

¹ Day-to-day Variability and Solar Preconditioning of ² Thermospheric Temperature over Millstone Hill

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Abstract.

We use a continuous 30 day incoherent scatter radar experiment at Millstone Hill in October 2002 to examine day-to-day thermospheric variability in exospheric temperature T_{ex} . Solar flux and magnetic activity influences as the main driving factors for day-to-day variability are investigated quantitatively. Solar ultraviolet flux levels are based on the TIMED/SEE space weather product, allowing for analysis of ultraviolet flux- T_{ex} correlation. T_{ex} is most sensitive to solar EUV flux with approximately a 2-day delay at wavelengths of 27–34 nm (including 30.4 nm). In particular, a 20–60-hour time delay occurs in T_{ex} response to EUV flux at 27–34 nm band, with shorter delays in the morning and longer delays in the afternoon and at night. The 1~2-day delayed T_{ex} response to solar ultraviolet flux and associated thermospheric solar preconditioning (“memory”) are most significant in the daily mean for the 27–34 nm band, in the diurnal and semidiurnal amplitudes for the soft X-ray flux at 0.1–7 nm, and in the diurnal amplitude for longer wavelengths. An empirical model driven only by EUV flux at 27–34 nm from two days in advance reproduces 90% of the observed variability in the T_{ex} daily mean. With a two-day time delay, solar X-ray flux at 0.1–7 nm is correlated positively with T_{ex} diurnal amplitude, and negatively with T_{ex} semidiurnal amplitude. Finally, magnetic activity control, as represented by the Dst index, is weaker during the day and stronger at night, and is important for the semidiurnal amplitude but not important for the daily mean.

1. Introduction

26 Variability in the physical state of the upper atmosphere can be significant but in gen-
27 eral is not well understood. Some progress has recently been achieved primarily in char-
28 acterizing variability in ionospheric electron density (see Rishbeth and Mendillo [2001])
29 and plasma temperatures (see Zhang and Holt [2008]). However, variability in thermo-
30 spheric parameters, and in particular their day-to-day variability, has been less pursued
31 due to the relatively fewer observations available. Advancing knowledge of thermospheric
32 variability is very important not only for understanding of the neutral atmosphere but
33 also of the ionosphere, since the relatively smaller plasma densities in the ionosphere are
34 embedded in and heavily influenced by the much larger neutral densities in the thermo-
35 sphere. Thus, thermosphere variability provides a major source of ionospheric variability.
36 The ionospheric plasma is created through photoionization of neutrals, with losses to the
37 neutral atmosphere and whose kinematics are directly under the influence of ion-neutral
38 collision. Solar irradiation and magnetic activity are the main direct external drivers of
39 thermospheric variability. Various thermospheric momentum and energetic processes such
40 as acoustic, tidal, and planetary waves, as well as meteorological processes can result in
41 thermospheric variability due to coupling between different atmospheric layers, imposing
42 significant impacts on the ionosphere (Forbes and Zhang [1997], Forbes [2000], Rishbeth
43 and Mendillo [2001], Altadill and Apostolov [2001], Mendillo et al. [2002], Laštovička
44 [2006], Rishbeth [2006], Goncharenko et al. [2010]).

45 An incoherent scatter radar (ISR) is one of the very few instruments that can be used
46 to monitor thermospheric variations from the ground, through observations of ionospheric

47 parameters combined with energy balance equations. A well-established method for de-
48 riving the neutral temperature profile originated in work by Bauer et al. [1970] based on
49 energy balance equations for ionic species, and is still being used (e.g. Nicolls et al. [2006]).
50 Many prior ISR observations of exospheric temperature were used as a major source of
51 data for climatology and detailed temporal variations used to construct the MSIS neutral
52 atmospheric models (Hedin [1987]; Picone et al. [2002]). Millstone Hill ISR observations
53 were first used by Salah and Evans [1973] to conduct thermospheric temperature studies.
54 Most prior studies on exospheric temperature involve climatology derived from a variety
55 of solar-geophysical conditions. For example, Hagan and Oliver [1985] uses ISR data to
56 examine thermospheric solar cycle variability. Oliver and Salah [1988] reported results of
57 the Global Thermospheric Mapping Study (GTMS) campaigns, which covered two 3-day
58 periods. Buonsanto and Pohlman [1998] examined exospheric temperature climatology
59 above Millstone Hill, and Oliver [1997] uses similar observations to focus on the O^+O
60 collision cross-section. Other techniques have also been developed to extract information
61 of the thermospheric temperature from ISR measurements, e.g. data assimilation ap-
62 proaches using electron density profiles [Zhang et al, 2001; Mikhailov and Lilensten, 2004]
63 along with key ionospheric parameters [Zhang et al, 2003]. These data assimilation ap-
64 proach techniques are applicable for electron density observations obtained by techniques
65 other than ISR (e.g. ionosonde). However, in this paper we focus on the energy balance
66 method using as input ISR measurements of plasma temperatures T_i and T_e , in addition
67 to electron density N_e .

68 While ground-based observations are relatively few for thermospheric studies, long time
69 series of ground-based thermospheric temperature observations sufficient for day-to-day

70 variability investigations are truly rare but do exist. Using an unique dataset from Oc-
71 tober 2002 providing a consecutive 30-day ISR exospheric temperature observation at
72 Millstone Hill, the present paper deals with day-to-day variability of the thermosphere
73 at medium to high solar activity. Ionospheric variability during this long duration ISR
74 experiment was discussed previously. Zhang et al. [2005] found quasi-periodic electron
75 density oscillations with periods >1 day. While some of those fluctuations were corre-
76 lated with changes in the neutral composition originating from geomagnetic activity, the
77 wave-like oscillations in electron density exhibited phase changes with height which per-
78 sists up to 600 km and prevailed until a large storm appears to impose a phase change
79 in an opposite direction. In a study of the E-region variability, Moore et al. [2006] noted
80 that photochemical modeling can reproduce the electron density variability at mid- and
81 low-latitudes, and the variability is dominated mostly by solar flux variations, modified
82 by solar declination, and least affected by neutral density changes. In an analysis of an-
83 other 30-day ISR experiment at Millstone Hill (September 2005), Zhang and Holt [2008]
84 indicated that with increasing solar flux, electron density decreases between 170 km and
85 the F2 peak and increases elsewhere, being essentially unchanged near the F2 peak. A
86 time lag of ionospheric responses to changes in the 10.7 cm solar flux was also found: in
87 the E region, the lag is almost zero; above the F2 peak, the lag for either electron density
88 or ion temperature is ~ 2 days.

89 Here, we characterize thermospheric day-to-day variability during geomagnetic quiet
90 conditions, where solar flux is a dominant day-to-day variability driver. In addition to the
91 traditional 10.7 cm solar flux proxy, we focus on different effects of EUV/FUV flux at var-
92 ious wavelength bands, including the time delay of thermospheric responses to solar flux

93 and issues related to thermospheric solar preconditioning or so-called “memory” [Rish-
94 beth, 2007]. We also study thermospheric temperature changes in response to frequent
95 weak to moderate magnetic activity, and quantitatively gauge relative contributions of
96 solar flux and magnetic activity conditions to the observed temperature variability.

2. Solar geophysical conditions and ISR measurements of plasma parameters

97 From October 4 to November 4, 2002, a consecutive 30-day incoherent scatter radar
98 (ISR) campaign was conducted at Millstone Hill (42.6°N, 288.5°E, Invariant Lat. 53.4°),
99 using a high power large aperture UHF radar system at MIT Haystack Observatory. The
100 radar’s 68-m diameter zenith antenna was used to measure at 4 minute cadence vertical
101 profiles of electron density N_e , electron temperature T_e , ion temperature T_i , and line-of-
102 sight velocity V_o . A set of interleaved single pulses and alternating-coded pulses provided
103 E and F region ionospheric observations with an altitude resolution ranging from 4.5 km
104 (E region) to >40 km (F region).

105 During this period, the 10.7 cm solar flux proxy F107 varied between 155 to 185 units
106 (1 unit = 10^{22} W m⁻² Hz⁻¹) from October 4 to November 4, 2002 (day number = 277 to
107 308) whereas its 81-day average was around 169 units, peaked at 174 units on day 283,
108 and decreased in general toward the end of the period reaching a minimum of 164 units
109 on day 306. The F107 proxy, which was larger near the middle of the month, also showed
110 a gradual change with a 27-day periodicity due to solar synodical rotation. Magnetic
111 disturbances were noticeable only on three occasions. On October 7 (day 280), the hourly
112 Dst index [Sugiura, 1964] dropped to -100 nT where it stayed for about 1 full day before
113 it recovered. On October 14 (day 287), a sharp and brief drop in Dst to a minimum of
114 -100 nT occurred. On October 24 (day 297), a major storm was launched with a Dst

115 minimum of -90 nT, main phase of 12 hours and recovery phase of several days, causing
116 severe ionospheric storms. Detailed information about the daily solar 10.7 cm radio flux
117 index F107, hourly Dst index, and 3-hourly ap index are shown in Figure 1 of Zhang et al.
118 [2005]. In this current paper, our primary interest is day-to-day variability not apparently
119 associated with strong magnetic activity (already investigated extensively by numerous
120 researchers). Therefore, we select data with hourly Dst > -75 nT at any given time, and
121 furthermore where, immediately prior to the current time, 6-hourly and 3-hourly average
122 Dst values > -60 nT. These -60/-75 nT bounds were determined based on examining the
123 histogram of Dst data for the entire period, so that enough data points are available for
124 robust statistics while observations with medium to high magnetic activity are effectively
125 eliminated. These bounds are slightly smaller but close to the typical -50 nT threshold for
126 classification of moderate to intense storms (cf. Wanliss and Showalter [2006] for results
127 from a very large dataset from 1963 to 2002).

128 The method for deriving $T_n(z)$ (and neutral oxygen density) is based on the ion energy
129 balance equation. Bauer et al. [1970], Salah and Evans [1973], Alcaydé et al. [1982], and
130 most recently Nicolls et al. [2006] describe methods in some detail which are valid for the
131 F2 region. The Oliver [1979] method is an extension of these techniques down to the
132 lower F region and the E-region, and determines additional quantities as well as providing
133 modest improvements in the profile shape of the neutral temperature. The present paper
134 will adopt this latter method since our alternating code measurements at 4.5 km minimum
135 altitude resolution provide excellent E and lower-F region data during this campaign.
136 The Oliver [1979] method assumes that the ions are heated by Coulomb collisions with
137 electrons and cooled by elastic collisions with neutrals. The energy transfer coefficients are

138 proportional to number densities of the involved particles, including in particular, oxygen
 139 ion density $[O^+]$ and oxygen density $[O]$. However, $T_n(z)$ is calculated from this energy
 140 equation through a profile fit to a Bates function-type height variation. In this function,
 141 $T_n(z)$ is determined by three parameters: the thermo-base temperature T_b for 120 km, the
 142 exospheric temperature T_{ex} and the shape factor s determining how fast T_n approaches
 143 T_{ex} from T_b , i.e., $T_n(z) = T_{ex} - (T_{ex} - T_b) \exp[-sz_g(z)]$, with $z_g(z)$ being geopotential height. In
 144 fact, $1/s$, the inverse of the shape factor, is equivalent to scale height with units of km.
 145 Atomic oxygen is assumed to be in diffusive equilibrium, so $[O]$ is determined by neutral
 146 temperature and the oxygen density at a reference height, normally set at 400 km. Neutral
 147 quantities needed for the energy equation calculations are obtained using the NRL-MSIS
 148 model [Picone et al., 2002]. The 4 parameters [T_{ex} , T_b , s and $[O]_{400km}$] are inserted into
 149 the energy equation (through T_n and $[O]$) and then T_i is calculated. The best set of the
 150 4 parameters is chosen in a least squares sense, such that the calculated T_i profile best
 151 fits the measured T_i profile. In practice, we set $[O]$ to MSIS values, as our fit results
 152 along with previous work on this algorithm [Litvin et al., 2000] indicate that the resulting
 153 T_{ex} is hardly affected by values of $[O]$. Similarly, O^+ - O collision cross-section is not an
 154 important parameter for the T_{ex} study reported here, although it can be important for
 155 determining the absolute value of $[O]$ as the temperature-density product defines energy
 156 transfer coefficients from O^+ to atomic oxygen [Oliver and Glotfelty, 1996].

157 Determination of T_b and s is sensitive in particular to measurements in the E region. In
 158 practice, midlatitude E region electron density is low at night leading to weak detected ISR
 159 signals and high measurement uncertainty in the resulting plasma parameters. Therefore,
 160 nighttime T_b and s data may be considered as first order quantities while corresponding

161 T_{ex} is zeroth order quantity. Additionally, nighttime conditions have a lack of significant
162 photoionization, and therefore strong heat coupling among plasma and neutrals leads to
163 approximately equal T_i , T_e and T_n values, increasing the difficulty of determining neutral
164 temperature from the detected plasma temperature.

165 There are two main assumptions involved in the somewhat simplified energy equation
166 method used in this study. First, frictional heating is ignored. In cases where frictional
167 heating is large enough, Litvin et al. [2000] shows that neutral temperature may be under-
168 estimated. Since we have selected data for relatively quiet magnetic activity as mentioned
169 earlier, we do not expect our results to be significantly affected by frictional heating. Sec-
170 ond, thermal conduction is ignored, and it is known that thermal conduction may become
171 significant in the upper F region. However, this assumption would not affect our T_{ex}
172 results significantly, because they are essentially determined by data below 300 km where
173 the ions and neutrals are in close thermal contact and thermal conduction is not impor-
174 tant. Therefore the accuracy of T_n depends strongly on the quality of the observed T_i ,
175 with a typical measurement uncertainty of 10-30 K (varying with geophysical conditions
176 and observational facility systems). At this uncertainty level, Nicolls et al. [2006], using
177 a least squares fit matching the energy transfer rate between electrons to the ions with
178 the rate between the ions to the neutrals, provided a detailed error analysis for Arecibo
179 incoherent scatter radar observations. The resulting fractional error in T_{ex} was found
180 typically within 0.01, equivalent to 10-20 K for the geophysical conditions in this study.

3. Day-to-day thermospheric variability

181 Diurnal variations and their variability for the set of three derived thermospheric pa-
182 rameters [T_{ex} , T_b , $1/s$] over the 30-day October 2002 run period are plotted in Figure 1,

Figure 1

183 showing the monthly average and standard deviation for each hourly bin along with cor-
184 responding NRL-MSIS model averages. The percentage variability, defined as standard
185 deviation over the monthly average, is shown at the bottom of each panel.

186 T_{ex} maximizes in the afternoon between 1500–1600 LT, delayed by 3-4 hours from
187 local noon (maximum solar zenith angle), and minimizes at 0600 LT before local sunrise.
188 The observed T_{ex} monthly average agrees exceptionally well with MSIS during daytime
189 hours (with deviation typically well less than 10K or 1%), while the NRL-MSIS model
190 underestimates the observation by up to 50 K at night. The day-to-day variability is at
191 the 5% level or 50–60 K, and changes little with local time, although T_{ex} itself changes
192 substantially over 24 hours. The thermo-base temperature T_b is stable during the day,
193 remaining at 340-350 K. However MSIS is close to or slightly more than one standard
194 deviation away from the observed values in the afternoon. Overnight values are widely
195 scattered, differing from MSIS predictions by up to 20%. However, this difference is within
196 the day-to-day variability in the data. The inverse of the shape factor $1/s$ is on the order
197 of 50 km during the day, and differences between the observation and MSIS model are
198 particularly large at night (over 25 km). Variability in the observed $1/s$ is within 15-25%,
199 and is small during the day. The large observational scatter at night for both T_b and
200 $1/s$ is most likely due to weak ISR signals in the E-region as described earlier. However,
201 further analysis of T_b and $1/s$ is beyond the scope of this paper which has a focus on T_{ex} .

202 We will first address variations at individual local times in Section 3, then in Section 4,
203 we will discuss tidal components derived from the same dataset shown in Figure 1.

3.1. Solar irradiation effects

204 Solar geophysical conditions are known to be major sources of T_{ex} variability. To
205 quantify these effects on thermospheric temperature, we take a straightforward approach
206 by calculating the correlation coefficient between T_{ex} and geophysical indices. Figure 2
207 presents these correlation results as a function of local time, with shaded areas indicating
208 areas where the null hypothesis of no correlation cannot be rejected (i.e., no significant
209 correlation exists). The shaded areas are estimated based on p-values >0.05 .

Figure 2

210 In this section, we discuss the correlation between T_{ex} and the solar flux. F107 is a
211 daily index for the solar radio flux at a wavelength of 10.7 cm and is widely used as a
212 representation of overall solar activity level. In particular, it is a common solar EUV
213 flux proxy for aeronomy studies. F107 is measured at local noon (2000UT) at Penticton,
214 Canada, corresponding to 1500LT at Millstone Hill. Overall, there is a clear positive
215 correlation between T_{ex} and F107. However, Figure 2 indicates that at 2000–2100 UT
216 the correlation between T_{ex} and F107 maximizes, and after this time period (i.e. in the
217 afternoon) the correlation is higher than before (in the morning). This morning-afternoon
218 asymmetry can be associated partially with the 2000 UT observation time of F107, since
219 T_{ex} for earlier times is therefore not directly related. The lowest correlation is at 0800UT
220 (around 0300LT), 12 hours prior to the F107 data time. This also appears to be the time
221 when T_{ex} is stable and correlated least significantly to magnetic activity index Dst (see
222 Section 3.2).

223 To move beyond F107 proxy values, direct ultraviolet flux data are available from
224 TIMED/SEE in situ measurements. The SEE instrument observes the Sun for about
225 3 minutes out of every orbit (97 minutes), producing 14–15 measurements per day. For

226 this study, we use SEE Space Weather data (<http://lasp.colorado.edu/see/>). These data
227 contain 8 solar irradiance bands that are averaged over each 3-min solar observation with
228 corrections applied for instrument degradation, 1-AU distance, and atmospheric absorp-
229 tion. The available SEE bands are coronal proxies [0.1–7 nm band, Fe XVI 33.5 nm line,
230 and Mg IX 36.8 nm line], transition region proxies [27–34 nm band, He II 30.4 nm line,
231 and H I 121.6 nm line], and chromospheric proxies [C II 133.5 nm line and the 145–165
232 nm band]. The FUV flux at the 121.6nm and 133.5nm lines and within 145–165nm band
233 are also considered in this study, as their energy is deposited in the low thermosphere
234 and thus may affect indirectly the upper thermosphere. Our correlation analysis indicates
235 that T_{ex} is correlated insignificantly (falling well into the shaded area) to 0.1–7 nm band
236 flux, so this band is excluded from further study in this section; influences of this band,
237 including those from the variability of the emission, on tidal components will be discussed
238 in Section 4.

239 In our correlation analysis, we use hourly T_{ex} data, with solar flux data matched to the
240 nearest UT observation time from SEE. Initially, we examine EUV in the 27–34 nm band
241 since, as discussed later this section, this flux tends to show maximum correlation with
242 thermospheric temperature changes. Figure 2 indicates that correlation between 27–34
243 nm band EUV flux and T_{ex} is highest at 2000-2100 UT, when the diurnal variation of
244 T_{ex} reaches maximum. During daylight hours, the correlation coefficient remains around
245 0.5 or up to 0.75. We also note that daytime correlation between T_{ex} and F107 is less
246 robust than between T_{ex} and EUV at 27–34 nm. In fact, this is true also for 30.4 nm
247 He II (transition region proxy), and 36.8 nm Mg IX (coronal proxy) bands, but definitely
248 not true for the 0.1–7 nm band. Furthermore, better EUV data time resolution helps to

249 reduce the morning-afternoon correlation asymmetry seen with the F107 index. Some of
 250 these results for the high correlation between F107 and EUV agree with prior results, e.g.,
 251 for EUV in the 27-34 nm band and HeII [Hedin, 1984].

252 We can further compare correlations for T_{ex} vs F107 and for T_{ex} vs EUV at 27–34 nm
 253 using T_{ex} residuals calculated for the entire period. The residuals are T_{ex} values after
 254 subtraction of dependencies on local time, season, and magnetic activity, and therefore
 255 should be dominated by solar flux variations. Dependencies are represented by a combi-
 256 nation of diurnal, semidiurnal and terdiurnal harmonics (local time dependence), along
 257 with linear functions of the day number and Dst. Figure 3 shows these residuals (dots) as
 258 a function of either EUV (top panel) and F107 (bottom panel). Both EUV and F107 are
 259 shifted and normalized to be within -1 and 1 for easy comparison. The results show that
 260 T_{ex} residuals are more tightly clustered and have better linearity with EUV variations as
 261 compared to F107. The T_{ex} increase with F107 becomes saturated for high F107 values
 262 (~ 180).

Figure 3

263 3.1.1. Exospheric temperature relation as a function of solar flux band

264 T_{ex} response to solar flux depends on specific irradiation wavelength bands and emission
 265 lines. We sort all T_{ex} data for different days and local times into 24 hourly local time
 266 (converting to UT) bins. For each hourly bin, we calculate the correlation coefficient
 267 between T_{ex} and each band of EUV flux observations obtained at the nearest UT time.
 268 Then for each band we determine p_m , the maximum correlation among these 24 possible
 269 hourly correlation coefficients (circles in the upper panel of Figure 4). We also determine
 270 p_a , the average correlation over the 10 highest correlation coefficients in the 24-hour period
 271 (dots in the upper panel of Figure 4). The results show that large correlations for both p_m

Figure 4

272 and p_a appear consistently in the 27–34, 30.4 and 36.8 nm bands, and low or no correlation
273 occurs consistently at 133.5 nm. p_m at 121.5 nm is larger compared to p_m at other bands,
274 but p_a at 121.5 nm is around the median value p_a of all other bands.

275 For each hourly UT time, the wavelength band f_{mx} with maximum correlation coefficient
276 among all bands is shown by circles in the bottom panel of Figure 4. The band f_{mn} with
277 minimum correlation is shown by dots in the same panel. We find that during 1200–2100
278 UT (0700–1600 LT, i.e., daytime hours), the highest T_{ex} - flux correlation appears in
279 the 30.4 nm band, while at other times, the highest correlation appears at 27–34 nm.
280 However, the lowest correlation between temperature and solar flux measured during the
281 day is in the 145–165 nm band, while at other times the lowest correlation is at 133.5
282 nm. We conclude that among those solar flux bands that TIMED/SEE observes, the
283 wavelength bands at 27–34 nm and 30.4 nm, proxies for the solar transition region, are
284 most closely associated with T_{ex} . However, 133.5 nm and 145–165 nm bands, proxies for
285 the chromosphere, are not strongly associated with T_{ex} . In particular, during the daytime,
286 the correlation between the 145–165 nm band in the Schumann-Runge continuum and T_{ex}
287 is the smallest among all bands concerned. This agrees with the general understanding
288 that ultraviolet heating for wavelength region below Lyman β (102.6 nm) down to 8 nm
289 is more important for the upper thermosphere, while the Schumann-Runge continuum
290 heating may be more important for lower altitudes (e.g., around 120 km; see Banks and
291 Kockarts [1973]).

292 Atmospheric absorption of solar irradiation energy by the neutrals is affected by the
293 intensity of incoming solar flux and the photo-absorption cross-sections of neutral par-
294 ticles, both of which are wavelength dependent. The absorption is also dependent on

295 number density of specific neutral particles which are distributed as a function of height
296 based on diffusive equilibrium in the thermosphere. Deposition of solar ultraviolet energy
297 appears to reach a maximum at a specific altitude, where the product of the arriving
298 solar flux intensity and neutral density maximizes. The height of this maximum depends
299 on wavelength, because the photo-absorption cross-sections of different neutral species
300 are wavelength dependent. As a result, EUV energy is generally absorbed the most in
301 the upper thermosphere, soft X-ray energy is absorbed at ~ 110 km, and FUV energy is
302 absorbed in the lower thermosphere.

303 In the 8 bands/lines of solar emission observed by TIMED/SEE, the 27–34 nm, 30.4 nm,
304 33.5 nm and 36.8 nm bands correspond to the wavelengths at which photo-absorption, and
305 photo-ionization cross-sections are high for O, N₂ and O₂, and therefore we expect these
306 bands' solar flux effects on the ion density and neutral temperature to be effective. The
307 absolute value of 27–34 nm flux is the highest, and we accordingly expect high correlation
308 between T_{ex} and solar flux in this band. Of course, variability in the T_{ex} mean can be
309 better correlated with other bands that have greater variability; this will be addressed
310 in Section 4.5. The absolute value of 30.4 nm flux is the second highest, contributing
311 25–50% to the flux at 27–34 nm, and our results accordingly show a correlation between
312 27–34 nm and 30.4nm fluxes of 0.98 (compared to correlation coefficients of 0.94 for 27–34
313 nm vs 33.5 nm, and 0.93 for 27–34 nm vs 36.8 nm). We therefore expect equally high
314 correlation between T_{ex} and 30.4 nm flux. Relative to the flux at 27–34 nm, the flux at
315 33.5 nm is $\sim 10\%$, and at 36.8 nm $\sim 4\%$. We note that even though the FUV fluxes at
316 121.5 nm and 133.5 nm are larger by a factor of several than flux at 27–34 nm, these FUV
317 bands' effects on T_{ex} are much smaller, because at these wavelengths the primary neutral

318 species (e.g., O) in the thermosphere have generally small absorption cross-sections, while
 319 other neutral species (e.g., O₂) that absorb the FUV energy efficiently are abundant only
 320 at low thermospheric altitudes.

321 **3.1.2. Time delay of T_{ex} responses to EUV flux variations**

322 Earlier studies found that neutral density and T_{ex} are related to solar 10.7 cm flux for
 323 the previous day more than for the present day (see Roemer [1967] and Buonsanto and
 324 Pohlman [1998]). In fact, in the MSIS model, F107 for the previous day, rather than
 325 for the present day, is used to drive the model's variation with solar flux. It is unclear
 326 whether this delay is mostly due to the fact that F107 is measured at 2000 UT, i.e., at a
 327 later point in the UT day. However, Eastes et al. [2004] found that solar soft X-ray flux
 328 variations lead variations in neutral density by ~1.5 days. The TIMED/SEE EUV data
 329 used here and ground-based thermospheric data have much better time resolutions than
 330 the daily F107 data, allowing us to examine more precisely (on the order of hours) the
 331 delay in T_{ex} compared to EUV dynamic variations. We show results in this section for the
 332 27–34 nm band, with results comparable in other bands with high correlation coefficients.

333 We calculate correlation between T_{ex} at any given UT of the day and 27–34 nm flux
 334 observed at an earlier time, UT + t, where the lag time t (negative) is a variable. At a
 335 given lag time t , we compute the maximum correlation coefficient in each of 24 UT hourly
 336 bins, $p_m(t)$, and the average of the 10 highest correlation coefficients among these 24
 337 hourly ones, $p_a(t)$. In Figure 5, we plot in the upper panel $p_m(t)$ (circles) and $p_a(t)$ (dots)
 338 as a function of lag time t , ranging between -110 ~ 0 hours. We see that the maximum
 339 correlation $p_m(t)$ increases from 0.72 at $t \sim 0$ to 0.85 at $t \sim -32$ –66 hours, then decreases

Figure 5

340 at longer time delays. This same trend can be found for $p_a(t)$, with highest correlation at
341 a delay time of 1.33–2.75 days (32–66 hours).

342 The lag time of T_{ex} response to EUV flux is local time-dependent. $p_m(t)$ and $p_a(t)$
343 described in the previous paragraph are the correlation maxima and an approximation of
344 the average correlation across the entire UT day. For further information, in Figure 5 (top
345 panel), we also show the correlation curve for 2100 UT using cross symbols. The 2100 UT
346 correlation turns out to be close to the curve of $p_m(t)$, and maximum correlation occurs
347 at $t = \sim -54$ hours of lag time. We estimate this maximum correlation lag time through
348 a least-squared fit of the correlation (the crosses) to a parabolic curve (the dashed line).
349 For each UT time bin, the lag time with maximum correlation can be determined using
350 a similar least-squares fit approach, and the lag time for each UT hour is then shown
351 in the bottom panel of Figure 5. We see that temperature EUV response delay time
352 becomes increasingly longer as time progresses from morning hours (delay = 20–40 hours)
353 to afternoon hours (delay = 40–60 hours).

354 The fact that T_{ex} responds to the 27–34 nm flux more slowly in the afternoon than
355 in the morning may imply that thermospheric temperature solar flux preconditioning or
356 “memory” is shorter in the morning than in the afternoon. The morning-afternoon dif-
357 ference is very common in the upper atmosphere. During its diurnal course as shown in
358 Figure 1, T_{ex} has a minimum around 06-07LT near local sunrise, and increases gradually
359 from morning through noon into afternoon, till 16LT when it reaches the daily maximum.
360 Owing to different morning-afternoon atmospheric absorptions of solar UV energy arising
361 from different morning-afternoon neutral densities, it is reasonable to expect that T_{ex}
362 responses to solar flux variability in the afternoon can be quite different from those in

363 the morning. In fact, this scenario of local-time dependent thermospheric delay follows
364 logically since in the morning hours, solar EUV heating rapidly builds up from a cool tem-
365 perature background. Therefore, it dominates the thermal budget and provides a strong
366 control on the temporal variation of thermospheric temperature. In the afternoon for a
367 similar solar zenith angle and EUV intensity, neutral density and temperature are all close
368 to the highest of the day [Mayr et al., 1973], then the time derivative $\partial T_n / \partial t \sim 0$ implying
369 the thermospheric temperature responds only slowly to external heating. Apparently the
370 local time dependency in the lag time mirrors a simple fact of the varying state of the
371 non-stationary thermosphere throughout the day.

372 Zhang and Holt [2008] found the time delay of similar magnitude in ionospheric re-
373 sponses during another 30-day experiment at Millstone Hill in September 2005. The solar
374 activity was at medium to low solar activity. The delay was found to be strongly height
375 dependent: it occurred in the F2-region electron density and ion temperature, and mostly
376 vanished in the E-region. It is likely that these ionospheric F2-region delays may be orig-
377 inated from that in neutral temperature (as demonstrated in this study), which affects
378 the F-region ionospheric processes locally through neutral composition, ion-neutral en-
379 ergy exchange, plasma scale heights, and chemical reaction rates. A 0.8-1.3 day delay in
380 equatorial TEC to soft X-ray irradiances was also noted by Wang et al. [2006] in a study
381 using two-year long datasets between 1998-2000.

3.2. Other effects: magnetic activity and seasonal correlation

382 As stated earlier in Section 2, we have removed data with large negative Dst values
383 before correlation analysis, and therefore this analysis excludes the significant effects of
384 major magnetic activity on thermospheric circulation, composition and temperature. Al-

385 though not producing severe thermospheric/ionospheric variations, magnetic activity at
 386 weak to medium level exists much more often than these episodic but dramatic magnetic
 387 events, and therefore it provides an important source of upper atmospheric variability,
 388 with effects visible in our analysis. In general, T_{ex} tends to increase as ap increases or
 389 Dst drops, as shown in Figure 2. However, correlation between T_{ex} and ap is for the most
 390 part lower than that between T_{ex} and Dst. T_{ex} and Dst correlation is slightly lower dur-
 391 ing the day (1100–2400 UT) and slightly higher at night. The highest correlation values
 392 for T_{ex} -Dst occur around pre-midnight at 0300–0500 UT (2200–2400LT), and the lowest
 393 occur around near 0800UT (0300LT). Figure 6 plots correlation between T_{ex} and Dst at
 394 1530 LT and 0600 LT, where T_{ex} is calculated as the residual of removing EUV effects,
 395 defined as $T - b - d \times D - c_1 \times F - c_2 \times F^2$, where T is the original exospheric temperature
 396 data for the 30-day time period, D day number, F the corresponding SEE EUV data at
 397 27–34 nm band as a solar flux proxy, and b , c_1 and c_2 are obtained from a least squared
 398 fit based on this 30-day dataset. After removing EUV effects, T_{ex} and Dst correlation can
 399 be as high as -0.56 at 0600 hour LT, and negative correlation is also clear at 1530 hour
 400 LT when the diurnal thermosphere temperature maximum is reached. This pronounced
 401 correlation occurs consistently throughout the entire range of Dst values, including Dst
 402 values associated with low magnetic activity (more positive values). We conclude from
 403 this T_{ex} dependence on Dst that low magnetic activity also contributes to day-to-day
 404 variability in T_{ex} over Millstone Hill.

405 Similar to solar flux effects, the upper atmosphere responds to magnetic activity with
 406 a time delay, depending on the type of disturbances and atmospheric conditions. At
 407 Millstone Hill, T_i responses were found [Zhang and Holt, 2008] to be delayed by 6-9 h

Figure 6

408 from the 3-hourly ap index, and Ne responses are delayed by 0-3 h below the F2 peak,
409 and 9-12 h above the peak. Therefore we might expect a time delay of a few hours in
410 the thermospheric temperature, and this delay is much shorter than that associated with
411 solar UV flux. In general, thermospheric variability driven by magnetic activity is another
412 complicated subject and is beyond the primary scope of this study.

413 Seasonal dependence within the 30-day period is very significant, and produces con-
414 sistently high correlations for each hour of the day. Since the Millstone Hill experiment
415 took place in October 2002 toward winter solstice from the fall equinox, solar zenith angle
416 increases for the same local time each day, and T_{ex} decreases with the day number (also
417 seen in Figure 2). This implies that seasonal trends in the daily T_{ex} maximum at 1600
418 LT (2100UT) are the strongest seen over a full UT day.

4. Variability in T_{ex} tidal components

419 The analysis above has discussed variability at given local times. In this section, we
420 investigate day-to-day variability in the tidal components of thermospheric temperature,
421 and quantitatively examine effects of EUV and magnetic activity. For this study, we use
422 a tidal decomposition into daily mean, diurnal and semidiurnal components.

4.1. EUV effects on T_{ex} tidal components

423 In analysis of EUV effects on T_{ex} tidal components, we use daily averaged EUV flux
424 measured by TIMED/SEE in the same bands as above. The correlation coefficients be-
425 tween each of the three tidal components of thermospheric temperature (daily mean,
426 diurnal, semidiurnal) and solar EUV flux at each band are shown in Figure 7 where the
427 coefficients with and without a 2-day time lag in responses to EUV flux are also given.

Figure 7

428 The correlation between the T_{ex} daily mean and all the EUV bands examined (except
429 for the X-ray proxy at 0.1–7 nm) is very strong, with correlation coefficients generally
430 above 0.6. Furthermore, the two-day delay values show a large increase in correlation for
431 short wavelength bands (27–34, 30.4, 33.5, and 36.6 nm, except for 0.1–7 nm), but not
432 for long wavelength bands.

433 The T_{ex} diurnal amplitude (day-night difference) is weakly correlated, or not correlated
434 at all, to EUV flux. This implies that the day-night difference in T_{ex} responses to EUV
435 is not significant, even though the solar EUV flux disappears at night. This is another
436 example of the thermospheric solar preconditioning or “memory” effect. We also find
437 that the 2-day time delay effect is much stronger at long wavelengths with positive and
438 significant correlation (121.5, 133.5, and 145–165 nm) as compared to short wavelengths
439 (27–34, 30.4, 33.5, and 36.6 nm). This may indicate that the delayed response of exo-
440 spheric temperature, in particular its diurnal amplitude, is related to heating in the low
441 thermosphere. Also interestingly, the delay effect is particularly significant at 0.1-7 nm
442 where the correlation is merely 0.2 (and not statistically significant) if the delay is not
443 considered, but is 0.6 if the delay is considered.

444 The T_{ex} semidiurnal amplitude is also weakly correlated to the EUV flux. The 2-day
445 time delay effect can be seen clearly in a resulting larger negative correlation (or smaller
446 positive correlation) value. Once again, the 0.1–7 nm band contains unusual correlation
447 to T_{ex} that is very different from other bands. For this band, the time delay effect is so
448 significant that the correlation is improved from -0.2 (when the delay is not included) to
449 -0.6 (when it is included).

450 The direct impact of the soft X-ray flux (from the same day) on T_{ex} diurnal and semid-
451 iurnal amplitudes is in general weak, and the correlation with the solar X-ray from 2
452 days earlier is high. Very strong soft X-ray events have the potential to impact deep
453 into the lower atmosphere, and then the deposited energy may propagate to the upper
454 thermosphere with a lag time. However, for the data we are examining, the intensity and
455 frequency of such X-ray events do not appear to be substantial, as the percentage vari-
456 ability (standard deviation/mean) is only $\sim 10\%$, and therefore their role in producing
457 delayed thermospheric variations should not be overestimated. On the other hand, these
458 observations of delayed thermospheric response may be associated with some processes
459 accompanying solar X-ray changes, such as high energy particle flows taking more than 1
460 day to reach Earth's upper atmosphere with the effect of different responses of T_{ex} dur-
461 ing different times. We conclude that time-shifted solar X-ray (0.1–7 nm) data may be
462 used as another proxy to account for some thermospheric temperature variations caused
463 by solar-geophysical disturbances. (In fact, results in subsequent sections do show some
464 similarity between solar flux effects and Dst effects.)

465 Discussions on time delay so far have addressed effects of individual prior times (days),
466 and in particular, the question about which prior time is most strongly correlated to T_{ex} .
467 However, if solar flux history is important, solar flux effects can be accumulated over time
468 with different weighting on different days. We further examine this possibility by using a
469 composite solar flux proxy E_w to consider integrated influences on T_{ex} daily means. We
470 define $E_w = c_0 E_0 + c_{-1} E_{-1} + c_{-2} E_{-2} + c_{-3} E_{-3}$, where E_0 , E_{-1} , E_{-2} and E_{-3} are solar UV
471 flux (at a given wavelength or band) for the current day, one, two and three days prior to
472 the current day when a particular T_{ex} daily mean is taken. Coefficients c_0 , c_{-1} , c_{-2} and

473 c_{-3} are determined by varying E_w (through varying these coefficients) and searching for
 474 the largest correlation between daily E_w and daily mean T_{ex} . These different coefficients
 475 obtained with the 30-day datasets, listed in Table 1, may represent relative importance
 476 of the solar flux on individual days to overall solar irradiation conditions that correlate
 477 to daily mean T_{ex} . Results show that the significance of the 2-day delay becomes less
 478 important compared to that of the 3-day delay with increasing solar irradiation wavelength
 479 (from EUV to FUV), and the current day flux remains a significant factor for soft X-ray
 480 and FUV bands. As a result of using the weighted contributions from different days, the
 481 correlation between E_w and daily mean T_{ex} (squares in Figure 7) is normally higher than
 482 using the solar flux from an individual day.

4.2. T_{ex} daily mean

483 The observed T_{ex} daily mean peaks at day 288 then drops to a minimum 8 days later
 484 (cf. solid line the upper panel of Figure 8). This variation is mostly due to solar EUV
 485 changes. In fact, a simple EUV-based empirical model containing a linear EUV term and
 486 a quadratic EUV term in the form $f_0 + f_1 \times F + f_2 \times F^2$ can reproduce the observed daily
 487 mean rather well (triangles in the top panel). In the model, the EUV flux F is the daily
 488 average flux at 27–34 nm with a 2-day time delay considered (cf. previous section) and
 489 f_0, f_1 and f_2 are obtained through a least squared fit. However, the daily mean is not
 490 very sensitive to Dst. A similar polynomial model using Dst instead as an independent
 491 variable does not generally reproduce absolute values of the daily mean well. However, the
 492 relative fluctuations in daily mean between days 300–305 are in fact well represented by a
 493 Dst only empirical model, while they are not well represented by the EUV only empirical
 494 model. We therefore find that an empirical model which combines these EUV and Dst

Figure 8

495 terms and further includes a seasonal variation term can almost perfectly reproduce T_{ex}
 496 observations (cf. line and dots).

497 To quantify relative contributions of these various factors on variability in the T_{ex} daily
 498 mean, we derive the percentage variability in both the observational data and in the model
 499 regression data. This percentage variability is defined as the standard deviation from the
 500 average divided by the average, computed over the entire 30 day observational period.
 501 We can estimate relative contributions by calculating the standard deviation above the
 502 average in the model regression data over the standard deviation in the observational
 503 data. The results are shown in Figure 9, with observed T_{ex} percentage variability of
 504 4–5% (upper panel). EUV flux variability alone (i.e., variability generated by the above-
 505 mentioned EUV only empirical model) can account for 90% of the observed variability,
 506 while variability in Dst alone (i.e., variability generated by the above-mentioned Dst only
 507 empirical model) produces 45% of the observed variability. We find that the combined
 508 effects of EUV, Dst and seasonal changes (as given by an empirical model with EUV and
 509 Dst terms) can explain nearly all of the observed variability (bottom panel).

Figure 9

4.3. T_{ex} diurnal amplitude

510 We apply the same analysis technique as in the previous section for the T_{ex} daily mean
 511 to the T_{ex} diurnal and semidiurnal amplitudes. The diurnal amplitude (the middle panel
 512 in Figure 8) is in the range between 100–140 K, approximately 10% of the daily mean,
 513 and fluctuates more than the daily mean. The large and rapid fluctuations between days
 514 295 and 305 appear to be highly correlated with EUV flux at 0.1–7 nm band from two
 515 days in advance, and accordingly the EUV-based empirical model of T_{ex} based on such
 516 flux values captures these fluctuations well. The Dst-based empirical model does generate

517 some fluctuations with a major drop from day 296 to 299, similar to observations, but
518 their phases do not always agree with observations. Overall, the T_{ex} diurnal amplitude
519 in the empirical model combining all the three factors (EUV flux, Dst and season) again
520 reproduces those main fluctuations in the data.

521 The observed variability in T_{ex} diurnal amplitude is 12% (Figure 9). The EUV-based
522 empirical model generated variability is 9% and the Dst generated variability is 6%. Fi-
523 nally, the T_{ex} empirical model including EUV, Dst and seasonal changes generates 10%
524 variability, or 80% of the total observed variability in the diurnal amplitude. We can
525 therefore quantify the remaining 20% of variability seen in diurnal amplitude observa-
526 tions as due to other controlling factors beyond those considered here. These may include
527 various wave activities due to vertical coupling processes from the lower atmosphere into
528 thermosphere, residual magnetic activity effects, additional ionospheric energy inputs to
529 the thermosphere, and possibly measurement uncertainty.

4.4. T_{ex} semidiurnal amplitude

530 The T_{ex} semidiurnal amplitude (bottom panel of Figure 8) is about 1/3 of the T_{ex}
531 diurnal amplitude (See Figure 8), and fluctuates between 20–50 K, with a day-to-day
532 variability of 31%. Both EUV-based (based on the EUV flux at 0.1–7 nm band for 2
533 days in advance) and Dst-based empirical models can capture some of the fluctuations,
534 and the combined T_{ex} empirical model for the semidiurnal component generates 78% of
535 the total observed variability (Figure 9), once again with the remaining 22% of variability
536 due to other factors besides EUV, Dst, and seasonal effects. For semidiurnal variations,
537 Dst control is now as significant as in the EUV flux. We note with interest that both in
538 T_{ex} diurnal and semidiurnal amplitudes, there are some obvious 3–5 day fluctuations that

539 seem to be associated with Dst changes, while for the T_{ex} daily mean, Dst effects are less
540 important and EUV flux effects are dominant.

4.5. Day-to-day fluctuations

541 Our correlation analysis has addressed the direct relationship between T_{ex} and EUV
542 flux, both of which experience strong day-to-day variability. A further question is how the
543 day-to-day fluctuation in T_{ex} is correlated to that in EUV. Here, fluctuations are defined
544 as deviation of daily values from means or expected values. Hedin [1984] indicated that
545 fluctuations of EUV and neutral density, obtained with deviation of daily values from
546 the slow-varying 81-day running averages, show correlation that varies with wavelength
547 of the solar irradiation flux, being high with EUV bands of significantly low total energy.
548 To examine this type of day-to-day variability using our 30-day observations, we consider
549 daily fluctuations relative to the 3-day running means. Figure 10 is similar to Figure
550 7 (top) but here we use solar flux fluctuations (residuals of daily means from its 3-day
551 running means), as well as the T_{ex} daily fluctuations defined in the same way as solar flux
552 fluctuations. Results show that there still exists very strong correlation between the
553 main EUV bands and the time-delayed T_{ex} . For instance, correlation with the 36.8 nm
554 flux is among the strongest; the correlation appears low at FUV bands/lines and the soft
555 X-ray band. The delay time is 2 days for the EUV flux, and 3 days for the FUV flux.

556 These results confirm that during this 30-day experiment, short-term variability in the
557 EUV flux is very likely the primary driver for T_{ex} short-term variability. They are also
558 consistent with Hedin [1984] indicating that EUV fluxes at wavelengths slightly longer
559 than 30.4 nm are more important to the short-term variability in the exospheric temper-
560 ature than the 30.4 nm emission, and that the fluxes at wavelengths shorter than 30.4

Figure 10

561 nm are also more important in producing the short term variability. Although the 30.4
562 nm emission contains significantly more energy, it varies less and therefore produces less
563 thermospheric variations.

564 Eastes et al. [2004] indicated that variability (relative to the 81-day means) in the soft
565 X-ray flux has much better correlation with that in neutral density than does the F107
566 variability. However, we show very low correlation between variabilities (relative to the
567 3-day mean) in the 0.1-7 nm emission and in the T_{ex} diurnal mean. It appears that the
568 short-term (3 days) and long-term (81 days) variability in this 0.1-7 nm emissions has
569 different influences on the corresponding thermospheric variability. The most significant
570 influence of the 0.1-7 nm emission that was found in this work (see the last two sections)
571 is on the amplitudes in diurnal and semidiurnal tides with a 2-day lag.

5. Summary and conclusion

572 We have quantified thermospheric temperature variability in response to solar and ge-
573 omagnetic effects using a 30-day ISR observation at Millstone Hill during October 2002.
574 We analyzed exospheric temperature T_{ex} , derived from the radar observation, to examine
575 day-to-day variability at fixed local times and also in the temperature daily mean and
576 the two tidal components (diurnal and semidiurnal amplitudes). The driving factors con-
577 sidered responsible for the observed variability include solar EUV flux, magnetic activity,
578 and season, and these relationships have been explored quantitatively. The solar EUV
579 flux used is from the TIMED/SEE space weather product, allowing for detailed studies of
580 the correlation between EUV variability and T_{ex} variability, EUV band dependence, and
581 time delay of thermospheric solar preconditioning response (thermospheric “memory”).
582 Our main findings can be summarized as follows:

583 (1) During the day, correlation between T_{ex} and EUV flux (except for at the 0.1–7 nm
584 band) is much higher than that between T_{ex} and F107. We conclude that EUV data,
585 as compared to daily F107, is essential to a quantitative understanding of thermospheric
586 temperature T_{ex} day-to-day variability.

587 (2) There is a ~ 20 –60 hour delay in T_{ex} response to solar EUV flux. The delay time is
588 shorter in the morning when solar heating changes most rapidly in the upper atmosphere,
589 and longer in the afternoon and at night.

590 (3) T_{ex} is most sensitive to the EUV flux at wavelengths of 27–34 nm and 30.4 nm.
591 The short-term variability in T_{ex} , however, is better correlated with that in wavelengths
592 of 27–34 nm than at wavelength 30.4 nm, consistent with Hedin [1984]. T_{ex} is relatively
593 less sensitive to the flux at 133.5 nm and 145–165 nm.

594 (4) Magnetic activity control of T_{ex} tends to be weaker during the day and stronger
595 at night. We attribute this to the nighttime absence of solar ultraviolet irradiation,
596 constituting the majority of upper atmospheric heat input.

597 (5) The daily mean of T_{ex} strongly depends on EUV flux. An empirical model driven
598 only by the EUV flux at 27–34 nm with a 2-day time delay can generate 90% of the
599 observed variability in the daily mean. The two-day delay effect is less significant for
600 EUV fluxes at longer wavelengths (121.5, 133.5, and 145–165 nm).

601 (6) The diurnal T_{ex} amplitude is not sensitive to solar EUV flux unless a 2-day time delay
602 is applied for long wavelengths, implying similar daytime and nighttime T_{ex} responses,
603 even though significant solar irradiance is absent at night. Additionally, the 0.1–7 nm
604 band EUV flux is clearly positively correlated to diurnal T_{ex} amplitude with a two-day

605 time delay, implying oppose daytime and nighttime responses. Effects of the time delay
606 for other than 2 days are weaker.

607 (7) Semidiurnal T_{ex} amplitude variability is negatively correlated only with the 0.1–7
608 nm band with a 2-day time delay. With a delay time other than 2 days the correlations
609 are much weaker.

610 (8) Magnetic activity as represented by the Dst index is, across T_{ex} daily mean, diurnal
611 and semidiurnal components, most important for the semidiurnal amplitude and least
612 important for the the daily mean. This behavior is similar to T_{ex} soft X-ray response
613 at 0.1-7 nm band with a 2-day delay, implying that there might be a direct connection
614 between magnetic activity and time-shifted solar data.

615 This study provides a detailed and quantified insight into EUV flux effects on thermo-
616 spheric temperature variability at midlatitudes (or sub-auroral latitudes during distur-
617 bances). However, some of those findings listed above need to be fully explained with the
618 help of theoretical models, in particular, the delayed T_{ex} response to EUV flux and the
619 associated thermospheric solar preconditioning or “memory”. These delayed responses
620 appear to be wavelength band dependent, being significant in the daily mean for the
621 27-34 nm band, in the diurnal and semidiurnal amplitudes for soft X-ray flux at 0.1–7
622 nm, and in the diurnal amplitude for longer wavelengths. Further studies focusing on
623 different levels of solar activity and different seasons, and combining theoretical modeling
624 with observational data analysis, are needed to better understand day-to-day variability
625 in the thermosphere.

626 **Acknowledgments.** We thank the members of the Atmospheric Sciences Group at
627 MIT Haystack Observatory for assembling and maintaining Millstone Hill observations

628 and the Madrigal distributed database. SRZ is indebted to Prof. William L. Oliver
629 for making available the thermospheric calculation program which forms the main ba-
630 sis of deriving neutral temperatures from ISR measurements as presented in this work.
631 Observations and analysis at Millstone Hill are supported by a cooperative agreement
632 between the National Science Foundation and the Massachusetts Institute of Technol-
633 ogy (AGS-1242204). This work is also supported by the NSF award AGS-1042569 to
634 MIT. SEE space weather data products have been obtained from the SEE web site at
635 <http://lasp.colorado.edu/see/>. The TIMED spacecraft was developed by the Johns Hop-
636 kins University Applied Physics Laboratory. The TIMED mission, including the SEE
637 instrument, is sponsored by NASA's Office of Space Science.

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731 *Geophys. Res.*, *108*, 1131, doi:10.1029/2002JA009521, A3.

732 Table 1. Composed EUV index Ew with weighted contribution from prior days.

733

nm	$c_0(0d)$	$c_{-1}(-1d)$	$c_{-2}(-2d)$	$c_{-3}(-3d)$
0.1-7	0.77	0.13	0.05	0.05
27-34	0.05	0.05	0.85	0.00
30.4	0.05	0.05	0.77	0.13
33.5	0.03	0.03	0.47	0.47
36.8	0.32	0.04	0.11	0.53
121.5	0.53	0.03	0.03	0.41
133.5	0.53	0.03	0.03	0.41
145-165	0.56	0.04	0.04	0.36
$Ew = c_0E_0 + c_{-1}E_{-1} + c_{-2}E_{-2} + c_{-3}E_{-3}$				

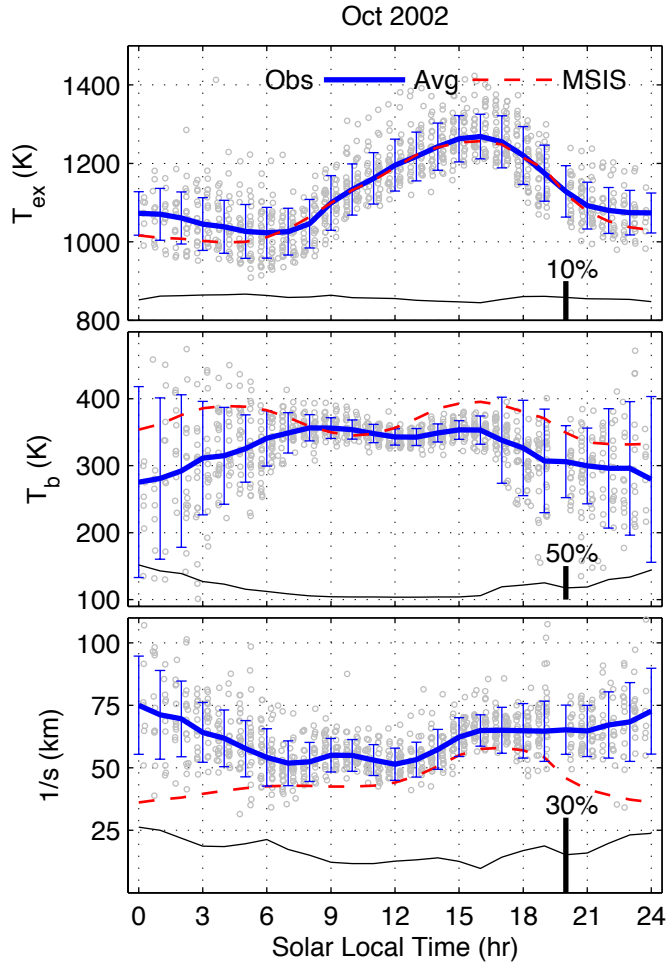


Figure 1. Diurnal variations of thermospheric temperature parameters: exosphere temperature T_{ex} , base temperature T_b , and the inverse of shape factor $1/s$ (see text), as well as their day-to-day variability. The gray dots are data points, the blue line is the hourly average of the month with error bar representing the standard deviation, and the dashed line shows MSIS model averages. The dark thin line near the bottom of each panel shows the percentage variability; a vertical thick line on the dark thin line provides the scale for the corresponding percentage variability marked above the vertical line.

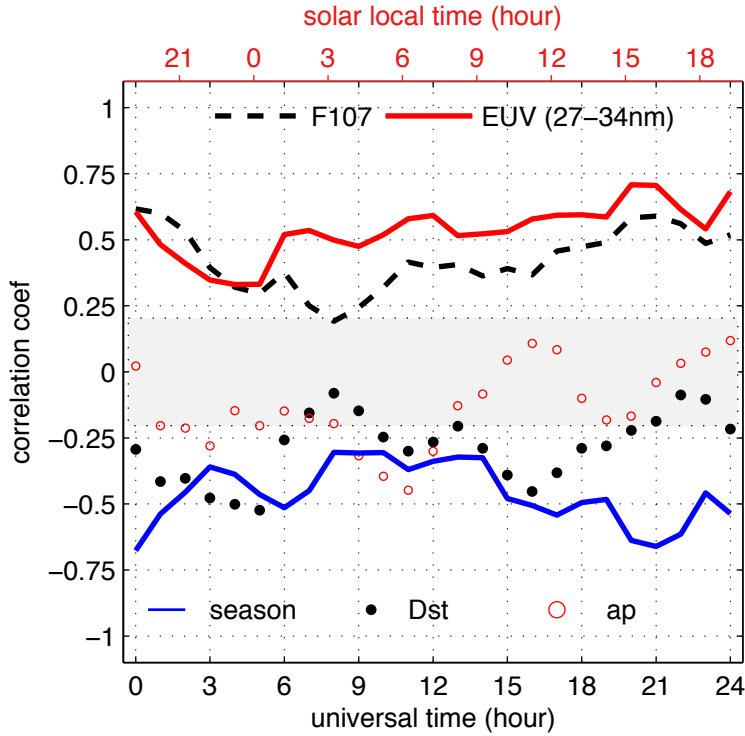


Figure 2. Diurnal variations of exospheric temperature correlation with solar-geophysical parameters. These parameters include solar irradiation indices of daily F107 and EUV flux at 27–34 nm observed with TIMED/SEE, along with magnetic activity indices of 3-hourly ap (converted to negative values, -ap, to place the correlation curve on the negative side for easy comparison with the Dst curve) and hourly Dst. Seasonal dependency of T_{ex} is expressed as its correlation to the day number. The shaded area represents regions where $p\text{-values} > 0.05$ (typically 66 data samples for an hourly window of 30 individual days that pass the Dst filters) indicating a failure to reject the null hypothesis of no correlation. $UT - SLT = 4.76$ hr at Millstone Hill.

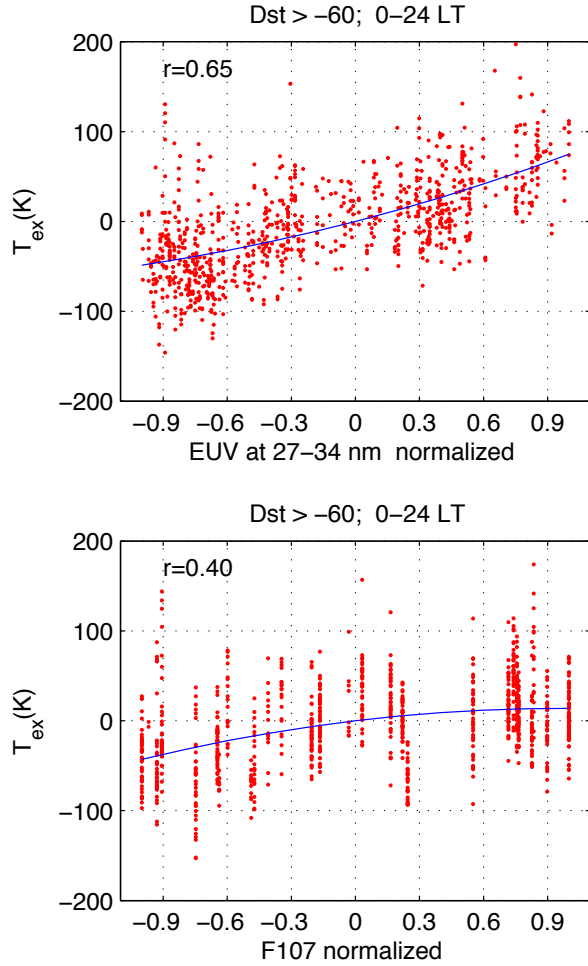


Figure 3. Correlations between T_{ex} residuals and F107 (bottom), and between T_{ex} residuals and EUV flux at 27-34 nm (top). The residuals are T_{ex} data after subtraction of dependencies on local time, season, and magnetic activity, and therefore should be dominated by solar flux variations. Dependencies are represented by a combination of diurnal, semidiurnal and terdiurnal harmonics (local time dependence), along with linear functions of the day number and Dst, and are determined through least squares fitting. The T_{ex} data are subtracted by regression data representing those dependencies, yielding T_{ex} residuals. Both EUV and F107 are shifted and normalized to be within -1 and 1 for easy comparison. Blue curves are fitting results with parabolic functions.

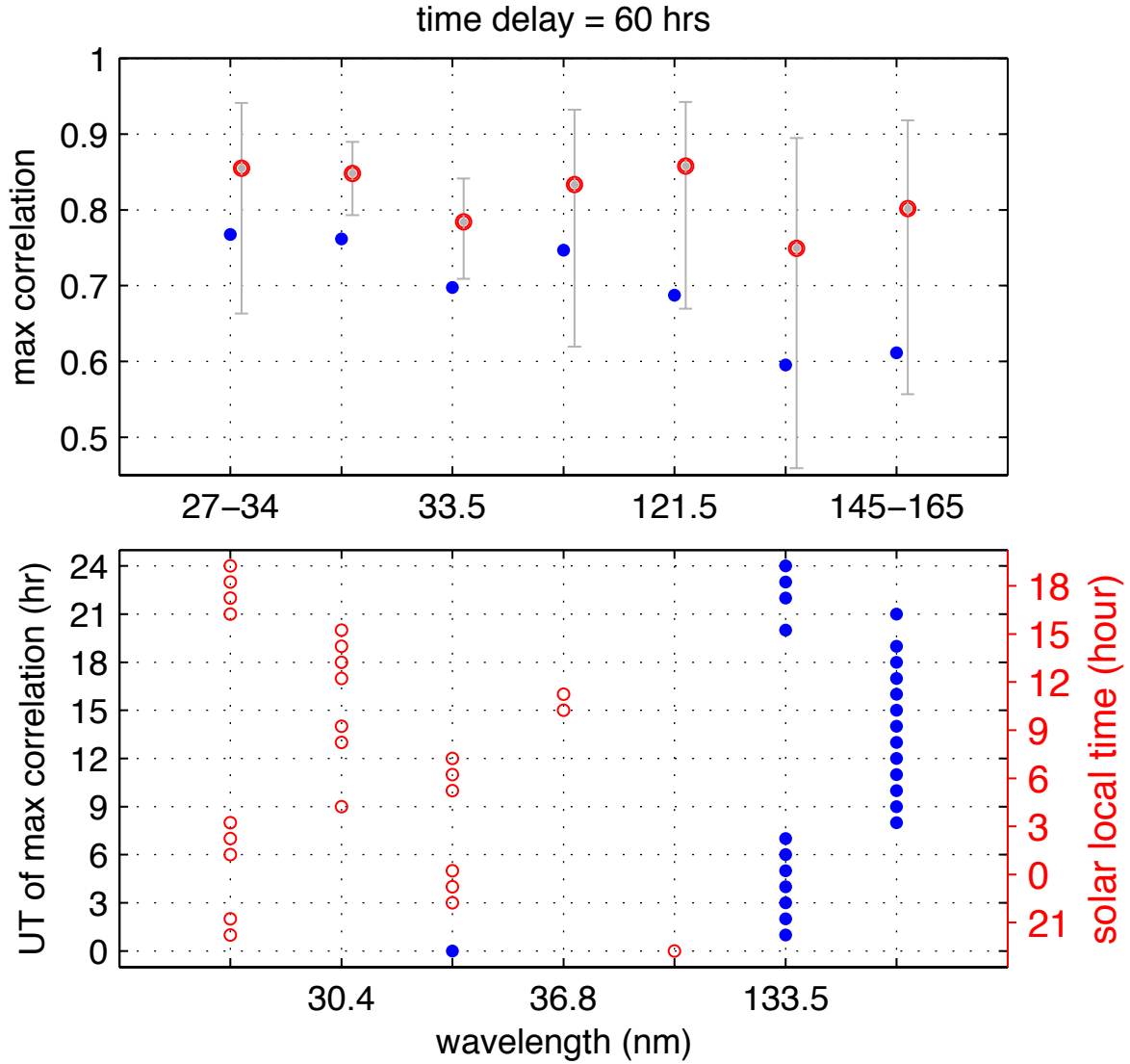


Figure 4. Correlation between T_{ex} and EUV flux at different wavelengths. Top panel: highest correlation (circles) and the average of the first 10 highest correlation (dots) for the 24 hourly time bins as a function of wavelength. The vertical bars indicate 95% confidence intervals. Bottom panel: the wavelength for each UT hour when highest correlation (circles) and lowest correlation (dots) occur.

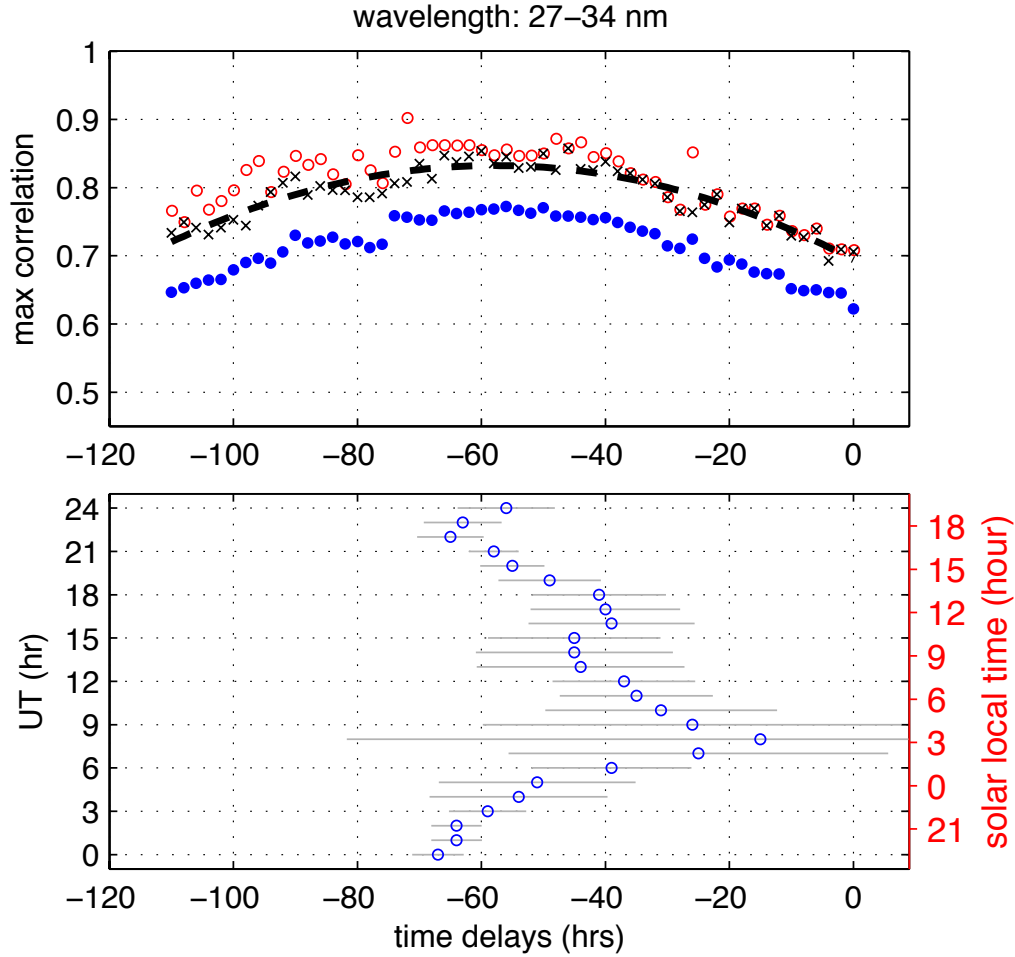


Figure 5. Time delay of T_{ex} response to EUV flux at different wavelengths. The plots show correlation between T_{ex} and the EUV at a given band (27-34 nm) with a variable delay from 0 (now) to 110 hours before (i.e., delay time) with 2-hour resolution. Top panel: highest correlation (red circles) of the day and the average of the first 10 highest correlation (blue dots) in the 24 hourly time bins as a function of delay hours; also shown is the correlation for 2100 UT (black crosses) and a parabolic fit (dashed line). Bottom panel: delay values in hours for each UT hour at which maximum correlation is obtained. The largest correlation is determined from a least-squared fit of the correlation curve to a parabolic curve at a given UT time, as indicated by the crosses and the dash line in the upper panel. The horizontal bars provide standard deviation estimation based on least-squares fitting residuals and the parabolic model function.

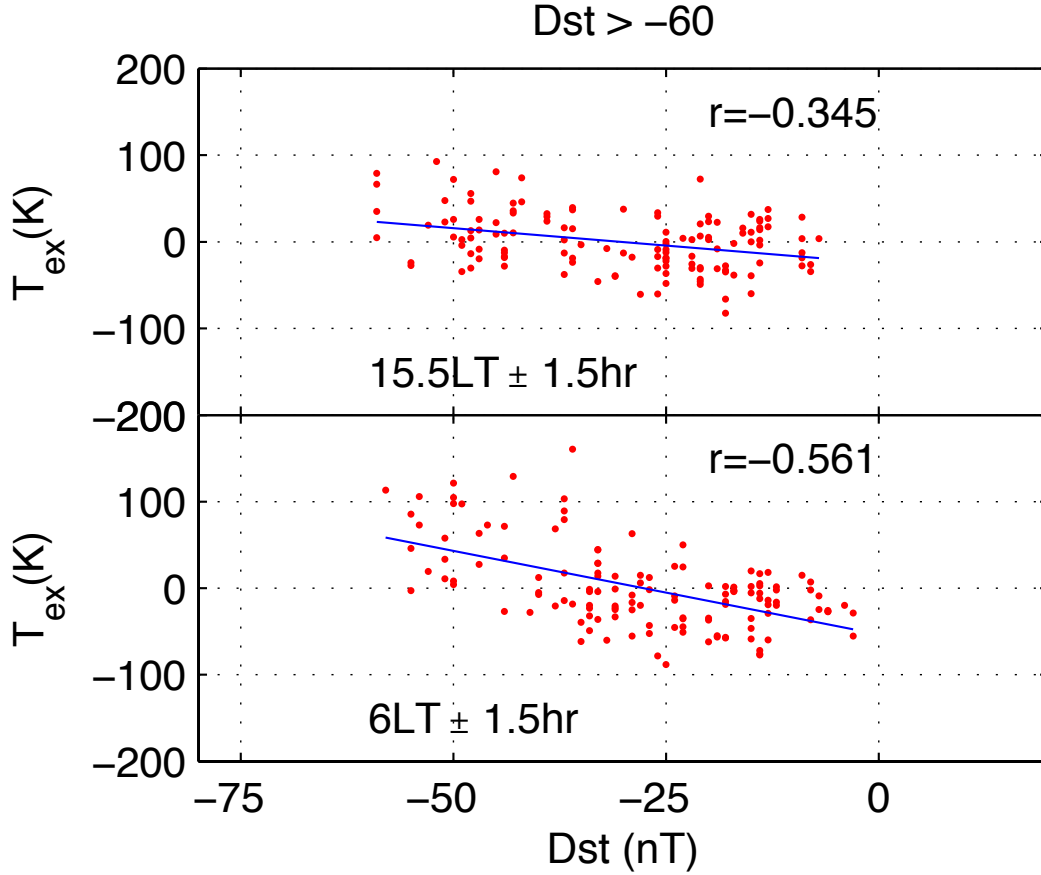


Figure 6. Correlation between T_{ex} and Dst at 1530 LT and 0600 LT, where T_{ex} is computed as the residual T_{ex} after removing EUV effects. The residual is defined as $T - b - d \times D - c_1 \times F - c_2 \times F^2$, where T is original exospheric temperature data, D day number, F the solar EUV at 27–34 nm band, and b , c_1 , c_2 are obtained from a least squared fit. Blue lines are linear fitting to the red data points

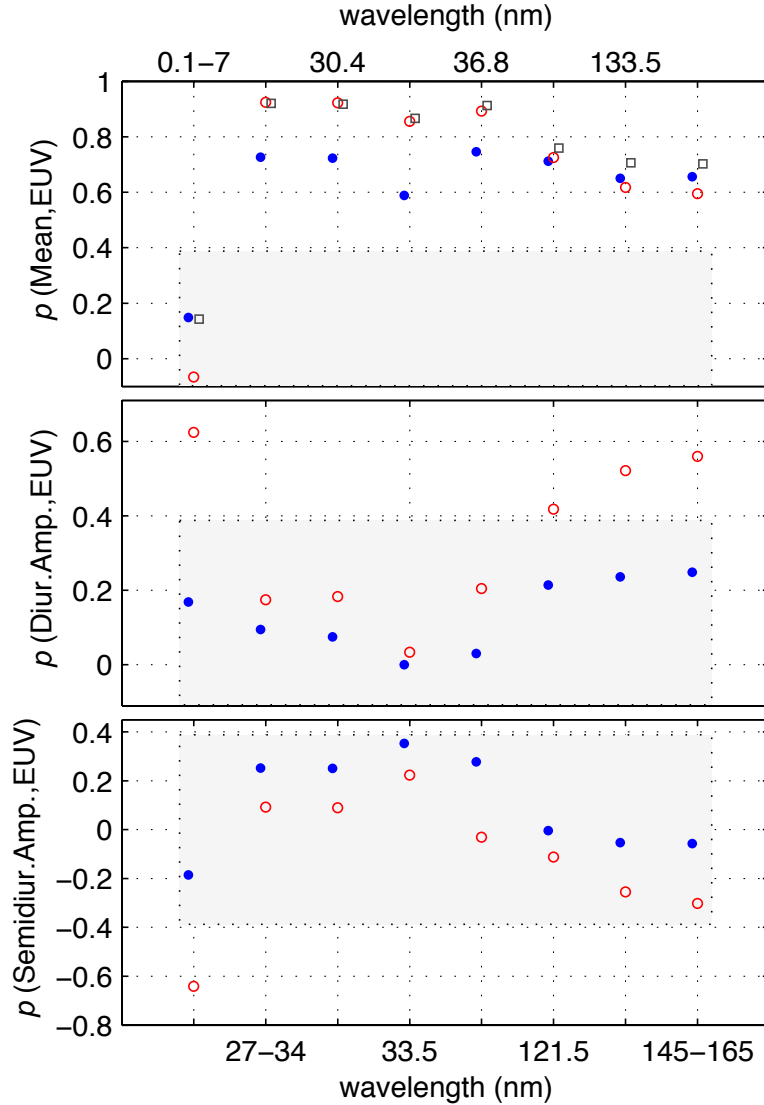


Figure 7. T_{ex} tidal component dependence on solar EUV flux. TIMED/SEE daily average flux at 8 bands is used to evaluate correlations between specific tidal components (mean, top panel; diurnal amplitude, middle panel; semidiurnal amplitude, bottom panel) and EUV flux. Results with a two day time delay (circles) without the delay (dots) are given. Correlation between a composite solar flux proxy E_w at various wavelengths and daily mean T_{ex} is also shown (squares), where E_w contains weighted contributions not only from the current day but also from prior days (see text and Table 1). Shaded areas represent weak correlation, with p-values >0.05 for failure to reject the null hypothesis of no correlation with a sample size of ~ 20 .

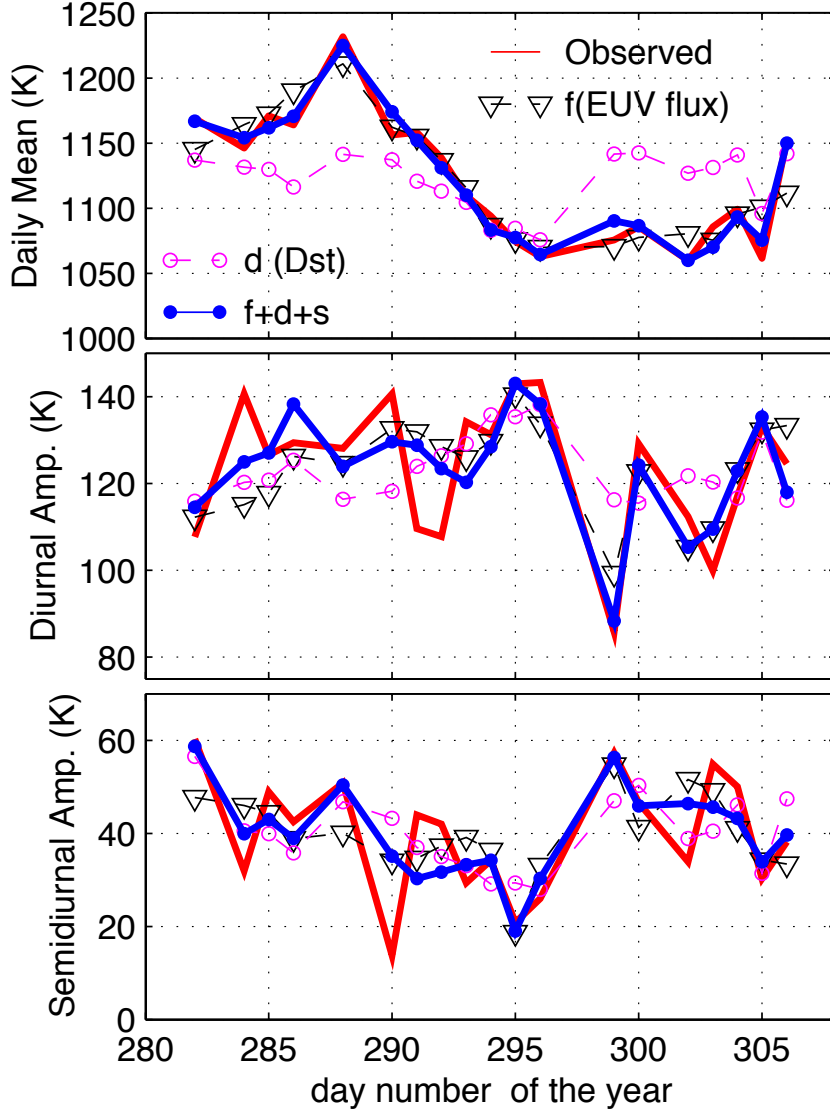


Figure 8. Solar flux, magnetic activity and seasonal effects on T_{ex} daily mean (upper panel), diurnal (middle panel) and semidiurnal (bottom panel) amplitudes. Model functions for the tidal components shown are: **f**: EUV terms; $f_0 + f_1 \times F + f_2 \times F^2$ where F is EUV flux from 2-days in advance at 27–34 nm for T_{ex} daily mean modeling, at 0.1–7 nm band for T_{ex} diurnal and semidiurnal amplitude modeling; **d**: Dst terms, $d_0 + d_1 \times Dst + d_2 \times Dst^2$; **s**: seasonal variation terms, $\sin[2\pi(D + D_0)/365] + \sin[\pi(D + D_0)/365]$ where D is day number of the year. In these terms, coefficients $f_0, f_1, f_2, d_0, d_1, d_2, D_0, D_{00}$ are determined through least-squares fitting.

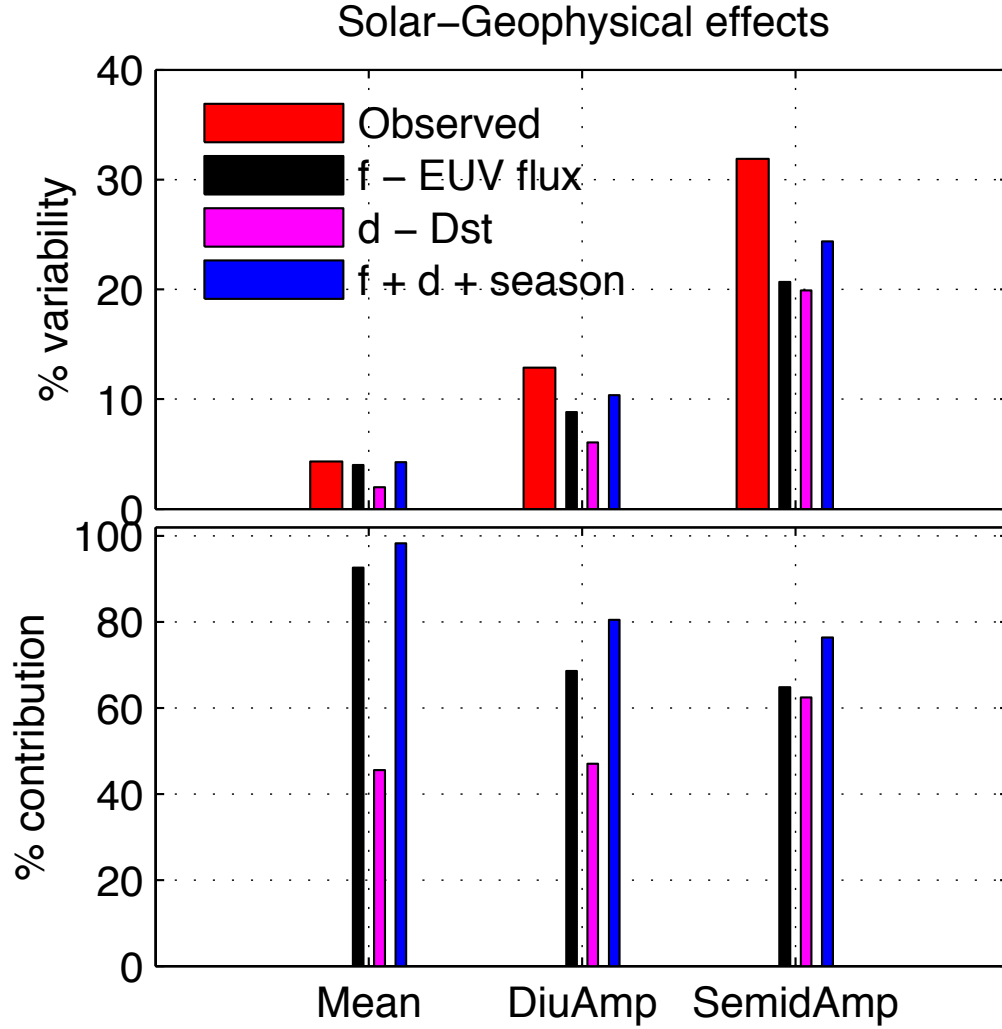


Figure 9. Relative contributions of various factors to day-to-day variability in T_{ex} daily mean, diurnal and semidiurnal amplitudes. Model functions are: f , EUV flux; d , Dst index, and s , season. In the upper panel, a percentage variability of T_{ex} is defined as the standard deviation from the average over the average value. In the bottom panel, the percentage contribution is defined as the standard deviation from the average of empirical model data over the standard deviation from the average of the observational data. The solid line is for observation, and other curves are for results of the modeled variability. The model functions used are the same terms as in Figure 8 (see text).

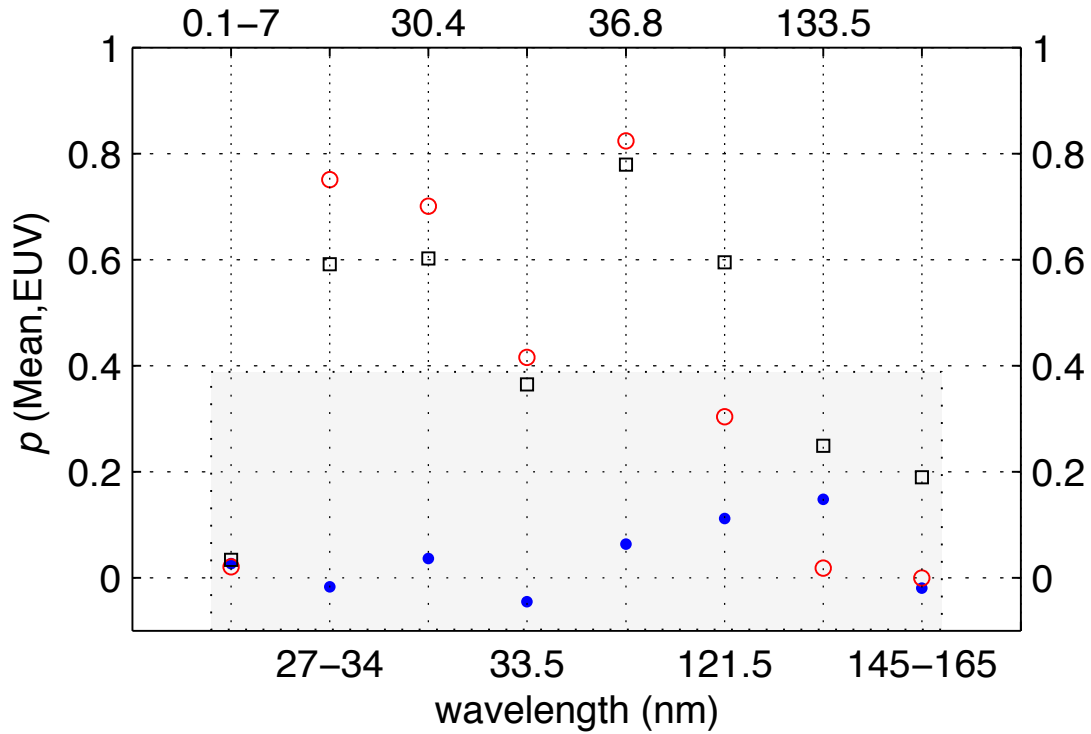


Figure 10. Correlation coefficients between fluctuations in the daily mean T_{ex} and in the solar flux at various wavelengths. Fluctuations are residuals of daily means from the 3-day running means. The solar flux fluctuations are calculated for the same day (dots) as, one day prior (circles) to, and two days prior to (squares) the day of the calculated T_{ex} fluctuation.