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Gravity wave activity in the mesopause region from airglow measurements at El Leoncito

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Abstract

Based on almost 1000 nights of OH(6-2) and O_2b(0-1) airglow data measured during1998-2002 at El Leoncito (31.8ºS, 69.2ºW), seasonal variations of gravity wave activity are determined from temperature and intensity variances. The photon-counting technique used permits to derive the individual statistical errors a-priori, and to quantitatively isolate the geophysical variance. The two airglow emissions yield results for the altitudes of 87 and 95 km. Tidal activity contains most of the variance (especially between March and October) and therefore must be suppressed to obtain gravity wave activity. There are strong night-to-night variations, from completely quiet to variances of more than 80 K^2 in temperature. The interannual variability was small enough to define a meaningful seasonal climatology. The wave activity variation is semiannual, similar to previous radar wind results, including those at the same latitude, and has its main maximum in southern winter and a weaker maximum in summer. The growth of wave activity from 87 km to 95 km, when interpreted in terms of an amplitude growth factor, leads to a value of 1.35 ± 0.01, similar to the one obtained for tides, in a previous paper of ours. From the comparison of intensity and temperature variance for a given emission, mean values of Krassovsky's η are derived (5.60 ± 0.09 for OH, and 5.08 ± 0.08 for O_2), that compare favourably with results obtained from individual wave signatures. This proves the consistency between the wave activities derived from intensities and temperatures.

Keywords: Airglow; Mesopause region; Atmospheric dynamics; Gravity waves; Wave activity

1. Introduction

Gravity waves play an important role in momentum and energy transport in the middle atmosphere, thus affecting the mean circulation and the thermal structure. An extensive review of the present state of gravity wave studies is given by Fritts and Alexander (2003).

A better knowledge of the seasonal climatology of gravity wave activity is necessary for any realistic modelling of the atmosphere. Gravity wave activity is expected to be a highly local phenomenon, strongly controlled by the geographical distribution of sources. In the mesopause region, most of the reports have been based on radar wind data (e.g., Vincent and Fritts, 1987; Thorsen and Franke, 1998; Manson et al., 2002) or lidar-derived density and wind data (e.g., Senft and Gardner, 1991). The use of mesopause region temperature data has been limited to studies of short duration. Such was the case of Hauchecorne et al. (1994) where gravity wave activity during the DYANA campaign (January to March 1990) was discussed, using temperature and wind data from different sites in Europe and Canada.

Here, we present results on the climatology of gravity wave activity based on airglow observations at El Leoncito (31.8º S, 69.2º W, in the Argentine Andes). Temperature and intensity data of the OH(6-2) band (corresponding to an altitude of approximately 87 km), and the O_2b(0-1) band (at 95 km) are used. The recently published paper by Gavrilov et al. (2002) on the seasonal variation of gravity wave parameters at Shigaraki (34.9º N, 134.1º E) is based on the same airglow bands.

We determine gravity wave activity from the variance of the data. Although spectral frequency resolution would add useful information, a benefit of the variance approach is that the results are not contaminated by the Doppler effect. Therefore, spectral decomposition is here needed only to discriminate against tidal variations, where the Doppler effect is unimportant. Gravity waves with vertical wavelengths smaller than about 12 km (Swenson and Gardner, 1998; Reisin and Scheer, 2001) are unobservable with the airglow technique.

In this paper, we take advantage of the photon-counting technique used to determine the instrumental contribution from photon-counting statistics, a-priori, for its separation from the total observed variance.

2. Data and method

A tilting filter spectrometer (Scheer, 1987) is used to measure nightglow OH and O_2 band intensities and rotational temperatures in a rectangular zenith area of 0.41º x 2.0º. For details about data reduction and instrumentation enhancements, see also Scheer and Reisin (2001). The four parameters together are obtained in about 80 seconds, with mean statistical errors of 1.8 ± 0.5 % (2.4 ± 0.5 %) for O_2 (OH) intensities, and 5.4 ± 1.3 K (4.3 ± 0.9 K) for O_2 (OH) temperatures.

Here, we use only data from January 2, 1998, until September 4, 2002. The 1997 data are excluded because of the unusually low intensities (Scheer and Reisin, 2000) attributed to untypical geophysical conditions. Each month is still documented by at least 50 nights of data and some by more than 100 nights. From 930 nights with data, the selection criteria applied to improve data quality leave 670 to 860 nights available for the present purpose (depending on context).

The geophysical variance is calculated as $\sigma^2 = \sigma_t^2 - \sigma_e^2$, where σ_t^2 is the total observed variance, and $\sigma_e^2 = \langle\varepsilon_i^2\rangle$ is the variance due to the instrumental statistical error, ε_i. Photon counting statistics allows us to calculate a-priori the error for each individual data point. From the counts corresponding to the intensities sampled at seven spectral positions, the ε_i values are calculated by error propagation and, alternatively, by Monte-Carlo simulation, giving practically identical results, as expected.

The subtraction of the instrumental contribution is vital, especially for temperature data, where σ_e^2 represents (on average) about 70% of σ_t^2 (when tides are removed). This percentage varies considerably with airglow brightness. The instrumental contribution to intensity variances is considerably smaller, about 12%. The technique used by Hauchecorne et al. (1994) to eliminate the noise contribution via the variance of the difference of two consecutive data points relied on the assumptions of white noise and a negligible contribution of high frequency waves. None of these assumptions is needed here.

Unless suitably removed, tides generally contribute most of the observed variance. To subtract the tidal contribution for each night, the diurnal and semidiurnal components are determined by consecutive least-squares fits (of course, including the constant term). To minimize sidelobe interference, the higher amplitude component is subtracted first, in the spirit of the technique we usually employ (see Reisin and Scheer, 2001). This technique gives reasonable tidal amplitudes, unlike simultaneous fits of both tidal components, which tend to exaggerate amplitudes considerably, owing to the partial coverage of the diurnal period.

Fig. 1 shows a typical example of the nocturnal variation before and after the subtraction of the tidal components. The strong reduction of amplitude is evident. Note that this subtraction only involves two sinusoids, and that other spectral components in the tidal period range are not removed.

To assure quality and improve homogeneity, data with excessive noise were discarded. For OH, only temperatures with $\varepsilon_i < 6$ K are admitted, while for O_2 temperatures, this limit is 9 K. An additional requirement of at least 4 hours of data per night is easily met with little loss of data.

The complete analysis is done not only for entire nights, but also for different data windows of shorter length. Shorter data windows result in better counting error correction, but underestimate oscillations with periods longer than the window. The effect of different window lengths will be shown in the next section.

Because wave amplitude is proportional to the *relative* variation of each parameter (intensity or temperature), the great dynamic range of airglow intensities requires that intensity variances must be normalised by the mean intensities of the data window. This normalisation is not necessary for temperatures, where it would not alter significantly the geophysical results.

3. Results and discussion

The nocturnal geophysical variances for data with tides removed are shown in Fig. 2. The data points during the five years 1998-2002 are superposed on a single annual scale, showing a fairly uniform seasonal coverage. Note the large dispersion of the points. Also, there are strong variations between consecutive nights (not discernible in Fig. 2 because the different years are not distinguished), similar to those reported for radar and lidar observations (e.g. Vincent and Fritts, 1987; Wilson et al., 1991). However, the visual impression from the figure is that this intermittency does not prevent the less dramatic variability from dominating the mean seasonal variation of wave activity. This impression is also confirmed by the behaviour of the standard deviations as will be shown later. There are many nights with practically no gravity wave activity, in the four parameters. With respect to nights with high gravity wave activity, the greatest variances are reached for the O_2 airglow emission. For intensities, these values are around 0.07, and for temperatures, around 80 K^2 (ignoring a single case with 140 K^2). The temperature variances, in relative terms, are about 30 times smaller than for intensities. This is not only true for these high values, but also on average (see below, where an interpretation of these different scales related to Krassovsky's η is discussed).

For climatological studies of the seasonal variation, an average is required. Here, we use running means over 29-night intervals. Fig. 3 shows the running means for the individual years. Except for the March/April 2001 temperatures, the interannual variations are relatively small, and it is therefore reasonable to build a mean seasonal variation based on these data. This is done by gathering the nocturnal variances of the different years corresponding to the same time of the year. The results are shown in the lower panels of Fig. 4. Each panel in this figure compares results for the two airglow emissions (solid lines: O_2; dotted lines: OH). Shaded regions denote the standard deviation of the means, and there is no evidence of a disproportionate impact of the greatest variances.

In order to demonstrate the importance of the tidal correction, tides have not been subtracted for the upper panels of Fig. 4. It is clear from the figure that tides contain most of the variance, as mentioned before (but note the different scales); gravity wave variance only represents 20 ± 8 % of the total variance for intensities, and $30 \pm 10\%$ for temperatures. With tides included, variances of the four parameters are high between March and October and low in the rest of the year. This is consistent with what we usually see in the seasonal behaviour of the tides at El Leoncito. The shapes of the seasonal variation are much more irregular than for the gravity waves only. Therefore, we limit the analysis to the tide-removed case.

Gravity wave activity shows a semiannual behaviour, in all the parameters (Fig. 4, lower panels, or more clearly in Fig. 5, solid lines). For OH, the main maxima are reached in southern winter (after solstice), and about one month later in the upper airglow layer (O_2). The weaker maxima appear during the month following summer solstice (late December and most of January). Wave activity is low during about one month before and after the autumn equinox, and during the two months after the spring equinox. A semiannual behaviour of wave activity is well known from radar and lidar wind observations at different Northern Hemisphere sites (e.g., Senft and Gardner, 1991; Manson et al., 2002; and other references in Fritts and Alexander, 2003), including Southern Hemisphere observations at a latitude similar to El Leoncito (at Adelaide; Vincent and Fritts, 1987). However, some details are different, and none of these other observations refers to the South American sector. The strong presence of the semiannual variation at 95 km distinguishes our results from those obtained at Urbana (40º N; Thorsen and Franke, 1998), where it nearly disappears above 90 km.

A main winter maximum in gravity wave activity is a global feature that is present in most observations, also at lower altitudes. This feature and the seasonal variation as a whole (semiannual at low latitudes, annual at higher latitudes) are believed to be due to variable background conditions modulating vertical wave propagation by wind filtering or because of temperature-dependent amplitude growth (as discussed in the Fritts and Alexander review). It is not clear how much of the seasonal variation at El Leoncito may be due to the variability of gravity wave sources (probably from orographic forcing), in addition to the background modulation.

Activity is greater in the O_2 layer than in the OH layer, especially in winter. For temperatures, the variance ratio $<\sigma^2_{O2} / \sigma^2_{OH}>$ between the emissions is 1.81 ± 0.02 (averaged over all data). Its square root, 1.35 ± 0.01, can be interpreted as a mean amplitude growth factor, with the implied assumption that the same waves are involved at both altitudes. This is quite similar to the factor 1.27 ± 0.07 obtained by Reisin and Scheer (1996) from individual wave observations in the tidal period range, and indicative of considerable damping. The agreement suggests at first sight that, on average, dissipation is independent of wave period. However, the situation is complicated by the considerable fraction of the gravity waves that where found to propagate downwards (Reisin and Scheer, 2001), in contrast to the upward-propagating tides. The mean variance ratio for intensities is 1.28 ± 0.01, less than for temperature. This difference is consistent with the amplitude responses to gravity waves of the two emissions (Krassovsky's η, see below).

To obtain a coarse isolation of the high frequency range, the nocturnal geophysical variances were alternatively determined from data windows shorter than one night. As mentioned, this method reduces the weight of waves with (observed) periods greater than the window duration. The results for windows of one and three hours in contrast to complete nights are included in Fig. 5 (as dashed and dotted lines). For 3-h windows, the curves are only slightly below the corresponding full-night curves, during most of the year. For 1-h windows, the variances are much smaller than for the full night (varying between 26% and 68%). This is because gravity wave activity is higher in the long-period range, and these waves are more strongly suppressed by the shorter window. However, the *shapes* of the seasonal variations are similar, suggesting that the gravity wave spectrum does not vary appreciably with season.

Models suggest a simple relation between the seasonal variations of airglow intensity and gravity wave activity, as expressed by Hecht et al. (1997). These authors interpret the Le Texier et al. (1987) and Garcia and Solomon (1985) models as being based on the idea that low wave activity in the mesopause region leads to low eddy diffusion, build-up of atomic oxygen and therefore, enhanced airglow brightness. In order to find out whether there is such an anticorrelation, we compare our results with seasonal intensity variations at El Leoncito (averaged over the years 1998-2001). This is shown in Fig. 6, for both emissions. For OH (lower panel), there is a certain correlation between the parameters (with the intensity variation leading the gravity wave activity by one or two months). On the other hand, there is a clear anticorrelation for O_2, consistent with the model view. The different behaviour at the OH altitude may suggest that the seasonal airglow brightness variation is not related to gravity wave activity in a simple, height-independent way. However, our results do not necessarily contradict the mechanism underlying the model explanation. The argument relating low eddy diffusion with high atomic oxygen concentration, as stated, is valid only where the atomic oxygen source (photodissociation) dominates over loss (recombination). Where recombination dominates, a reduction of vertical atomic oxygen transport would lead to *lower* atomic oxygen concentration. This is what may be happening in the OH layer.

What information is contained in the relative scales of the intensity and temperature variances? For a given airglow emission, the mean amplitudes (i.e., the square root of the variances) of the intensity variation in relation to those of temperature depend on the mechanism of the airglow response to atmospheric waves. This relation is expressed as Krassovsky's η, the ratio of the relative intensity and temperature amplitudes corresponding to a single monochromatic wave. In the present context, one would expect the following relationship to hold, approximately (assuming, that the same waves are involved in the observed variances) :

$$\eta = \frac{\sigma_B}{\sigma_T / <T>}$$

where σ_B^2 and σ_T^2 are the normalised intensity and the absolute temperature variances, respectively (the division by the mean temperature $<T>$ is necessary to reestablish normalisation for temperature variance). Here, the five-year averages are $<\eta_{O2}> = 5.08 \pm 0.08$ and $<\eta_{OH}> = 5.60 \pm 0.09$ (and these values squared are close to the factor of 30 mentioned above). These mean values are in agreement with statistical results for individual waves obtained previously. For the tidal period range, Reisin and Scheer (1996) reported $\eta_{O2} = 6.7 \pm$

0.3 and $\eta_{OH} = 5.5 \pm 0.6$ and confirmed the monotonic growth of η with period consistent with the Hines and Tarasick model (Hines and Tarasick, 1987; Tarasick and Shepherd, 1992). For observed periods between 1000 seconds and 3 hours, the arithmetic averages (applicable here) corresponding to the results obtained by Reisin and Scheer (2001) are $\eta_{O2} = 3.10 \pm 0.06$ and $\eta_{OH} = 3.47 \pm 0.07$. The present mean η values are closer to the long-period results. This is probably because of the greater contribution of longer-period waves to the variance, as mentioned. Therefore, the values of Krassovsky's η derived here mean that the wave activity results for intensities and temperatures (for a given emission) are compatible with each other.

4. Conclusions

Gravity wave activity in the mesopause region at El Leoncito during the years 1998-2002 can be well represented by the mean seasonal variation. The results show that gravity wave activity is clearly different from tidal activity, in scale as well as seasonal behaviour. This underlines the need to remove tidal signatures from the data. On the other hand, we find that long-period gravity waves have a similar seasonal behaviour to short-period waves.

Our results confirm the very strong night-to-night differences of wave activity, as reported for radar and lidar observations, but fortunately, the highest activity events have no overwhelming impact on the climatology.

For each of the four parameters, the seasonal variation is semiannual, in approximate agreement with previous radar and lidar observations at other sites. The winter maximum is stronger than the summer maximum. For the OH airglow layer (at 87 km), the main maximum is in late June / early July, whereas for O_2 (at 95 km), it appears about one month later.

The relation between gravity wave activity and seasonal intensity variations changes from a certain correlation for OH to a strong anticorrelation for O_2, complicating the possible causal relationship.

Wave activity tends to be greater at 95 km than at 87 km, especially in (southern) winter, when temperature variance for O_2 is about twice that for OH. The ratio of the temperature variances at 95 and 87 km is consistent with previous experimental results about the amplitude growth factor of tidal-period waves.

The relative scales of the intensity and temperature variances for each airglow emission are consistent with previous results for Krassovsky's η. We have thus shown the consistency of the four independent determinations of gravity wave activity.

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Fig. 1. Example of tidal subtraction (O_2 intensity, El Leoncito, 14 April 1999). Original data (solid line), and data after subtraction of 12 h and 24 h tidal components (dotted line).

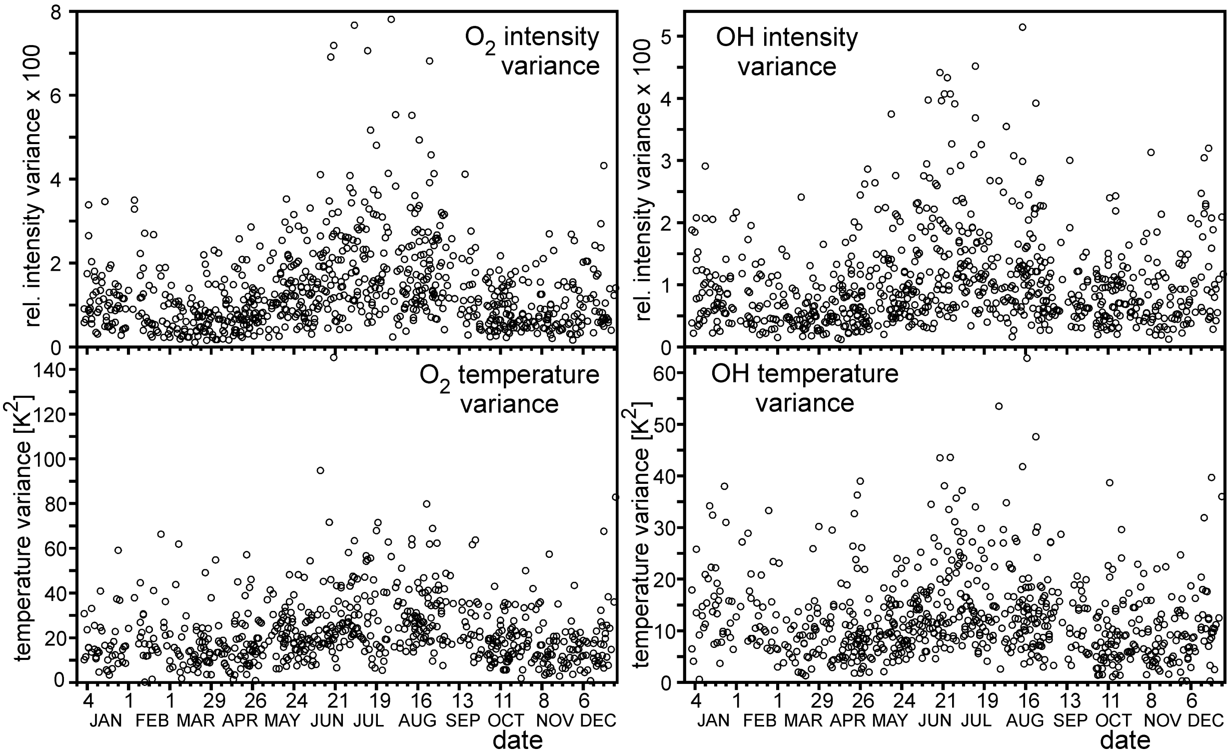

Fig. 2. Nocturnal mean variances for 1998 - 2002 with respect to the four different observed parameters (as given in each panel; tides have been subtracted). Each circle corresponds to one night.

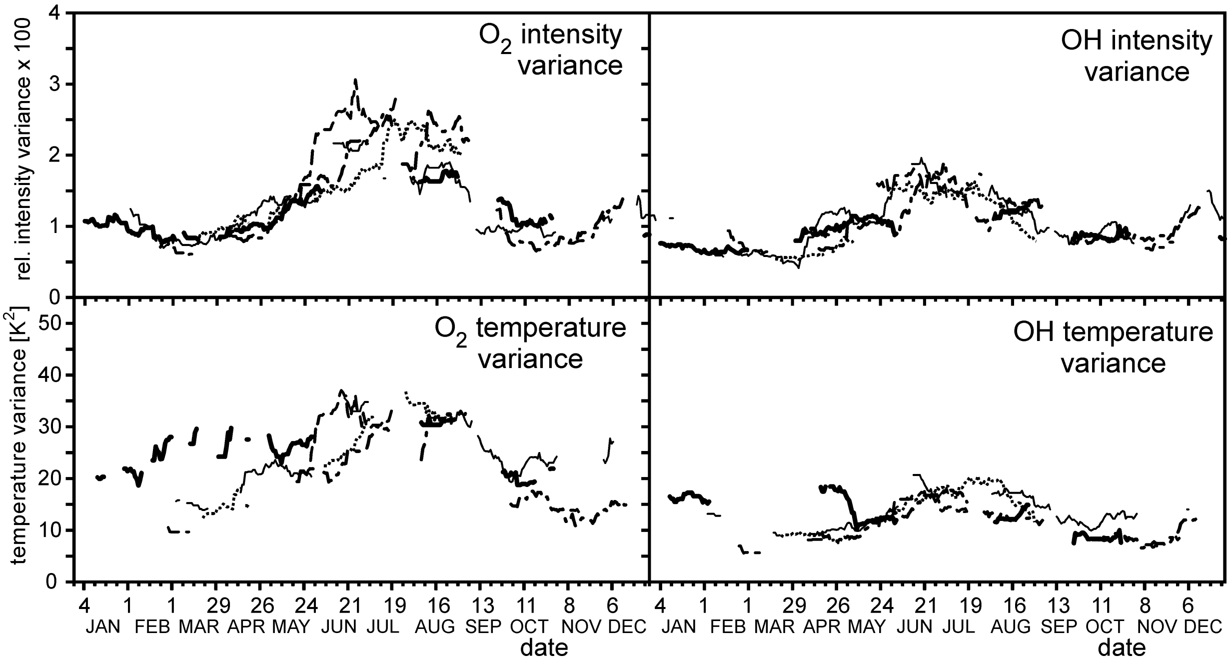

Fig. 3. Seasonal variation of variance in different years (29-day running means; curves are interrupted when less than 15 nocturnal values are available in the data window). Shown are the years 1998 (dashed-dotted line), 1999 (dashed), 2000 (narrow solid), 2001 (wide solid), and 2002 (dotted).

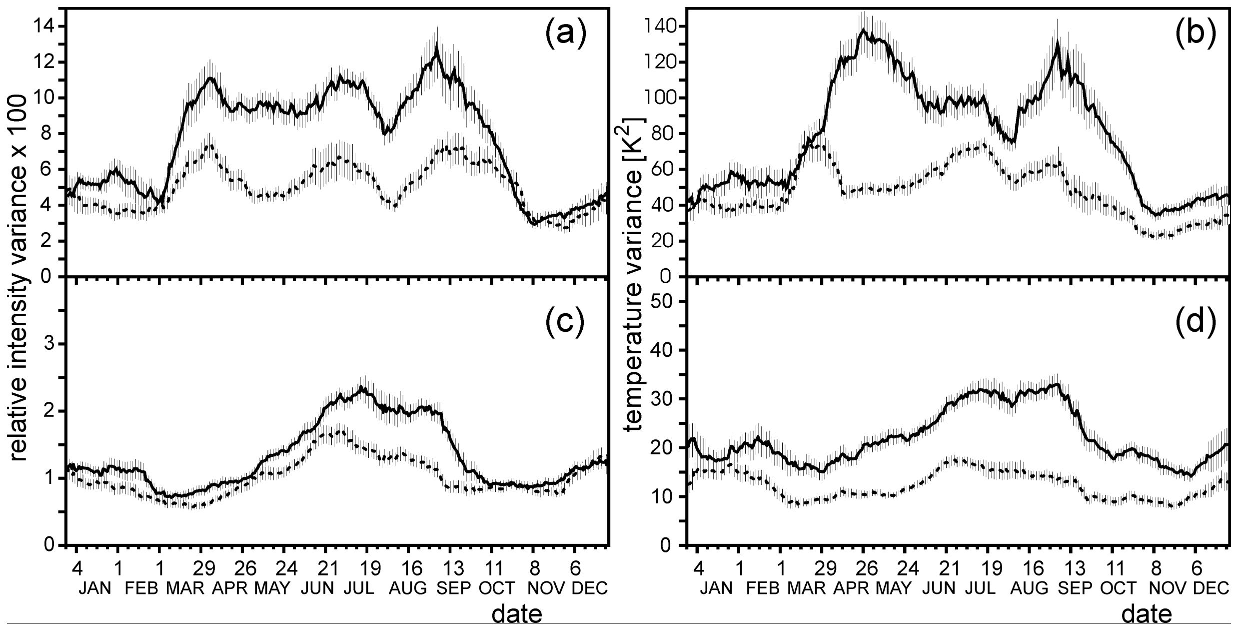

Fig. 4. Average seasonal variation of data variance (1998-2002). The curves show 29-night running means. Shaded aereas represent one standard deviation. Solid lines are for O_2 (95 km), dotted lines for OH (87 km). Upper panels still include tides, lower panels show data after subtraction of tides (different vertical scales). Panels (a) and (c) show intensity variance, (b) and (d), temperature variance (the curves have no gaps because none of the data windows falls below the limit mentioned in Fig. 3).

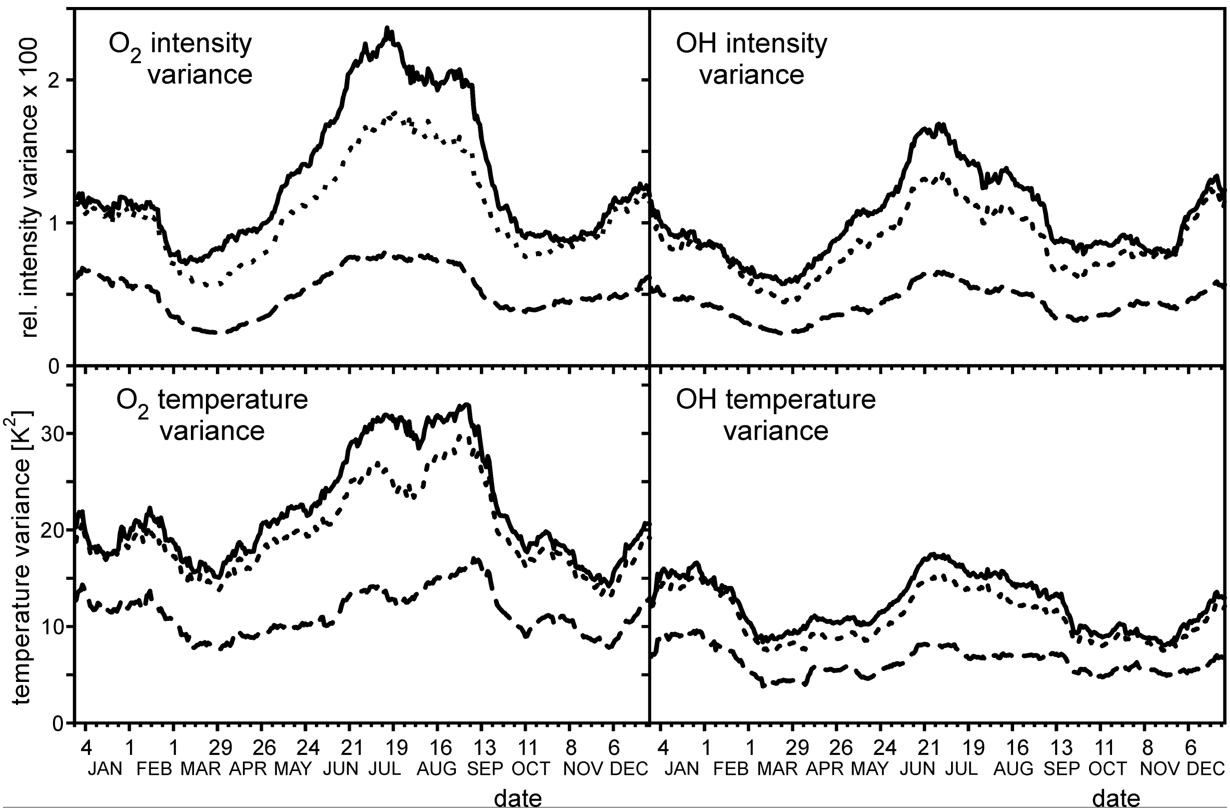

Fig. 5. Gravity wave activity results for the four observed parameters (solid lines; same as curves in lower panels, Fig. 4). Panel assignment same as Figs. 2 and 3. For comparison, results with shorter data windows (3 hours, dotted; 1 hour, dashed) are also shown.

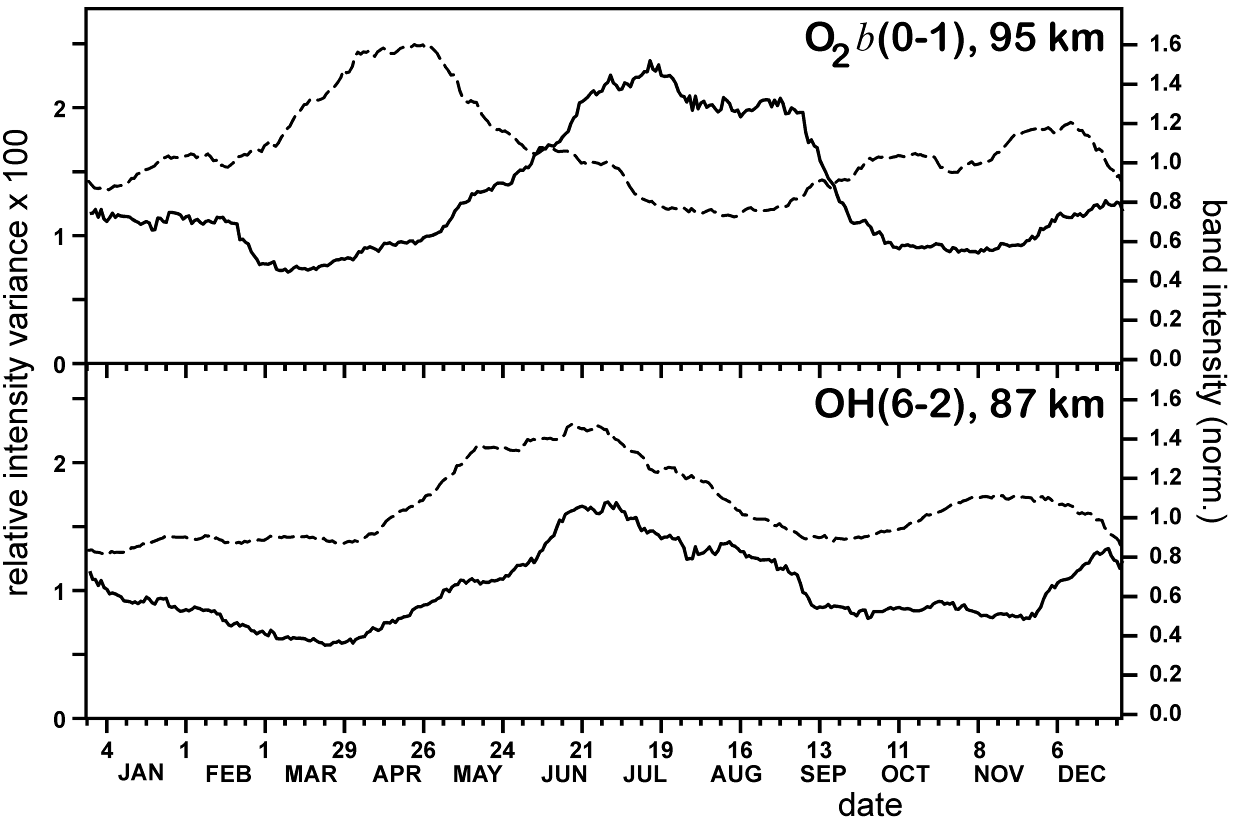

Fig. 6. Seasonal mean airglow brightness variation (for 1998-2001; normalized with respect to long-term means; dashed lines) in comparison to intensity variance (solid lines; same as Fig. 4 c, and solid lines Fig. 5, upper panels), for the two emissions.