



A response of the polar winter upper mesosphere to short-period solar variations

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Abstract

Effects of short-period variations in the flux of solar UV radiation on the intensity of airglow emissions coming from the hydroxyl (OH) airglow layer and temperature variations in the upper mesosphere over Kiruna, Sweden, have been investigated. Measurements were performed with the OH airglow imager, measuring selected emission lines in the OH(3-1) Meinel band. Measurements for four winter seasons from 2022 to 2026 have been considered. Solar activity is represented by diurnal flux changes in the Lyman alpha (α) line. It has been shown that short-period changes in the Lyman- α flux lead to statistically significant changes in the temperature and intensity of OH(3-1) emissions with a positive response and with about zero time delay (0-5 days). This result indicates the dominance of the mechanisms of direct radiative and photochemical influence of Lyman- α on change in the physical-chemical state of the polar winter upper mesosphere. Average temperature amplitudes due to short-period changes in the Lyman- α flux are approximately 2–4 K, which are comparable in magnitude to temperature variations due to atmospheric planetary waves. A relationship has been found between characteristic features of the power spectrum of the Lyman- α flux and the time delay in the mesospheric response at time intervals of about 4–6 months.

Short plain summary

Influence of Solar Lyman- α flux on the hydroxyl emission layer at ~87 km over Kiruna (Sweden) have been considered for four winters between 2022 and 2026. Results show a statistically significant positive response of temperature changes to variations in the Lyman- α flux, with average temperature amplitudes of about 2–4 K, which are comparable to temperature changes due to atmospheric planetary waves.



34 **1 Introduction**

35 The upper mesosphere (80-100 km) is the boundary between the middle and upper
36 atmospheres. This region of the atmosphere actively absorbs solar ultraviolet (UV) radiation,
37 which leads to changes in the thermal and chemical state as well as dynamic changes occur in
38 it due to wave activity coming from the lower atmospheric layers (Andrews et al., 1987;
39 Brasseur and Solomon, 2005). The upper mesosphere is also a nonlinear system in which
40 feedback mechanisms arise between dynamic, chemical and radiation subsystems
41 (Grygalashvily et al., 2025). Therefore, the physical and chemical state of the upper
42 mesosphere is a complex function of helio-geophysical processes that change both in space
43 and time.

44 Solar radiation affects the Earth's atmosphere with a set of periodicities, of which the most
45 attention is paid to studies of the 27-day and 11-year cycles. The latter oscillation is the most
46 powerful and its influence on the middle and upper atmosphere is well studied (e.g.,
47 Sonnemann et al., 2015; Gao et al., 2016; Perminov et al., 2021). The 27-day cycle, which is
48 less powerful, is the result of the rotation of the Sun. Its effect on the middle and upper
49 atmosphere has been studied to a lesser extent since active regions on the Sun modulating the
50 flux of UV radiation appear and disappear sporadically, which leads to a change in the
51 intensity of the UV flux, and as a result, to a violation of the 27-day period, that is, to a
52 change in its period, amplitude and phase (Shpynev et al., 2014). It can be stated that the
53 study of the effect of short-period solar variations on the mesosphere and lower thermosphere
54 is still a relevant topic of atmospheric research (Hood et al., 1991; Hall et al., 2006; Gruzdev
55 et al., 2009; von Savigny et al., 2012; Thomas et al., 2015; Lednyts'kyi et al., 2017;
56 Thuraiajah et al., 2017; Perminov et al., 2022).

57 Airglow emissions provide information on the physical and chemical states of the upper
58 mesosphere and lower thermosphere. In particular, neutral temperature is determined based on
59 intensities of lines of airglow emissions. Spatial and temporal variations of the emission
60 intensities and temperature provide us with knowledge on the short- and long-term dynamical
61 state of the upper mesosphere, which in turn is a hot topic of current atmospheric research
62 (e.g., Reid et al., 2014; Perminov et al., 2022; Wüst et al., 2023; Gavrilov et al., 2024).

63 In the present paper, we investigate the effects of solar UV radiation on airglow emission
64 intensities and the neutral temperature of the polar upper mesosphere over northern Sweden
65 during four winter seasons. Such a short time series does not yet allow us to analyze the
66 effects of the 11-year solar activity cycle (this will be the topic of future research), but the
67 effect of the 27-day solar cycle can already be investigated. Section 2 describes analyzed data



68 and method, Sect. 3 presents the results, Sect. 4 discuss the results, and Sect. 5 presents the
 69 conclusions.

70

71 **2 Analyzed data and method**

72 The solar flux in the Lyman- α line was obtained from the LASP Interactive Solar
 73 Irradiance Data Center (<https://lasp.colorado.edu/lisird>). The data represent a series of daily
 74 mean values currently obtained from direct measurements using satellite instruments (Machol
 75 et al., 2019). The unit of solar radiation flux in the Lyman alpha ($\text{Ly}\alpha$) line at 121.6 nm is 10^{11}
 76 photons $\text{cm}^{-2} \text{s}^{-1}$, which is one solar flux unit (sfu).

77 The hydroxyl (OH) airglow imager was put into operation in November 2022 at the
 78 Swedish Institute of Space Physics in Kiruna, Sweden (67.86°N , 20.42°E). The OH imager
 79 records selected emission lines P1(2) at 1524 nm and P1(4) at 1543 nm in the OH(3-1) Meinel
 80 band, acquiring intensity and temperature maps at ~ 87 km altitude. The instrument operates
 81 during the winter period from mid-September to mid-April at solar zenith angles of more than
 82 96° . The temporal resolution is 2.75 minutes, the spatial resolution varies from 0.3 km to 1.1
 83 km depending on the zenith angle from zero to its limit value of 60° . For statistical analysis
 84 purposes, the data are averaged over time and space for each night to obtain hourly and daily
 85 mean intensities of the P1(2) and P1(4) emission lines as well as the neutral temperature of
 86 the upper mesosphere, both over Kiruna and in the surrounding area within a radius of 150
 87 km. A detailed description of the instrument, the measurement technique, error analysis and
 88 early scientific results can be found in Dalin et al. (2024).

89 In the present paper, daily mean P1(2), P1(4) line intensities and the OH(3-1) rotational
 90 temperatures which is close to the kinetic temperature weighted over the hydroxyl airglow
 91 layer (Noll et al., 2020). Measurements were performed over Kiruna during four winter
 92 seasons: 2022-2023, 2023-2024, 2024-2025 and 2025-2026. Their original time series are
 93 shown in Fig. 1, Fig. 2 and Fig. 3. Figure 4 shows the time series for the daily mean $\text{Ly}\alpha$ flux
 94 values for the corresponding four winter seasons. The red dotted line represents the 35-day
 95 running average for all analyzed time series.

96 It should be noted that the first winter measurement season, 2022-2023, was short, since in
 97 December 2022 and the first half of January 2023, the instrument was in the commissioning
 98 phase, searching for optimal parameters for recording OH airglow emissions. Actual
 99 continuous measurements began in the second half of January and lasted until mid-April
 100 2023. The next three winter seasons can be considered complete, with measurements
 101 beginning in mid-September and ended in mid-April. It should also be noted that the P1(2)

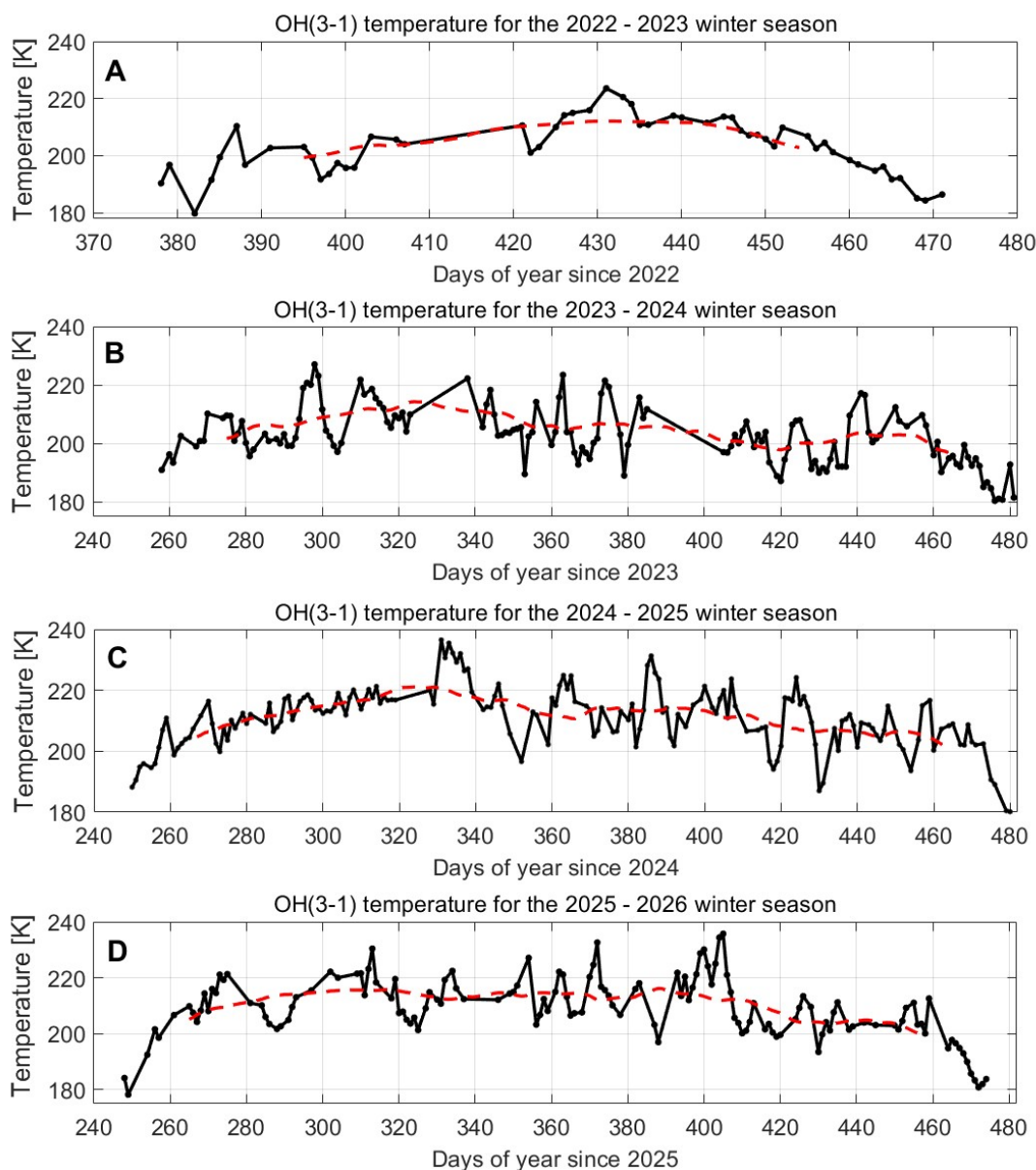


102 and P1(4) line emissions and temperature estimates are obtained on clear and semi-clear
 103 nights only. Nights with dense cloud coverage, fog, rain or snowfall were excluded from the
 104 data analysis. Therefore, the analyzed measurements are interrupted time series. The number
 105 of missed nights is about 25-35% of the total number of nights for each winter season.

106 The method of data analysis includes the following steps.

- 107 1. Data gaps in the temperature and airglow intensities time series are interpolated using a
 108 linear mean to create time-homogeneous series, and thus to match the continuous series of
 109 the Ly α flux. Note that the interpolated data are only used to calculate running averages.
 110 The interpolated values are not used for subsequent linear regression analysis and super
 111 epoch analysis as will be shown below; only actual measurements and actual residuals
 112 (anomalies) of the temperature and intensities of the P1(2) and P1(4) emission lines are
 113 considered.
- 114 2. A 35-day running average with a central window is calculated for all analyzed series (Ly α ,
 115 temperature and line intensities). This removes seasonal variations and possible trends in
 116 the evaluated parameters. The resulting average values are subtracted from the original
 117 time series, and thus the residual values (anomalies) for each time series are estimated.
- 118 3. The residual values obtained for each time series are additionally smoothed by a 7-day
 119 running average. This smoothing reduces random diurnal variations and increases
 120 statistical significance. The result is broadband filtering of the data with periods from 7 to
 121 35 days, i.e., the analyzed series contain short-period variations that are potentially
 122 associated with short-period changes in the Ly α flux, including the 27-day Carrington
 123 cycle. A similar technique for filtering atmospheric and solar data has been used in
 124 previous studies (Robert et al., 2010; von Savigny et al., 2012; Thomas et al., 2015;
 125 Lednyts'kyi et al., 2017; Rong et al., 2020), and we also apply the same filtering technique
 126 to match the data analysis method of the previous works.
- 127 4. Spectral analysis is applied to all analyzed unfiltered time series to determine the main
 128 periodicities in the range from 2 to 40 days.
- 129 5. To determine the response of hydroxyl emissions to short-period variations in the solar UV
 130 flux, a linear regression analysis with a time lag is performed between anomalies in the
 131 Ly α flux and anomalies in the temperature and intensity of the P1(2) and P1(4) emission
 132 lines for each winter season.
- 133 6. Super Epoch Analysis (SEA) is applied to temperature and Ly α anomaly time series for the
 134 four winter seasons in order to minimize the influence of atmospheric quasi-period
 135 processes and maximize the effect of solar UV radiation on temperature.

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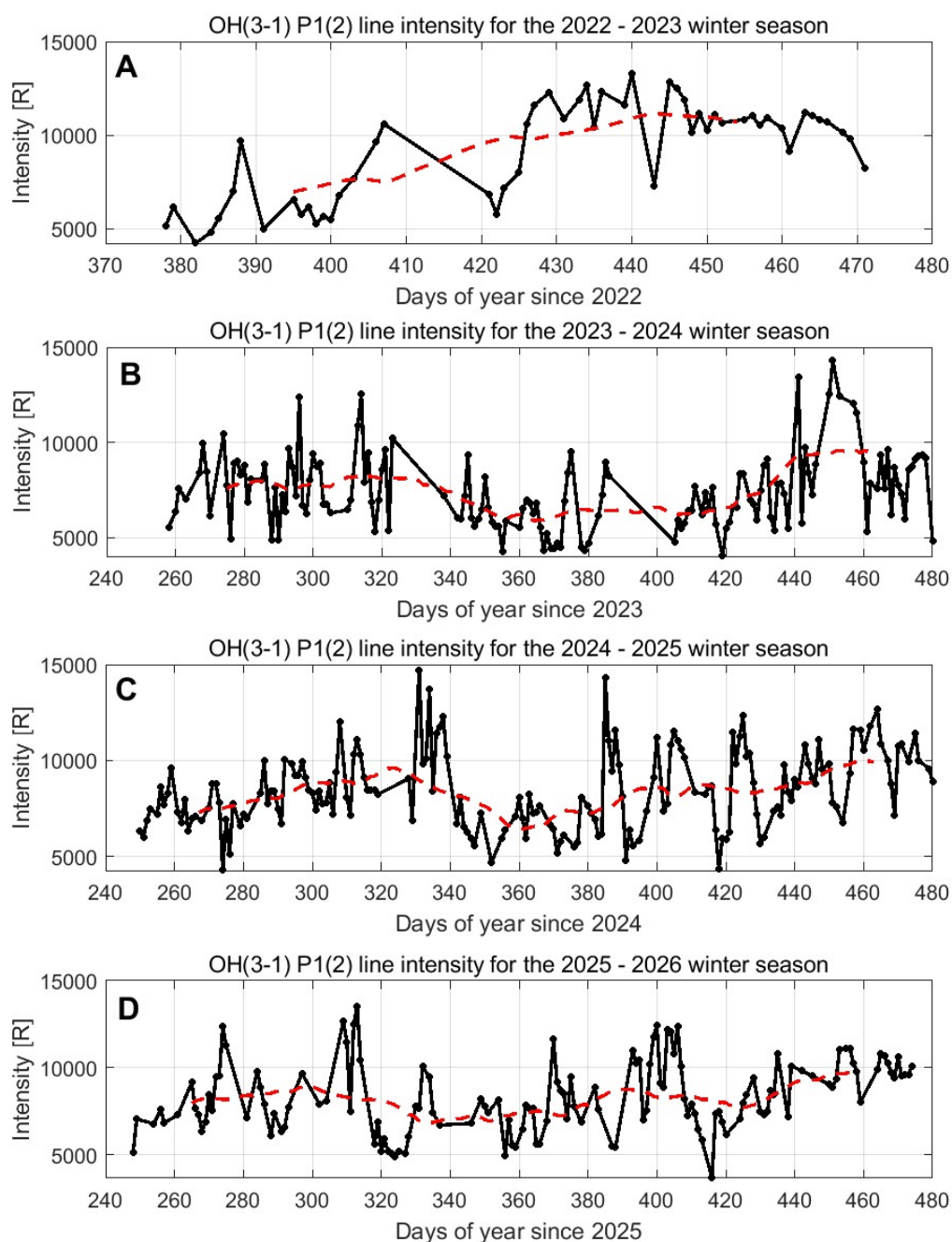


138 **Figure 1.** Nightly mean OH(3-1) rotational temperature (solid black line) and its 35-day
 139 running mean (dashed red line) for the winter seasons of 2022-2023 (A), 2023-2024 (B),
 140 2024-2025 (C) and 2025-2026 (D). Measurements represent the temperature at ~87 km over
 141 Kiruna, Sweden.

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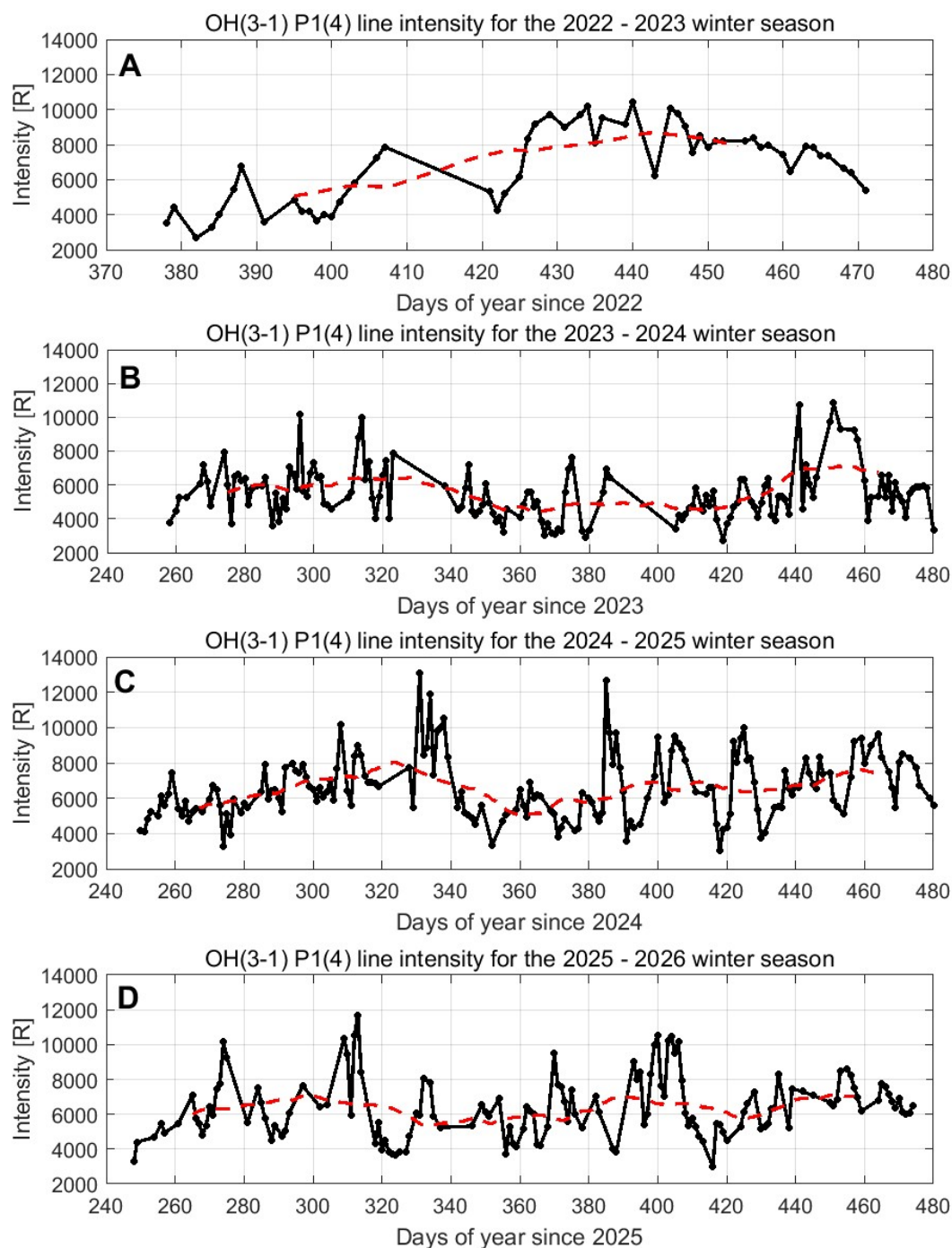
14

144 **Figure 2.** Same as in Fig. 1 but for the OH(3-1) P1(2) line intensity at 1524 nm.

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14

147 **Figure 3.** Same as in Fig. 1 but for the OH(3-1) P1(4) line intensity at 1543 nm.

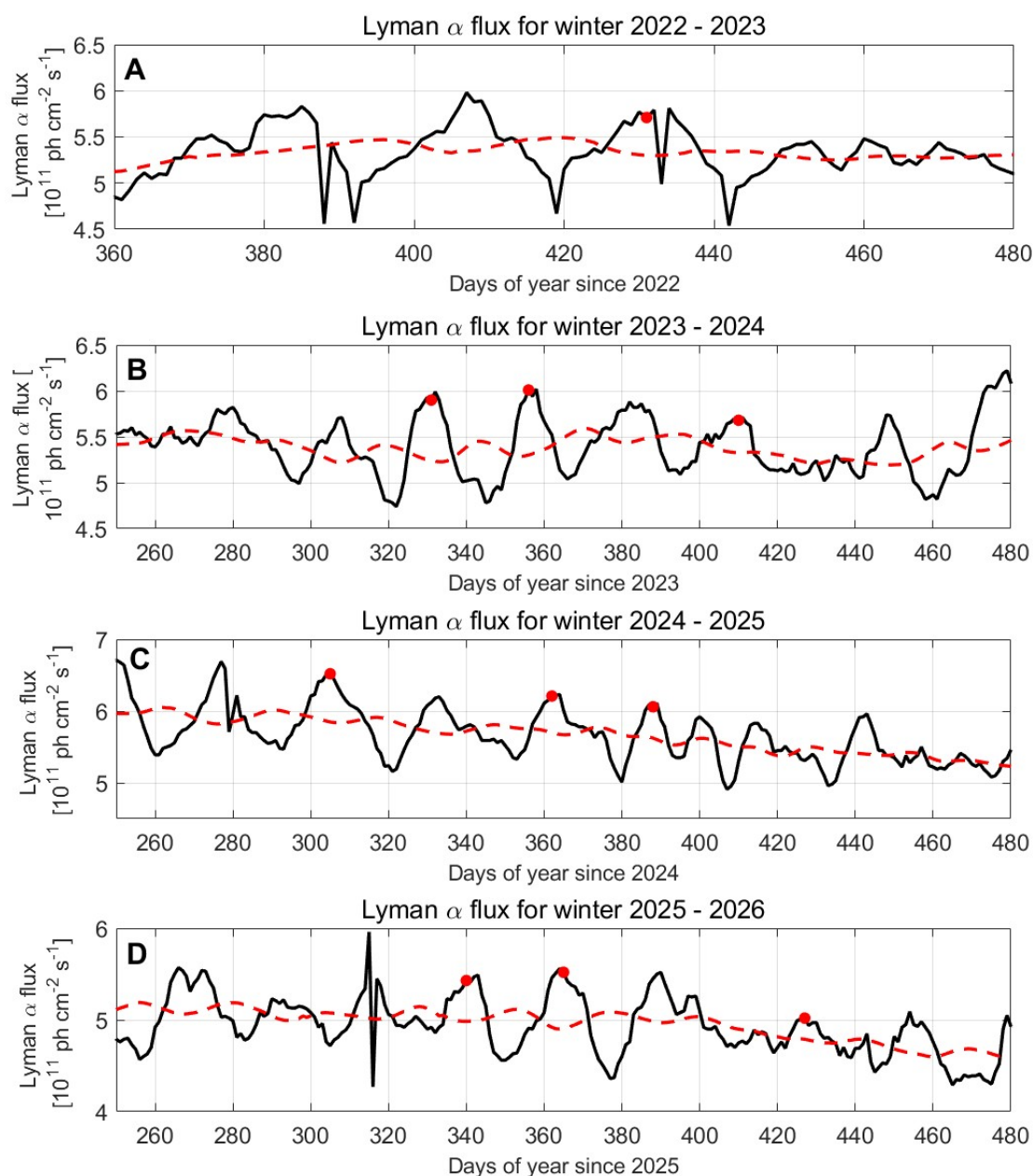


Figure 4. Same as in Fig. 1 but for the Lyman α flux. The red dots mark the maxima of quasi 27-day solar cycles selected for the super epoch analysis (see the text).



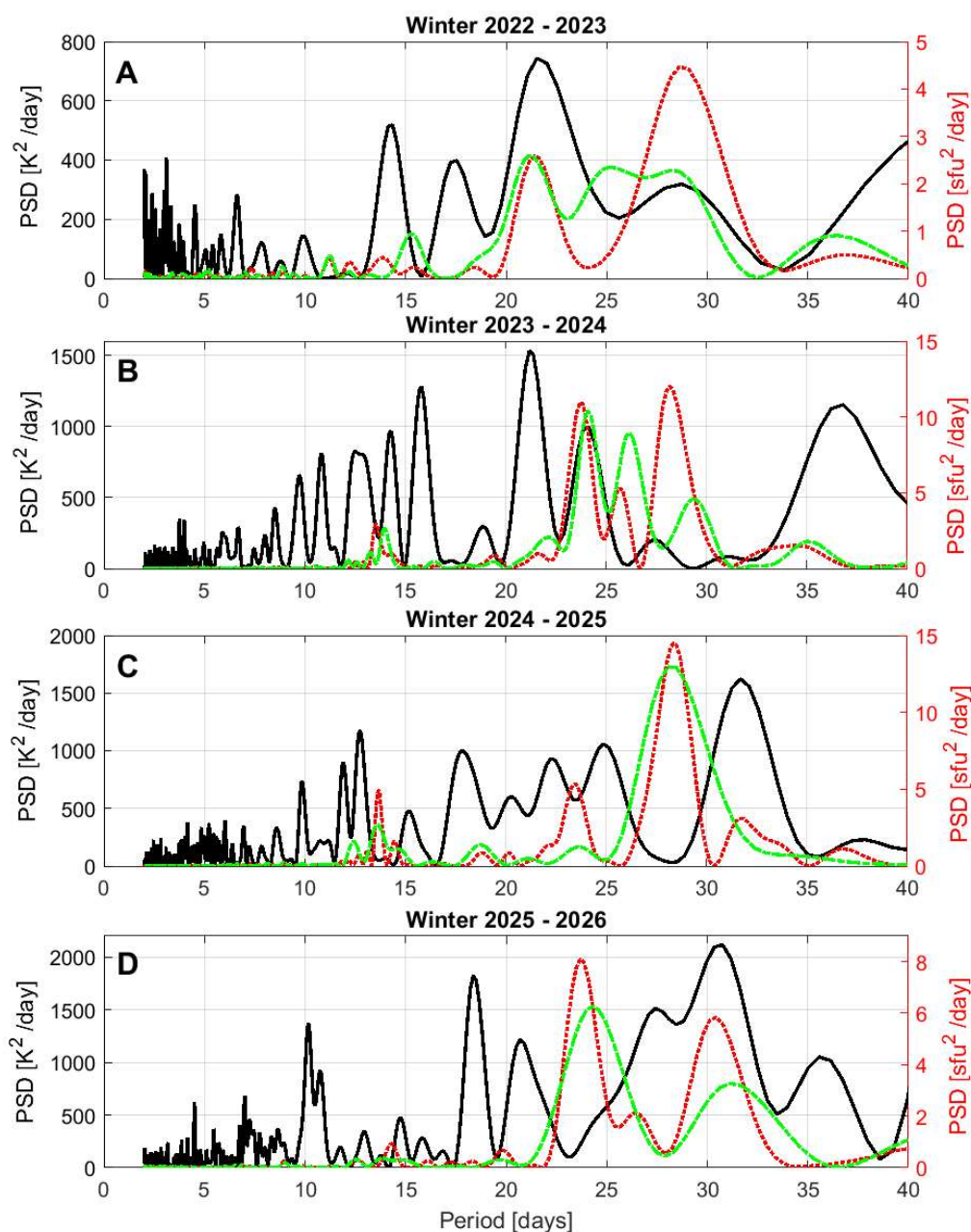
3 Results

3.1 Spectral analysis of solar and temperature time series

To determine short-period oscillations in the solar and upper mesosphere temperature time series, we use spectral analysis of the data based on the Lomb-Scargle power spectral density (PSD), or the least-squares (LS), spectra (Lomb, 1976; Scargle, 1982). This method allows the spectral power estimation for data with gaps (i.e., data need not be uniformly spaced). LS spectra for the Ly α flux (red dashed line) and temperatures (black line) are shown in Fig. 5. The solar spectra show the following features. There is a quasi-27-day Carrington cycle, although its maximum ranges between 28 and 31 days for the analyzed time series. Note that for the two winter periods of 2023-2024 and 2025-2026, there are two solar peaks, around 27 days, comparable in power. The impact of this factor on the temperature will be addressed in the Discussion. The third spectral peak is located around 13.5 days and is associated with the well-known solar cycle due to two active solar regions located about 180° in longitude apart, occurring mainly near solar maxima (Donnelly and Puga, 1990). For comparison with the discontinued temperature time series, we illustrate the Ly α flux spectra with corresponding discontinuities in the time series for the four winter seasons (green dashed-dotted line). One can see that the green line approximately corresponds to the red line.

The temperature spectra show spectral peaks ranging from a few days to 37 days, with a number of oscillations close to the solar periods: 21.5 and 28.7 days for winter 2022-2023, 24.1 days for winter 2023-2024, 31.7 days for winter 2024-2025, and 30.4 days for winter 2025-2026. At the same time, there are periodic processes in the temperature whose periods differ from the solar ones, such as 21.2 and 36.8 days for winter 2023-2024, 22.2 and 25.0 days for winter 2024-2025, 20.7 and 35.5 days for winter 2025-2026. There is also a large set of periods of atmospheric origin ranging from 2 to 20 days, but these signals are not considered in the present study.

Power spectra do not allow us to estimate the amplitude-phase relationship between the response of OH temperature and emission intensities to solar influence. Therefore, we further use a linear regression analysis with a time lag to determine the amplitude-phase response of the polar upper mesosphere to solar forcing.



188 **Figure 5.** Power spectral density (PSD) of the original OH(3-1) temperature data (black solid
 189 line), the continuous solar Ly α flux data (red dashed line) and the solar Ly α flux having gaps
 190 corresponding to those in the temperature data (green dashed-dotted line) for the winter
 191 seasons of 2022-2023 (A), 2023-2024 (B), 2024-2025 (C) and 2025-2026 (D). The PSD for
 192 the temperature and Ly α flux data are shown on the left and right vertical axis, respectively.



193 **3.2 Linear regression analysis with time lag**

194 To determine a quantitative measure of the impact of solar short-period variations on the
195 state of the winter mesosphere, a linear regression analysis is utilized between the residual
196 smoothed values (anomalies) of the Ly α flux and the OH emission intensities and
197 temperature. Such an analysis has been used in many papers (e.g., von Savigny et al., 2012;
198 Thomas et al., 2015; Lednyts'kyy et al., 2017; Perminov et al., 2022). It should be noted that
199 we use actual (not interpolated) measurements of the P1(2) and P1(4) line intensities and
200 temperature, as described above in Sect. 2.

201 The results of the regression analysis of residual temperature values (anomalies) on solar
202 variations for the four winter periods is shown in Fig. 6. All regression coefficients
203 (sensitivity values β) for the four winters have a high statistical significance exceeding 95%.
204 Sensitivity values for the winter periods of 2022-2023 and 2024-2025 have been determined
205 for zero lag between the analyzed time series, while regression relationships for the winter
206 periods of 2023-2024 and 2025-2026 have been found for time lags of +2 days and +4 days,
207 respectively. The time lag is defined as a time of a maximum of the regression coefficient
208 closest to zero. Note that we have also determined the regression coefficients for the residual
209 values of the P1(2) and P1(4) line intensities, but since they are similar to the temperature
210 ones, we do not show them in figures.

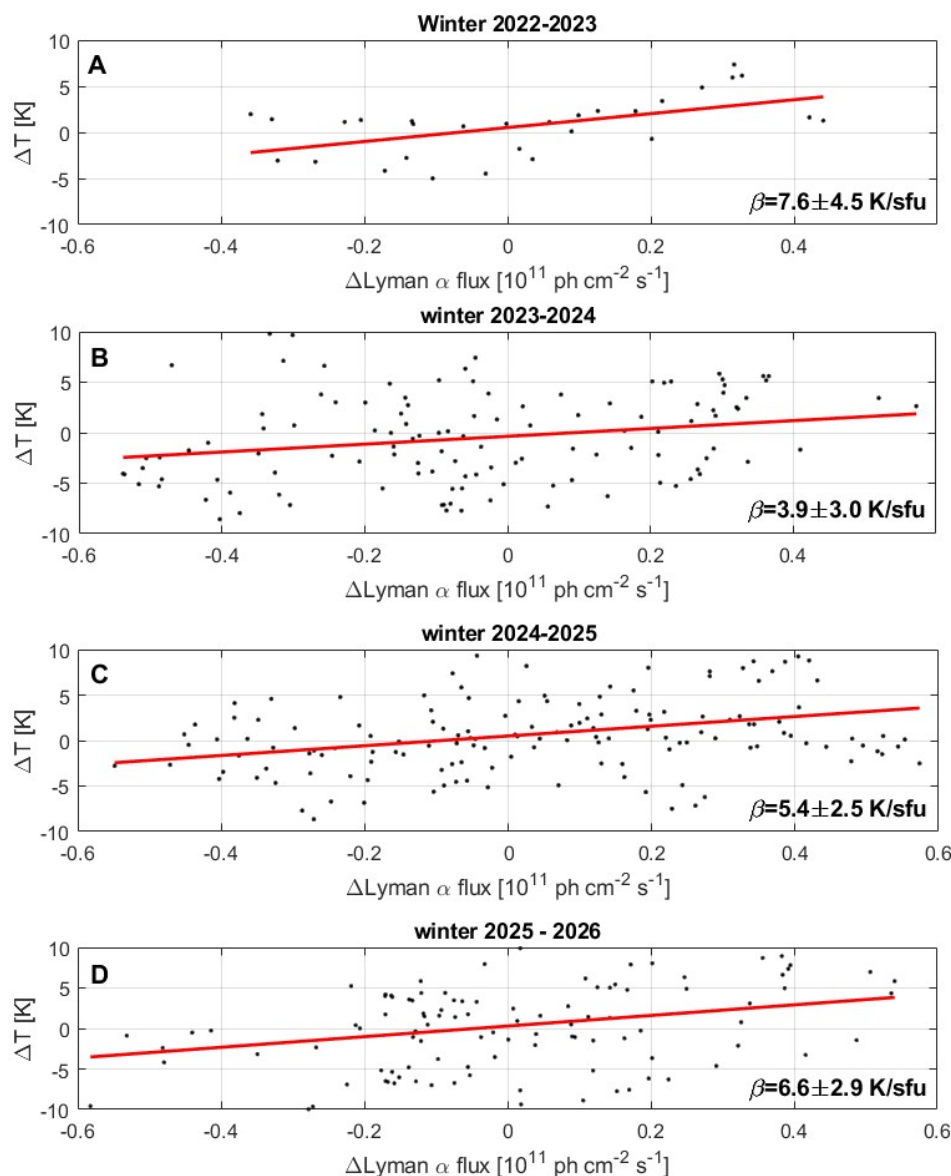


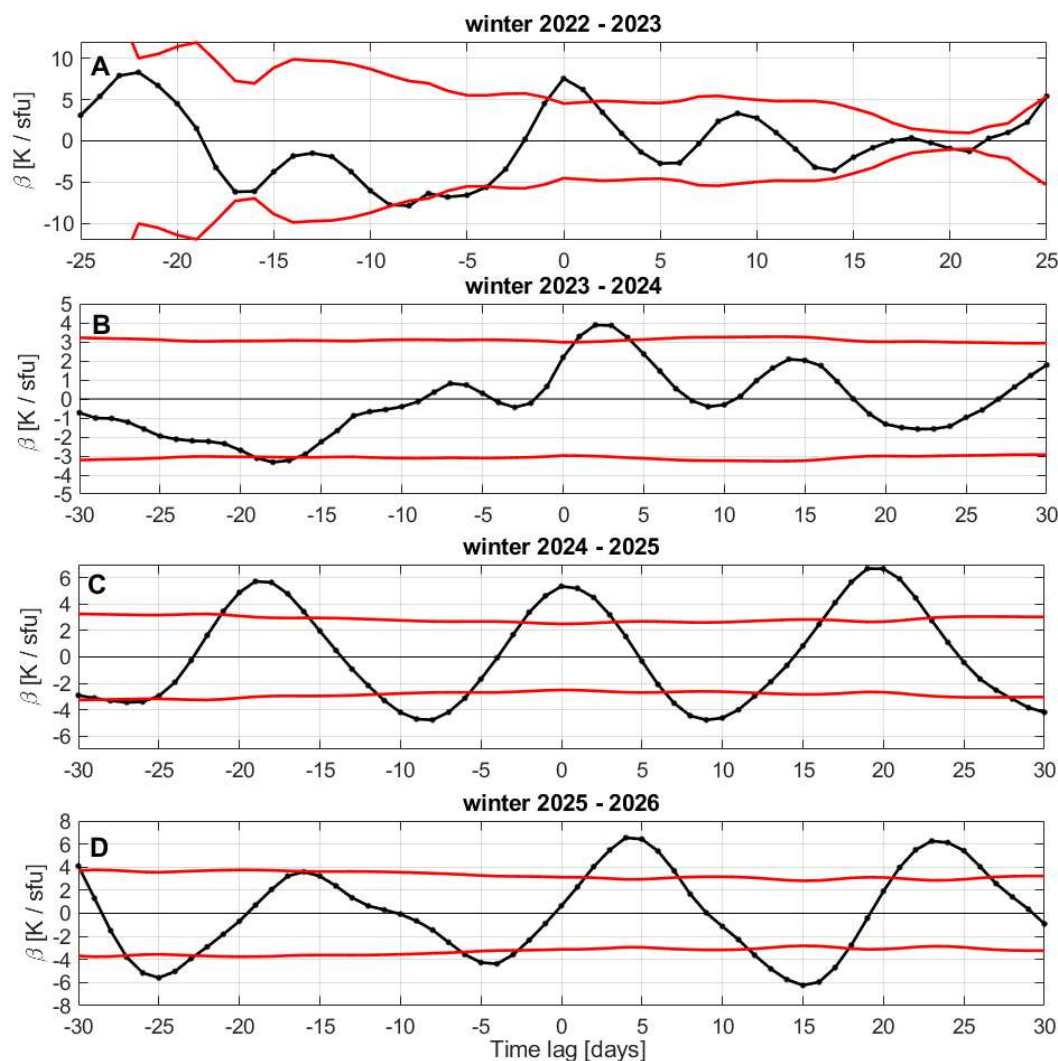
Figure 6. Scatter plot of the Lyman α and OH(3-1) temperature anomaly values for the winter seasons of 2022-2023 (A), 2023-2024 (B), 2024-2025 (C), and 2025-2026 (D). The slope of the regression line (red line) corresponds to the sensitivity value β . The error of β is two standard deviations at the 95% confidence level.

The regression coefficients for the dependence of the temperature on Ly α anomalies as a function of time lag (from -30 to +30 days) are shown in Fig. 7. An exception is made for the



219 winter of 2022-2023, in which the lags are represented from -25 to +25 days due to the short
220 measurement period. Negative/positive time lags mean that the temperature time series
221 leads/lags the Ly α flux time series, respectively. It can be seen that for the winters of 2022-
222 2023 and 2024-2025, the regression coefficient has a local positive maximum at zero lag. For
223 the winters of 2023-2024 and 2025-2026, the local β maxima are shifted by +2 days and +4
224 days, respectively.

225 All regression coefficients have a high statistical significance, exceeding 95%. The
226 regression coefficients exhibit periodicities of 9, 13 and 22 days for the winter of 2022-2023;
227 9, 12 and 26 days for the winter of 2023-2024; 18-20 days for the winter of 2024-2025 and
228 19-20 days for the winter of 2025-2026. Thus, there is a statistically significant effect of solar
229 short-period changes in the Ly α flux on periodic changes in the temperature of the upper
230 mesosphere. Similar regressions have also been obtained for P1(2) and P1(4) line intensities
231 but we do not show them in figures. All regression coefficients with their errors and time lags
232 are shown in Tables 1, 2 and 3. The lags and periods in the regression coefficients are
233 addressed in the Discussion.



235

236 **Figure 7.** The regression coefficient or sensitivity β (black line) in the linear regression model
 237 between time series of temperature and Lyman α flux anomalies as a function of time lag for
 238 the winter seasons of 2022-2023 (A), 2023-2024 (B), 2024-2025 (C) and 2025-2026 (D). Red
 239 lines are the 95% confidence levels.

240

241 We have also estimated other statistical parameters characterizing the effect of solar
 242 radiation on changes in the temperature and OH intensities, which are summarized in Tables
 243 1, 2 and 3. The elasticity coefficient (E) shows the percentage change in the temperature or
 244 OH intensity as one percent change in the Ly α flux. For the temperature, E values range from

0.10 to 0.15 %/%, while for the OH intensities, E values are 0.4–1.1 %/%, excluding the first short winter season of 2022-2023. The mean amplitudes of temperature and OH intensity variations are estimated from half the amplitude of the regression lines (see Fig. 6). Mean amplitudes of temperature variations lie in the range of 2–4 K. Relative mean amplitudes (in percent), calculated relative to the mean value of each estimated atmospheric parameter, are also shown in Tables 1, 2 and 3. Relative temperature variations are in the range of 1–2%.

251

Table 1. Statistical parameters for the dependence of OH(3-1) rotational temperature on short-period variations in the Ly α solar flux. β is the regression coefficient (sensitivity) in the linear regression model, Lag is the time lag between the temperature and Ly α time series, E is the elasticity coefficient, A is the mean amplitude of temperature changes in the regression model, and A_{rel} is the mean amplitude relative to the mean temperature. Statistically significant regression coefficients, exceeding the 95% confidence level, are marked in bold.

258

Winter period	β T/Ly α [K/sfu]	Lag [day]	E [%/%]	A [K]	A_{rel} [%]
2022-2023	7.6±4.5	0	0.19	3.0	1.5
2023-2024	3.9±3.0	+2	0.10	2.2	1.1
2024-2025	5.4±2.5	0	0.14	3.0	1.4
2025-2026	6.5±2.9	+4	0.15	3.7	1.7

259

Table 2. Statistical parameters for the dependence of the P1(2) line intensity on short-period variations in the Ly α solar flux. The parameters are similar to those shown in Table 1. Note that all the parameters shown in Table 2 are statistically significant at the 90% confidence level.

263

Winter period	β P1(2)/Ly α [R/sfu]	Lag [day]	E [%/%]	A [R]	A_{rel} [%]
2022-2023	4167±1426	0	2.38	1666	18.2
2023-2024	654±519	+2	0.48	363	4.9
2024-2025	597±673	0	0.40	335	4.0
2025-2026	1599±762	+5	0.95	897	10.8

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Table 3. Statistical parameters for the dependence of the P1(4) line intensity on short-period variations in the Ly α solar flux. The parameters are similar to those shown in Table 1.

266

Winter period	β P1(4)/Ly α [R/sfu]	Lag [day]	E [%/%]	A [R]	A_{rel} [%]
2022-2023	3354±1262	0	2.58	1341	19.6
2023-2024	576±456	+2	0.57	320	5.8
2024-2025	705±626	0	0.60	395	6.0
2025-2026	1479±698	+5	1.14	830	13.0



267 Note that the regression coefficients and amplitudes for the first winter of 2022-2023 are
 268 noticeably larger compared to the next three winters. However, this is due to the short time
 269 interval of measurements in the winter of 2022-2023, as noted in Sect. 2. We do not insist on
 270 quantitative estimates of the derived parameters for the first short winter of 2022-2023,
 271 instead we consider these results at a qualitative level, as being consistent with the next three
 272 full winter seasons. The main result, demonstrated by all four winter seasons, is a statistically
 273 significant positive response of atmospheric parameters with an approximately zero time lag
 274 for the winters of 2022-2023 and 2024-2025, and with small positive lags of 2-5 days for the
 275 winters of 2023-2024 and 2025-2026. This indicates a mechanism of direct radiative and
 276 photochemical effects on the physical and chemical state of the upper mesosphere region as
 277 addressed in Discussion.

278

279 **4 Discussion**

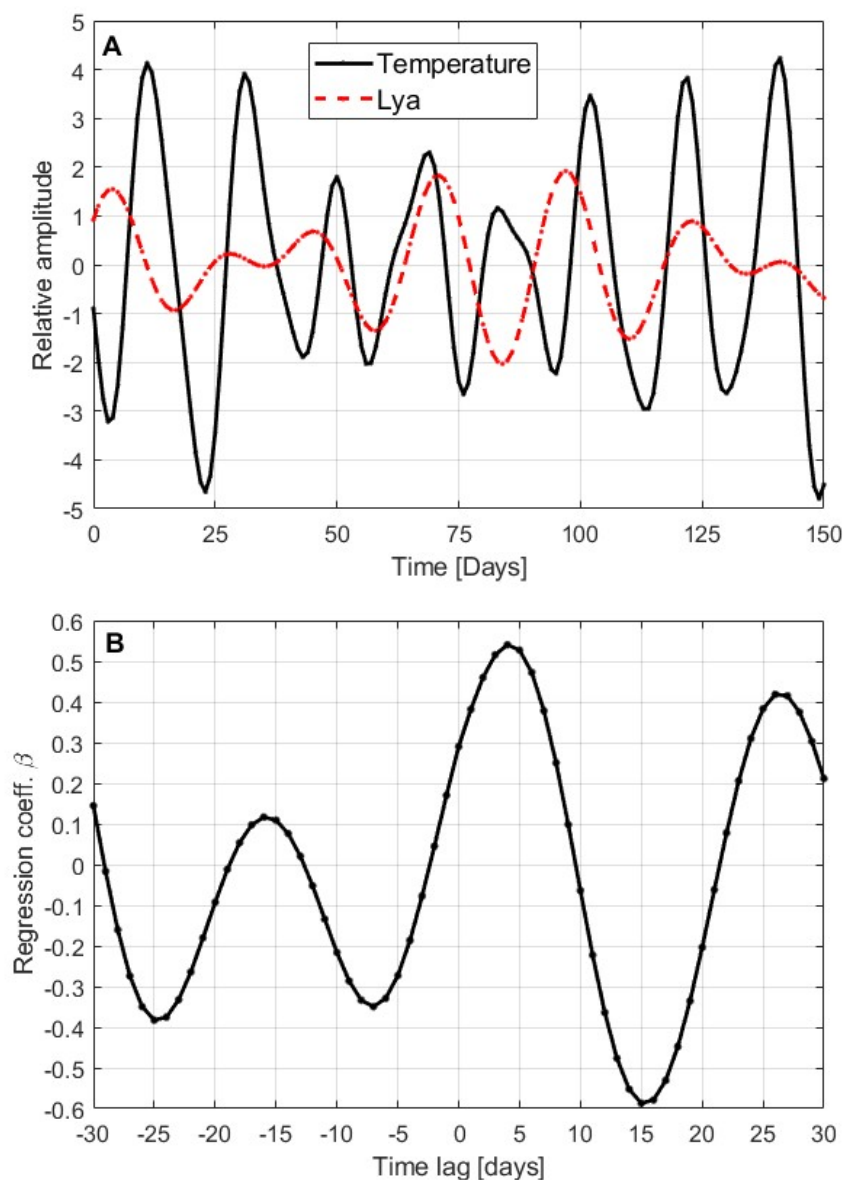
280 We obtained the values of the regression coefficients (sensitivity β) for the temperature in
 281 the range of 4–7 K/sfu. These values are in good agreement with those (within their errors)
 282 obtained by Thomas et al. (2015) and Perminov et al. (2022). The elasticity coefficients E lie
 283 in the range of 0.10–0.15 %/%, which corresponds well to similar values estimated by von
 284 Savigny et al. (2012) and Thomas et al. (2015). It should be noted that these studies were
 285 conducted at different latitudes (low, middle and high), but all these results, including the
 286 present one, demonstrate consistent values of the response of the upper mesosphere
 287 temperature to variations in short-wave solar radiation during the Carrington solar cycle.
 288 Mean amplitudes of the temperature changes due to $\text{Ly}\alpha$ flux variations obtained in the
 289 present study are in the range of 2–4 K. Such temperature changes are comparable in
 290 magnitude to temperature disturbances in the upper mesosphere due to atmospheric planetary
 291 waves (Espy and Witt, 1996; Pogoreltsev, 1999; Merkel et al., 2008, 2009; Dalin et al., 2011).

292 Variations of the regression coefficient for the winter of 2022-2023 have a complex (non-
 293 harmonic) form, but a basic period of about 9 days can be traced (Fig. 7A). This period is
 294 absent in both the temperature spectrum and the $\text{Ly}\alpha$ spectrum (Fig. 5A). The regression
 295 coefficient variation for the winter of 2023-2024 also has a complex form, with a major
 296 period of approximately 12-13 days (Fig. 7B). This period is absent in both the temperature
 297 spectrum and the $\text{Ly}\alpha$ spectrum (Fig. 5B). The regression coefficient period for the winter of
 298 2024-2025 is 18-19 days (Fig. 7C). This period is absent in both the temperature spectrum and
 299 the $\text{Ly}\alpha$ spectrum (Fig. 5C). The period of the regression coefficient for the winter of 2025-
 300 2026 is 19-20 days (Fig. 7D). This period is also absent in both the temperature spectrum and



301 the Ly α spectrum (Fig. 5D). All these results mean that such periods in the regression analysis
302 are created by the "interaction" of eigen periods in the temperature and Ly α flux. This
303 conclusion can be demonstrated mathematically by considering the sum of sinusoids with
304 different amplitudes, periods, and phases for Ly α flux time series.

305 As an example, we consider the last winter season of 2025-2026, in the spectra of which
306 the following main periodic components are present for the Ly α flux: 23.6 and 30.4 days; for
307 the temperature: 10.2, 18.4, 20.7, 27.4 and 30.4 days (see Fig. 5D). Here we regard periods
308 only in the range of 7 to 35 days in order to fit the Ly α and temperature anomalies as
309 described above. The phases and amplitudes of such sinusoidal oscillations have been
310 determined by the least squares method to correspond to the regression curve shown in Fig.
311 7D. The total synthetic signals are shown in Fig. 8A for the Ly α flux (red dotted line) and for
312 the temperature (black line). It can be clearly seen that these integral signals are essentially
313 non-harmonic oscillations.



314
 315 **Figure 8.** (A) Synthetic model signal of the Ly α flux (red dashed line) and temperature
 316 anomalies (black solid line). The Ly α flux synthetic signal is composed of two periodic
 317 oscillations, while the temperature synthetic signal is composed of five harmonic oscillations
 318 (see the text). (B) Regression coefficient (sensitivity β) as a function of time lag between the
 319 Ly α flux and temperature model signals.



320 It is important to note that the maximum of the regression curve is located at +4 days, the
 321 main minimum is located at 15-16 days and the regression curve has a period of about 22
 322 days. That is, the shape of the regression curve for the synthetic signals corresponds well to
 323 the regression curve obtained for the actual data (Fig. 7D). An important conclusion can be
 324 drawn from this: different lags in regression and correlation analysis between temperature (or
 325 another atmospheric parameter) and solar activity can be obtained by considering the sum of
 326 two or more sinusoids with different amplitudes, periods and phases for such time series. It
 327 should be emphasized that it is possible to obtain any form of the regression (correlation)
 328 curve with any predetermined lag by considering sums of harmonic oscillations that result in
 329 essentially non-harmonic oscillations in the temperature and $\text{Ly}\alpha$ time series. This is what
 330 leads to a complex nonharmonic form of a regression curve with an approximately zero or
 331 significantly non-zero time lag.

332 In a number of papers, a near-zero lag was obtained between temperature of the upper
 333 mesosphere of the Northern Hemisphere and the quasi-27-day solar cycle (Robert et al., 2010;
 334 von Savigny et al., 2012; Thomas et al., 2015; Thurairajah et al., 2017; Rong et al., 2020),
 335 while other works have demonstrated substantially non-zero lags between these processes, as
 336 well as between atomic oxygen and $\text{Ly}\alpha$, in the range of 9-17 days (Lednyts'kyy et al., 2017;
 337 Perminov et al., 2022). Model studies by Gruzdev et al. (2009) showed intermediate time lags
 338 of about 3–7 days. The question of lags is important since different time lags suggest different
 339 mechanisms of the solar activity impact on the upper mesosphere. Near zero lags imply the
 340 direct transfer of solar short-wave energy into the physical-chemical state of the upper
 341 mesosphere due to the absorption of UV radiation by ozone and molecular oxygen, the
 342 photodissociation of molecular oxygen and ozone, changes in number densities of chemical
 343 components and subsequent changes in heating rates associated with exothermic reactions.
 344 Model calculations by Schmidt et al. (2006) demonstrate that chemical heating is the key
 345 factor to the heating of the upper mesosphere–lower thermosphere (~80-105 km). As the
 346 chemical composition changes atomic oxygen is increasing by the enhanced dissociation of
 347 molecular oxygen, that, in turn, results to an increase in emission intensities of hydroxyl and
 348 molecular oxygen. Note that Grygalashvyly et al. (2025) have recently found that exothermic
 349 chemical heat provides a negative nonlinear feedback in the upper mesosphere and lower
 350 thermosphere, with heating of about 1–2 K/day by a temperature decrease of 10 K.

351 On the other hand, large time lags may indicate the dominance of atmospheric dynamics
 352 with a source in the lower atmosphere. Huang et al. (2015) demonstrated that quasi-27-day
 353 planetary Rossby waves can penetrate from the troposphere owing to convective activity



354 variations by changes in the 27-day solar period. Pancheva et al. (2003) found a positive
 355 correlation between variations of the semidiurnal tide and the solar rotation cycle. The authors
 356 demonstrated that in winter time lags between the F10.7 solar radio flux and meridional and
 357 zonal amplitudes of the semidiurnal tide in the mesopause region can be of 13 and 15 days,
 358 respectively. In turn, dynamic variations alter the vertical wind speed (adiabatic
 359 heating/cooling) and the vertical transport of atomic oxygen and other atmospheric
 360 constituents. The large-scale mesospheric meridional circulation and eddy diffusion are also
 361 important at high latitudes (Lednyts'kyi et al., 2017). Additionally, the 27-day variation in the
 362 solar magnetic field modulates the flux of galactic cosmic rays (GCRs) with the same period
 363 (Lagoyda et al., 2019). In turn, GCRs ionize atmospheric components that which leads to
 364 modifications in the atmospheric composition, neutral wind and temperature (Calisto et al.,
 365 2011). Using the 3D Chemistry Climate Model SOCOL v2.0, the authors demonstrated that
 366 temperature variations due to GCRs can reach ~ 1 K in the polar winter mesopause at 80 km.

367 It is also important to note the following. The atmosphere is a complex nonlinear wave
 368 system. When two or more primary oscillations interact with each other, new secondary
 369 oscillations arise in the wave system. Mathematically, this can be described as follows: if two
 370 waves with frequencies ω_1 and ω_2 act on a system with quadratic nonlinearity, then secondary
 371 waves with frequencies of $2\omega_1$, $2\omega_2$, $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$ are generated. Apparently, such an
 372 effect for planetary waves and tides was first described by Spizzichino (1969). The
 373 importance of nonlinear effects in the atmosphere for the 27-day solar oscillation was
 374 highlighted by Ebel et al. (1981). Dameris et al. (1986) used 3D model simulations to
 375 investigate the dynamical response of the atmosphere to the 27-day solar forcing. The authors
 376 demonstrated that nonlinear dynamical effects are important for production of secondary
 377 oscillations of 23–32 days and 25–29 days when interacting with the semiannual (~ 180 days)
 378 and annual (~ 360 days) atmospheric variations, respectively. Luo et al. (2001) analyzed long-
 379 period oscillations in mesospheric and lower thermospheric winds, and also found broadband
 380 periodic features (20–40 days) in daily wind spectra, especially in winter. It is possible that
 381 nonlinear dynamical interaction between the 27-day solar period and quasi-semiannual and
 382 annual atmospheric variations form a broadband spectral response in the temperature as
 383 demonstrated in the present study.

384 As demonstrated above, in the winter of 2025–2026, non-zero lags can be obtained by
 385 considering the sum of two or more sinusoidal oscillations (with different amplitudes, periods,
 386 and phases) in the temperature and $Ly\alpha$ flux time series. This conclusion is justified by the
 387 presence of two or more harmonic oscillations (in the vicinity of 27 days) in the actual



388 temperature and Ly α data at time intervals on the order of 4–6 months, as analyzed in the
 389 present study. Larger lags are naturally expected in cases where the spectrum of solar
 390 excitation consists of spectral peaks of comparable power spaced in the vicinity of 27 days.

391 For all four winter periods, we have obtained highly statistically significant (>95%)
 392 regression dependences of variations in the OH emissions and temperature on changes in the
 393 Ly α flux. In this sense, no additional analysis is required to verify the statistical significance
 394 of the results obtained. However, this result may be “contaminated” by various atmospheric
 395 processes in the upper mesosphere in the same frequency range. In order to minimize the
 396 influence of atmospheric processes not related to solar activity and to maximize solar forcing,
 397 the Superposed Epoch Analysis (SEA) method, also called the composite technique, is
 398 applied (Robert et al., 2010; von Savigny et al., 2012; Thomas et al., 2015; Lednyts’kyy et al.,
 399 2017; Rong et al., 2020). In general, SEA highlights the response of a test signal, which may
 400 contain extraneous signals and noise, to the impact of a reference signal (Howard, 1820;
 401 Chree, 1912, 1913).

402 We use 41-day windows (or epochs) around well-defined maxima of 27-day anomalies in
 403 the Ly α flux. The time of each maximum is denoted as day 0. From the first winter season of
 404 2022-2023, we selected only one epoch, as it was a short measurement season. Over the next
 405 three winter seasons, we identified three Ly α flux epochs each. Thus, ten epochs of Ly α flux
 406 anomalies have been extracted from the four winter seasons. Figure 4 shows the positions of
 407 the maxima of the 27-day solar cycles (red dots) used in the SEA. These epochs are then
 408 averaged to obtain the mean epoch of the Ly α flux anomaly. Similarly, epochs of the
 409 temperature anomalies have been extracted, with reference to the Ly α epochs, which are then
 410 also averaged. Theoretically, the averaged temperature response will have a stronger signal-
 411 to-noise ratio, since the contribution from random atmospheric processes (wave activity, eddy
 412 diffusion, interhemispheric coupling), unless they are regression dependent on solar activity,
 413 will tend to be minimized thereby highlighting the maximum influence of the solar cycle on
 414 temperature changes (Thomas et al., 2015). We then apply a standard regression analysis to
 415 the mean epochs of Ly α and temperature as described above.

416 The results of SEA are shown in Fig. 9. The mean epoch (for all four winter seasons) of the
 417 Ly α anomaly (Fig. 9A) illustrates the maximum at zero lag with a period of 26-27 days. The
 418 regression coefficient for the mean temperature and Ly α anomalies is shown in Fig. 9B. It can
 419 be seen that the maximum β has a lag of +2 days with a period of 25-27 days. It is worth
 420 investigating a possible cause of such a lag. For this purpose, we apply SEA only for the two
 421 winter seasons of 2023-2024 and 2025-2026 due to the fact that in each of these seasons there



422 were two solar periods of approximately equal power in the vicinity of 27 days (see Figs.
423 5B,D). The result of the regression analysis for the mean temperature and $Ly\alpha$ anomalies,
424 averaged over the two winter seasons, is demonstrated in Fig. 9D. The maximum β has a lag
425 of +5 days. Now we apply SEA only for the two winter seasons of 2022-2023 and 2024-2025,
426 in which only one solar peak dominates in the power spectra in the vicinity of 27 days (see
427 Figs. 5A,C). The result of the regression analysis for the mean temperature and $Ly\alpha$
428 anomalies is illustrated in Fig. 9F. The maximum β is present at zero lag.

429 This analysis proves that the time lag of +5 days for the two winter seasons of 2023-2024
430 and 2025-2026 is caused by the presence of two approximately equal solar periods in the
431 vicinity of 27 days and several periodic processes in the temperature anomaly. This approach
432 also proves that the resulting maximum β with the time lag of +2 days for all four winter
433 seasons is caused by the combined influence of two or more periodic oscillations in the
434 analyzed solar and the temperature data. The large lags obtained in Lednyts'kyy et al. (2017)
435 and Perminov et al. (2022) may have been caused by the presence of two or more cyclic
436 processes with different amplitudes, phases and periods (in the vicinity of 27 days) in solar
437 and atmospheric data.

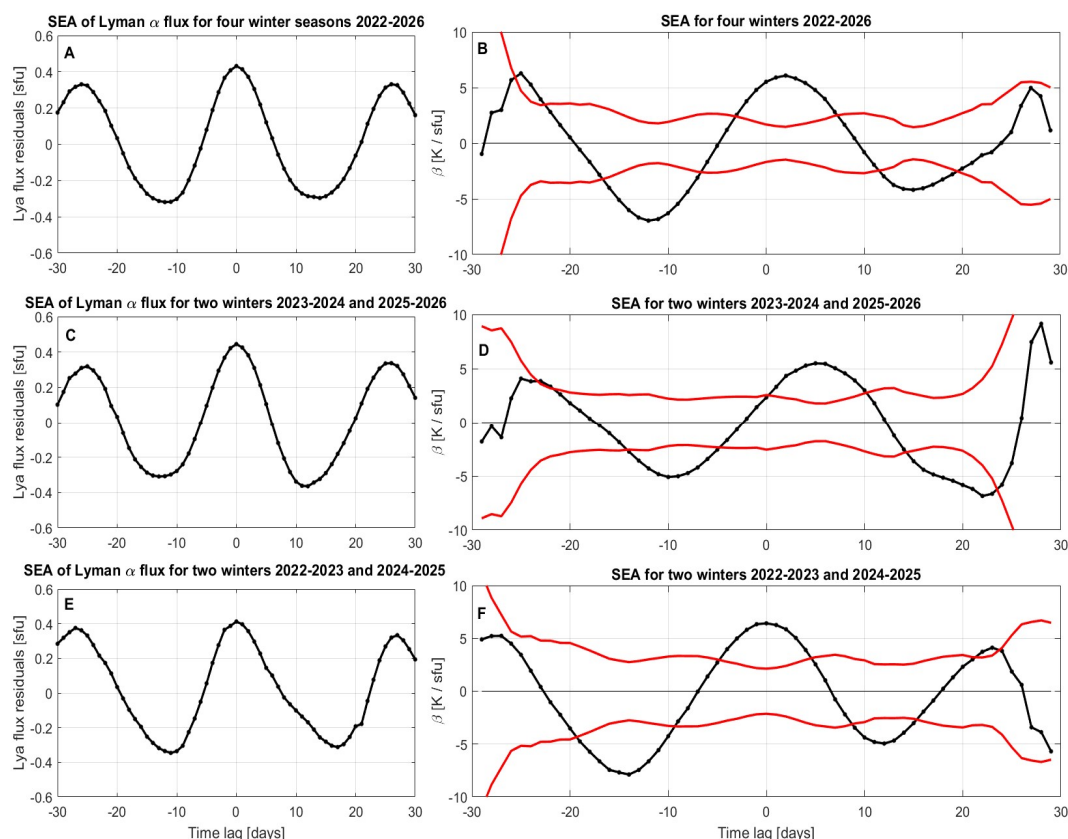


Figure 9. Superposed epoch analysis (SEA) for anomalies of Ly α flux and OH(3-1) rotational temperature measured in Kiruna for four the winter seasons of 2022-2023, 2023-2024, 2024-2025 and 2025-2026 (A, B); for the two winter seasons of 2023-2024 and 2025-2026 (C, D); and the two winter seasons of 2022-2023 and 2024-2025 (E, F). Panels A, C and D represent the averaged Ly α epoch for respective winter seasons. Panels B, D and F show the regression coefficient (sensitivity β) based on mean temperature and Ly α epochs (see the text). Red lines are the 95% confidence levels.

5 Conclusions

The effect of short-period variations in the solar Lyman α flux on changes in hydroxyl emissions and temperature in the winter polar upper mesosphere over northern Scandinavia for four winter seasons (2022-2023, 2023-2024, 2024-2025 and 2025-2026) has been investigated. The following results have been obtained:



1. Short-period changes in the Lyman- α flux lead to statistically significant changes in the intensity of OH(3-1) emissions and in the temperature, with positive responses and zero or small delays (0-5 days) for the winter periods considered. Near-zero lags imply the direct transfer of solar short-wave energy into changes in the physical-chemical state of the upper mesosphere through the absorption of UV radiation by molecular oxygen and ozone, the photodissociation of molecular oxygen and ozone, changes in the chemical composition and subsequent changes in heating rates associated with exothermic reactions.

2. Average temperature amplitudes due to short-period changes in the Ly α flux are about 2–4 K (about 1–2% of the mean value), which are comparable in magnitude to temperature changes caused by atmospheric planetary waves in the upper mesosphere. Average amplitudes of P1(2) and P1(4) line emission intensities are in the range of 300–900 R (4–13% of the mean value).

3. When analyzing the effect of short-wave solar radiation on temperature changes, it is important to pay attention to the power spectrum of Ly α flux, in which two or more oscillations with periods in the vicinity of 27 days can occur. This can lead to significant time lags between the total solar Ly α flux and the mesospheric response when considering regression and cross-correlation methods.

Code availability

The MATLAB and Python codes used in this study for the OH image processing are available <https://gitlab.irf.se/kago/kago-software/oh-imager>.

Data availability

Research data are available for noncommercial scientific usage, in accordance with other data obtained from the Kiruna Atmospheric and Geophysical Observatory (KAGO, <https://www.irf.se/forskning/kago/>) at the Swedish Institute of Space Physics (IRF), and are available upon request from Peter Dalin (pdalin@irf.se).

Author contributions

PD: conceptualization, methodology, installation of the OH imager, data processing and validation, writing MATLAB and Python codes, statistical analysis, data visualization and archiving, geometrical calibration of the OH imager, and writing the original manuscript. VP and NP: conceptualization, methodology, assistance with the interpretation of scientific results. All co-authors contributed to writing and reviewing the manuscript.



486 **Competing interests**

487 The authors declare that they have no conflict of interest.

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