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Identifying possible Stratification phenomenon in ionospheric F2 Layer using the data observed by the Demeter satellite: Method and Results

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Abstract: Many studies have revealed the stratification phenomenon of the topside ionospheric F2 layer using ground-based or satellite-based ionograms, which can show direct signs of this phenomenon. However, it is difficult to identify this phenomenon using the satellite-based in situ electron density data. Therefore, a statistical method, using the shuffle resampling skill, is adopted in this paper. For the first time, in situ electron density data, recorded by the same Langmuir probe onboard the Demeter satellite at different altitudes, are analyzed and a possible stratification phenomenon is identified using the proposed method. Our results show that the nighttime stratification, possibly a permanent phenomenon, can cover most longitudes near the geomagnetic equator, which is not found from the daytime data. The arch-like nighttime stratification decreases slowly on the summer hemisphere and thus extends a larger latitudinal distance from the geomagnetic equator. All results, obtained by the proposed method, indicate that the stratification phenomenon is more complex than what has previously been found. The proposed method thus is an effective one, which can also be used on similar studies of comparing fluctuated data.

Key words: stratification, ionospheric F2 layer, in situ electron density, Demeter satellite, significance test

1 Introduction

Stratification of the F2 layer, an enhancement in electron density at heights above the F2 layer maximum in the ionosphere at low latitudes and mid-latitudes, was first reported in the mid-twentieth century (Heisler, 1962; Sen, 1949; Skinner et al., 1954). Sayers et al. (1963) was then the first to detect topside ledges in the equatorial ionosphere using a Langmuir probe onboard the Ariel-I satellite and predicted that the topside ionograms would reveal the ledges as cusps, as later proved by many studies using the topside sounding technique (Lockwood & Nelms, 1964; Raghavarao & Sivaraman, 1974; Sharma & Raghavarao, 1989).

There were few studies of the stratification phenomenon until the mid-1990s. Balan and Bailey (1995) then explained the formation mechanism of the F3 layer using the SUPIM (Sheffield University Plasmasphere–Ionosphere Model). They referred to the layer as G layer and was later renamed as F3 layer because it has the same chemical composition as the F region (Balan et al., 1997). Since then, many more studies on the mechanism and spatial and temporal distributions of the phenomenon have been carried out (Batista et al., 2002; Depuev & Jenkins, 1997; Depuev & Pulinets, 2001; Hsiao et al., 2001; Rama Rao et al., 2005; Tardelli et al., 2016; Uemoto et al., 2007; Zain et al., 2008; Zhao et al., 2011a, 2001b).

However, most research has used ionograms or total electron content data recorded on the ground (Balan et al., 1998; Bastica et al. 2002; Jenkins et al., 1997; Nayak et al., 2014; Rama Rao et al., 2005; Zhao et al., 2011a), where the distribution features of the stratification phenomenon cannot be obtained because only data of discontinuously distributed observation stations can be used. Studies on the stratification of the F2 layer at the topside ionosphere were therefore carried out using sounding techniques onboard low-Earth-orbiting satellites (Karpachev et al., 2012; Thampi et al., 2005; Uemoto et al., 2004, 2006; Zhao et al., 2011b). Topside ionograms can reveal the occurrence of the F3 layer when the peak electron density of the F3 layer, namely N_mF_3, is smaller than N_mF_2, which cannot be observed using an ionosonde on the ground. However, the short-term global scale distribution of the stratification phenomenon still cannot be obtained from satellite-based ionograms even though such ionograms can provide more data because the obtained data are still discontinuous.

In addition, nearly all the above-mentioned F2 layer stratification studies were carried out using indirect observation data, in which case some detailed information may be missed. A method therefore is proposed in this paper, which can compare the in situ electron density data obtained at different altitudes and identify their differences. Based on this method, the in situ electron density data, recorded by the Demeter satellite at the topside ionosphere, is used to study the stratification phenomenon, enabling us to investigate the characteristics of the global-scale distribution and other information about the stratification phenomenon.

The result that the electron density observed at higher altitude is greater than that observed at lower altitude suggests a stratification phenomenon distributed in a large area. This result was obtained using in situ electron density data obtained before and after an altitude adjustment of the Demeter satellite in a relatively short time, which is the first direct comparison of in situ data recorded by the same instrument but at different altitudes. The results of the distribution features of this phenomenon, obtained by the proposed method, are in accord with those obtained by previous studies, but some features also suggest that the stratification phenomenon is more complicated than previously found, thus demonstrating that the proposed method is effective.

2 Data and Method

2.1 Data

The data used in this study were obtained from Demeter (Detection of Electro-Magnetic Emission Transmitted from Earthquake Regions), a French micro-satellite operated by CNES (Centre National d’Etudes Spatiales) and devoted to the investigation of ionospheric disturbances due to seismic, volcanic and tsunami activities. The Demeter satellite was launched in June 2004. Observation data were recorded from the end of November 2004 to December 2010. Owing to its specific orbit, Demeter is always located at about 10:30 or 22:30 local time. The satellite made continuous measurements between invariant latitudes of −65° and +65°. The ISL (Instrument Sonde de Langmuir) is one of the five scientific payloads and recorded in situ data of the electron density, ion density and electron temperature (Lagoutte et al., 2006; Lebreton et al., 2006).

The Demeter satellite adjusted its flying altitude in its initial flight stage and between the end of 2005 and the beginning of 2006, as shown in Fig. 1, which presents the average flight altitude of the ascending (nighttime) and descending (daytime) orbit between southern and northern geographical latitudes of 50° from November 17, 2004 to December 31, 2006.

The history of the altitude of the satellite can be divided into four stages.

(1) The altitude of the satellite was not fixed but varied between about 703 and 725 km from

November 17, 2004 to March 10, 2005.

(2) The average orbital altitude was fixed at around 709 km after March 10, 2005.
(3) The average altitude was adjusted to approximately 677 km from January 1 to 9, 2006.
(4) The altitude was fixed at an average value of about 669 km from January 14, 2006.

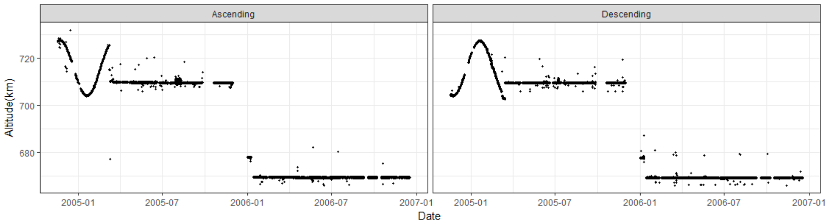

Fig. 1 Average altitude of the Demeter satellite from November 2004 to December 2006

The data recorded by the Demeter satellite before and after its altitude adjustment provide an opportunity to study the vertical gradients of electron density in a small height range of the topside ionosphere using in situ electron density data recorded by the same instrument. Since the altitude of the satellite was not fixed at a constant value from November 2004 to March 2005, and there was no data in December 2005, data recorded before and after the adjustment at the beginning of 2006 are selected in the study; during this periods, the orbit altitude was respectively fixed at 677 and 669 km.

The geomagnetic index Dst and the solar activity index F10.7 in January 2006 are presented in Fig. 2. The figure shows geomagnetically quiet days from January 1 to 25, 2006, and the F10.7 index of solar activity before altitude adjustment was roughly equal to or smaller than that after the adjustment. Therefore, data from January 1 to 25, 2006 will be used in this paper, because the differences in geomagnetic and solar influences are negligible during this period.

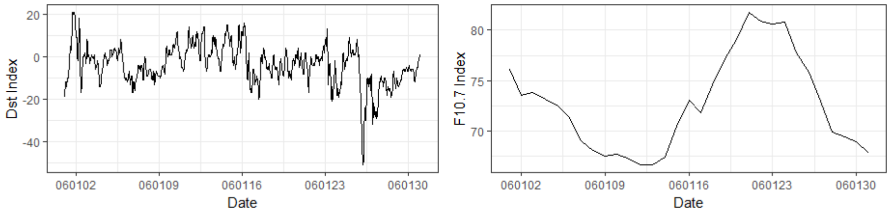

Fig. 2 Geomagnetic index Dst and solar activity index F10.7 in January 2006

Many studies have shown that the electron density in the F2 layer is characterized by periodic changes in the diurnal, seasonal, annual and solar activity cycles and fluctuations due to other random factors, such as geomagnetic storms and sunspot eruptions. Issues therefore need to be addressed before carrying out this study.

As mentioned above, the local time that the Demeter Satellite passed over a location was roughly fixed at about 10:30 in the morning and about 22:30 in the evening, which means that diurnal changes in the data can be ignored when comparing the data before and after the altitude adjustment at the same place because the local time is consistent. Another issue, which is the focus of this study, is that when the electron density data are recorded over a relatively short time under quiet observation conditions, say a few days, variations due to the long-period trend in the data (e.g., seasonal and annual variations) can be ignored, that is to say, the data observed in a few days is usually similar to that observed a few days ago.

Against this background, the data, observed before and after the altitude adjustment of the Demeter satellite in a relatively very short time, are compared and analyzed by seeking a suitable mathematical method.

2.2 Method

The electron density is known to dynamically change both spatially and temporally. It is therefore uncertain that the difference before and after the adjustment of the orbital altitude is the result of normal data fluctuation or the result of the altitude adjustment. It is necessary to design a reasonable scheme with which to distinguish the cause of the difference.

A significance test is a statistical method of determining whether the difference between two groups of data is significant. Employing this method, if the *p*-value, the probability that a given result occurs under the null hypothesis of no difference between the two groups, is less than a predefined significance level, then the null hypothesis is rejected at the chosen level of significance and the alternative hypothesis of a difference between the two groups is accepted. However, if the *p*-value is not less than the chosen significance threshold, then the evidence is insufficient to support a conclusion. Significance tests can therefore be conducted to determine whether the difference between before and after the adjustment of the altitude can be ascribed to the randomness of the data variation. If not, it may be caused by the altitude adjustment because all the other conditions are the same.

However, the significance test assumes data to be normally distributed, which the electron density data are not. This paper thus conducts a permutation test (Hesterberg et al., 2003), a distribution-independent computer simulation approach of resampling advised by Fisher and Yates (Wikipedia).

The basic idea of the permutation test is to resample the data many times to check whether the same pattern of results is observed if the observation data are randomly assigned to experimental groups. If the statistics calculated from the obtained data fall outside the confidence limits, say 95%, the observed difference is far out in the left or right tail, and one can conclude that there is a significant difference between the groups. A permutation test is based on available data rather than a set of standard assumptions about underlying populations. It is therefore distinct from traditional statistics and can give accurate *p*-values with which to check the significance of the difference between two data groups.

We therefore adopt the permutation test method to compare the data observed at different altitudes by the Demeter satellite, and to check whether the differences between the data observed at different altitudes are significant. Using this method, the general process of data analysis in this study is as follows.

(1) Construct data groups using the data observed before and after the altitude adjustment, or data observed at same altitude.
    - Divide the area covered by the satellite orbit between latitudes of 50° south and 50° north into cells of 5° latitude and 10° longitude.
    - Calculate the mean electron density before and after the adjustment of altitude in each cell.
    - Divide the data into different regions every 5° latitude and obtain 20 regions from 50° south to 50° north in the latitudinal direction.

(2) Compare the data groups constructed from observation at different altitudes and check

the significance of their differences by employing the permutation test method.

(3) Compare the data groups constructed from observation at similar conditions but with same altitude and check the significance of their differences as a reference.

(4) Draw conclusions by analyzing different results.

A uniform significance level of 0.05 and one-side test are adopted in this paper, and no special explanation is given in the following.

3 Data comparison

3.1 Data construction

According to Section 2.1, the data obtained from January 1 to 25, 2016 is selected to carry out the analysis. During this period, the data from January 1 to 9 was obtained before the altitude adjustment, and the data from January 14 to 25 was obtained after the altitude adjustment. In addition, the geomagnetic and solar activity indices were every low during this period; that is, the data obtained before and after the altitude adjustment were measured under similar observation conditions.

In order to construct the data groups for comparison, a scheme is designed to divide the data into different groups. Ascending data (data recorded during the night) from January 1 to 8 and from January 15 to 23, 2006, are both divided into two groups, to give a total of four groups of data with each having equal observation days. Details of the grouping are given in Table 1.

Table 1 Grouping information of the data from January 1 to 23, 2006

Group No.	Date of observation	Average Altitude	Altitude Adjustment
Group 1	1, 2, 3, 4	677.76km	Before
Group 2	5, 6, 7, 8	677.78km	Before
Group 3	15, 16, 17, 18	669.34km	After
Group 4	20, 21, 22, 23	669.33km	After

Based on this grouping scheme, comparative data are constructed using the cells of 5° in the latitudinal direction and 10° in the longitudinal direction as mentioned in section 2.2. The average value of the recorded data in each cell is computed using data from Group 1 to Group 4; there are thus 36 cells × 4 groups of data for each latitudinal region. Data analysis involves comparing the data between groups in each latitudinal region, including both the cases of data comparisons between different altitudes and between the same altitudes.

3.2 Comparison in one latitudinal region

The four groups of data, in the region of geographical latitude −5° to 0°, are compared with each other as a demonstrative example of the proposed method.

In order to determine the differences between two groups of data are caused by random data fluctuation or by altitude differences, significance tests are carried out for each pair of groups using the improved Fisher–Yates permutation test method (Durstenfeld, 1964), in which the distribution of the mean data difference is obtained by resampling the data 10,000 times. The actual mean data differences of each pair of groups are then compared with the 5% confidence level of the corresponding distribution.

The significance test results of each pair of groups using the data located in geographical latitude (−5, 0) are shown in Fig. 3, and the corresponding permutation test *p*-values are given in

Table 2.

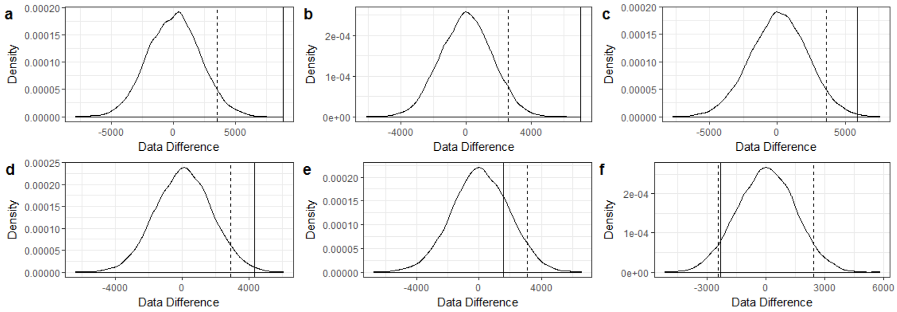

Fig. 3 Density distributions of the mean difference obtained in the permutation test

(The dashed line is the mean difference corresponding to the 5% confidence level while the solid line is the observed mean difference between two groups. The lower 5% confidence level is also shown for f because the data difference is negative. Here, a is the permutation test result for Groups 1 and 3; b, Groups 2 and 3; c, Groups 1 and 4; d, Groups 2 and 4; e, Groups 1 and 2; f, Groups 3 and 4.)

Table 2 Permutation test results of ascending data at a geographical latitude of −5° to 0°

Latitude region	Group1-3		Group 2-3		Group 1-4		Group 2-4		Group 1-2		Group 3-4	
	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p
(-5,0)	8797.95	0.0000	7031.11	0.0000	5909.50	0.0025	4325.02	0.0049	1584.48	0.2136	-2312.43	0.0593

(M_{Diff} represents the mean of differences between two groups, while *p* is the probability that the mean data difference calculated in the permutation simulation is greater than the observed M_{Diff} if it is positive or less than the observed M_{Diff} if it is negative.)

In Fig. 3, the solid lines represent mean values of data differences before and after the altitude adjustment in each cell:

$$M_{Diff} = \frac{1}{N}\sum_{i=1}^{N}(B_i - A_i) = \frac{1}{N}\sum_{i=1}^{N}B_i - \frac{1}{N}\sum_{i=1}^{N}A_i. \qquad (1)$$

Here, N is total number of cells in each latitude region, B is the average value in cell i before altitude adjustment, and A is the average value in the same cell after the adjustment. Equation (1) shows that the mean value of data differences is equal to the data difference between average values of all cells before and after the adjustment. Therefore, mean values of data differences can be calculated using two average values. As shown in Fig. 3, the data differences, between the average data in the two groups in random permutation tests conducted 10,000 times, follow a normal distribution with a mean value of zero, and the probability of the occurrence of the original data difference is zero or extremely small, which indicates that data recorded before the adjustment in most cells are obviously greater than those recorded after the adjustment because the mean differences are much greater than zero.

Figure 3 and Table 2 show that the differences between Groups 1 and 3, Groups 2 and 3, Groups 1 and 4, and Groups 2 and 4, representing the differences before and after the adjustment of altitude, are significant because the *p*-values are zero or close to zero, much less than the predefined significance level of 5%. This means that the likelihood of observing the actual data difference given that the two groups have no difference is unlikely. Therefore, the null hypothesis of no difference can be rejected, and significant difference between the two groups is determined. Meanwhile, the *p*-values of Groups 1 and 2 and Groups 3 and 4, representing differences at the same altitude before and after the adjustment respectively, are greater than the predefined significance level, which means the difference between the two groups is not significant and the hypothesis of no difference between the two groups cannot be rejected.

The permutation test results of data at different altitudes and data at similar altitudes show a significant contrast, indicating that the significant differences between the data before and after the adjustment are by no means accidental but due to potential causes. Moreover, an interesting point is that the electron density data recorded at higher altitude is higher than that of lower altitude because all differences (i.e., values before adjustment minus values after adjustment) are positive, different from the normal attenuation law at the topside ionosphere, which implies the possible stratification phenomenon during the selected time segment.

3.2 Comparison in all latitudinal region

Obvious difference between the data groups in one latitudinal region show some information. To obtain the distribution of this significant difference, permutation test results for the 20 regions from 50° south to 50° north in geographical and geomagnetic latitude (where the geomagnetic latitude refers to the dipole coordinates given in the Demeter satellite dataset) are obtained, and the variations of *p*-values with latitude are presented in Fig. 4. Table 3 only gives the permutation test results in geomagnetic latitudes because the results calculated from geographical latitudes are similar to those of geomagnetic latitudes.

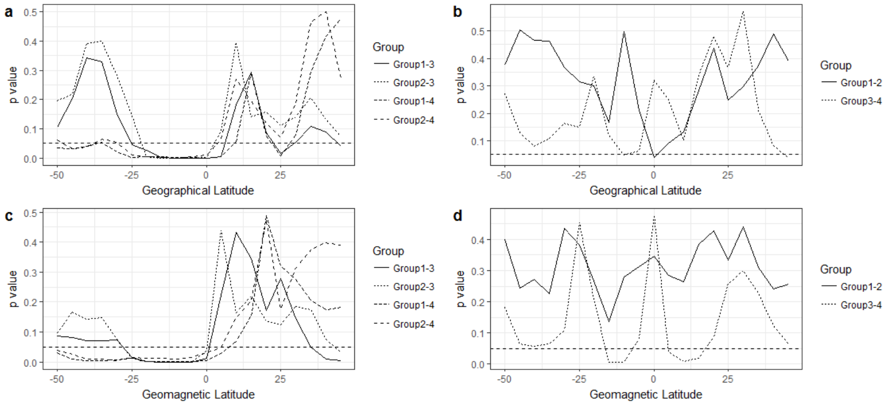

Fig. 4 Variations of *p*-values with geographical/ geomagnetic latitude

Table 3 Permutation test results of ascending data in the 20 geomagnetic latitude regions

Latitude region	Group1-3		Group 2-3		Group 1-4		Group 2-4		Group 1-2		Group 3-4	
	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p	M_{Diff}	p
45,50	-2258.44	0.0040	-1717.80	0.0299	-839.74	0.1835	-299.10	0.3889	-540.64	0.2569	1418.71	0.0639
40,45	-1950.41	0.0091	-1335.83	0.0770	-903.82	0.1739	-289.24	0.3966	-614.58	0.2418	1046.59	0.1243
35,40	-1184.69	0.0507	-810.07	0.1748	-718.42	0.2075	-343.80	0.3748	-374.62	0.3093	466.27	0.2284
30,35	-868.94	0.1464	-770.15	0.1845	-473.54	0.2745	-378.75	0.3120	-98.79	0.4401	279.48	0.2990
25,30	-578.48	0.2779	-822.49	0.1246	-372.14	0.3199	-585.42	0.1744	213.29	0.3327	324.59	0.2562
20,25	-901.29	0.1727	-975.20	0.1385	-28.67	0.4882	-72.08	0.4747	43.41	0.4284	966.15	0.0866
15,20	-600.00	0.3450	-986.37	0.2207	1347.41	0.1533	961.04	0.2034	386.37	0.3848	1947.41	0.0185
10,15	-269.15	0.4330	-1374.58	0.1644	2329.54	0.0676	1224.11	0.1490	1105.43	0.2632	2598.68	0.0082
5,10	1374.33	0.2236	237.71	0.4381	3227.69	0.0272	2283.55	0.0466	1136.61	0.2854	2253.04	0.0395
0,5	4013.46	0.0112	3112.33	0.0373	4305.87	0.0052	3404.74	0.0302	865.87	0.3455	292.40	0.4765
-5,0	6854.30	0.0000	5875.57	0.0002	4616.65	0.0024	3791.28	0.0150	825.37	0.3137	-1747.23	0.0792
-10,-5	8723.66	0.0000	7919.08	0.0000	4863.00	0.0013	4219.73	0.0107	643.27	0.2788	-3586.31	0.0069

-15,-10	9649.68	0.0000	7727.16	0.0000	5994.04	0.0013	4071.51	0.0129	1922.53	0.1363	-3655.64	0.0069
-20,-15	7437.61	0.0003	6051.83	0.0011	6151.21	0.0017	4279.33	0.0119	1385.78	0.2656	-1481.91	0.2102
-25,-20	4618.32	0.0148	4044.56	0.0118	4679.33	0.0118	3894.36	0.0152	573.76	0.3826	80.28	0.4544
-30,-25	2682.88	0.0741	2609.11	0.0766	4594.21	0.0060	4408.26	0.0056	185.95	0.4363	1884.87	0.1072
-35,-30	2792.20	0.0717	1732.04	0.1484	5047.46	0.0034	3864.55	0.0083	1182.90	0.2264	2257.67	0.0655
-40,-35	2560.95	0.0711	1597.18	0.1422	4972.26	0.0040	4008.49	0.0097	963.76	0.2713	2411.31	0.0564
-45,-40	2449.71	0.0804	1420.34	0.1663	5032.67	0.0086	3779.51	0.0258	1198.12	0.2432	2573.52	0.0640
-50,-45	2701.66	0.0879	2697.81	0.0934	4126.46	0.0300	4025.30	0.0377	94.91	0.4008	1601.15	0.1813

The permutation test results in Figs. 4 and Table 3 have obvious regular distribution patterns.

(1) There are significant differences in data only before and after the adjustment of altitude in continuous latitudinal regions; i.e., there are significant differences in data between Groups 1 and 3, Groups 2 and 3, Groups 1 and 4, and Groups 2 and 4. Meanwhile, the differences between observation data for the same orbital altitude, namely differences between Groups 1 and 2 and Groups 3 and 4, are not obvious and no regular distribution pattern exists in the data.

(2) The data having a statistically significant difference are mainly distributed near the geographical or geomagnetic equator regions, and are more skewed towards the Southern Hemisphere, where the time of the observation data is just summer.

(3) Comparing the distribution of data with significant differences in Figs. 4, it is seen that the distribution is 5° south in geomagnetic latitude, which indicates that this regular distribution of the data with significant differences may be mainly controlled by the geomagnetic latitude, and the regular distribution in terms of the geographical latitude is due to the distribution region in geographical latitude overlapping with regions beside the geomagnetic equator.

(4) Table 3 shows that the data differences change from being positive from lower to higher mid-latitudes in the Southern Hemisphere to being negative in the corresponding latitudes in the Northern Hemisphere, just like an arch extending toward the higher latitudinal direction in both hemispheres, as shown in Fig. 5. This regular distribution cannot be a coincidence, because although most *p*-values in the mid-latitude regions do not reject the null hypothesis of no significant difference between the data observed at different altitudes, the probability that positive differences appear simultaneously in several continuously latitudinal regions (multiplication of the *p* values in each latitudinal region) is extremely low according to the obtained *p*-values, which indicates an underlying control factor. Regarding all differences in the Northern (winter) Hemisphere being negative, this is the normal attenuation pattern of the F2 layer.

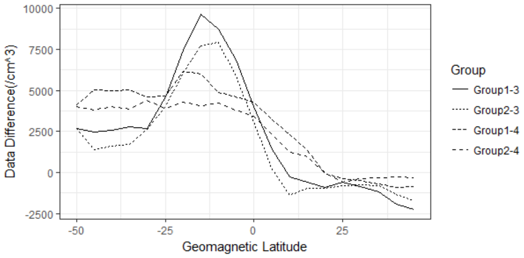

Fig. 5 Variations of data differences with geomagnetic latitude

The distribution characteristic, that data with significant differences are distributed in the vicinity of the geomagnetic equator, is consistent with the regions where stratification of the F2 layer has been found in many studies, and the stratification phenomenon can exactly explain the electron density at higher altitude being greater than that at lower altitude.

Figure 6 presents all the regular patterns summarized above using the average electron density data of the four groups before and after altitude adjustment in each latitudinal region. The figure shows that the curves of the average electron density data vary with latitude, with the maximum differences being located at about 10 in the southern hemisphere.

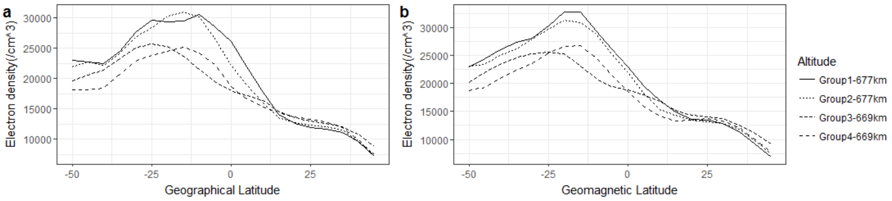

Fig. 6 Variation of the average ascending electron density with latitude

Figure 6 shows that the difference between the two groups of data before the adjustment of the orbital altitude, namely Groups 1 and 2, is small while the difference between the two groups after the adjustment, namely Groups 3 and 4, is also small. However, when comparing the four groups together, obvious differences between the groups before and after the adjustment are seen in the vicinity of a geographical latitude of −10° or a geomagnetic latitude of −15°. Moreover, the difference is more pronounced in the Southern Hemisphere than in the Northern Hemisphere. Although the greater data fluctuations in the summer Southern Hemisphere are a cause of this phenomenon, the regular distribution cannot be explained by random fluctuation in the data.

3.4 Reference Comparisons

To further demonstrate that the phenomenon found above is caused by non-random factors, several sets of data other than the above mentioned data are constructed to compare whether the same regular distribution patterns can be found.

1. Descending data for the same period

The permutation test results of descending data, data recorded during the day, are calculated according to the grouping information in Table 1. The results show that there are both cases of significant differences and insignificant differences between the data observed at different altitudes and between the data observed at same altitudes. Variations in the average electron density with latitude are given in Fig. 7. The figure clearly shows that the observation data for the same altitude during the day fluctuate greatly and there are no consistent regularities among different data groups. Therefore, although there are cases that a higher altitude has higher electron density, a definite conclusion cannot be drawn from these descending data.

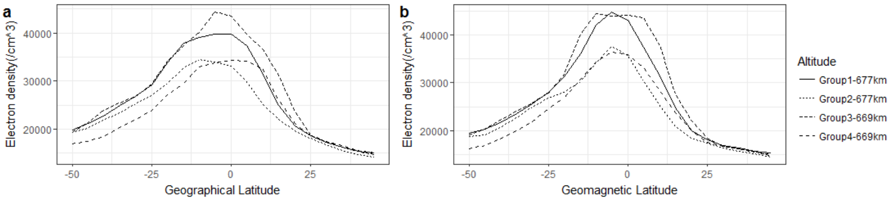

Fig. 7 Variation of the average descending electron density with latitude

2. Ascending data in different periods

Besides the above analysis, groups of reference data are also calculated to further confirm that the regular distributions in Fig. 4 are not accidental. Because there were small geomagnetic storms in January 2007 and 2008, only data in 2009 and 2010 are used here for comparison. Data groups, with the same geomagnetic and grouping conditions and using the ascending data (data observed during nighttime) for 2009 and 2010, are calculated using the permutation test method. Figures 8 and 9 show the variations of ascending electron density data with geographical/ geomagnetic latitude using the data recorded in 2009 and 2010 respectively; no obvious differences are found from these data. Therefore, the significant differences shown in Figs. 4 are not coincidental.

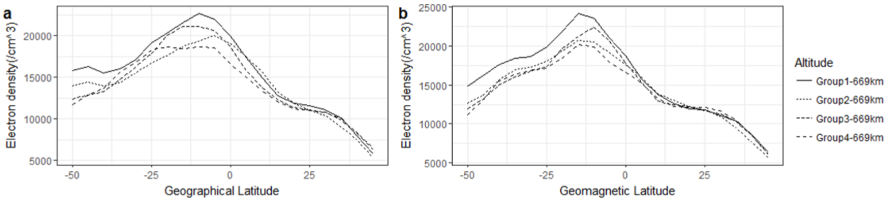

Fig. 8 Variation in the ascending electron density with latitude obtained using data for 2009

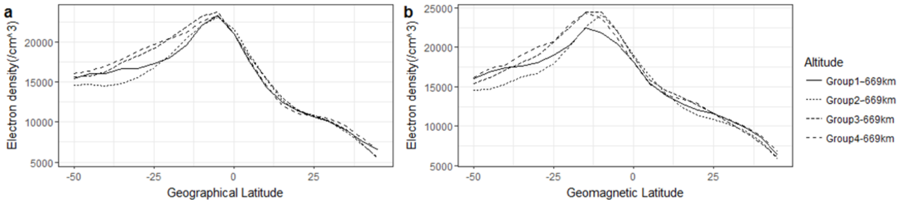

Fig. 9 Variation of the ascending electron density with latitude obtained using data for 2010

4 Discussion

We conclude from the above data analysis that the phenomenon that the in situ electron density observed at higher altitude is greater than that observed at lower altitude and that significant differences are distributed regularly in the vicinity of the geomagnetic equator on a global scale, is the stratification phenomenon of the F2 layer. Although the data were not recorded at the same time, the data variation can be neglected because the time interval is short and observing conditions are similar.

According to the data grouping and calculation method, if the phenomenon is only due to random data fluctuation, the possibility that this phenomenon appears only for data recorded at different altitudes and at several latitudinal regions in the vicinity of the geomagnetic equator at the same time is extremely low. Moreover, the same regular distribution from data recorded at other times with similar grouping conditions cannot be observed. The possibility that the regular data distribution is due to random factors can therefore be excluded definitely.

In addition, the significant difference between two data groups before and after the altitude adjustment near the geomagnetic equator region indicates that most data in the 36 cells in each latitudinal region have a significant difference. It is thus deduced from the data that the stratification phenomenon in the F2 layer covers a large longitudinal area near the geomagnetic equator region. This is different from the conclusion of those studies (Balan et al., 1998; Rama Rao et al., 2005; Zhao et al., 2011a) that the phenomenon can only be observed at special longitudes, which may be due to the fact that the peak of the stratification is less than that of the

F2 layer in most of the longitudinal area for most of the time, and thus invisible to the ground-based observation.

In fact, the stratification phenomenon has been observed at many locations using ionosonde; e.g., Brazil (Balan et al., 1997, 1998, 2000; Batisca et al., 2002; Jenkins et al., 1997), Southeast Asia (Hsiao et al., 2001; Lynn et al., 2000), India (Rama Rao et al., 2005; Thampi et al., 2005) and China (Jiang et al., 2015), illustrating that the stratification phenomenon is distributed across a large longitudinal area in spite of the scatter discoveries. The study of Zhao et al.(2011b) using long-time satellite-based ionograms also showed that the stratification is distributed in all longitudinal areas along the magnetic equator. The results obtained from the in situ data are thus in accordance with the results of those studies, and further approve that this phenomenon may be continuous distributed along the longitudinal direction. The global scale in situ electron density data of the Demeter satellite observed in a short time provides an opportunity to study the distribution features of the stratification phenomenon, which are difficult to detect through scattered ground-based or satellite-based sounding data.

Section 3 showed that the recording time of the data used in this study, namely the time of the stratification, happened to coincide with the downward cycle of the 23rd solar cycle, when the solar activity was relatively low. The season of stratification found in the data in this study coincided with summer in the Southern Hemisphere, and the stratification was almost entirely located in the Southern Hemisphere in terms of the geomagnetic latitude. These spatial and temporal distribution characteristics, distinct on the summer side of low solar activity, are exactly the same as those of the F2 layer stratification phenomenon obtained in many studies (Balan et al., 1998; Batista et al., 2002; Nayak et al., 2014; Rama Rao et al., 2005; Sharma & Raghavarao, 1989)

As for the local time at which stratification occurs, many studies have suggested that the stratification phenomenon mainly occurs during the day, just as Balan et al. (1998) reported that the F3 layer occurs mainly during the morning–noon period owing to the combined effect of the upward E × B drift and neutral wind that provides upward plasma drifts at and above the F2 layer. However, more and more studies have confirmed the existence of nighttime stratification. Zhao et al. (2011a) studied the post-sunset stratification phenomenon and suggested that the sunset F3 layer should be distinguished from the traditional morning–noon F3 layer. Lockwood and Nelms (1964) suggested that the stratification of the F layer can be observed until about local midnight using the topside sounder data of the ionogram onboard the Alouette satellite. Karpachev et al. (2012) examined the large data set of IK-19 and found that the F3 layer can permanently exist until 02:00–03:00 LT. Nevertheless, the F3 layer is rarely recorded at night.

Depuev and Pulinets (2001) also found midnight stratification and showed that the critical frequency of the nocturnal F3 layer is always essentially lower than f_0F_2. It is thus impossible to observe midnight stratification from the bottom side. They also reported that the real peak height (h_mF_3) of the F3 layer defined by electron density profiles varied from 670 to 730 km. Rama Rao et al. (2005) pointed out that the altitude of the F3 layer is high at the magnetic equator (600–700 km). The altitude of the stratification in these studies is almost the same as the altitudes of the in situ data used in this paper.

Klimenko et al. (2012) suggested that the formation mechanism of additional layers in the equatorial ionosphere is due to the action of the non-uniform in height zonal electric field at the geomagnetic equator, and can happen at any time, which can explain the occurrences of the F3 layer and multilayer at different local times, especially at night.

An interesting point, which has not been discussed in earlier studies, is that all differences in each latitude region on the summer hemisphere are positive though some do not pass a significance test. This consistent distribution cannot be obtained if data fluctuate randomly. We therefore speculate that this feature may be related with the stratification phenomenon and small stratification may exist in the summer hemisphere a little distance away from the traditional geomagnetic equator region of stratification.

Summarizing the above discussions, we believe that the results obtained in this paper are the stratification phenomenon in the ionospheric F2 layer, and the proposed method is effective. The results of this method indicate that the stratification phenomenon may extend to a larger area in the summer hemisphere, but it is difficult to detect because the differences are small. The distribution features obtained by the data analytic results also indicate that the stratification phenomenon is more complex than what has been found previously.

5 Conclusion

To compare the in situ electron density data observed by the Demeter Satellite at different altitudes, a statistical method, using the permutation resampling skill, is adopted and used to carry out the data comparison and analysis work. The results of 10,000 permutation tests, using the ascending data (data observed during nighttime) obtained before and after the altitude adjustment, show that there are significant differences between data recorded at different altitudes near the geomagnetic equator, but no significant differences can be found from the multiple reference datasets. The stratification phenomenon can explain the regular distribution patterns summarized from the data analytic results. In addition, the location, altitude, season and local time of this phenomenon are accordance with the results of many studies on the F2 layer stratification phenomenon. We therefore believe that the significant difference between the observations of the Demeter satellite at different altitudes is the stratification phenomenon, and the proposed method is effective and applicable to similar data analytic studies.

Some features of the stratification phenomenon can also be summarized from the data analysis results.

1. The possible stratification phenomenon is found from the nighttime data but cannot be obtained from the corresponding daytime data, though many studies have pointed out that this phenomenon occurs mainly during the day, which implies the nighttime stratification may be a permanent phenomenon.
2. The phenomenon can occur in most longitudinal regions, which is not in accordance with the finding of studies that the phenomenon can only appear in special longitudinal regions. This may be due to the peak of the stratification being less than f_0F_2 in most longitudinal regions for most of the time.
3. The significance of differences decreases with latitude away from the geomagnetic equator, indicating that the stratification is just as an arch along the latitude.
4. Data differences, all of which are positive at lower to higher mid-latitudes in the summer hemisphere, indicate that the latitudinal extent of the stratification phenomenon is much larger in the summer hemisphere than the winter hemisphere and small stratification may exist away from the traditional stratification region. Stratification phenomenon is more complex than what has previously been found.

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