Evidence of change after 2001 in the seasonal behaviour of the mesopause region from airglow data at El Leoncito

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Abstract

Airglow intensities and rotational temperatures of the OH(6-2) and O_2b(0-1) bands acquired at El Leoncito (32°S, 69°W) provide good annual coverage in 1998 to 2002, 2006, and 2007, with between 192 and 311 nights of observation per year. These data can therefore be used to derive the seasonal variations during each of these seven years, in airglow brightness and temperatures at altitudes of 87 and 95 km. From 1998 to 2001, seasonal variations are similar enough so that they can be well represented by a mean climatology, for each parameter. On the other hand, these climatologies do not agree with what is usually observed at other sites, maybe due to the particular orographic conditions at El Leoncito. With respect to the last three fully documented years (2002, 2006, and 2007), the similarity from year to year deteriorates, and there are greater differences in the seasonal behaviour, more or less in all the parameters. The differences include, e.g., maxima occurring earlier or later than "normal", by one or two months. All this may suggest the build-up of a new regime of intraseasonal variability, with a possible relationship to corresponding changes in wave activity.

1. Introduction

Since the mesopause is defined as the height of the temperature minimum in the terrestrial upper atmosphere between about 80 and 100 km, the observation of its temporal evolution requires temperature measurements. Observations of the temperature profile in this height range with potassium and sodium resonance lidars led to the discovery of the existence of two different mesopause heights between which the atmosphere switches in the course of the year (von Zahn et al., 1996; She and von Zahn, 1998; Xu et al., 2008). During most of the year, the mesopause is close to 100 km, but around summer solstice, it is at about 86 km. This means that it makes no sense to use the term "mesopause" associated to a fixed altitude, and is another good reason to refer to the entire height range of 80 to 100 km as the "mesopause region".

Temperature time series from the OH airglow emission corresponding to a nominal altitude (87 km) practically at the ideal summer mesopause height, and from the O_2 emission at about 95 km, not far from the upper mesopause level, are available at different sites of the world. These data are suitable to study the temperature and airglow brightness climatology in the mesopause region, adding valuable information to the one obtained from lidars and satellite instruments. Since airglow observations can easily be automated and do not require extremely good weather conditions, they are capable of supplying data sets which are long and dense enough to describe the seasonal variation and its eventual changes from year to year.

Seasonal airglow intensity climatologies have been derived as early as the 1920s, for the 558 nm line emission of atomic oxygen (see Hernandez and Silverman, 1964), strongly correlated with the O_2 airglow. This line has also been used to measure temperature from its Doppler width (Armstrong, 1968), but the greatest amount of data presently is obtained as rotational temperatures for the molecular bands of OH and O_2.

A number of recent papers discuss mean temperature climatologies for the mesopause region at tropical and lower midlatitudes from several years of ground-based observations. These are based on lidars (States and Gardner, 2000; Chu et al., 2005; Yuan et al., 2008) and airglow instruments (Takahashi et al., 1995; López-González et al., 2004; Zhao et al., 2007; Gelinas et al., 2008). Most of these airglow studies also discuss the seasonal climatology of airglow intensities which supply complementary geophysical information to the seasonal behaviour of temperatures.

Here, we report airglow results obtained at lower midlatitudes in Argentina, which describe a somewhat unusual seasonal pattern. Another major objective is the analysis of interannual differences.

2. Instrumentation, Data, and Processing

Zenith intensities of the OH(6-2) and O_2b(0-1) airglow bands and the corresponding rotational temperatures were measured with the Argentine airglow spectrometer (Scheer, 1987) at Complejo Astronómico El Leoncito (31.8°S, 69.3°W). The instrument uses a tilting interference filter to sample the airglow spectrum at seven positions, obtaining a time resolution of 81 seconds (Scheer and Reisin, 2001). Since the instrument operates in photon counting mode and uses only one single filter well protected against environmental humidity in a hermetic enclosure, eventual aging effects are well under control and a consistent intensity scale (expressed in relative units) can be assured. This stability can be verified by comparison with the galactic stellar background; see, e.g., Scheer and Reisin (2000), and also the more recent comparison at *http://www.iafe.uba.ar/aeronomia/stabilit.html*. Of course, rotational temperatures are completely unaffected by the intensity scale.

The observing site at 2500 m above sea level and located about 50 km east of the Andes mountain range with peaks above 6000 m can be expected to exhibit aeronomical conditions influenced by orographic forcing in a way not encountered at other places, so that the data from this site are not necessarily representative of the whole latitude zone.

The number of nights with useful data, and the total number per year of groups of data (each group comprises the four measured parameters) are shown in Fig. 1 (data for 1988, 1990, and 1994 were obtained at other sites in Argentina, and in Spain). The data before 1998 have been obtained in campaign mode, and therefore only cover a few weeks or a few months per year, which is not enough for this climatological study (unless interannual variability is assumed to be negligible).

During the five years since the onset of fully automatic data acquisition in 1998, a yearly coverage of about 200 nights or more has been established. There is a data gap from 2003 to 2005 due to instrument failure, repair and refurbishment. After a new calibration to take the modifications in the filter tilt mechanism and the spectral sensitivity of the new photomultiplier into account, measurements continue since early 2006. In 2007, the greatest coverage of 311 nights was reached. The data set used here is composed of 65 thousand to nearly 100 thousand independent groups of good data per year. Assuming that each measurement corresponds to 88 seconds of observation (the mean value for a complete night without data gaps), this means that a single year contained between 1600 and 2400 measurement hours (discounting data gaps).

Note that the temperature scales for OH and O_2 are independent to a certain degree, because rotational temperatures for both emissions are based on completely different molecular physics which introduces different systematic errors for both bands. This means that the exact absolute temperature scales are still unknown. A satellite intercomparison based on the second mission of the CRISTA instrument in 1997 (Scheer at al., 2006) has permitted to establish a common temperature scale for both emissions. However, the precision of this determination was limited by the short duration of the flight, and its validity terminates with the instrument modifications mentioned above. Therefore, the corresponding adjustment will here only be applied where a direct comparison of both temperatures makes this necessary.

The detailed seasonal distribution of the data for the years 1998 to 2002, and 2006 to 2008, which we use in this study, is shown in Fig. 2. The only longer data gaps (between one and two months) are present in 1998, 2001 and 2006, but in the other years, gaps are short and leave the seasonal coverage quite uniform. Since mid-2002, there are even long runs of several months of data without any missing nights.

As an example of the behaviour of the nocturnal means in a year with rather uniform seasonal coverage, and which exhibits a typical seasonal variation, we take the year 1999. Fig. 3 shows the nocturnal means corresponding to the four observed parameters. The quality of most of the data is good, because on average, for all our data, nights are documented almost completely (only about 15% short of the maximum possible given by the duration of darkness; for more details, see Scheer et al., 2005a). Note that the intensity scale used here and in the rest of the paper is normalized (independently for both airglow emissions) by a long-term mean (as defined at one time in the past).

For comparison, the figure also shows the mean behaviour of the years 1998 to 2001 (as will be discussed below). With only a few exceptions, the data for 1999 follow the general tendency of the mean behaviour quite well. There are some individual nights which exceed the mean level considerably, especially for intensities. These are not bad data. Quite the contrary, they are the data with the lowest noise level that we have. They represent special geophysical conditions with an origin not yet firmly established (see the discussion in Scheer and Reisin (2002) and an attempted explanation of some cases in Scheer et al., 2005b). Because of the excessive variance these cases would contribute, they eventually have to be excluded from statistical analysis.

Note that the nocturnal means may occasionally be affected by the diurnal tide (while the semidiurnal contribution should be well suppressed for a data span of about one period). However, the tidal effect does not only depend on amplitude: even a strong tide would have only a small effect, for certain values of phase. So, while the use of nocturnal means does not completely remove a tidal bias, at least it reduces it as far as possible. According to our tidal analysis (yet unpublished) in the context of the CAWSES global tidal campaigns (Ward, 2008), the minima of most of the diurnal signatures we have detected correspond to night hours, so that nocturnal means underestimate the unperturbed seasonal level. In a few cases of morning or evening tidal phase, the tidal bias would tend to be negligible. Even if continuous measurements during 24 hours were possible, as some lidar investigations have achieved (e.g., Yuan et al., 2008), only an ideally stationary tide could be completely suppressed.

To better describe the seasonal variation, the remaining effect of the day-to-day variability, which is mainly due to planetary wave activity and tidal variations, has to be removed. We simply use a running mean (a moving average over 29 consecutive nights) to achieve this, although better ways to suppress high-frequency oscillations or to reduce the effect of extreme values could have been devised. To avoid poor statistics, we require a minimum of ten nights in the 29-day data window. Also, the average is weighted by the number of data per night, to reduce the impact of nights with incomplete coverage.

As mentioned above, there were instrument changes after 2003 (accounted for in a completely new calibration), which may have caused shifts with respect to the previous years in the rotational temperature scales (within the absolute uncertainty margins of each calibration estimated to be of the order of 5K). In principle, these uncertainties can only be eliminated completely by a new intercomparison with respect to a transfer standard available before and after our instrument change. For the moment, an additive ad-hoc adjustment has been applied separately for OH and O_2 temperatures, by subtracting the mean of all data for 2006 to early 2008 from the pre-2002 mean. The lower sensitivity due to the detector change was corrected by a scale factor determined from the galactic background signal, so that a consistent intensity scale is maintained.

3. Results

The seasonal variation so defined is shown in Fig. 4, for each individual year and the four observed parameters. For better legibility, the years are separated into two groups, 1998-2001, and 2002/2006/2007. In general, there is considerable similarity between the seasonal variations among the earlier years, while for the later years, similarities are less evident. What especially strikes the eye is the position and duration of the seasonal maximum for O_2 intensity, for 1998 through 2001 (Fig. 4d), which remains near maximum during most of April. This is not so, in the later years (Fig. 4c): 2002 peaks only at the end of April, 2007 already in late February, and 2006 does peak in mid-April, but at a much lower level.

OH intensity exhibits an even better interannual agreement, in 1998-2001 (Fig 4b). In all these years, intensities start rising in April to a wide maximum, after remaining approximately constant, since early January. All curves return to the April level only at the end of August. On the other hand, in the later years, this timing is clearly different (Fig. 4a). In 2002, while the mid-April rise agrees with the previous years, the return is already in late July, much earlier than in 1998-2001. The peak in 2007 is the highest of all, but much narrower, and also returns to normal in late July. In 2006, OH intensity starts to rise in early March, and the behaviour is quite different from the other years. Intensity still rises at the beginning of a data gap in mid-July, and no return to "normal" is documented, for the rest of the year.

For temperatures (Fig. 4e,f,g,h), there is also a consistent behaviour for 1998-2001, while the interannual differences among the later years appear less dramatic than for intensities. O_2 temperatures in 1998-2001 again show an April maximum (Fig. 4h), as do the O_2 intensities already mentioned. Not so much the position of the maximum but its width and general shape differ in the later years (Fig. 4g). The most notable anomalies for OH temperature in the later years occur in 2002, especially the low temperatures after September (Fig. 4e). In general, there are considerable timing differences among the later years (Fig. 4 a,c,e,g). This means that these years do not define a new pattern of mean seasonal variations.

According to all these remarks, it makes sense to define a reference climatology based only on the years 1998 to 2001, because of the small interannual variability. Including the later years would only deteriorate the statistical homogeneity. This mean seasonal variation (or “climatology”) is obtained by calculating a 29-day running mean over the nocturnal means accumulated according to day of year (where December is connected to January to complete the 29-day window).

The result is shown in Fig. 5, for each parameter. Note that the error of the mean (based on all the nights in the 29-day window) is below 1 K for OH and O_2 temperatures, and less than 4% for intensities. The principal features of this climatology will be discussed in the next section. OH and O_2 temperatures as shown in Fig. 3 and 4 are not directly comparable because the systematic errors of both temperature scales are independent, as mentioned above. The recent satellite intercomparison has resulted in an offset of 22.3 K ± 4.3 K between both temperature scales (Scheer at al., 2006). To make the temperature scales compatible in Fig. 5, OH temperatures are shifted upwards by +22.3 K. However, no attempt has been made here to get the absolute level right, since for our present purpose it is not necessary.

For each parameter, we can now express the interannual variability in terms of the deviation from this climatology, in any single year. This permits to identify more easily the time of the year when the differences are greatest. Already from the visual impression (see Fig. 6), one can clearly tell that the variability in the three later years is greater than in the previous ones. Also the duration of the anomalies is generally larger than for the earlier years, with respect to all the four parameters.

In order to quantify the observed changes, we calculate the variance of the deviation from the mean 1998-2001 climatology for each year. Although this approach permits a more objective evaluation, it is inevitably accompanied by a loss of the detailed information contained in the seasonal variations. Note that the ad-hoc temperature adjustments (mentioned at the end of section 2), which brought the average temperatures before and after the instrument change to the same level, imply that the resulting variances since 2006 tend to be lower limits. The results for the four parameters, together with error bars, are shown in Fig. 7. The error bars were calculated from standard statistics, taking as the degree of freedom the number of non-overlapping 29-day windows (which ranges from 9 to 13, according to the year). The errors are meant as a guide, but their strict validity is questionable because the underlying assumption of stationarity is supposed to be violated.

The figure confirms the visual evidence from Fig. 4 and 6, in that the residual variance is low for all the years from 1998 to 2001, and is higher, for the more recent years. In some cases, this variance, which represents the power of the interannual variability, is about a factor of four greater than in the early years. The maximum residual variance is reached in 2007, for all parameters. One might even be tempted to interpret the figure as exhibiting a systematic trend. However, we would caution against such a view, because of the unknown behaviour during the data gap years 2003, 2004, and 2005., and because the trend is not sustained in 2008 (see below).

4. Discussion

4.1 Mean Climatology

Different previous versions of the mean seasonal variation of the El Leoncito data had been used earlier, but have not been discussed in detail. They have only been used as an intermediate step to compare with the intensity anomaly of 1997 (Scheer and Reisin, 2000), to analyze long-term trends (Reisin and Scheer, 2002) and solar cycle effects (Scheer et al., 2005a), and to compare with gravity wave activity (Reisin and Scheer, 2004). In spite of some differences in the years these versions were based on, they already exhibited the principal characteristics of the 1998-2001 climatology.

For each airglow emission, there is considerable similarity among the main features of this climatology between intensities and temperatures (see Fig. 5). For O_2, a pronounced maximum exists in April. For OH, the highest values occur in May and June, only after the end of the O_2 maximum. There is a local minimum in September, for OH. Both emissions exhibit a short minimum in early January, which is the only feature simultaneously present in all the four parameters. The good correlation between intensity and temperature variations, for OH and for O_2, can also be seen in the annual and semiannual components, as discussed below (in the context of Table 2). The reason for this correlation is likely to be dynamically induced vertical atomic oxygen transport. On the one hand, atomic oxygen controls airglow brightness, while on the other hand, the corresponding flow of chemical energy affects mean temperature in the same sense as it affects intensity.

There are secondary maxima in October, for O_2 temperature, in November, for OH intensity, and in early December, for OH temperature and O_2 intensity. A pronounced broad minimum from mid-July to early September is present in O_2 intensity.

Note that the April maximum we observe in O_2 brightness is reminiscent of a similar finding for the OI green line by Lord Rayleigh in 1926 and 1927 at Canberra (35°S, 149°E; data published by Hernandez and Silverman, 1964, and shown in figure 7 of Armstrong, 1968). Armstrong (1968) also reported an April maximum for OI green line intensity and Doppler temperature at Camden (34°S, 151°E) for 1964. Recent observations from Adelaide (35°S, 139°E) by Reid and Woithe (2007) show OI green line intensity variations which appear to peak also in April 1997, but with an additional broad maximum (similar to the April level) from September to November.

Another noteworthy feature in Fig. 5 are systematic timing differences between both emissions. What most strikes the eye is the (about one month) delay of the May maximum in OH intensity and temperature, with respect to the April O_2 peak. The September minimum in OH intensity seems to be similarly related to the O_2 intensity minimum centered on August. This may be a consequence of the emission height difference between both airglow layers and therefore an expression of the frequently observed downward phase progression in the mesospheric seasonal variation. For example, the analysis of SABER temperatures by Huang et al. (2006) reports a phase speed of about 8 km/month for the semiannual oscillation at low latitudes (however, at 44º latitude the phase progression was already upward, in the mesopause region). On the other hand, the seasonal variation we observe is not purely semiannual (see below for details) so that the relevance of this agreement is questionable. Models can still not replicate exactly these observations (Huang et al., 2006; Yuan et al., 2008), which shows that the mechanism behind the observed phase progression is not yet well understood.

The range of the seasonal temperature variation at El Leoncito is 14 K (peak-to-peak) for OH, and 16 K for O_2. The maximum O_2 intensity exceeds the minimum by slightly more than a factor of two. For OH, the corresponding ratio is 1.6. To put these numbers into context, we have compiled Table 1 from published data for other sites at comparable latitudes.

The most relevant comparison may be expected for the closest latitude, that is, at Adelaide (3° apart). There, the data obtained with the Aerospace imager (Gelinas et al., 2008) showed a 50% greater peak-to-peak variation for OH temperature, but a smaller variation by about 20%, for O_2. At the next lower southern latitudes, at 23°S, the airglow photometer at Cachoeira Paulista (Takahashi et al., 1995), and the Aerospace imager at Alice Springs (Gelinas et al., 2008), observe seasonal variations with about half the variation of El Leoncito, for OH and O_2 temperature. This difference is probably a latitude effect.

For the next higher latitudes in Table 1 (all in the Northern Hemisphere), the OH airglow temperatures at Sierra Nevada (López-González et al., 2004), and the 87-km temperatures from the sodium lidars at Starfire Optical Range (Chu et al., 2005), Urbana (States and Gardner, 2000), and Fort Collins (Yuan et al., 2008) show peak-to-peak variations that are from 7 to 26 K greater than at El Leoncito. On the other hand, the seasonal range of the O_2 temperatures and of the lidar temperatures at 95 km for these sites varies between 11 and 25 K. This interval encloses the value for El Leoncito; but there is no apparent relation to latitude.

At El Leoncito, the slightly greater seasonal temperature variation at 95 km than at 87 km (not only as peak-to-peak variations, but also as annual and semiannual amplitudes; see below) contradicts the expectation from the 2-level mesopause height concept (von Zahn et al., 1996) which was strongly supported by the Fort Collins data (She and von Zahn, 1998) and which is valid at middle and high latitudes. At the greater height, the seasonal variation should be much smaller than near the center of the OH layer. The most recent results from Fort Collins (Yuan et al., 2008) locate the summer mesopause as low as 84 km, where the seasonal variation approaches 49 K, while at 95 km, the variation is only 16 K and decreases even further, above that height. This means, that the O_2 temperature variation at El Leoncito is not in conflict with the Fort Collins data (see Table 1), as could be expected from the observed latitudinal behaviour at this height (von Zahn et al., 1996). The inconsistency with the midlatitude 2-level concept then stems from the behaviour at 87 km, and this may be related to the specific geographic location of El Leoncito. The situation expected for low latitudes is a constant high-altitude mesopause level throughout the year. According to the analysis of SABER data by Xu et al. (2007), the transition latitude between the low and midlatitude regimes is at about 35ºS. This places El Leoncito in a region where the situation is not clearly defined.

Taken at face value, the bottom panel of Fig. 5 shows that the only time of the year when the mesopause is at the lower, "summer", level is in March and April but not in summer when the temperature at the lower level is equal to or greater than at 95 km. During the rest of the year, except in September and most of October, the situation expected from the 2-level concept prevails. But note that the details of this description depend somewhat on the 4.3 K uncertainty (due to the CRISTA intercomparison mentioned in section 3) in the separation between both temperature curves of Fig. 5.

With respect to the range of intensity variations, there is surprisingly little spread among all the airglow measurements in Table 1. In spite of the different geographic locations, the ratios of seasonal maxima and minima are within the close margins of 1.4 to 1.6 for OH, and 1.9 to 2.1 for O_2. This even includes the tropical sites and Sierra Nevada, which exhibit a clearly different temperature variation, as mentioned.

We have performed a harmonic decomposition of the seasonal variations, with the hope to simplify comparison with previous publications. It turns out that the higher harmonics still have appreciable amplitudes, with as far as the seventh component still exhibiting one fourth of the amplitude of the principal component (for OH and O_2 temperatures). For OH temperature, the superposition of the annual and semiannual oscillations alone only explain 8 K of the observed peak-to-peak variation of 14 K, while for O_2 temperature, the superposition supplies 11 K to the observed total of 16 K. Moreover, the timing of the seasonal maxima and minima in Fig. 5 is not reproduced at all, by this superposition. This confirms the need to take more than only the annual and semiannual component into account to fully describe the main details of the climatology. On the other hand, the higher components themselves are difficult to interpret geophysically, and it seems questionable whether a relation to intraseasonal variations like the Madden-Julian oscillation in the tropical lower atmosphere (Madden and Julian, 1994) could be proved, in our case. Therefore, we limit our discussion here to the annual and semiannual components, as usual in the literature.

The similarity between the seasonal variations of intensities and temperatures for a given airglow emission (mentioned above) are reflected quite well in a certain agreement between the characteristics of the annual (and also the semiannual) component, as shown in Table 2. For example, the phases of the annual oscillation of OH intensity and temperature differ by only 18 days. For the semiannual oscillation, this phase difference is 5 days. For O_2, the differences are greater by about a factor of two, but represent less than 35°, only.

The annual and semiannual oscillations contribute by similar amounts to the seasonal variation at El Leoncito, for all four parameters (see the amplitudes in Table 2). This feature is also present in the OH and O_2 intensity components at Sierra Nevada (López-González et al., 2004), but not in temperatures, where the annual amplitudes considerably exceed the semiannual ones. The discrepancy has to do with the different shapes of the seasonal intensity and temperature variations at Sierra Nevada.

At Adelaide, in contrast to the situation at El Leoncito, and in spite of the similar latitude, the annual component dominates for the OH layer (in temperature and intensity), while for O_2, the semiannual oscillation prevails (Gelinas et al., 2008). We note that the Adelaide imager data belong to years past those that define our climatology, except for overlap in the second half of 2001. However, the behaviour at Adelaide is too inconsistent with that at El Leoncito to be attributable only to interannual variations. The different behaviour is maybe mainly a longitude effect. Longitudinal differences are known to have considerable impact on the seasonal variation, as for example shown by Smith (1997) for the equatorial semiannual wind variation. The physical reason for the longitudinal particularities at El Leoncito may perhaps be related to local orography, because it is the geographic condition that most distinguishes this site from any other one at a similar latitude. However, it is not clear which orographic effect to expect, a-priori.

In an attempt to explain the shape of the seasonal intensity variation at El Leoncito, we have previously discussed the influence of gravity wave activity on the mean intensity climatology 1998-2001 (Reisin and Scheer, 2004). There was clear evidence of an anticorrelation between gravity wave activity and the seasonal intensity variation, for O_2, but a (weak) correlation, for OH. This might be explainable by an increase of vertical atomic oxygen transport into or out of the observed region, due to increased wave activity (Reisin and Scheer, 2004). It seems that the same argument could also explain the seasonal temperature variations due to the corresponding deposition of chemical energy. This mechanism may thus be responsible for part of the observed downward phase progression mentioned above.

4.2 Interannual Variations

In addition to the particular characteristics of the mean climatology at El Leoncito, the increased interannual variation in the years after 2001 would need to be explained. This topic does not seem to have been treated explicitly in the literature about mesopause region temperature observations, although interannual differences can be appreciated from published figures showing seasonal variations during consecutive years (e.g., Zhao et al., 2007; Gelinas et al., 2008).

The year 2002, when deviations from our standard climatology first became evident, is known from the literature to have been quite unusual (e.g., Hernandez 2003; Dowdy et al., 2004; French et al., 2005; Espy et al., 2005). This was due to the appearance of major sudden stratospheric warmings in the Southern Hemisphere (where none had been observed before), which are related to anomalously strong planetary wave activity (e.g., Becker et al., 2004; Liu and Roble, 2005).

From our own data, we can however not find evidence of planetary wave activity in the mesopause region to be responsible for the observed differences in seasonal variation. To see this, we use the information on planetary waves contained in the day-to-day variation of temperatures: the day-to-day variances about the corresponding 29-day running mean represent the power of essentially all the planetary waves (with periods up to and not much longer than 29 days). This is the high-frequency complement of the low-pass filtered seasonal variations that are our main topic. The total annual planetary wave variance for OH and O_2 temperature are shown in Fig. 8, for each year. The error bars are based on the same standard statistics as in Fig. 7 (but here the degree of freedom is close to the number of nights for each year). The behaviour for OH and O_2 is quite similar, as one can expect for planetary waves (the slightly greater power for O_2 temperature may be the altitude effect). The years of the standard climatology, from 1998 to 2001, were accompanied by an upward tendency in planetary wave power. This tendency even continues smoothly in 2002, but without any evidence of an unusual change that could be expected for this atypical year (according to the discussion above, and the anomaly in Fig. 7).

For the later years with the greatest deviations with respect to the seasonal variation, planetary wave activity was contradictory: in 2006, it was back to the low initial level, while in 2007, it was high again (Fig. 8). All this means that there is no clear pattern that could relate the growth of interannual variability to planetary wave activity in the mesopause region. This does not exclude the possibility of stratospheric planetary wave activity playing a role, but we can not tell from the information available to us.

Model studies by Mayr et al. (2003) identified a mechanism supposed to be able to generate intraseasonal variability at low latitudes, due to meridionally propagating gravity waves. This mechanism produces variations with periods around 3 months and amplitudes (at 80 km) comparable to the normal seasonal variation. This may be consistent with the interannual anomalies that we observe at El Leoncito (see Fig. 6a,c,e,g). If this is so, the question remains, whether (and why) the meridional part of gravity wave activity should have increased since 2002. The analysis of gravity wave activity alone without directional discrimination would then not be expected to lead to new insights.

According to our data, the main perturbation with respect to the standard climatology was in 2007. So, the question arises how the situation will develop in the following years. Some hint may be gleaned from the behaviour in 2008, as far as the data have been acquired and analyzed. The deviation from the climatology until 7 September 2008 is shown in Fig. 9. Comparison with Fig. 6 clearly gives the impression that the deviations are smaller than in 2006 and 2007, but still somewhat greater than in 1998 to 2001. This impression is confirmed by the yearly values of the residual variance that are 0.022 and 0.020 for O_2 and OH intensity, and 3.7 K^2 and 5.2 K^2 for O_2 and OH temperature, respectively. (Note added later: these numbers were preliminary, but are essentially confirmed by the complete data for 2008). While in terms of intensities the anomaly is stronger than in 2002, for temperatures it is already smaller (see Fig. 7). This suggests that the situation may be returning to normal, but data for the next years will be needed for confirmation.

5. Summary

From the large data base of OH(6-2) and O_2(0-1) airglow intensities and rotational temperatures corresponding to the nominal altitudes of 87 and 95 km, acquired with the airglow spectrometer operating at El Leoncito, the seasonal variations in the years 1998-2002, 2006, 2007, and part of 2008 have been studied.

From 1998 to 2001, the interannual variations have been small enough to permit the definition of a mean seasonal climatology, for temperatures and airglow intensities at the two altitudes. The seasonal variations of intensity and temperature are correlated, for a given airglow emission.

On the other hand, significant differences exist between the behaviour at 87 km, with maximum temperatures and OH intensities in May and June, and at 95 km, where temperatures and O_2 intensities peak in April.

Similarities and differences with respect to the 2-level mesopause concept and observations at other tropical and lower midlatitude sites have been discussed.

The later years 2002, 2006, and 2007 deviate progressively from the mean behaviour of the previous years. Moreover, the different shapes of the seasonal variations in these years can not be accommodated by a new mean climatology. The partial information for 2008 suggests a certain tendency for normalization.

Although there may be a relation between gravity wave activity and the mean climatology, it is not clear whether changes in gravity wave activity alone can explain the observed interannual variability.

We can exclude a direct link to planetary wave activity in the mesopause region at the same site, but a relation to stratospheric planetary wave activity, as discussed in the literature for 2002, could not be tested.

Unfortunately, there is no information about the behaviour from 2003 to 2005 for the El Leoncito site. Temperatures derived from the SABER instrument (Russell et al., 1999) on the TIMED satellite, available since early 2002 should however be suitable to fill in the missing data.

Since solar cycle and long-term trend studies usually require the subtraction of the mean seasonal climatology, interannual variability as discussed here may be a complicating factor in such analyses, and has to be adequately dealt with.

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Figure captions:

Fig. 1. Annual data acquisition with the Argentine airglow spectrometer. Number of nights with good data (upper panel), amount of data per year (lower panel), for each of the four measured parameters. The arrows for 2008 reflect the status until 7 September.

Fig. 2. Seasonal distribution of data used in this study.

Fig. 3. Nocturnal means of O_2 and OH airglow intensity and rotational temperature for 1999. Nights with less than 100 (but at least 40) data are shown as open circles. Error bars (not shown) would not exceed symbol size (temperature errors are generally less than 1 K). Symbols for consecutive nights are connected by straight lines to guide the eye. The curves represent the climatologies for the years 1998 to 2001.

Fig. 4. Seasonal variation (29-day running mean) for individual years with respect to OH intensity (a, b), O_2 intensity (c, d), OH temperature (e, f), and O_2 temperature (g, h). Panels a, c, e, g refer to the years 2002 and 2006-2007, and b, d, f, h to 1998-2001.

Fig. 5. Mean climatology for 1998-2001, with respect to OH (solid line) and O_2 (dotted line) intensity (upper panel) and temperature (lower panel). The 1-σ error margins of the running mean are marked by thin lines. OH temperatures are brought to a scale consistent with O_2 temperature (see text).

Fig. 6. Deviation with respect to the 1998-2001 climatology of OH and O_2 intensities and temperatures, for the years shown. Panel layout and notation as in Fig. 4.

Fig. 7. Variance of the deviation from the 1998-2001 climatology for intensity (upper panel) and temperature (lower panel), in each year. Dots correspond to the OH emission, and circles to the O_2 emission. Error bars represent 1-σ uncertainties of the variances according to standard least-squares statistics. The symbols are slightly displaced with respect to the corresponding year mark to avoid overlap.

Fig. 8. Total annual planetary wave activity derived from the day-to-day variation of OH (dots) and O_2 (circles) temperature at El Leoncito. Error bars, and symbol shift as in Fig. 7.

Fig. 9. Deviation of seasonal variation for 2008 from 1998-2001 climatology of OH and O_2 intensity (upper panel) and temperature (lower panel).

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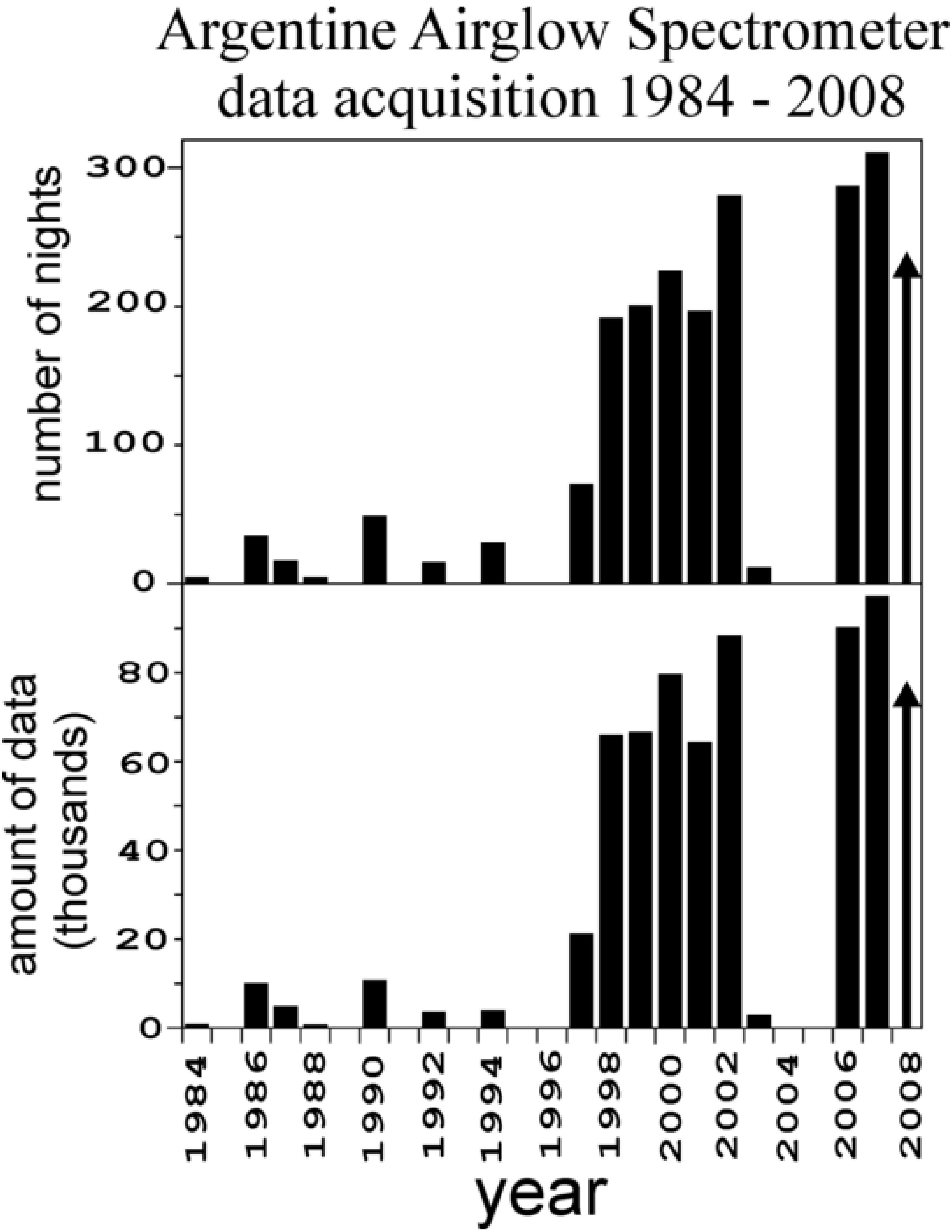

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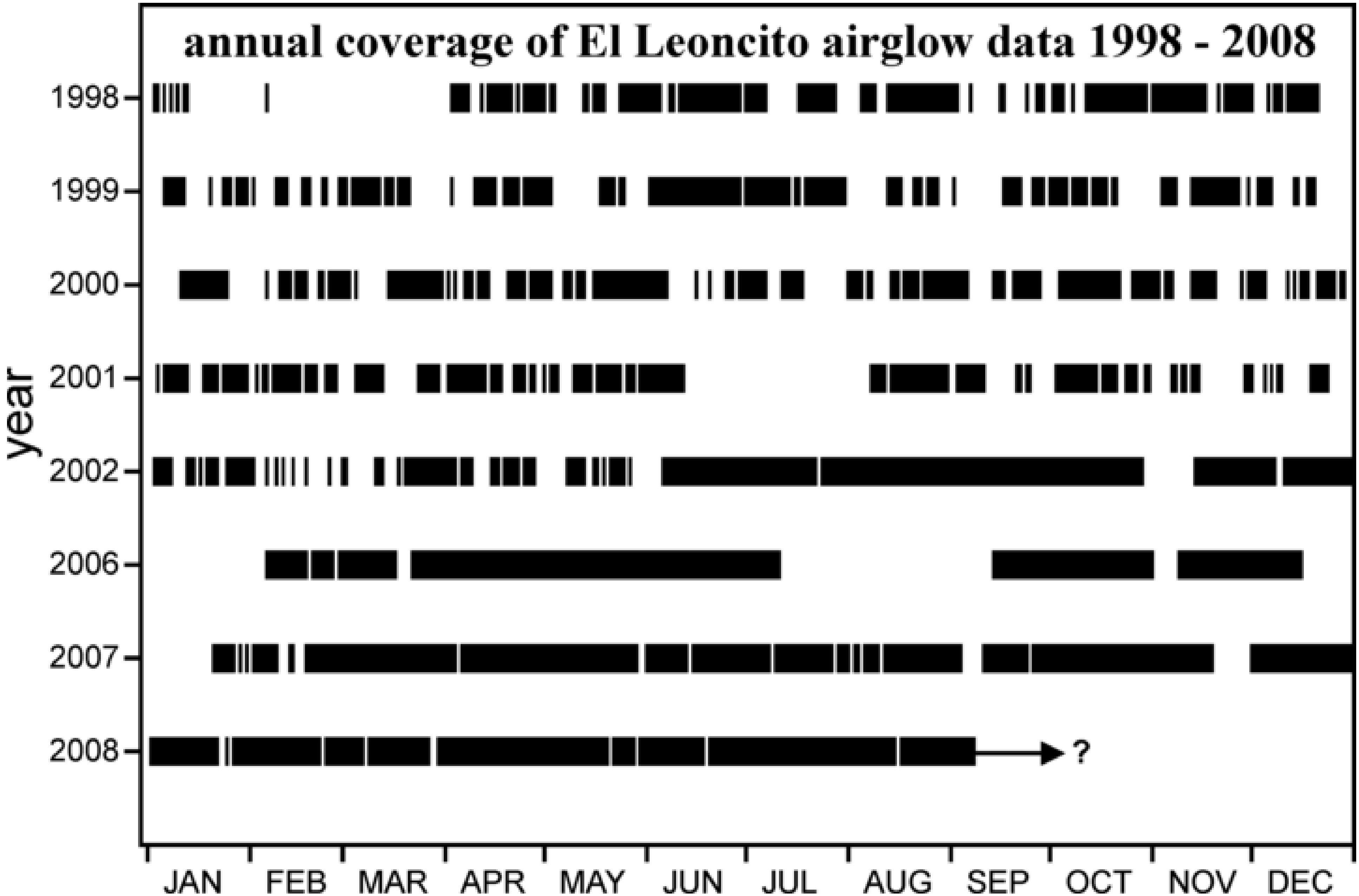

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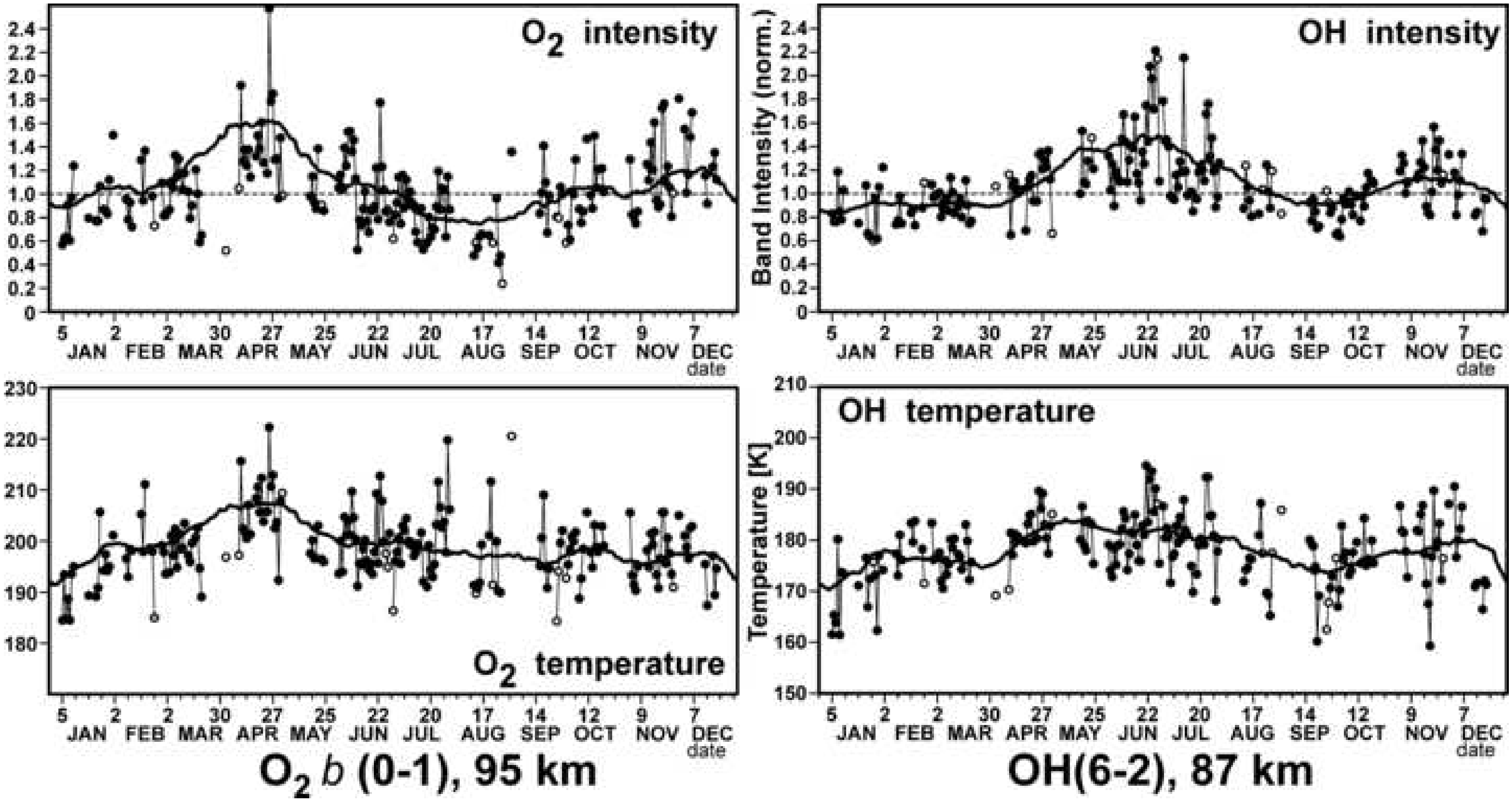

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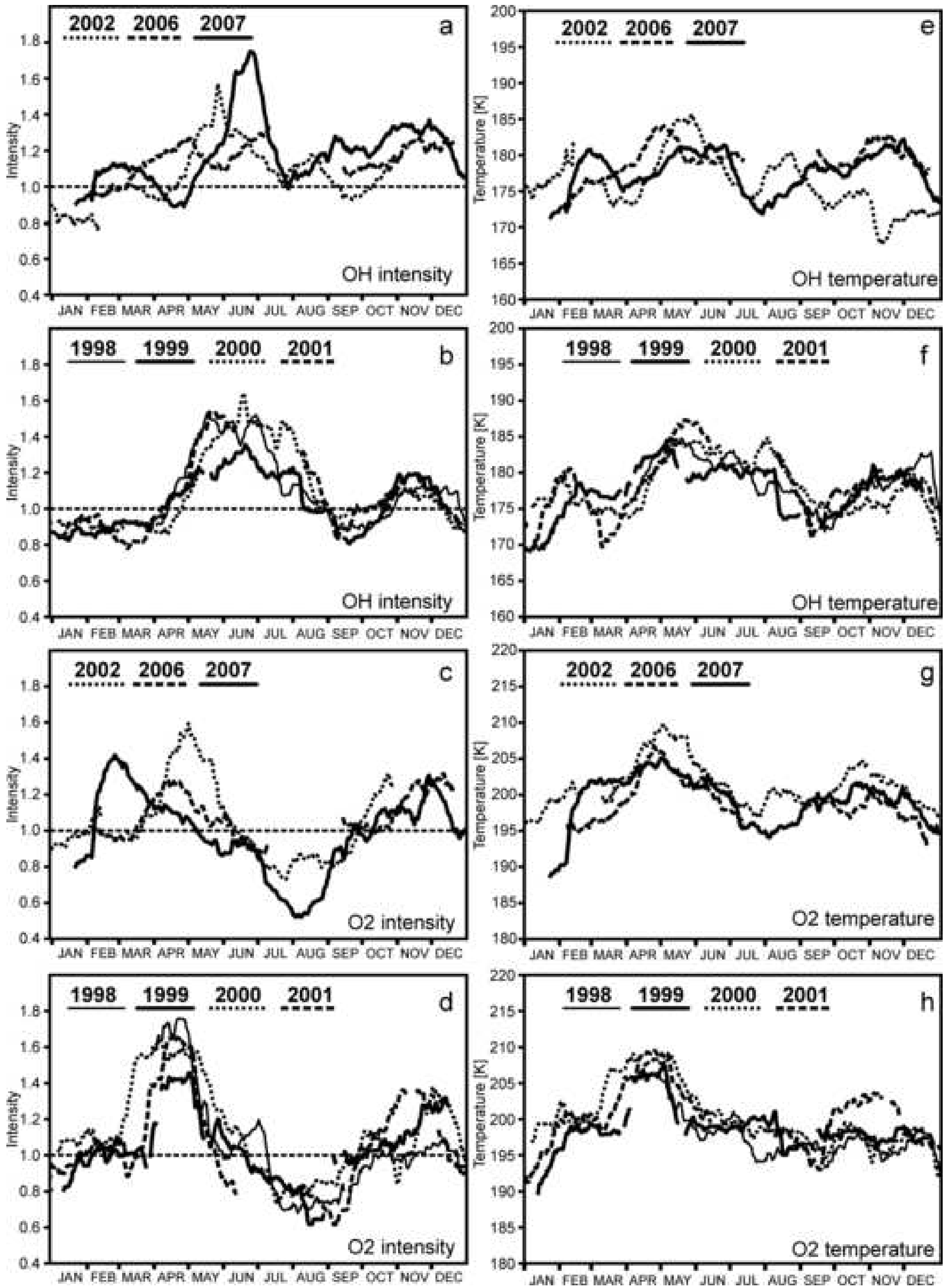

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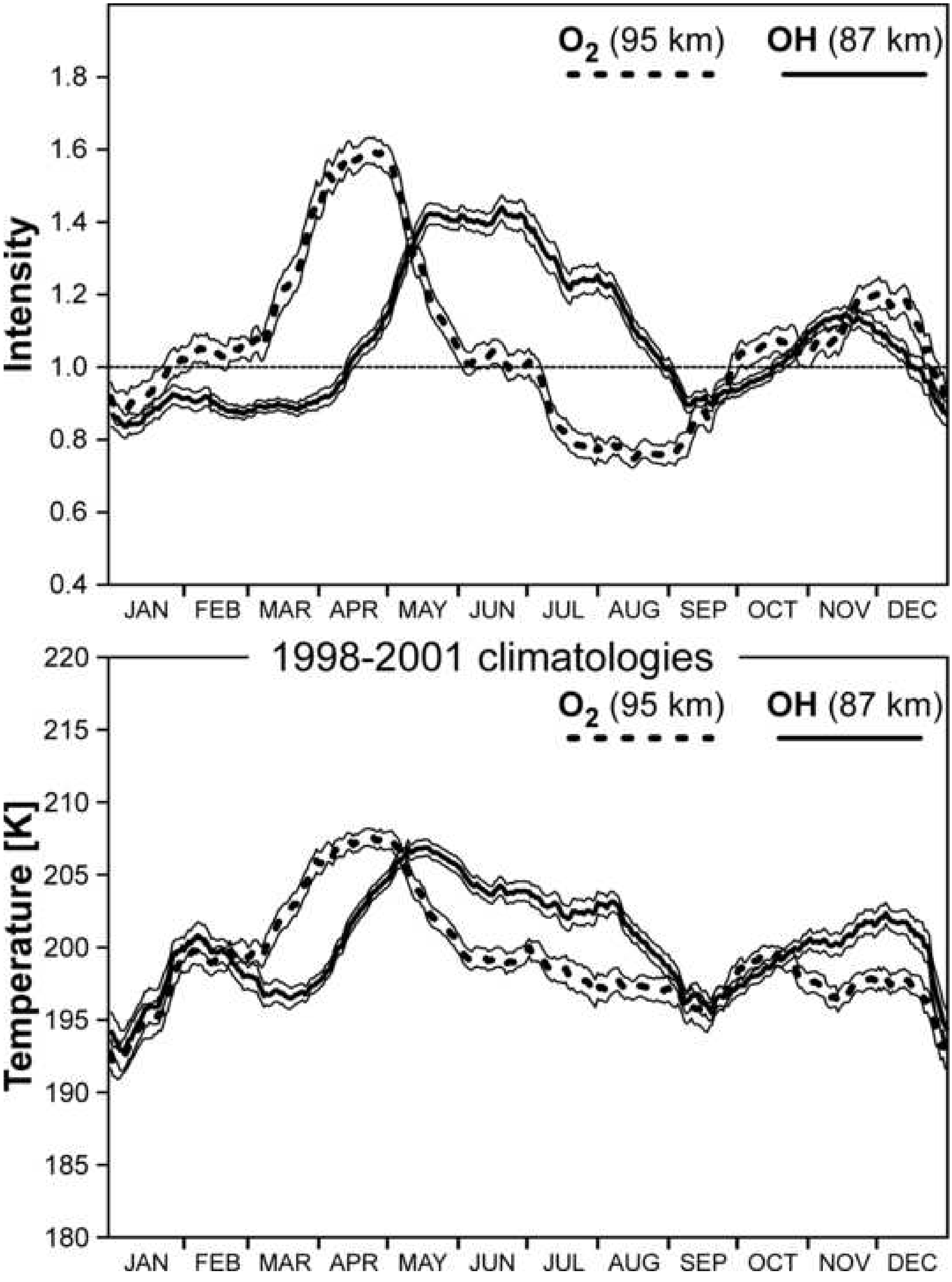

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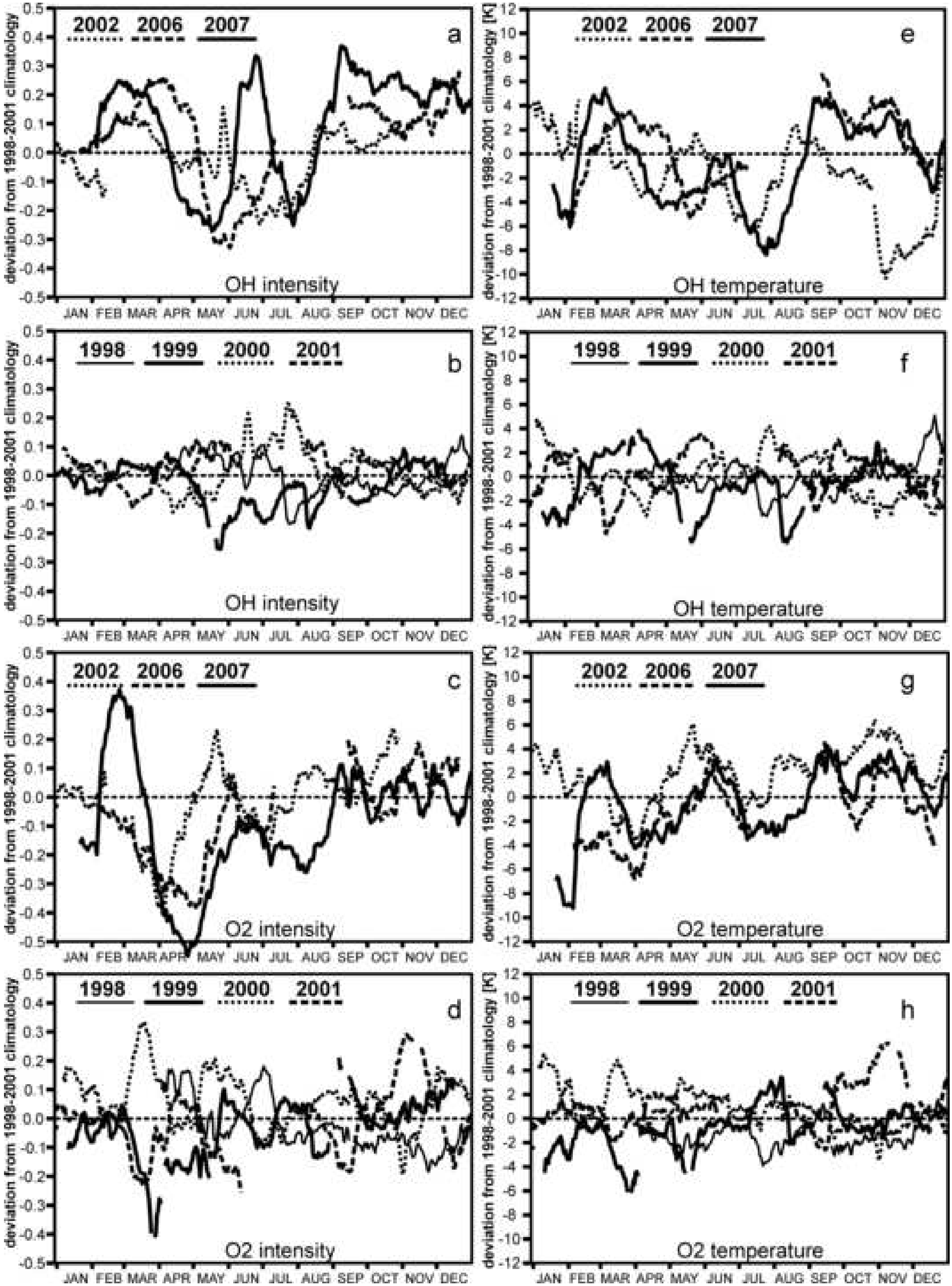

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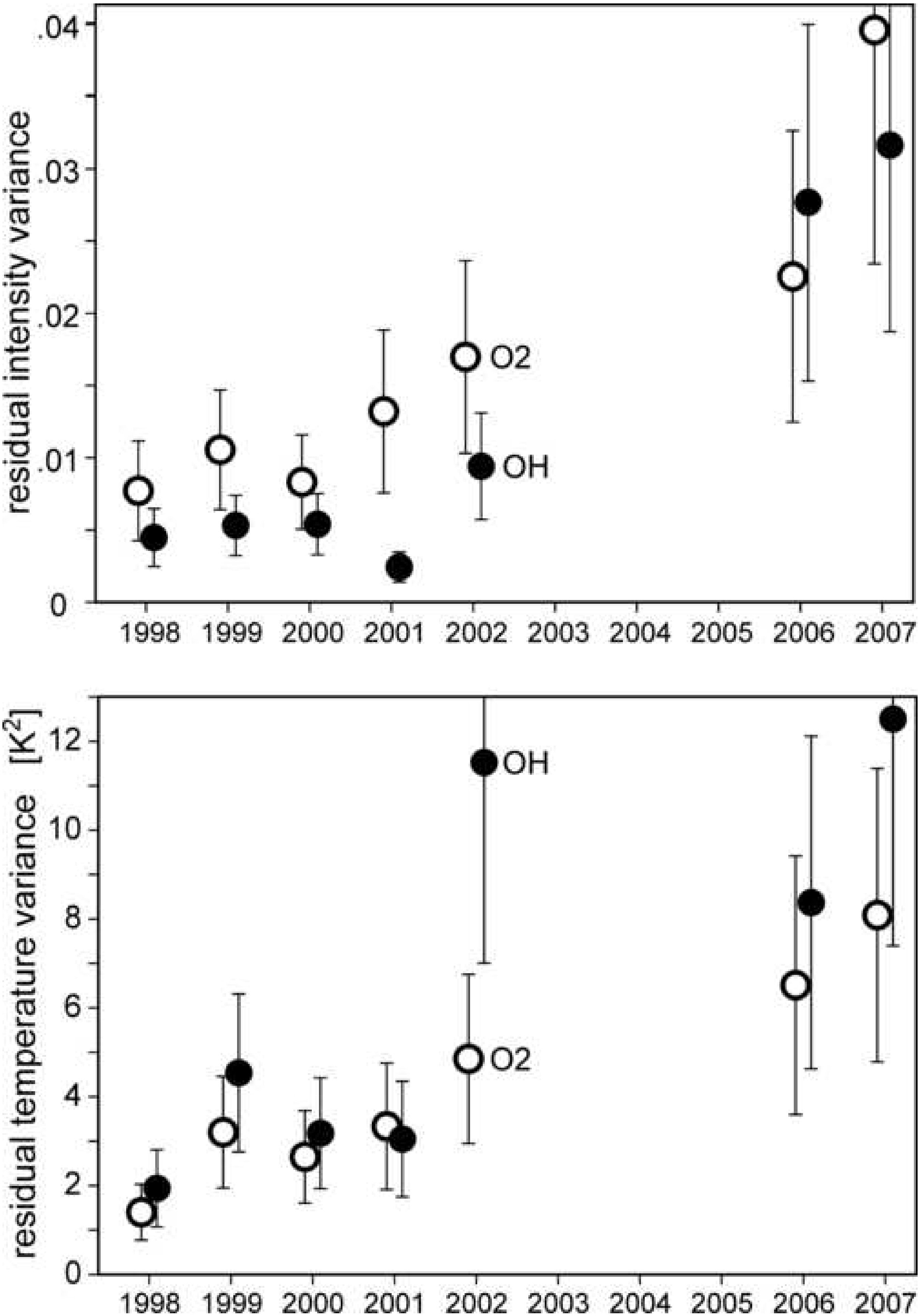

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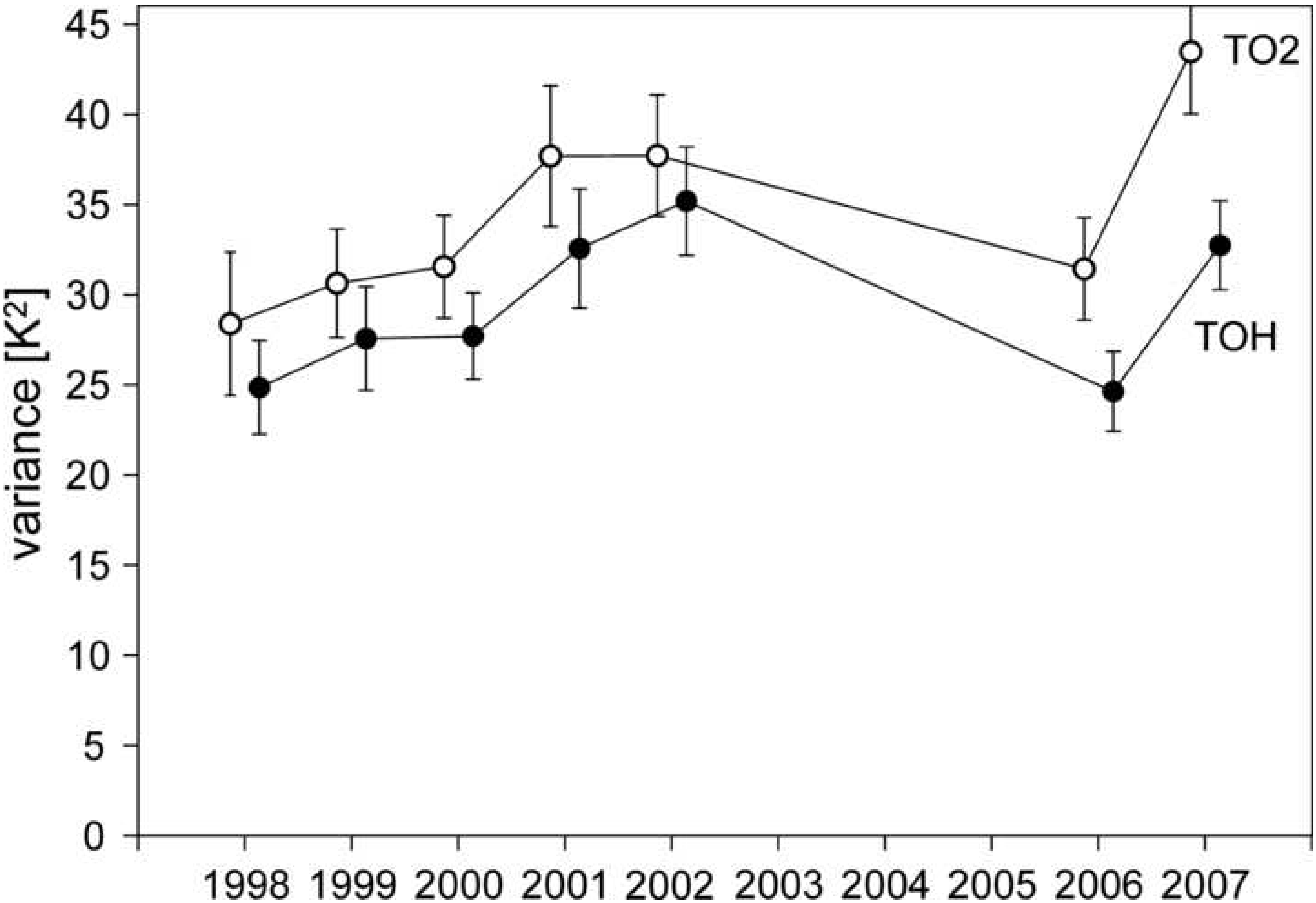

Fig. 9

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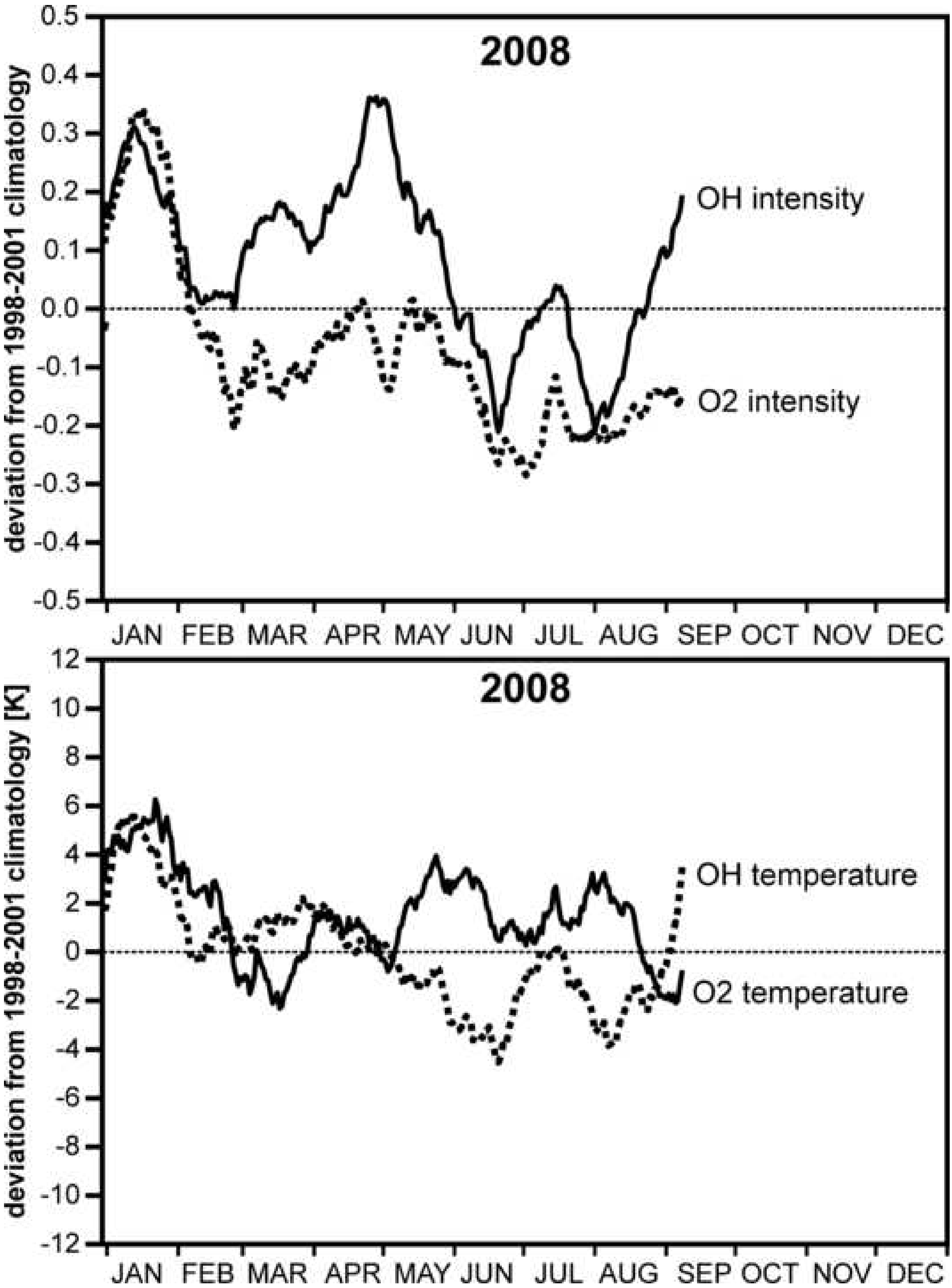

Table 1. Seasonal peak-to-peak variations of temperatures and maximum-to-minimum ratios of airglow intensities for different sites. The first five lines are airglow data, followed by sodium lidar temperatures, corresponding to the nominal airglow centroid heights. The "years" column gives the approximate time span from which the respective climatologies are derived. ΔTOH and ΔTO_2 are the peak-to-peak ranges for airglow temperatures, or the lidar temperatures at 87 and 95 km, respectively. rIOH and rIO_2 are the maximum to minimum intensity ratios. Data not explicitly mentioned in the papers cited have been extracted from figures or tables.

site	location	years	ΔTOH [K]	ΔTO_2 [K]	rIOH	rIO_2	reference
Alice Springs	23°S 133°E	2002-2005	8	8	1.4	2.1	Gelinas et al. 2008 *
Cachoeira Paulista	23°S 45°W	1987-1991	7		1.5		Takahashi et al. 1995
El Leoncito	32°S 69°W	1998-2001	14	16	1.6	2.1	this paper
Adelaide	35°S 139°E	2002-2005	21	13	1.4	2.0	Gelinas et al. 2008 *
Sierra Nevada	37°N 3°W	1998-2002	29	25	1.4	1.9	López-González et al. 2004
Starfire Optical Range	35°N 107°W	1998-2000	38	21			Chu et al. 2005
Urbana	40°N 88°W	1996-1997	22	11			States and Gardner 2000
Fort Collins	41°N 105°W	2002-2006	40	16			Yuan et al. 2008

* reconstructed from published annual and semiannual components

Table 2. Amplitudes and phases of the annual and semiannual components for the 1998-2001 climatology at El Leoncito. Phase refers to day of the year for maximum (for semiannual, the first maximum)

	O_2 intensity		O_2 temperature		OH intensity		OH temperature	
component	ampl. [%]	phase[d]	ampl. [K]	phase[d]	ampl. [%]	phase[d]	ampl. [K]	phase[d]
annual	19	81	3.6	116	18	182	2.8	164
semiannual	19	121	2.7	109	15	159	2.5	154