Longitudinal variations in thermospheric parameters under summer noontime conditions inferred from ionospheric observations: A comparison with empirical models

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Longitudinal variations in the thermospheric neutral composition ([O] and [N₂]) and exospheric temperature Tex have been inferred from June monthly median noontime fF₁ and fF₂ observations at mid-latitudes to check for consistency with empirical MSIS models. In general, a similarity in longitudinal variations has been demonstrated, and this is interesting, as similar variations were obtained with very different methods and different data sources. Both inferred and MSISE-00 modelled height-integrated O/N₂ ratios are comparable to TIMED/GUVI observations only under solar minimum conditions but differ substantially under high solar activity. The retrieved height-integrated O/N₂ ratio longitudinal variations are small (∼15%) in comparison to the observed NMF₂ variations under high solar activity. The height-integrated O/N₂ ratio cannot be incorporated into the F₂-layer formation mechanism; therefore, such observations cannot be used for any quantitative interpretation of NMF₂ variations.

Ionospheric parameters during the daytime reflect the state of the surrounding thermosphere and the intensity of incident solar extreme ultraviolet (EUV) radiation; therefore, thermospheric and ionospheric parameters should demonstrate consistent spatial variations. However, historically, global ionospheric IRI1 and thermospheric models, for instance, MSISE-00 empirical model, have been developed independently of each other, and there is no certainty in their consistency. A direct use of the MSIS model to calculate electron concentration in the ionospheric F region may give unsatisfactory results, and model parameters must be corrected to fit the observed NMF₂ (electron concentration in the F₂-layer maximum) under specific geophysical conditions3–7. Existing global first-principle (physical) models cannot yet compete with empirical models for many reasons8,9 and cannot answer the question of consistency between thermospheric models and ionospheric observations.

A recently developed method10 solving an inverse problem of aeronomy allows us to retrieve a consistent set of main aeronomic parameters responsible for the formation of the daytime mid-latitude ionospheric F-region. Using observed near noontime fF₁ and fF₂ (critical frequencies of the F₁ and F₂ layers, respectively, related to an electron concentration of Ne = 1.24 × 10⁴ cm⁻³) and the standard indices of solar (F₁₀.7) and geomagnetic (Ap) activity as the input information, the method10 provides a neutral composition ([O], [O₂], and [N₂]); exospheric temperature Tex; vertical plasma drift W, which may be converted into effective thermospheric meridional wind Vnx; and total solar EUV flux, with λ ≤ 1050 Å. The inferred aeronomic parameters determine plasma production, as well as its dynamics and recombination at F-region heights. Thus, by solving the inverse problem of aeronomy, we have an opportunity (via the inferred thermospheric parameters) to check the consistency between the observed longitudinal variations in ionospheric parameters (fF₁ and fF₂) and modern empirical thermospheric parameters.

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models. Unlike recent analyses of longitudinal variations dealing with integrated thermospheric characteristics, such as neutral gas density\(^1^1\) or height-integrated O/N\(_2\) ratio\(^1^2\), the proposed method provides individual thermospheric parameters ([O], [O\(_2\)], and [N\(_2\)]). The electron concentration in the maximum of the F\(_2\)-layer (NmF\(_2\)) depends on individual [O] and [N\(_2\)] concentrations rather than on the height-integrated O/N\(_2\) ratio, as is suggested in some publications\(^1^3\). In the beginning of the space era, thermospheric neutral composition ([O] and [N\(_2\)]) was measured with mass-spectrometers, and these two species were shown to demonstrate different spatial variations\(^1^4\).

The aims of the paper may be formulated as follows:

(a) To analyse longitudinal variations in available noontime monthly median foF\(_1\) and foF\(_2\) observations for June under solar minimum and maximum conditions;
(b) To retrieve thermospheric parameters from foF\(_1\) and foF\(_2\) observations and to analyse their longitudinal variations in comparison with the empirical thermospheric models to check the consistency between them;
(c) To discuss the physical mechanism of the longitudinal variations in thermospheric and ionospheric parameters under June noontime conditions while considering the inferred neutral composition and recent height-integrated O/N\(_2\) ratio observations.

Method

The method used in our analysis was described in a previous paper\(^1^0\). It is based on solving an inverse problem of aeronomy. The idea is to use routine ground-based foF\(_1\) (or f\(_{0180}\) - plasma frequency at a 180 km height) and foF\(_2\) near-noontime observations to find a consistent set of main aeronomic parameters responsible for the F-region formation under given geophysical conditions. The method has two versions that are used depending on the available input information. As long as we consider historical monthly median ionospheric observations, only summer foF\(_1\) data are available, and we use June foF\(_1\) observations when the F\(_1\) layer is distinct on ionograms and gaps in the data are practically absent. Historical monthly median electron density profiles Ne(h) used to read f\(_{0180}\) are absent. Daytime (10–14 LT) monthly median NmF\(_2\) and NmF\(_1\) observed by the worldwide ground-based ionosonde network in the Northern Hemisphere were used in our analysis. Such observations are available for 50–70 years at some stations.

By solving continuity equations for the main ionospheric ions and applying the method of multi-parametric optimization\(^1^5\), it is possible to fit the calculated NmF\(_2\) and NmF\(_1\) to the observed ones and to infer factors for the MSIS-86 model exospheric temperature Tex, neutral composition ([O], [O\(_2\)], and [N\(_2\)]), and the total solar ionizing EUV flux with \(\lambda \leq 1050\) Å from the model\(^1^6\). Under known neutral composition and temperature, the vertical plasma drift W can be obtained by fitting the calculated NmF\(_2\) to the observed one. In fact, all aeronomic parameters are found simultaneously in the iterations. The method was tested using CHAMP/STAR neutral gas density observations under various geophysical conditions, and it was shown to demonstrate advantages over modern empirical thermospheric models\(^1^0\).

Results

An inspection of available simultaneous foF\(_1\) and foF\(_2\) June noontime observations over the Northern Hemisphere has shown that the largest amount of data was available in 1975, 1976, 1985, and 1986 for the solar minimum and in 1969, 1970, 1980, and 1981 for the solar maximum. Observations at 26 mid-latitude stations (http://spidr.ngdc.noaa.gov/spidr/) were used in our analysis (Table 1).

Observations were grouped by years with solar minima and maxima. Before this grouping, the observed foF\(_1\) and foF\(_2\) were reduced to the same latitude of 50°N and the same level of solar activity using the internal structure of the IRI model. The IRI model dependences of foF\(_1\) and foF\(_2\) on coordinates and solar activity were used.

| Station | Lat, N deg | Lon, E deg | Mag. Lat deg | Station | Lat, N deg | Lon, E deg | Mag. Lat deg |
|---------|------------|------------|--------------|---------|------------|------------|--------------|
| Adak    | 51.9       | 183.4      | 47.5         | Ottawa  | 45.4       | 284.1      | 56.3         |
| Alma-Ata| 43.2       | 76.9       | 33.3         | Petersburg | 60.0      | 30.7       | 56.0         |
| Boulder | 40.0       | 254.7      | 48.7         | Point Arg | 35.6       | 239.4      | 42.1         |
| Ekaterinburg | 56.7      | 58.6       | 48.6         | Rome    | 41.9       | 12.5       | 42.0         |
| Goosebay | 53.3      | 299.6      | 64.1         | Rostov  | 47.2       | 39.7       | 42.2         |
| Gorky   | 56.1       | 44.2       | 50.0         | Julisuru | 54.6       | 13.4       | 54.3         |
| Irkutsk | 52.5       | 104.0      | 41.2         | Slough  | 51.5       | 359.4      | 53.8         |
| Kaliningrad | 54.7     | 20.6       | 52.7         | St. Johns | 47.6      | 307.3      | 57.9         |
| Karaganda| 49.8       | 73.0       | 40.2         | Tomsk   | 56.5       | 84.9       | 45.9         |
| Kiev    | 50.5       | 30.5       | 46.9         | Tunguska| 61.6       | 90.0       | 50.7         |
| Kokubunji | 35.7     | 139.5      | 25.7         | Wakkanai| 45.4       | 141.7      | 35.5         |
| Magadan | 60.1       | 151.0      | 50.9         | Winnipeg| 49.8       | 265.6      | 59.6         |
| Moscow  | 55.5       | 37.3       | 30.6         | Yakutsk | 62.0       | 129.6      | 51.2         |

Table 1. Stations with available June monthly median foF\(_1\) and foF\(_2\) observations used in the analysis. Geographic latitudes, longitudes and magnetic latitudes of the stations are given.
for this reduction. The input index of solar activity to the IRI is a 12-month running mean sunspot number \( R_{12} \) or a 12-month running mean index \( F_{10.7} (F_{12}) \), which is averaged for June over the years with a solar minimum \( R_{12} = 15 (F_{12} = 75) \) and for the years with a solar maximum \( R_{12} = 125 (F_{12} = 177) \).

The reduced \( f_0 F_2 \) and \( f_0 F_1 \) are given in Fig. 1 in comparison to the IRI-2016 (https://ccmc.gsfc.nasa.gov/model-web/models/iri2016_vitmo.php) model variations. Pronounced \( f_0 F_2 \) and \( f_0 F_1 \) longitudinal variations are observed under both levels of solar activity. The IRI-2016 model describes the observed \( f_0 F_2 \) with sufficient accuracy, while the \( f_0 F_1 \) model values are overestimated under solar minimum.

The interpolated positions of maxima at 50°–60°E and minima at 240°–250°E are very close for \( f_0 F_2 \) and \( f_0 F_1 \) (Fig. 1), but they do not coincide with the longitude of the magnetic pole \( \lambda_{\text{pol}} \) and \( (\lambda_{\text{pol}} + 180°) \) longitudes. The extrema are shifted to the west with respect to the magnetic pole meridian. Ionospheric \( F_1 \) and \( F_2 \) layers have different formation mechanisms, but they both depend on the same neutral composition, and the coincidence of extreme positions confirms the controlling role of neutral composition in longitudinal variations.

The application of method\(^{10} \) to ionospheric observations at 26 stations has given us neutral temperature and composition at F-region heights (>140 km). The retrieved neutral composition and temperature were reduced to the same latitude of 50°N and fixed levels of solar activity using the MSIS-86 model\(^ {17} \) internal structure. The input June monthly \( F_{10.7} \) and Ap indices averaged over the years of solar minimum are \( F_{10.7} = 71 \) and Ap = 10 nT and \( F_{10.7} = 167 \) and Ap = 11 nT for years with a solar maximum. When reduced this way, \([O],[N_2], \text{O/N}_2 \) ratio, and \( T_{\text{ex}} \) are given in Fig. 2 for the solar minimum and maximum in a comparison to thermospheric models MSIS-86 and MSISE-00.

Both the retrieved and modelled values manifest pronounced longitudinal variations (Fig. 2). The extrema in Fig. 2 are also shifted to the west with respect to the magnetic pole meridian. In general, MSISE-00 (which has nothing in common with the retrieval method) is closer to the retrieved variations in thermospheric parameters compared to MSIS-86. Although the model and retrieved longitudinal variations appear very similar, the absolute differences are also observed. Modelled \( T_{\text{ex}} \) values are systematically larger than the inferred ones, especially with MSIS-86. This results in larger \([N_2]\) concentrations, especially in the American longitudinal sector. It is interesting to note that despite noticeable differences in \( T_{\text{ex}}, [N_2] \), and \([O]\) between the two versions of the MSIS model, the longitudinal variations in the \( \text{O/N}_2 \) ratio are very similar (Fig. 2).

The similarity between the retrieved and modelled longitudinal variations in thermospheric parameters looks interesting, as the compared variations were obtained with very different methods using very different source data. This similarity is also confirmed by the relative (maximum/minimum ratio) variations given in Table 2. Perfect coincidence is observed for the \( \text{O/N}_2 \) ratio under both levels of solar activity and for other parameters.
under solar maximum conditions. The largest difference occurs for atomic oxygen under a solar minimum when MSISE-00 underestimates the magnitude of [O] longitudinal variations (also Fig. 2). This is mainly due to lower [O] values in the American longitudinal sector.

Figure 2. Longitudinal variations in the inferred thermospheric parameters at 300 km and 50°N for years with a solar minimum and maximum. Solid lines – polynomial approximations with error bars (SD values are given); dashes – MSIS-86 model; and circles – MSISE-00 model. Points from 0°–40°E are repeated at 360°–400°E longitudes. Arrows indicate the longitude of the geomagnetic pole meridian.
and O/N2 compared to the European sector at the same geographic latitudes, as shown in Fig. 2. The reduction in Boulder (40.0°N, 254.7°E; Φ = 48.5°), and a pair of stations with close geomagnetic latitudes, Juliusruh (54.6°N, 13.4°E; Ψ = 54°) and Millstone Hill (42.5°N, 288.5°E; Ψ = 53.3°), which are located in the European and American longitudinal sectors, respectively. The last deep solar minimum in 2009 (F10.7 = 68.6; Ap = 4.1) and solar maximum in 2000 (F10.7 = 179.8; Ap = 15.2) were taken for our analysis, where F10.7 and Ap are June monthly indices. Observed June noontime monthly median NmF2 values are given in a comparison to IRI-2016 values to show that the selected stations manifest NmF2 similar to the modelled results. (Table 3)

The observed monthly median fF2 and fF1 at the four stations were used to retrieve thermospheric parameters and calculate column O/N2 ratios above the level with a column N2 abundance of 1017 cm−2, as was done in the observations15. Table 4 gives a comparison with the MSISE-00 modelled column O/N2 ratios.

Table 4 shows that both the inferred and MSISE-00 modelled height-integrated O/N2 ratios increase with solar activity. Our results and the MSISE-00 values are comparable with the TIMED/GUVI observations12 at 12 LT in June under solar minimum conditions at ~45°N with a column O/N2 ratio ~ 0.5. However, the TIMED/GUVI observations and IRI model results of June noontime monthly median NmF2 for solar minimum and maximum conditions.

Table 2. Magnitudes of longitudinal variations for the retrieved and modelled thermospheric parameters at 300 km, 50°N, and 12 LT in June during solar minimum and maximum conditions.

| Parameter | Solar minimum | Solar maximum |
|-----------|---------------|---------------|
|           | Retrieved     | MSIS-86       | MSISE-00     |
| [O]       | 1.30          | 1.22          | 1.19         |
| [N2]      | 1.31          | 1.44          | 1.45         |
| O/N2      | 1.73          | 1.76          | 1.71         |
| Tm        | 1.09          | 1.12          | 1.10         |

Table 3. Observations and IRI model results of June noontime monthly median NmF2 for solar minimum (2009) and maximum (2000) years.

| Years | Stations   | NmF2 × 105, cm−3 | NmF2 × 105, cm−3 (IRI) |
|-------|------------|------------------|------------------------|
| 2009  | Rome       | 5.22             | 3.51                   |
|       | Juliusruh  | 2.87             | 2.74                   |
|       | Boulder    | 2.86             | 2.87                   |
|       | Millst. Hill | 2.62           | 2.87                   |
| 2000  | Rome       | 10.71            | 9.56                   |
|       | Juliusruh  | 6.76             | 6.43                   |
|       | Boulder    | 5.78             | 6.54                   |
|       | Millst. Hill | 6.60            | 6.07                   |

Discussion

From the very beginning, the mechanism of longitudinal/UT variations in neutral composition has been associated with high-latitude heating and displacement between the geomagnetic and geographic poles14,18,19. Due to Joule and particle precipitation heating in the auroral zone, the upper atmosphere expands, and this upwelling results in a decrease in the O/N2 ratio at a fixed height. Equatorward solar driven and/or disturbed thermospheric circulation transfers this disturbed neutral composition to lower latitudes. This mechanism has been discussed in the literature20–22. The near-to-pole longitudinal (American) sector should manifest larger [N2] and lower [O] compared to the European sector at the same geographic latitudes, as shown in Fig. 2. The reduction in the retrieved thermospheric parameters at the same geomagnetic latitude Φ = 50° (not shown in the paper) only slightly changes the pattern of longitudinal variations, shifting the extrema farther to the west.

One may conclude that June auroral heating is systematically larger in the American sector. A plausible explanation for this extra heating is the larger Joule heating due to the larger conductivity in the auroral zone. The auroral oval (http://www.sws.bom.gov.au/Aurora/3/1) receives more sunlight in June in the American sector than in the European sector. The noontime solar zenith angle χ = 42° at the longitude of the magnetic pole (73°W), but noontime χ = 61° at the antipode longitude of 107°E. Considering the electron concentration in the E-region NmE = (cos χ)3/2, the expected difference in the electron concentration is ~30%, which provides a larger conductivity.

A westward shift in the extrema of the longitudinal variations with respect to the longitude of the magnetic pole meridian taking place both in the ionospheric (Fig. 1) and retrieved parameters, as well as in the modelled thermospheric parameters (Fig. 2), reveals the reality of this shift, which may be related to dominating westward circulation at mid-latitudes during the June solstice24. A westward tilt was also observed in the mean thermospheric mass density11.

Longitudinal variations in the daytime column O/N2 ratio from TIMED/GUVI observations on solstices were analysed by the authors12. The column O/N2 ratio in those observations25 was calculated above the level where the column N2 abundance of 1017 cm−2 was located at a 147–150 km height. It is interesting to compare the observed column O/N2 ratio to our retrieved and MSISE-00 modelled longitudinal/solar activity variations. For this comparison, we selected stations with close geographic latitudes, Rome (41.9°N, 12.5°E; Φ = 42°) and Boulder (40.0°N, 254.7°E; Φ = 48.5°), and a pair of stations with close geomagnetic latitudes, Juliusruh (54.6°N, 13.4°E; Ψ = 54°) and Millstone Hill (42.5°N, 288.5°E; Φ = 53.3°), which are located in the European and American longitudinal sectors, respectively. The last deep solar minimum in 2009 (F10.7 = 68.6; Ap = 4.1) and solar maximum in 2000 (F10.7 = 179.8; Ap = 15.2) were taken for our analysis, where F10.7 and Ap are June monthly indices. Observed June noontime monthly median NmF2 values are given in a comparison to IRI-2016 values to show that the selected stations manifest NmF2 similar to the modelled results. (Table 3)

The observed monthly median fF2 and fF1 at the four stations were used to retrieve thermospheric parameters and calculate column O/N2 ratios above the level with a column N2 abundance of 1017 cm−2, as was done in the observations15. Table 4 gives a comparison with the MSISE-00 modelled column O/N2 ratios.

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The stability of the MSISE-00 modelled $[\text{N}_2]$ column under varying solar activity is due to relatively unchanged. The increase in the atomic oxygen abundance under high solar activity may be attributed to an increase in the intensity of the Schumann-Runge continuum, which is responsible for the dissociation of O$_2$ in the upper atmosphere. The stability of the MSISE-00 modelled $[\text{N}_2]$ column under varying solar activity is due to relatively unchanged.

Following vertical plasma drift, may be related to the O/$\text{N}_2$ ratio taken at the F$_2$-layer maximum height\(^2\). Indeed, a simplified formation mechanism of the mid-latitude daytime F$_2$-layer, ignoring vertical plasma drift, may be related to the O/$\text{N}_2$ ratio taken at the F$_2$-layer maximum height\(^2\). The increase in the retrieved and MSISE-00 modelled height-integrated O/$\text{N}_2$ ratio with solar activity indicates an increase in atomic oxygen abundance under solar maximum conditions. This is determined from the following.

Above the turbopause, which is located at 110–120 km (while the level with column $\text{N}_2$ content of $10^{17}$ cm$^{-2}$ is at $\sim$150 km), the neutral species are distributed in accordance with the barometric law; therefore, the column content of any species above the height $h$ is $N_h H$, where $N_h$ is the concentration and $H$ is the scale height $kT/mg$ of a given species. Therefore, the O/$\text{N}_2$ column ratio is independent of neutral gas temperature but depends only on the [O]/[N$_2$] ratio at a fixed height $h$. Atomic oxygen is completely produced and lost in the upper atmosphere\(^2\), forming a layer with a maximum at $\sim$97 km and zero concentrations below 80 km\(^2\). Therefore, height-integrated [O] above 70 km gives the total column content of atomic oxygen. Table 5 gives the MSISE-00 modelled total column contents of [O] and [N$_2$] above 70 km under solar maximum (2000) and minimum (2009) conditions, in addition to Tex and neutral temperature at a 70 km height, at four locations.

Table 4. Inferred and MSISE-00 model (in parentheses) height-integrated June noontime O/$\text{N}_2$ ratios in the European and American sectors under solar maximum (2000) and minimum (2009) monthly median conditions.

| Parameter                | Rome  | Boulder | Juliasruh | Millstone Hill |
|--------------------------|-------|---------|-----------|----------------|
| $[\text{O}]_{\text{col}} \times 10^{15}$, cm$^{-2}$ | 8.12  | 7.13    | 6.39      | 6.90           |
| $[\text{N}_2]_{\text{col}} \times 10^{20}$, cm$^{-2}$ | 9.81  | 9.65    | 9.96      | 9.84           |
| Tex, K                   | 1265  | 1308    | 1296      | 1312           |
| $T_{\text{hm}}$, K       | 209   | 210     | 210       | 209            |
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Table 5. MSISE-00 modelled total column contents of [O] and [N$_2$] above 70 km under solar maximum (2000, first line) and solar minimum (2009, second line) conditions, in addition to Tex and neutral temperature at a 70 km height, at four locations.

observations manifest the inverse dependence on solar activity, and the observed height-integrated O/$\text{N}_2$ ratio is $<0.4$ at $\sim$45°N under high solar activity\(^2\) (their Fig. 4), while our inferred and MSISE-00 modelled O/$\text{N}_2$ ratios are 0.6–0.8 in 2000 (Table 4). On the other hand, qualitatively TIMED/GUVI observations demonstrate correct longitudinal variations with a larger column O/$\text{N}_2$ ratio in the European sector compared to the American sector in accordance with our results and the MSISE-00 model results.

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Table 4 shows that (O/$\text{N}_2$)$_{\text{col}}$ longitudinal variations are small (<15%) in comparison with the observed $N_\text{hm} F_2$ variations under high solar activity. They are close only during the deep solar minimum in 2009, while the (O/$\text{N}_2$)$_{\text{max}}$ longitudinal variations are much closer to the observed $N_\text{hm} F_2$ variations under both solar activity conditions. This is not a surprise, as the level with a $N_2$ column density of $10^{17}$ cm$^{-2}$ (used to calculate the column O/$\text{N}_2$ ratio) is located at heights of 147–150 km, i.e., much further below the F$_2$-layer maximum; however, these concentrations provide the main contribution to the column density, but they do not participate in the F$_2$-layer formation.

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$$N_m F_2 = 0.75 \frac{\beta_m}{\beta_m}$$

where $\beta_m$ is the O$^+$ ion production rate and $\beta_m$ is the linear loss coefficient taken at $h_m F_2$. With some reservations, $\beta_m$/$\beta_m$ may be considered to be proportional to (O/$\text{N}_2$)$_{\text{max}}$, but this ratio taken at $h_m F_2$ is not the same as the height-integrated O/$\text{N}_2$ ratio. Our method\(^6\) provides the necessary $h_m F_2$ to calculate (O/$\text{N}_2$)$_{\text{max}}$. Table 6 gives the Rome/Millstone Hill and Rome/Boulder ratios for the observed $N_m F_2$ and (O/$\text{N}_2$)$_{\text{max}}$ and (O/$\text{N}_2$)$_{\text{col}}$ ratios for the two levels of solar activity.

Table 6 shows that (O/$\text{N}_2$)$_{\text{col}}$ longitudinal variations are small (<15%) in comparison with the observed $N_\text{hm} F_2$ variations under high solar activity. They are close only during the deep solar minimum in 2009, while the (O/$\text{N}_2$)$_{\text{max}}$ longitudinal variations are much closer to the observed $N_\text{hm} F_2$ variations under both solar activity conditions. This is not a surprise, as the level with a $N_2$ column density of $10^{17}$ cm$^{-2}$ (used to calculate the column O/$\text{N}_2$ ratio) is located at heights of 147–150 km, i.e., much further below the F$_2$-layer maximum; however, these concentrations provide the main contribution to the column density, but they do not participate in the F$_2$-layer formation.
Another problem with using the column \((\text{O}/\text{N}_2)\) ratio to interpret any spatial, seasonal, or solar activity \(N_m\text{F}_2\) variations is the smoothing temperature effect. The atomic oxygen concentration is a crucial parameter for \(F_2\)-region formation as \(N_m\text{F}_2\sim\langle\text{O}\rangle^{4/3}\) during daytime hours\(^{29}\). Its concentration in the American sector is 30% less than that in the Eurasian sector (Table 2), and this difference is mainly responsible for the observed \(N_m\text{F}_2\) longitudinal variations. However, \(T_{\text{ex}}\) and, correspondingly, the atomic oxygen scale height are larger in the American sector (Fig. 2), which decreases the difference in the height-integrated \(\text{O}/\text{N}_2\) ratios between the two sectors. Keeping all of this in mind, one may conclude that the column \(\text{O}/\text{N}_2\) ratio cannot be used for any quantitative interpretation of \(N_m\text{F}_2\) variations.

### Conclusions

The obtained results are summarized as follows.

1. The observed longitudinal \(f_{\text{F}_2}\) and \(f_{\text{F}_1}\) variations are similar to the retrieved and MSISE modelled thermospheric parameter variations, indicating their general consistency. The best coincidence with the empirical model is related to the inferred \(\text{O}/\text{N}_2\) ratio, while MSISE-00 underestimates the magnitude of \([\text{O}]\) longitudinal variations under solar minimum conditions. In general, similar variations in thermospheric parameters obtained with different methods and different data sources are interesting.

2. The American sector manifests larger Tex values (independent of both the geographic and geomagnetic latitudes considered) under both solar maximum and minimum conditions. A plausible explanation for this extra heating is the larger conductivity in the aural oval, which receives more sunlight in June in the American sector compared to the European sector.

3. A westward shift in the extreme position in terms of longitudinal variations with respect to the longitude of the magnetic pole meridian, taking place both for ionospheric and thermospheric parameters, may be related to dominating westward circulation at mid-latitudes during the June solstice\(^{24}\).

4. The inferred and MSISE-00 height-integrated \(\text{O}/\text{N}_2\) ratios are comparable to the TIMED/GUVI observations only under solar minimum conditions, with a column \(\text{O}/\text{N}_2\) ratio \(\sim 0.5\) at 12 LT in June at \(\sim 45^\circ\text{N}\)\(^{12}\) (their Fig. 2). However, the TIMED/GUVI observations manifest an inverse dependence on solar activity with a height-integrated \(\text{O}/\text{N}_2\) ratio \(< 0.4\) under high solar activity, which is contrary to the retrieved and MSISE-00 modelled column \(\text{O}/\text{N}_2\) ratios (0.6–0.8).

5. The retrieved height-integrated \((\text{O}/\text{N}_2)\) ratio longitudinal variations are small (~15%) in comparison with the observed \(N_m\text{F}_2\) variations under high solar activity. A 30% difference in atomic oxygen concentration between the American and European sectors is mainly responsible for the observed \(N_m\text{F}_2\) longitudinal variations and is strongly compensated in \((\text{O}/\text{N}_2)_{\text{col}}\) by a larger Tex in the American sector. The height-integrated \(\text{O}/\text{N}_2\) ratio cannot be incorporated into the \(F_2\)-layer formation mechanism; therefore, such observations cannot be used for any quantitative interpretation of \(N_m\text{F}_2\) variations.

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| Parameter | 2009 | 2000 |
|-----------|------|------|
|           | Rome/ Mill. Hill | Rome/ Boulder | Rome/ Mill. Hill | Rome/ Boulder |
| \(\Delta(N_m\text{F}_2)_{\text{col}}\) | 1.23 | 1.13 | 1.62 | 1.85 |
| \(\Delta(\text{O}/\text{N}_2)_{\text{max}}\) | 1.27 | 1.00 | 1.49 | 1.97 |
| \(\Delta(\text{O}/\text{N}_2)_{\text{col}}\) | 1.25 | 1.14 | 1.16 | 1.15 |

Table 6. Rome/Millstone Hill and Rome/Boulder ratios for observed \(N_m\text{F}_2\), retrieved \(\text{O}/\text{N}_2\) ratio at \(h_m\text{F}_2\), and column \(\text{O}/\text{N}_2\) ratio calculated from the retrieved \([\text{O}]\) and \([\text{N}_2]\) for June 2009 and 2000.


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Author Contributions

The paper is the result of common investigations. A. Mikhailov conceived the study and contribute to the data analysis and to the preparation and finalization of the manuscript. L. Perrone contribute to the data analysis and to the preparation and finalization of the manuscript.

Additional Information

Competing Interests: The authors declare no competing interests.

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