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Solar EUV flux, exospheric temperature and thermospheric wind inferred from incoherent scatter measurements of the electron density profile at Millstone Hill and Shigaraki

Shun-Rong Zhang,[1,2,3] William L. Oliver,[1,4] John M. Holt,[5] and Shoichiro Fukao[6]

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[1] We explore a method for inferring solar EUV flux, atmospheric composition and wind using ionospheric electron density N_e profile measurements. Incoherent scatter radar data from Millstone Hill and Shigaraki measured on October 5, 1989 are assimilated into a theoretical model whose driving forces, solar EUV flux, exosphere temperature T_{ex}, and meridional wind, are adjustable. Adjustments are made to give best match between the model N_e profile and the data. The derived T_{ex} values, found to be low near noon at Millstone and high in the afternoon at Shigaraki, are essentially those required to give the [O]/[N_2] ratio necessary to fit the data. Our inferred EUV fluxes for the two sites are similar. Our technique of using profile data may resolve the ambiguity in deriving EUV and [O]/[N_2] from electron-density measurements. *INDEX TERMS:* 2443 Ionosphere: Midlatitude ionosphere; 2447 Ionosphere: Modeling and forecasting; 6952 Radio science: Radar atmospheric physics; 0355 Atmospheric Composition and Structure: Thermosphere—composition and chemistry

1. Introduction

[2] F_2 layer electron density N_e is strongly dependent upon the solar EUV flux, thermospheric concentration, temperature, and wind. Approaches have been developed to acquire some of these variables from the maximum electron density $N_{\max}$ and its altitude $h_{\max}$ [see *Miller et al.*, 1986; *Buonsanto et al.*, 1989; *Titheridge*, 1993; *Richards et al.*, 1998]. *Sojka et al.* [2001] have developed local and regional ionospheric assimilation methods based upon ionosonde $N_{\max}$ and $h_{\max}$. *Zhang et al.* [2001b] have studied the use of N_e complete-profile data to see what further can be extracted. They addressed ambiguity problems in inferring multiple variables and concluded that if only the wind and one other variable are unknown, then the ambiguity is small. Their approach assimilates incoherent scatter (IS) radar data into a theoretical ionospheric model whose driving forces/variables are adjusted to give best match between modeled and measured N_e. Following this conceptual work, the present paper describes a concrete and operable method of using two-station IS measurements of the N_e profile to infer the solar EUV flux, T_{ex}/neutral composition, and meridional wind. We present these N_e-based results looking towards the feasibility of monitoring the thermosphere and solar flux from analyses of routinely measurable N_e height profiles and other data.

2. Data and Model

[3] We consider data measured on October 5, 1989 by the Millstone Hill (42.6°N, 288.5°E) IS radar (MHR) and Shigaraki (34.85°N, 136.1°E) middle and upper atmosphere radar (MUR). The daily solar 10.7-cm flux level was 218 units, and the *Ap* index was 5. We use hourly data measured by day, when effects of EUV flux and neutral composition are both critical to N_e determination. The N_e data has a range resolution of 48 km for the MHR and 9.6 km for the MUR. Ion drifts were measured by the MHR but not by the MUR for the day we are studying.

[4] The model, developed by *Zhang and Huang* [1995], solves the O^+ diffusion equation and the continuity equations for NO^+, O_2^+, and N_2^+ to compute N_e over 100 to 500 km altitude. Plasma temperatures are set to the measured data. To allow for the $\mathbf{E} \times \mathbf{B}$ drift contribution to the ion vertical motion, we use the measured meridional ion drift perpendicular to the geomagnetic field for MHR's computation and an empirical MU radar ion drift model [*Zhang et al.*, 2001a] for MUR's computation. Neutral composition, temperature, winds, and solar flux are the driving variables to be determined. They are obtained by their adjustment from initial climatology values to give best match between the modeled and measured N_e profile. We use the mass spectrometer and incoherent scatter (MSIS86) model [*Hedin*, 1987] to generate an initial atmosphere. T_{ex} determines the scale height of atmospheric species and thereby affects the neutral composition at all altitudes above the base of the thermosphere. We adjust the MSIS T_{ex}, insert this adjusted value back into MSIS, and let the MSIS model code then compute neutral densities in a self-consistent manner. As initial values for the meridional wind, we use, for MHR, the wind derived from the ion drift measurements and, for MUR, 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. 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 independent of wavelength.

3. Method and Result

[5] Our variable adjustment and determination to gain 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 parameters determined and their interparameter binary correlations. See *Zhang et al.* [2001a] for details. Ideally we would like to have simultaneous determination of the parameters controlling temperature, wind, and solar flux. *Zhang et al.* [2001b] have shown that such a three-variable fit yields binary parameter

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[1] Center for Space Physics, Boston University, Boston, Massachusetts, USA.

[2] Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan, China.

[3] Now at Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA.

[4] Department of Electric and Computer Engineering, Boston University, Boston, Massachusetts, USA.

[5] Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA.

[6] Radio Science Center for Space and Atmosphere, Kyoto University, Kyoto, Japan.

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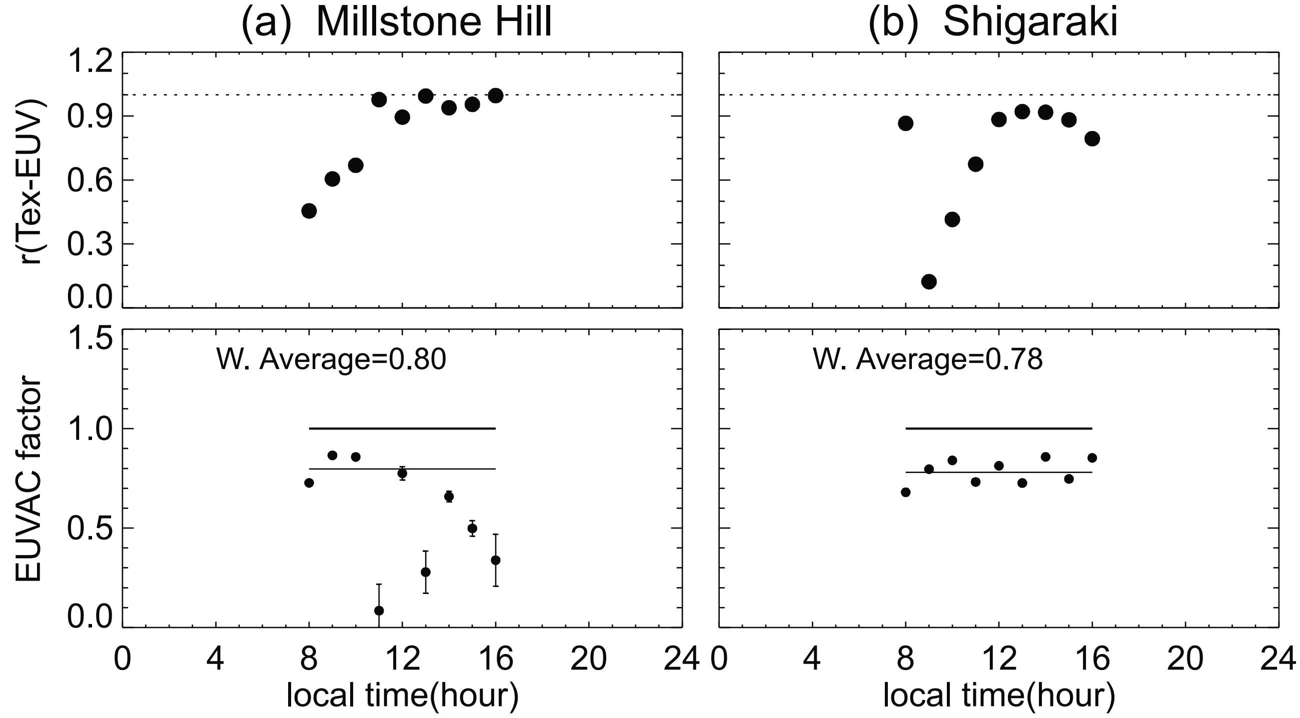

Figure 1. The uniqueness of the inferred EUV flux. The top panel shows the EUV-T_{ex} correlation coefficient in fitting the F layer N_e profiles; the bottom panel shows the derived multiplicative factor (dots) for EUVAC when the model EUV flux and T_{ex} variables are simultaneously adjusted for (a) Millstone Hill, and (b) Shigaraki.

correlations near unity so that nearly complete ambiguity prevails. We describe below various two-parameter fits.

3.1. EUV Flux

[6] Given that wind speeds are often available from IS radars or climatological models, we have implemented an EUV-T_{ex} 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 or predictable. Once actual information on drifts from collections of prior radar measurements is added into the assimilation, then we can determine the temperature and wind unambiguously.

[7] For the EUV-T_{ex} search, as shown in Figure 1, the correlation is low in the morning and high around noon for both sites. Changes in EUV flux produce proportional changes in the O^+ production rate. Changes in [O], resulting from changes in T_{ex}, produce very nearly proportional production changes in O^+ in the F region during the middle of the day when the optical depth remains small, resulting in high midday EUV-T_{ex} correlation. In the morning, however, due to the large solar zenith angle and associated optical depth, changes in neutral composition cause significant changes in optical depth. A meaningful EUV flux can be obtained for periods having a small EUV-T_{ex} correlation coefficient. Shown in the bottom panels in Figure 1 are hourly EUVAC multiplicative factors and an average EUVAC factor computed only for hourly results having correlation coefficients below 95% and weighted inversely as the variance of the hourly result. The factors obtained at 1100, 1300, and 1600 LT for MHR are not reliable due to the high correlation. We found the average factor for MHR to be 0.80 and for MUR 0.78. We take their average 0.79 as our optimal EUVAC factor for this particular case.

3.2. T_{ex}/Composition and Meridional Winds

[8] With this 0.79 EUVAC factor applied for all further model computations, we now determine T_{ex} and meridional wind. The T_{ex} and wind values are weakly correlated (Figure 2). In fact, an increase in T_{ex} generates higher [O] and [N_2] but lower [O]/[N_2] ratio, so gives rise to a higher chemical loss-diffusion balance height (h_{max}) but lower F_2 layer electron density (N_{max}). A wind change, which either raises ions to regions of greater N_e or vice versa, can not duplicate a T_{ex} change.

[9] For MHR, T_{ex} is ~1000–1400°K, varying with time, and on average 185°K lower than the MSIS T_{ex}. This result is similar to that given by the climatology study of *Buonsanto and Pohlman* [1998]. Also seen is the noon depression that has been reported by *Oliver and Salah* [1988]. However, compared with ion temperature T_i measurements at 300 km as another estimate of exospheric temperature, our T_{ex} is low and closer to T_i at 210 km. T_{ex} is basically an effective value that generates appropriate [O]/[N_2] in our model. The 300-km [O]/[N2] so generated, which may be physically more meaningful than T_{ex}, is about 1.1–1.3 times the corresponding MSIS value. For MUR, however, T_{ex} is as high as 1500–1800°K, which is nearly 300°K higher than the MSIS value, giving a 300-km [O]/[N2] ~0.75–0.85 times the corresponding MSIS value.

[10] The meridional wind for MUR is basically around the empirical HWMMU values. Shigaraki has a magnetic dip angle $I \sim 48°$, thus the neutral wind effect on O^+ vertical motion is almost as large as it can become ($\sin I \cos I \sim 0.5$). This effect is smaller at Millstone Hill ($\sin I \cos I \sim 0.3$), so its N_e profile is not as sensitive to wind changes and the derived winds show greater uncertainty and fluctuation. The MHR wind is generally offset northward from that derived from the observed ion velocity and computed diffusion velocity and closer to the HWM90 model value.

4. Discussion and Conclusion

[11] We have described a method of using IS measurements of the N_e profile to infer the solar EUV flux, T_{ex}, and meridional wind. They are the driving forces for an ionospheric model and

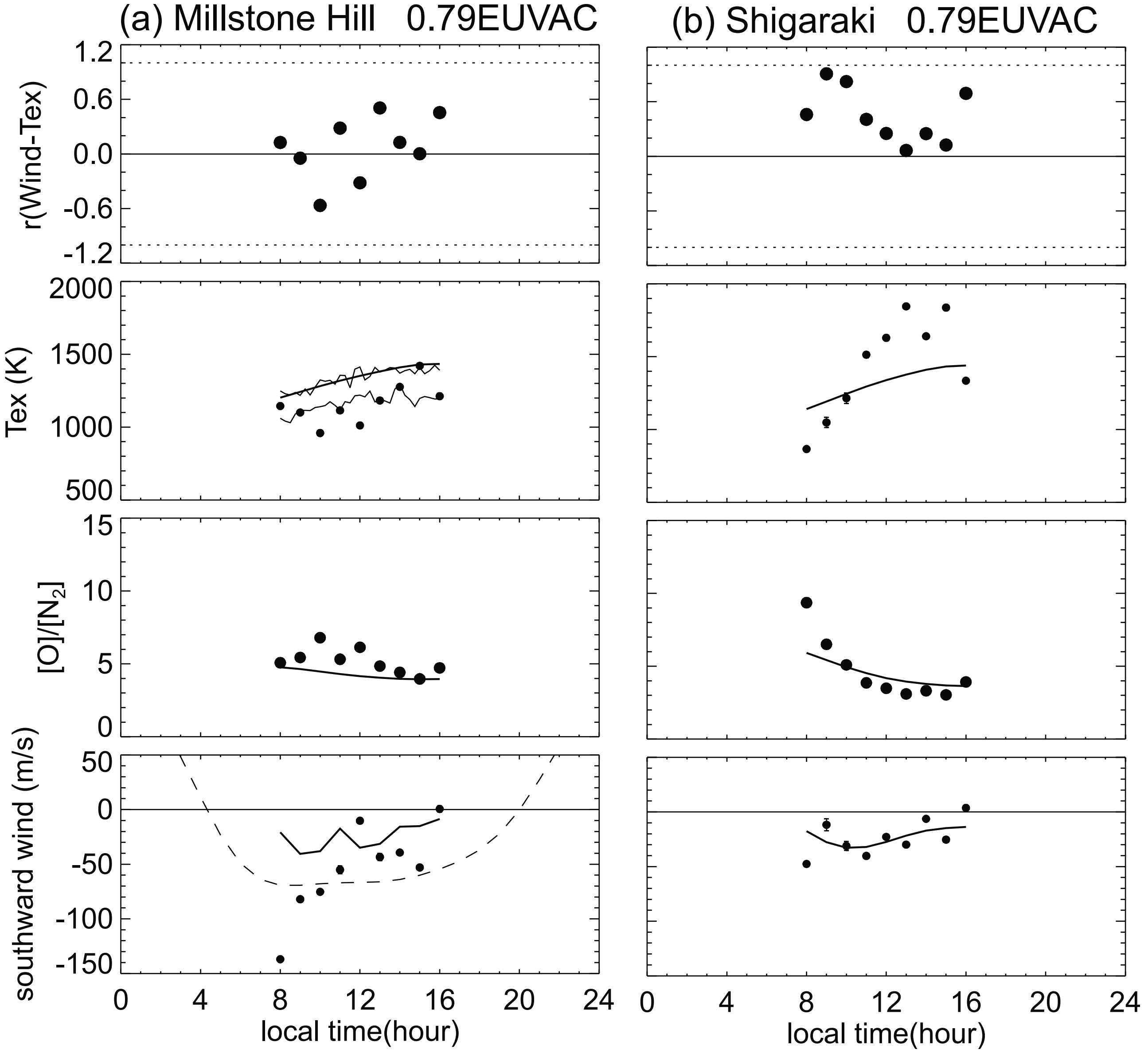

Figure 2. T_{ex} and southward wind derived with the EUVAC factor set to 0.79. The top panel shows the wind-T_{ex} correlation coefficient indicating variable uniqueness; the second panel shows T_{ex} (dots; the thick solid line is for the corresponding MSIS86 model values, the upper thin line is the ion temperature T_i at 300 km, and the lower thin line is T_i at 210 km); the third panel shows the $[O]/[N_2]$ ratio (dots) computed from MSIS86 for the T_{ex} of the second panel (the solid line shows the ratio computed from the MSIS T_{ex}); and the bottom panel shows the derived southward wind (dots). The solid line in the wind panel for Millstone Hill shows winds derived from drift measurements while the dashed line shows HWM values; for Shigaraki the solid line shows HWMMU values. The left panels (a) are for Millstone Hill and right panels (b) are for Shigaraki.

are adjusted to give best match of the model N_e profile to the data. Using MHR and MUR IS data, we found that the EUV flux can be inferred by adjusting it together with T_{ex} under the condition that the meridional wind is set to climatology values or measurements. A low EUV-T_{ex} correlation in the morning hours makes it possible for the EUV flux to be so determined without ambiguity. With this known EUV flux, T_{ex} and wind can be simultaneously inferred.

[12] The inferred T_{ex} is essentially a proxy for affecting $[O]/[N_2]$ change since N_e near the F_2 peak is known to be largely proportional to the $[O]/[N_2]$ ratio during the daytime. If factors other than thermal expansion have caused $[O]/[N_2]$ to change, our T_{ex} becomes an "effective" exospheric temperature, of reduced physical significance, whereas the $[O]/[N_2]$ ratio is still meaningful. Radar measurements of T_i are a valid measure of the neutral temperature, giving less freedom to adjust T_{ex}. Failing to reproduce 300-km T_i, our 20% adjustments to the MSIS T_{ex} may indeed indicate that other factors have affected $[O]/[N_2]$.

[13] It is not feasible to directly change [O] and $[N_2]$ due to the fact that EUV and [O] are highly correlated in fitting the F_2 region N_e profile (*Zhang et al.* [2001b]). The EUV result that we do obtain here (from EUV-T_{ex} fit) also depends on the [O] adopted from MSIS. If we should fit the N_e profile to lower altitudes, we would have a better chance to resolve the EUV and [O] ambiguity.

[14] While our technique of assimilating profile data may resolve the ambiguity in deriving EUV, $[O]/[N_2]$ and winds, the accuracy of results depends on that of the N_e data and the model. Although the physics and chemistry involved 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.

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S. Fukao, Radio Science Center for Space and Atmosphere, Kyoto University, Uji, Kyoto 611-0011, Japan. (fukao@kurasc.kyoto-u.ac.jp)

J. M. Holt and S.-R. Zhang, Haystack Observatory, Massachusetts Institute of Technology, Route 40, Westford, MA 01886, USA. (jmh@haystack.mit.edu; shunrong@haystack.mit.edu)

W. L. Oliver, Department of Electrical and Computer Engineering, Boston University, 8 Saint Mary's Street, Boston, MA 02215, USA. (wlo@bu.edu)