Swarm satellites data

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Abstract

Electron density (N_e) and electron temperature (T_e) observations collected by Langmuir Probes (LPs) on board the European Space Agency's Swarm B satellite are used to characterize the their correlation in the topside ionosphere (at around 500 km of altitude). Spearman rank correlation coefficient ($R_{Spearman}$) values are calculated based on joint probability distributions between N_e and T_e for specific conditions. The large dataset of Swarm B LP in-situ observations at 2-Hz rate, covering the years 2014–2021, allowed investigating the correlation properties of the topside ionospheric plasma on a global scale, for different diurnal and seasonal conditions, with a coverage and a detail never reached before. Results are given as maps of $R_{Spearman}$ as a function of the Quasi-Dipole (QD) magnetic latitude and magnetic local time (MLT) coordinates, for different seasons.

Swarm B observations dataset and sorting

Swarm B satellite flies in a circular near-polar orbit with an inclination of 87.75° and an initial altitude of 510 km, covering different local times at different periods. It is equipped with LPs which provide measurements of N_e and T_e along the satellite orbit with a sampling frequency of 2 Hz. In this work, we consider LP N_e and T_e observations collected by Swarm B from 1 January 2014 to 31 December 2021 in High-Gain mode.

Swarm B observations were sorted to highlight the main spatial, diurnal, and seasonal variations of the correlation. The seasonal dependence has been characterized by sorting observations in three bins:

- June solstice: May, June, July, and August;
- December solstice: November, December, January, and February;
- Equinoxes: March, April, September, and October.

For each season, observations were sorted on the base of QD magnetic latitude for the spatial characterization, and of the MLT for the diurnal characterization. Specifically:

- QD latitude: from -90° to 90° in steps of 1°;
- QD MLT: from 0 to 24 in steps of 4 minutes.

Spearman rank correlation coefficient calculation

$R_{Spearman}$ is calculated for each of the 194,400 bins (3 seasons, 180 QD latitudes, 360 MLTs) through the following formula:

$$R_{Spearman} = \frac{\mathrm{cov}\left(\mathrm{R}(N_e),\mathrm{R}(T_e)\right)}{\sigma_{\mathrm{R}(N_e)}\sigma_{\mathrm{R}(T_e)}} \in [-1,+1], \quad (1)$$

where R is the rank, cov is the covariance matrix, and σ the variance.

$R_{Spearman}$ is a nonparametric measure of the monotonicity of the relation between two datasets which does not require any assumption on the statistical distributions of both datasets. $R_{Spearman}$ varies between -1 and +1 with 0 implying no correlation, -1 and +1 implying instead an exact decreasing and increasing monotonic relation between ranked variables, respectively. The monotonicity does not imply any specific functional variation (like the linear one in the Pearson correlation coefficient); then, if the two variables change together, but not necessarily at a constant rate, the correlation between them will not be affected.

$R_{Spearman}$ values have been calculated from joint probability distributions (JPDs) between binned N_e and T_e observations (Figure 1). For each N_e bin (on x-axis), the mean and standard deviation of T_e values (on y-axis) conditioned by N_e are calculated (black points and error bars, respectively, in Figure 1). Eq. (1) is applied to mean conditioned T_e values to obtain the corresponding $R_{Spearman}$ value.

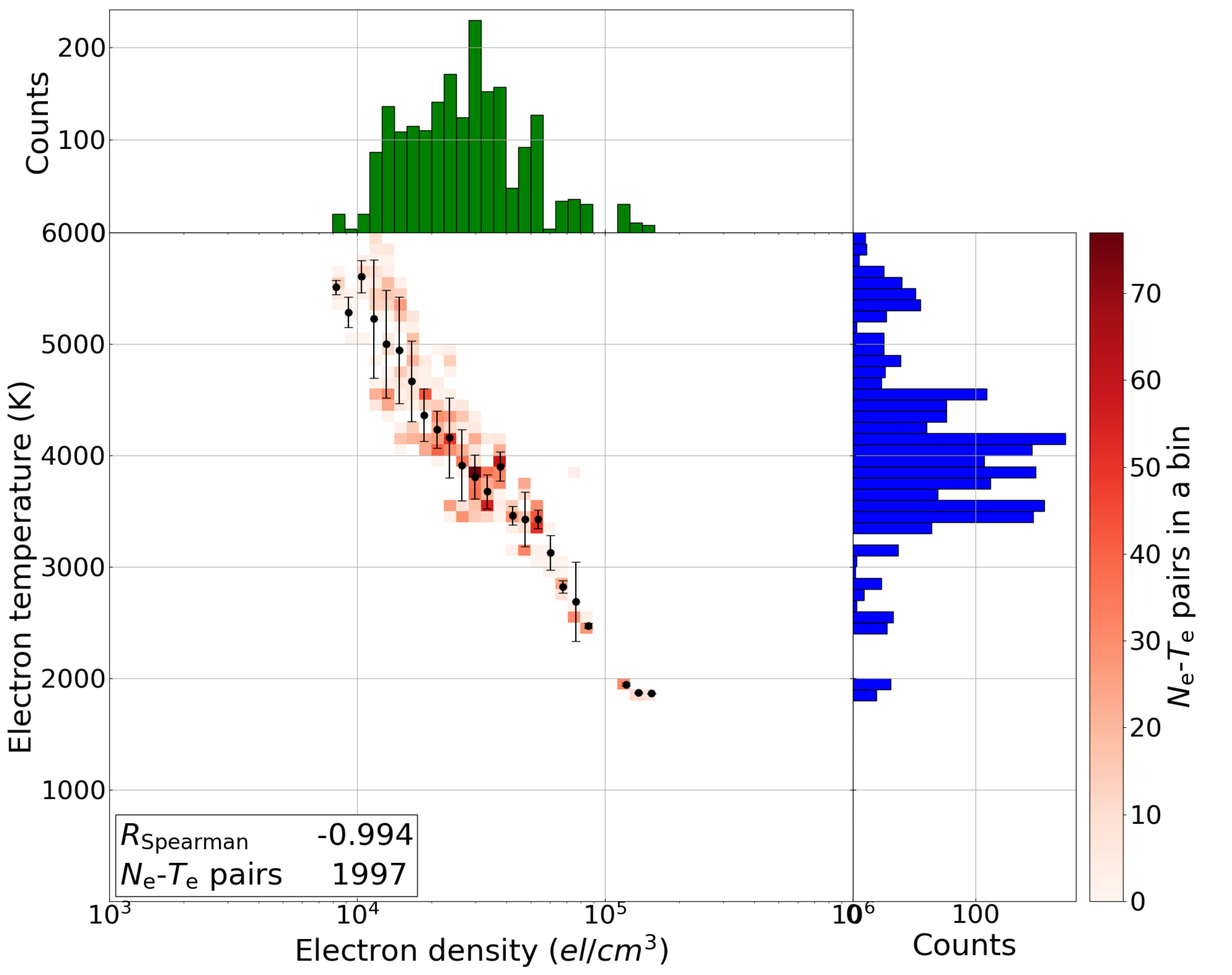

Figure 1. JPD between N_e (x-axis) and T_e (y-axis) observations by Swarm B for the Equinoxes, MLT = [05:44; 05:48), QD latitude = [0°; 1°). The number of (N_e,T_e) pairs of each bin is represented in scale of reds; N_e and T_e statistical distributions are represented in green and blue, respectively. Mean and standard deviation of conditioned T_e values are represented as black points and error bars, respectively. Calculated $R_{Spearman}$ value is highlighted in the bottom left legend, along with the number of total N_e - T_e pairs.

Results

The calculated $R_{Spearman}$ values are represented as maps in MLT and QD-latitude coordinates, for each season, to highlight the corresponding diurnal, latitudinal, and seasonal variations. Maps of $R_{Spearman}$ values are reported in Figure 2 in a planar global view, and in Figure 3 in a polar representation (from -50° to the South pole) for the Southern hemisphere. In the same Figures, we also represent the mean values of N_e and T_e to facilitate the discussion of correlation main patterns.

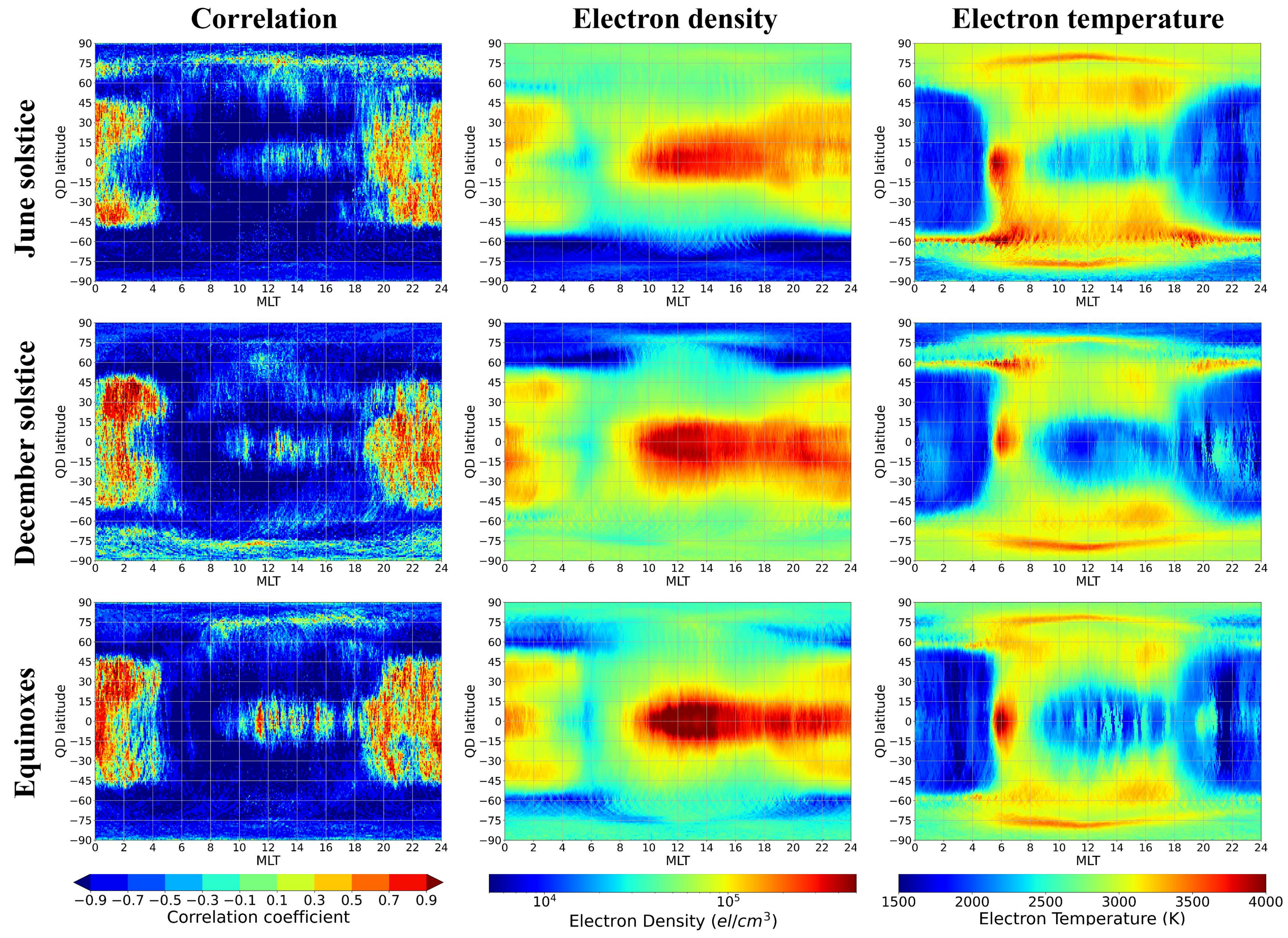

Figure 2. Maps of $R_{Spearman}$ correlation coefficient (first column), N_e mean values (second column), and T_e mean values (third column), obtained through observations collected by Swarm B in the period 2014–2021. First row are for the June solstice, second row for the December solstice, third row for the Equinoxes. Each map is in MLT (x-axis) vs. QD latitude (y-axis) coordinates.

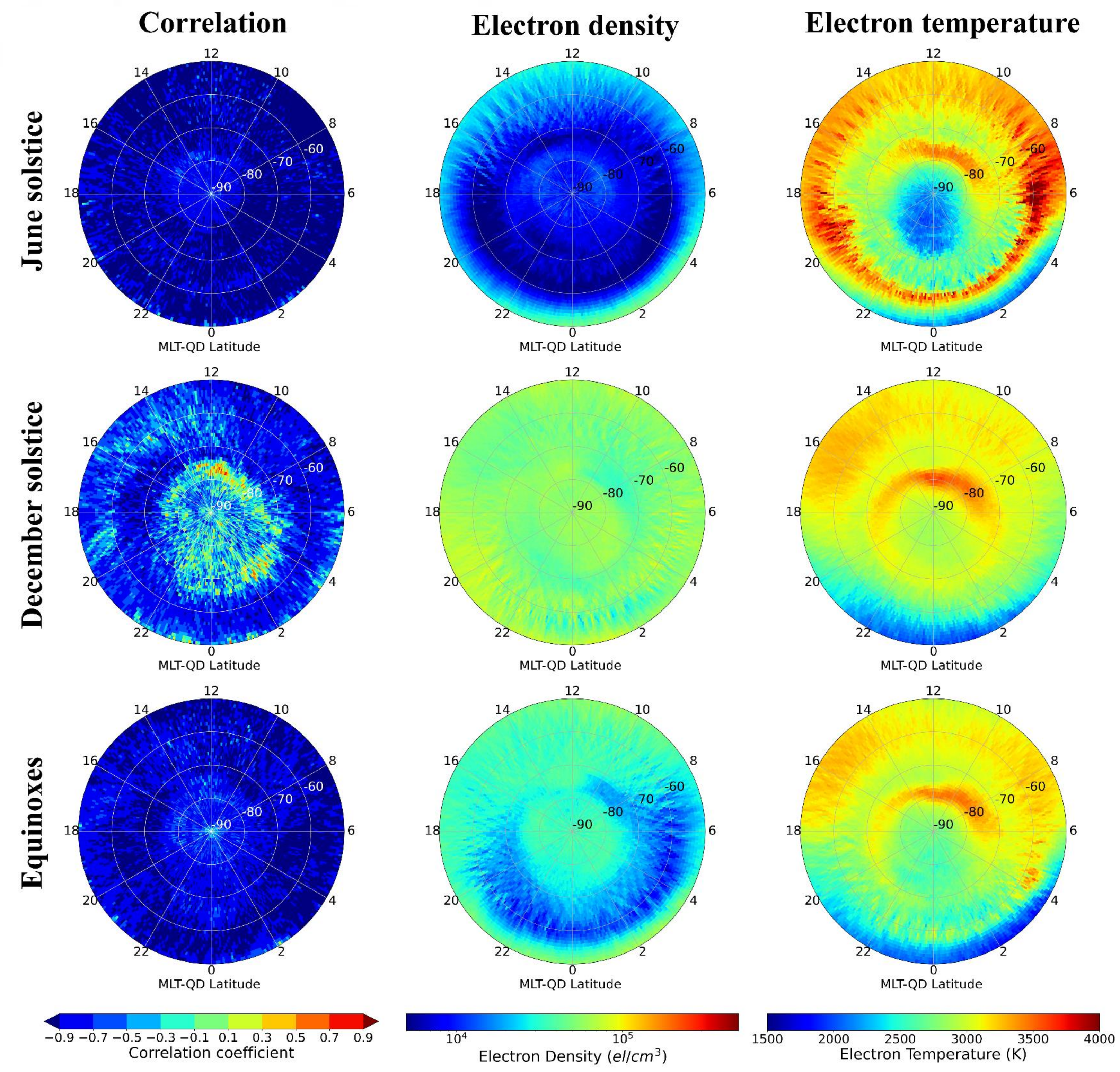

Figure 3. Same as Figure 2 but in a Southern hemisphere polar representation with MLT in azimuth and QD latitude in radius (from -50° to -90°).

Conclusions

The characterization of the correlation between N_e and T_e at high latitudes, along with the description of the diurnal and seasonal trends at all latitudes, are the new findings brought by this study. The results point out a negative correlation at the morning overshoot at equatorial latitudes, during daytime at mid latitudes, and during night-time at the ionospheric trough auroral latitudes. Conversely, a positive correlation dominates the night-time hours at mid and low latitudes, and to a minor extent the low latitudes from 09 MLT onwards. A seasonal dependence of the correlation is visible only at very high latitudes where the general pattern of anti-correlation is broken around ±75° in the Summer season.