Ionospheric data assimilation: Comparison of extracted parameters using full density profiles and key parameters

Shun-Rong Zhang, 1 William L. Oliver, 2,3 John M. Holt, 1 and Shoichiro Fukao 4

Abstract. This paper explores the relative accuracy of deriving solar EUV flux, exospheric temperature \( T_{\text{ex}} \), and meridional winds using complete altitude profiles of ionosphere electron density as compared to just using key parameters such as \( N_{\text{max}} \) and ionospheric electron content. Incoherent scatter radar observations at Millstone Hill and Shigaraki and an ionospheric model are used in this study. We can make the following points: (1) With either the profile or key parameter data, the EUV flux can be inferred with little ambiguity, given that background variables such as the meridional wind are known. (2) The southward wind and \( T_{\text{ex}} \) can be simultaneously derived from either type of data. The results, in particular the \([\text{O}]/[\text{N}_2]\) results, are similar for the two types of data. The accuracy of the wind result relies much on the accuracy of \( h_{\text{max}} \) as well as the geomagnetic dip angle. (3) A few key ionospheric parameters are not always sufficient to give a unique definition of ionospheric conditions. Additional parameters or even a full profile data are sometimes needed. In general, however, the key parameter pair \( h_{\text{max}}, N_{\text{max}} \) seems to be a suitable assimilation data source, at least for retrieving the local features of the \( T_{\text{ex}} \) and meridional wind variation.

1. Introduction

Ionospheric measurements provide diverse types of electron density \( N_e \) parameters. The \( N_e \) profile data from incoherent scatter (IS) radar gives detailed information about the vertical distribution but there is relatively sparse temporal and geographic coverage. Ionospheric characteristic key parameters (descriptors), such as the peak density \( N_{\text{max}} \) and its altitude \( h_{\text{max}} \) and height-integrated ionospheric electron content \( \text{IEC} \), are easily measured but do not reflect the complete features of the \( N_e \) distribution.

Some assimilation methods have been developed to make use of these data. Assimilation studies first aim at retrieving the basic chemistry and dynamics and then proceed to forecasting ionospheric behavior. The basic idea lies in inserting the data into a first-principles model whose driving forces, such as winds, composition, solar flux, etc., are adjustable. Optimal values of the driving forces are those giving the best match of the model output to the data. In inferring the neutral wind and sometimes the exospheric temperature, previous researchers have assimilated \( h_{\text{max}} \) [e.g., Miller et al., 1986; Buonsanto et al., 1989; Titheridge, 1993], IEC [Antoniadis, 1977], or both \( h_{\text{max}} \) and \( N_{\text{max}} \) [Richards et al., 1998; Zhang et al., 1999; Sojka et al., 2001]. Full electron density profiles have also been applied by Mikhaikov and Forster [1997, 1999] and Zhang et al. [2001b, 2002]. Such data assimilation methods are subject to ambiguity between the derived variables. First, when can we set variables to climatology values as approximations to their true status, or how does the use of background variables affect the inferred variables? Second, how is the ambiguity among the variables to be inferred? In partly answering these concerns, Zhang et al. [2001b] have assimilated IS radar \( N_e \) profile data to examine the uniqueness for paired variables. Then, by considering the ambiguity problems, Zhang et al. [2002] have derived a solar EUV flux scaling factor, effective exospheric temperature \( T_{\text{ex}} \), and meridional winds from the entire \( N_e \) profile measured by IS radars.

With this experience in \( N_e \) profile assimilation, it is now appropriate to address the accuracy of the use of ionospheric key parameters such as \( N_{\text{max}}, h_{\text{max}} \), and IEC for determining the information on EUV flux, neutral densities, and winds. The key parameters are being measured constantly with good geographic coverage and are essential for current space weather studies. For instance, the effort to perform assimilation with multiple ionospheric data sources has been under way very actively in a few research groups working on GAIM (Global Assimilation of Ionospheric Measurements) [e.g., Schunk et al., 2002], and the Kalman Filter has been applied to this study [Scherliess, et al., 2002; Hajj et al., 2002]. The ambiguity/uniqueness of inferred variables, however, has yet to be seriously considered in literature. We examine here the differences incurred when one, two, or three key parameters are used. We emphasize here the relative change in our results rather than absolute values, which were discussed by Zhang et al. [2002]. We hope our exercises will provide useful information on these ambiguities.

In this study we use a set of \( N_e \) data measured by IS radars at Millstone Hill (42.6°N, 288.5°E) and Shigaraki (34.85°N, 136.1°E). We first describe the data, the assimilative ionospheric model and the assimilation method in Section 2, then we compare results from the profile data assimilation with those from the key parameter data assimilation in Section 3, and in Section 4 we discuss results from various combinations of the parameters. Section 5 is our summary.

2. Data, Model and Method

The Millstone Hill IS radar (MHR) and the Shigaraki middle and upper atmosphere radar (MUR) both provide power profile measurements which, to get the \( N_e \) profile, are calibrated with ionosonde
Neutral composition, temperature, winds and solar flux are the model variables to be inferred. They are obtained by adjustment of their initial (climatology) values to give a best match with the measured data: the profile or key parameters. We use the mass spectrometer and incoherent scatter (MSIS86) model [Hedin, 1987] to generate an initial atmosphere where exosphere temperature $T_{es}$ is critical in determining the scale height of atmospheric species and thereby affects the neutral composition at all altitudes above the base of the thermosphere. We adjust $T_{es}$ by a multiplicative factor, $f_T$. As initial values of the meridional wind, we use, for Millstone Hill, the wind derived from ion drift measurements [see Vasseur, 1969 for this traditional wind determination method], and, for Shigaraki, an HWM-like [Hedin, et al., 1991] height-independent horizontal wind model called the MUR HWMMU model [Kawamura et al., 2000], developed from ten years of MUR measurements. Adjustments are made by adding a height-independent value, $A_w$. The solar EUV model for aeronomic calculations (EUVAC) [Richards et al., 1994] is our initial EUV flux specification and is adjusted with a multiplicative factor $f_E$.

Our variable adjustment and determination to gain the best $N_e$ fit is accomplished with a standard nonlinear least squares fitting algorithm of the type presented by Bevington and Robinson [1992]. This also provides estimates of the uncertainties of the variables determined and their interparameter binary correlations. See Zhang et al. [2001b] for details about the profile fitting. For the key parameter fitting, the function $\chi^2$ to be minimized takes the following form:

$$\chi^2 = \frac{[M_{\text{obs}}(f_T, A_w, f_E) - N_{\text{max}}]}{\delta N_{\text{max}}}^2 + \frac{[H_{\text{obs}}(f_T, A_w, f_E) - h_{\text{max}}]}{\delta h_{\text{max}}}^2 + \frac{[IEC_{\text{obs}}(f_T, A_w, f_E) - IEC]}{\delta IEC}^2.$$

In the above equation, $N_{\text{max}}$, $h_{\text{max}}$, and $IEC$ are the measured data and $M_{\text{obs}}$, $H_{\text{obs}}$, and $IEC_{\text{obs}}$ are the corresponding model values. $\delta N_{\text{max}}$, $\delta h_{\text{max}}$, and $\delta IEC$ are the uncertainty of the three key parameters. For this exploratory study, we set $\delta N_{\text{max}} = 10^{10}$m$^{-3}$, $\delta h_{\text{max}} = 1$km, and $\delta IEC = 125 \times 10^{13}$m$^{-2}$, which are very rough estimates of the data uncertainty. The uncertainty for $N_{\text{max}}$ and $h_{\text{max}}$ are relatively small; the uncertainty for IEC is assumed to be slightly large in order to account for the practical condition when a slant Total Electron Content (TEC) measurement, where longitude and latitude gradients are involved, are inverted into the vertical TEC. Of course, with all three parameters, we can determine 1-3 variables ($f_T$, $f_E$ and $A_w$), with two parameters we can determine 1-2 variables, and with one we can determined only one of the variables. We describe below various two-variable fits. The simultaneous determination of three variables (three-variable fit) is desirable but, as discussed by Zhang et al. [2001], usually yields binary parameter correlations near unity so that nearly complete ambiguity prevails.

### 3. The Profile Fit and the Parameter Fit

#### 3.1. EUV Flux

Given that wind speeds are often available from IS radars or climatological models, we have implemented an $f_E$-$f_T$ adjustment. This 2-variable-search method is good for climatological studies but might be more questionable during highly dynamic or unusual times when drifts are poorly known. Once accurate information on drifts is added into the assimilation, then we can determine the temperature and wind unambiguously. For our present study, since we care about the relative changes of derived variables due to changes of data type, this 2-variable search is suitable whether or not we know the wind accurately.

**3.1.1. Profile results and $N_{\text{max}}$-$h_{\text{max}}$-IEC results.** When adjusting the $f_E$-$f_T$ pair, as shown in Figure 1 (upper panel), the profile data assimilation (dots) for both sites yields a weak binary correlation in the morning and a strong one near noon; the $N_{\text{max}}$-$h_{\text{max}}$-IEC data assimilation yields similar correlation variations (diamonds). Changes in the EUV flux produce proportional changes in $O^+$ density. Changes in [O] produce proportional changes in [$O^+$] when the optical depth is small at $h_{\text{max}}$ but not when the optical depth is large. (The accurate calculation of the optical depth for large solar zenith angles may be susceptible to errors because of errors in cross sections and neutral densities). This optical-depth effect yields a large $T_{es}$-EUV correlation near noon but a smaller correlation in the morning when the slant path is long. A meaningful EUV flux can be obtained by averaging the hourly $f_E$, weighted inversely as the variance of the hourly result, for periods of weak EUV-$T_{es}$ correlations. Table 1 shows $f_E$ values so derived for both sites. The average for the two sites is 0.79 as the profile data are assimilated, and 0.77 as the three parameters are assimilated, indicating agreement for the two types of data.

**3.1.2. Profile results and $N_{\text{max}}$-$h_{\text{max}}$-IEC results.** We now drop the IEC data and use only $N_{\text{max}}$-$h_{\text{max}}$ fitting. This gives EUV-$T_{es}$ correlations (crosses in the upper panel, Figure 1) similar to what $N_{\text{max}}$-$h_{\text{max}}$-IEC fitting gives. The resulting $f_E$ is 0.76, close to the 0.77 given by the $N_{\text{max}}$-$h_{\text{max}}$-IEC fitting.

**3.1.3. Adjusting the $f_E$-$A_w$ pair.** $f_E$ can be obtained by adjustments of another variable pair, $f_E$ and $A_w$, assuming that $T_{es}$ can be set to the MSIS model value. It yields a weak correlation between $f_E$ and $A_w$ (dots in bottom panels) for the profile data and for the $N_{\text{max}}$-$h_{\text{max}}$ data as well (crosses in bottom panels), but relatively high for the $N_{\text{max}}$-$h_{\text{max}}$-IEC data (diamonds in bottom panels). The meridional wind basically alters $h_{\text{max}}$ and consequently the rates of production and recombination of ionization at $h_{\text{max}}$ while the EUV flux affects only the production rate; thereby the $f_E$-$A_w$ correlation is weak. $h_{\text{max}}$, being wind sensitive, is contained in the $N_{\text{max}}$-$h_{\text{max}}$-IEC data set with higher weighting than in the $N_{\text{max}}$-$h_{\text{max}}$-IEC data set, which is more “density-oriented.” It is well known that $N_{\text{max}}$ and IEC are highly correlated because the major contribution to IEC comes from near the peak. We therefore see the higher level of the $f_E$-$A_w$ correlation with the IEC data.
added. The $f_E$ value thus derived, however, is associated with the climatology of the MSIS $T_{ex}$.

### 3.2. $T_{ex}$ and Meridional Winds

Assuming that the EUV factor is known, $T_{ex}$ and meridional winds can be simultaneously determined. We take the $f_E$ factor to be 0.79, although any reasonable value can be taken for this study emphasizing the relative changes of derived variables. Figure 2 shows the derived $T_{ex}$ (panel (a)) and southward wind (panel (b)) for assimilating $N_{e_{obs}}$, $h_{obs}$-IEC data from the MHR. Error bars represent the standard deviation uncertainty. $T_{ex}$ exhibits a depression before noon and the wind shows fluctuations. The large errors at 13 LT result from the high wind-$T_{ex}$ correlation (panel (f)). Panels (c)-e display comparisons between the original $N_{max}$, $h_{max}$-IEC data (diamonds) and those generated by the model for the best match. The fitting is found to be excellent.

Zhang et al. [2002] have shown in detail $T_{ex}$ and meridional wind results from the profile data for the both sites. Here we compare those results to the $N_{e_{obs}}$, $h_{obs}$-IEC parameter-fitting results described above. We first examine the wind-$T_{ex}$ correlation coefficient (Figure 3). Both sites give basically small correlation coefficients for fitting either profile data (dots), $N_{max}$, $h_{max}$-IEC data (diamonds), or $N_{e_{obs}}$, $h_{obs}$ data (crosses). There seem no significantly patterned differences among the correlations obtained with the three types of data. A slight increase in $T_{ex}$ generates higher $[O]$ and $[N_2]$ but lower $[O]/[N_2]$, so a denser neutral atmosphere gives rise to higher $h_{obs}$ (diffusion less important) through decreasing the $O^+$ loss time constant (life-time) and increasing the diffusive time constant, and lower $[O]/[N_2]$ causes lower $N_{max}$. But a wind change cannot duplicate a $T_{ex}$ change, since a southward wind causes $h_{obs}$, and hence $N_{max}$ to increase (a higher $N_{max}$ is a result of a higher $h_{obs}$, where $[O]/[N_2]$ is larger), but no wind change can cause higher $h_{obs}$ and lower $N_{max}$ as can $T_{ex}$.

The inferred $T_{ex}$ and southward wind, together with the 300-km $[O]/[N_2]$ ratio shown in Figure 4. $T_{ex}$ values at Millstone are basically lower than the MSIS values (solid line) but similar to those given by the energy equation technique [Bauer et al., 1970] in a climatology study by Buonsanto and Pohhman [1998]. An interesting noon (and pre-noon) depression is seen and resembles the one reported by Oliver and Sahal [1988] with the MHR data and the Thermospheric General Circulation Model. The Shigaraki $T_{ex}$ does not show a depression around noon and is high in the afternoon, over the MSIS value. For 0800-1000 LT, our results for Shigaraki are similar to those given by Oliver et al. [1991], based on the energy equation method for similar geophysical conditions. $T_{ex}$, the effective exosphere temperature, is rather high at 1300 LT and 1500 LT reaching about 1850 K for reasons not quite clear to us. In fact, the $F_2$-layer peak density is largely proportional to the $[O]/[N_2]$ density ratio, because the $O^+$ production rate is basically proportional to $[O]$ while its chemical loss coefficient is proportional to the molecular gas density $[N_2]$, so a photochemical equilibrium solution of the electron density around the peak involves the term of $[O]/[N_2]$. In this sense, the effective exosphere temperature $T_{ex}$ can be regarded essentially as a proxy for affecting the $[O]/[N_2]$ change.

But more meaningful than the absolute values of $T_{ex}$ is the fact that the Shigaraki $T_{ex}$ from the profile data (dots) and from the $N_{e_{obs}}$, $h_{obs}$-IEC data (triangles) differ by less than 100 K, and so do the $T_{ex}$ results for Millstone Hill. The $[O]/[N_2]$ ratio differences for the two types of data are small; smaller than the offset from the MSIS ratio.

The meridional wind for Shigaraki is basically around the empirical HWMMU values (solid line), and the profile data-based wind (dots) agrees well with the $N_{e_{obs}}$, $h_{obs}$-IEC data-based wind. For Millstone Hill, both wind estimates deviate from the ion drift-based radar wind (solid line). It is true that that the radar winds are not always accurate when the neutral density assumption is questionable. But to go back to the original data and re-derive a wind every time we make a MSIS density adjustment is a complicated process, and the magnitude of the effect is uncertain. A further study needs to be done to determine the magnitude of its potential effect. In addition to that, several aspects associated with wind effects and our $N_e$ data may lead to the discrepancy between the $N_e$-based wind and the ion drift-based wind, and between the winds from the profile data and the key parameter data. Millstone Hill has a magnetic dip angle $I \sim 70^\circ$, thus the neutral wind effect on $O^+$ vertical motion is relatively weak due to $I \cos I \sim 0.28$, whereas $\sin I \cos I \sim 0.50$ for Shigaraki with $I \sim 48^\circ$, almost as large as $\sin I \cos I$ can become. Hence $N_e$ and $h_{obs}$ are less sensitive to wind changes at Millstone Hill. A significant wind yields a smaller profile change, and our attempt to get wind estimates from either the profile or the parameter data may have incurred large uncertainty. With the 48-km range resolution of Millstone Hill $N_e$ data applied for the present study, the accuracy of results may further worsen. The $h_{obs}$ data based on such profiles with coarse height spacing may not be accurate enough to give reliable winds.

### 3.3. Profile Comparisons

Now that the derived $T_{ex}$ values from the two types of data are in general agreement, and so are the winds, it is necessary to check if the calculated $N_e$ profiles agree with each other and with the original experimental profile. Three profiles are plotted for each of several hours for Millstone Hill in Figure 5. The solid line represents the calculated profile based on assimilating $N_{e_{obs}}$, $h_{obs}$-IEC data, and the dashed line represents the calculated profile based on assimilating the profile data represented by circles. For most times, agreements are seen for the three profiles. This is not surprising because the model driving forces (variables) derived do not differ significantly. However, there are cases, e.g., at 1400 and 1600 LT, when the profile assimilation (dashed line) reproduces well the original profile data (circles), while the parameter assimilation reproduces (solid line) well the original $N_{max}$, $h_{max}$-IEC data but not the full profile data. At these times, either $T_{ex}$ values or winds from the two types of data show departures too (see Figure 4).

This kind of ambiguity implies that the same set of key parameters could pertain to different $N_e$ profiles corresponding different atmospheric conditions, and only two or three parameters is sometimes insufficient to give a unique definition of the ionospheric conditions even for the $F_2$ region. When this happens, other assimilation methods or additional data should be considered. On the other hand, it is often desired for a physical model to reproduce the entire $N_e$ profile through fitting only key parameters $N_{max}$ and $h_{max}$, and having the correct plasma temperatures. Indeed, for the $N_e$ profile well above the $F_2$ peak, if $N_{max}$, $h_{max}$ are forced to follow observations by adjusting the solar EUV flux, neutral composition, and meridional wind, and plasma temperatures are set to observations, then the physics of the profile should be well determined, since the EUV flux and $[O]/[N_2]$ effects and the wind effects have been simply represented by, individually, $N_{e_{obs}}$ and $h_{obs}$, and the profile shape is associated with diffusion effects influenced by the plasma temperatures.

The shape of the $N_e$ profile around and below the peak, however, does not depend on variations of the EUV flux, $[O]/[N_2]$ and wind in a simple manner. It particularly depends on diffusion and chemical loss processes, for which the height distribution of atomic and molecular densities and the neutral temperature are important. Therefore additional $N_e$ data (other than the parameters) should be...
supplied for inferring unambiguously the complete physics of the profile. For some particular conditions, disadvantages of using peak parameters may become a problem, e.g., $N_e$ sometimes varies little with altitude around $h_{\text{max}}$ such that the “peak” height is either hard to locate or loses its practical meaning; there are occurrences (disturbed periods and summer conditions) when O may be depleted to an extent that the $N_e$ occurs at the peak of the lower-altitude molecular-ion layer; when an empirical method of deducing $h_{\text{max}}$ from the M3000F2 factor is applied, convenient for handling a large volume of historic data, it leads to an inherent uncertainty of 20-25 km, on average.

4. Various Key Parameter Fits

It is also desired to infer atmospheric information from certain ionospheric data, for example, to obtain winds from $h_{\text{max}}$ and to obtain $T_{\text{ex}}$ from $N_{\text{max}}$ or IEC. It is in particular the case when data availability is limited for ionospheric data assimilation studies. Here we investigate, in order to obtain one specific variable ($T_{\text{ex}}$ or wind), which key parameter ($N_{\text{max}}$, $h_{\text{max}}$ or IEC) or key parameter combination yields the best results. We compare the parameter-based variable to the profile-based one for examining the goodness of results. As samples of this effort, Figure 6 shows the results for inferring $T_{\text{ex}}$ at Millstone Hill and Figure 7 for inferring southward winds at Shigaraki. Tables 2-4 summarize the deviations from the profile data-based parameters. We see that certain parameters or their combinations deviate substantially from the profile result.

4.1. $T_{\text{ex}}$ and [O]/[N$_2$]

Table 2 gives the daytime average deviation of $T_{\text{ex}}$ in percentage, defined as $100 \times |T_{\text{ex}}(\text{parameters})/T_{\text{ex}}(\text{profile})|$. For Millstone Hill, there appears significant deviation (41%) for IEC, which contains electron density information over a wide height range but in a height-integrated sense. For $N_{\text{max}}$, the deviation is 13%; adding $h_{\text{max}}$ makes little difference (from 13% to 12% for Millstone). This is not the case for Shigaraki where there appears 20% or 17% deviation for $N_{\text{max}}$ or IEC, and adding $h_{\text{max}}$ to $N_{\text{max}}$ causes a significant reduction of the deviation (to 6%), suggesting the importance of the $h_{\text{max}}$ data for Shigaraki’s assimilation.

The balance height ($h_{\text{b}}$) between the chemical loss and diffusion, which the $F_{\text{2}}$ peak height is located around, depends on the geomagnetic dip angle $I$ because the diffusion velocity is proportional to $\sin^2 I$. In fact, $h_{\text{b}} \approx \beta/(d \sin^2 I)$ where $\beta$ and $d$ are O$^+$ loss frequency and diffusion coefficient. At Millstone Hill, $\sin^2 I \sim 0.91$ and at Shigaraki, $\sin^2 I \sim 0.55$. Therefore, the same rate of changes in the ratio $\beta/d$ as a result of $T_{\text{ex}}$ modifications will give rise to larger $h_{\text{max}}$ changes at Shigaraki than at Millstone Hill, or we can say $h_{\text{max}}$ is more sensitive to $T_{\text{ex}}$ changes at Shigaraki. In general, the data set $N_{\text{max}}$-$h_{\text{max}}$ provides $T_{\text{ex}}$ values with a fairly good accuracy (small deviation), and adding IEC data does not seem to improve the accuracy much. Table 3 shows the [O]/[N$_2$] ratio results, similar to those in Table 2. Again, the data set $N_{\text{max}}$-$h_{\text{max}}$ provides reasonable accuracy.

4.2. Winds

Table 4 is for the daytime average deviation of southward winds (not the percentage but the absolute deviation defined as $|\text{Wind}(\text{parameters})-\text{Wind}(\text{profile})|$). Inferring winds from $h_{\text{max}}$ data alone contains 35 m s$^{-1}$ error for Millstone Hill and 15 m s$^{-1}$ for Shigaraki. The greater deviation at Millstone Hill is due to the larger dip angle, which yields smaller $\sin I \cos I$ for inducing vertical motion of ionization, so that the meridional wind can not be so easily tracked as it can be for Shigaraki by the $N_e$ variations. The 25 m s$^{-1}$ average over both sites can be reduced to 16 m s$^{-1}$ by adding $N_{\text{max}}$ data.

5. Discussion

The accuracy of the absolute values of derived variables is a problem beyond the scope of this work. As stated by Zhang et al. [2002], the inferred $T_{\text{ex}}$ is essentially a proxy for affecting the $[\text{O}]/[\text{N}_2]$ change since $N_e$ near the $F_2$ peak is proportional to the $[\text{O}]/[\text{N}_2]$ ratio during the daytime. If factors other than thermal expansion have caused $[\text{O}]/[\text{N}_2]$ to change, our $T_{\text{ex}}$ becomes an “effective” exospheric temperature, of reduced physical significance, whereas the $[\text{O}]/[\text{N}_2]$ ratio is still meaningful. Our $T_{\text{ex}}$ tends to be very low around noon at Millstone Hill and high in the afternoon at Shigaraki, suggesting that other factors have indeed affected $[\text{O}]/[\text{N}_2]$ and our results at these times may not be considered as a true estimate of the exosphere temperature. The accuracy of the data and the assimilative model need also to be taken into account. Although the physics and chemistry are relatively simple during the day for the O$^+$ dominant regime, modeling errors due to effects of vibrationally excited N$_2$ and O$_2$, and in photoelectron production, cross sections and reaction rates may bias our results.

As stated before, our EUVAC modification factor $f_E$ of 0.79 has been obtained from the 2-variable ($f_E$-$f_T$) search with the third variable (meridional winds) set by a climatological model and not adjusted. Such $f_E$ depends generally on the validity of the third variable, although we do see weak binary correlations between $f_E$ and winds, the third variable, as indicated in Section 3.1.3. Using this $f_E$, we obtain neutral winds in the $A_n$-$f_T$ search (Section 3.2). This wind result is more than just a noisy version of the assumed climatological winds, because our 0.79 factor is an optimal value obtained by considering the individual $f_E$ as well as the fitting error information for each hour.

In spite of the uncertainty for deriving absolute values of the variables, our conclusions made for the relative changes of the variables in response to changes in the data type, from the profile points to various key parameters, are still valid.

6. Conclusion

Assimilation of incoherent scatter radar electron density data from Millstone Hill and Shigaraki into an ionospheric model has been performed to infer the solar flux, effective exospheric temperature $T_{\text{ex}}$ ([O]/[N$_2$]), and meridional wind. These ionospheric model variables are adjusted to give best match of the model $N_e$ to the data. We explore the relative accuracy of deriving these three variables using complete altitude profiles of the ionospheric electron density as compared to just using key parameters of the ionospheric peak ($N_{\text{max}}$ and $h_{\text{max}}$) and of the ionospheric $F'$ layer electron content (IEC). We find that:

1. With either the profile or key parameter data, the EUV flux can be inferred with little ambiguity, given that background variables such as the meridional wind are known.

2. The southward wind and $T_{\text{ex}}$ can be simultaneously derived from either type of data. The results, in particular the [O]/[N$_2$] results, are similar for the two types of data. The accuracy of the wind result relies much on the accuracy of $h_{\text{max}}$ as well as the geomagnetic dip angle.

3. A few key ionospheric parameters are not always sufficient to give a unique definition of ionospheric conditions. Additional parameters or even a full profile data are sometimes needed. In general, however, the key parameter pair $h_{\text{max}}$-$N_{\text{max}}$ seems to be a suitable assimilation data source, at least for retrieving the local features of the $T_{\text{ex}}$ and meridional wind variation.
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Figure 1. The uniqueness of the inferred EUV flux. Left panels are for Millstone Hill and the right for Shigaraki. Top panels are for $T_{ex}$-EUV correlation coefficients and the bottom for Wind-EUV. Dots are obtained with the profile assimilation, diamonds with $N_{\text{max}}$-$h_{\text{m}}$-IEC data, and crosses with $N_{\text{max}}$-$h_{\text{m}}$ data.

Table 1. EUVAC Factor $f_E$ for Different Assimilation Data Sets

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<th>Data</th>
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<th>Shigaraki</th>
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<td>profile</td>
<td>0.80</td>
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Table 2. Percentage Deviations of Inferred $T_{ex}$ from $N_{\text{max}}$, $h_{\text{m}}$, and IEC to Those from the $N_e$ Profile$^a$

$^a$ Values are daytime averages.

<table>
<thead>
<tr>
<th>Data</th>
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<th>Shigaraki</th>
<th>Average</th>
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<td>$N_{\text{max}}$-$h_{\text{m}}$-IEC</td>
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Table 3. Percentage Deviations of Inferred 300-km $[O]/[N_2]$ from $N_{\text{max}}$, $h_{\text{m}}$, and IEC to Those from the $N_e$ Profile$^a$

$^a$ Values are daytime averages.

<table>
<thead>
<tr>
<th>Data</th>
<th>Millstone</th>
<th>Shigaraki</th>
<th>Average</th>
</tr>
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<tbody>
<tr>
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<tr>
<td>$N_{\text{max}}$-$h_{\text{m}}$</td>
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</tr>
<tr>
<td>IEC</td>
<td>28</td>
<td>13</td>
<td>21</td>
</tr>
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</table>

Table 4. Absolute Deviations of Winds from $N_{\text{max}}$, $h_{\text{m}}$, and IEC to Those from the $N_e$ Profile$^a$

$^a$ Values are daytime averages in unit of m s$^{-1}$.

<table>
<thead>
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<th>Average</th>
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<tbody>
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<td>22</td>
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<tr>
<td>$N_{\text{max}}$-$h_{\text{m}}$</td>
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<tr>
<td>$h_{\text{m}}$</td>
<td>35</td>
<td>15</td>
<td>25</td>
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</table>
Figure 2. Assimilation results with $N_{\text{max}}$, $h_{\text{max}}$-IEC data set for Millstone Hill and EUV flux is 0.79 times the default model values. (a) The inferred $T_{\text{ex}}$ (dots and error bars; the solid line is for MSIS model), (b) the inferred southward wind (dots and error bars; the solid line is the default model values of horizontal wind model (HWM)-like model for MU radar (HWMMU)), (c) original $h_{\text{max}}$ data (diamonds) and fitted values (dots), (d) original $N_{\text{max}}$ data (diamonds) and fitted values (dots), (e) original IEC data (diamonds) and fitted values (dots), (f) Wind-$T_{\text{ex}}$ correlation coefficient.
Figure 3. The uniqueness of the inferred wind and $T_{ex}$ indicated by their correlation coefficient for Millstone Hill and Shigaraki. Dots are obtained with the profile assimilation, diamonds with $N_{max}-h_{max}$-IEC data, and crosses with $N_{max}-h_{max}$ data.
Figure 4. Comparisons of inferred variables for different assimilation data. Left panels are for Millstone Hill and right panels for Shigaraki. Top panels are for $T_{ex}$, middle panels for 300-km $[O]/[N_2]$ ratio calculated with the mass spectrometer and incoherent scatter (MSIS86) model for the inferred $T_{ex}$, and bottom panels are for southward winds. Dots are obtained with the profile data assimilation, triangles with $N_{max}$-$h_{max}$-IEC data, squares with $N_{max}$-$h_{max}$ data. Solid lines in the top and middle panels are for the MSIS model values, in the bottom panels they are ion drift-based wind measurements for the left panel, and HWMMU model values for the right panel.
Figure 5. Profile comparisons for Millstone Hill at each hour from 0800 LT to 1600 LT. Circles are for measurements (the error bars is an assumed 10% uncertainty for the data), solid lines are the best matched model profile from the profile data assimilation, and dashed lines are the best matched model profile from $N_{\text{max}}$-$h_{\text{max}}$-IEC data assimilation.
**Figure 6.** Comparisons of the inferred $T_{ex}$ and $[O]/[N_2]$ for different assimilation data over Millstone Hill. The top panel is for $T_{ex}$ and the middle panel for 300-km $[O]/[N_2]$ ratio calculated with MSIS86 model for the inferred $T_{ex}$. Dots are obtained with the profile data assimilation, diamonds with $N_{max}-h_{max}$-IEC data, triangles with $N_{max}-h_{max}$ data, squares with $N_{max}$ data, and crosses with IEC data. Solid lines are for the MSIS model values.

**Figure 7.** Comparisons of the inferred southward winds for different assimilation data over Shigaraki. Dots are obtained with the profile data assimilation, triangles with $N_{max}-h_{max}$-IEC data, squares with $N_{max}-h_{max}$ data, and crosses with $h_{max}$ data. The solid line is for HWMMU model values.