



Searching for trends in mesopause region airglow intensities and temperatures at El Leoncito

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Abstract

Using our large data base from the Argentine site at El Leoncito that covers the years from August 1997 to May 2001, and four individual campaigns in 1986, 1987, and 1992, we search for trends in temperatures corresponding to heights of 87 and 95 km. Also the variations in OH and O₂ airglow band intensities for these two altitudes supply complimentary information interesting in terms of trends. The seasonal variation is well documented with good reproducibility, since the end of a perturbation possibly due to the 1997 ENSO event, so that the time series of nocturnal mean values can be reliably freed from the seasonal effect. Some difficulties arise from the geophysical variations (mostly from planetary waves) still present in the data averages over 28 nights of observation. In spite of this, temperature trends of a fraction of 1 K/year should be detectable, using only the data from 1998 to 2001. However, only at 95 km, there is a significant positive temperature trend over the last 4 year. When the earlier campaigns are included, this 15 year data span shows a negative temperature trend of about -1 K/year and a positive (OH) intensity trend of about $+1\%$ /year, at 87 km. At 95 km, there is a similar (O₂) intensity trend, but a temperature trend compatible with zero. These results are similar to previous findings for Northern Hemisphere midlatitude sites, by other investigators. As a by-product of the trend analysis, we also estimate values for the 1997 ENSO temperature anomaly of about -3.5 K at 87 km, and -6 K at 95 km. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Most of the published temperature trends for the mesopause region (about 80–100 km) correspond to Northern Hemisphere sites (e.g., Lübken and von Zahn, 1991; Golitsyn et al., 1996; Semenov, 2000; Bittner et al., 2002). The number of different sites is still quite unsatisfactory for deriving global trends. Also, the lack of Southern Hemisphere trend determinations is a problem, because of the many existing interhemispheric differences.

Ideally, long-term, densely spaced, and homogeneous observations are desirable for trend detection. Our data obtained at a Southern Hemisphere midlatitude site span an interval of only 15 year, and the coverage during the first 11 year is very sparse. However, with due attention to error sources, our growing data set already becomes valuable, in this context. It includes, in addition

to information at 87 km, the same amount of data at 95 km (with similar quality), where only very little previous airglow work has been done. In the present paper, we analyze long-term trends from our measurements of two different airglow emissions in the mesopause region.

2. Data

We base our analysis on the nocturnal measurements of airglow intensities and rotational temperatures obtained for the OH (6–2) band (that originates at an altitude of about 87 km), and the O₂ (0–1) atmospheric band (from 95 km). All the measurements reported here were done with the same tilting filter spectrometer. The instrument design, calibration, data reduction, and performance are described in detail in Scheer (1987), Scheer and Reisin (2000, 2001). Here, we have included only the data taken at El Leoncito (31.8°S, 69.2°W). This high-altitude (2500 m) site in Argentina has particularly good optical observing conditions.

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The fact that the same instrument was used throughout does not automatically guarantee data homogeneity, but avoids errors due to differences in instrumentation or technique. A single instrument makes it easier to determine its characteristics so well that it is possible to correct for systematic performance changes.

The use of a solid-state interference filter allows a very stable instrument design that does not require frequent recalibration. The filter was replaced only once, in 1996, after deterioration was detected. Photon counting mode assures stable long-term instrument sensitivity, as verified by comparing stellar backgrounds (Scheer and Reisin, 2000). In addition to full-fledged instrument calibrations in 1986 and 1996, the stability of spectral characteristics was frequently (at least once per campaign, or several times per year) monitored by recording spectra of a neon lamp (see Scheer, 1987). The neon spectra never showed any visible sign of instrument deterioration. All the data were reprocessed consistently to improve homogeneity. Therefore, the older data do not agree exactly with previously published versions (e.g., Scheer, 1995).

Since we apply a correction for moonlight contamination of the spectral background (Scheer and Reisin, 2001), even full moon data are often usable without producing any bias. This feature avoids a considerable loss of data.

The airglow observations are column integrated, and therefore, auroral contamination by emissions originating at other altitudes might eventually pose a problem. Fortunately, the OI 844.8 nm auroral line that is the only candidate to affect the OH (6–2) band does not cause a problem because it lies just outside the instrument spectral range. In principle, auroral enhancements may affect the entire O₂ band. However, they should reveal themselves as irregular nocturnal variations, for which there is no evidence in our data. This is probably because El Leoncito is a low-geomagnetic latitude site.

From 1986 to 1992, measurements at El Leoncito were done in four discrete campaigns lasting 15–19 nights (see Table 1). Since August 1997, data acquisition has become more regular, resulting soon in quasi-continuous operation limited only by operating conditions. Recently, the number of data nights per year has risen to 225 (in 2000). The number of data per night (in winter) reached 390, before 1997, and later even 500. As discussed below, some of these data will be excluded from the analysis, but the trend results are still based on about 750 nights with a total of more than 250 thousand individual observations, for each of the four parameters. Each individual measurement has an average uncertainty of about 2%. This corresponds to mean temperature errors of about 4 K.

While the data span 15 year, the coverage is sparse during the first decade, but quite dense since 1997. To reduce variance due to statistical and geophysical noise

Table 1

Temporal distribution of data (the number of data corresponds to each of the four parameters: intensity and temperature of OH and O₂)

Range of dates	Number of nights	Number of data	Comment
26.06.1986–14.07.1986	19	6200	
26.10.1986–10.11.1986	15	3900	
14.09.1987–30.09.1987	17	5100	
10.10.1992–26.10.1992	16	3600	Not used for O ₂
05.08.1997–05.09.1997	28	9400	Excluded (ENSO)
06.09.1997–23.11.1997	28	6800	Excluded (ENSO)
24.11.1997–04.04.1998	28	7400	Excluded (ENSO)
05.04.1998–18.05.1998	28	9900	
23.05.1998–22.06.1998	28	10 400	
23.06.1998–06.08.1998	28	11 100	
07.08.1998–23.09.1998	28	10 700	
26.09.1998–31.10.1998	28	9100	
01.11.1998–07.12.1998	28	8300	
08.12.1998–30.01.1999	28	7800	
01.02.1999–19.03.1999	28	9600	
20.03.1999–21.05.1999	28	10 200	
23.05.1999–26.06.1999	28	10 900	
27.06.1999–27.07.1999	28	10 200	
28.07.1999–30.09.1999	28	6800	
01.10.1999–16.11.1999	28	9000	
17.11.1999–16.01.2000	28	7400	
17.01.2000–04.03.2000	28	8300	Outlier (used)
14.03.2000–20.04.2000	28	10 700	
21.04.2000–25.05.2000	28	10 900	
26.05.2000–12.07.2000	28	12 600	
13.07.2000–30.08.2000	28	10 300	
31.08.2000–11.10.2000	28	10 300	
12.10.2000–17.11.2000	28	8400	
18.11.2000–09.01.2001	28	7600	
10.01.2001–15.02.2001	28	8300	
17.02.2001–04.04.2001	28	8900	
05.04.2001–11.05.2001	25	8600	
Total	848	2 78 700	2 51 500 used for O ₂ 2 55 100 used for OH

from different sources, the data acquired in campaign mode are converted to campaign averages. For the same purpose, the more recent quasi-continuous data are divided into blocks each containing 28 data nights, to arrive at averages without excessive unbalance with respect to the campaigns (see Table 1).

The empirical statistical error for the averages of each block is thus reduced to less than 0.2 K for temperatures, and 0.3–0.4%, for intensities. These small values mean that short-period variability due to gravity waves (with temperature amplitudes of a few Kelvins) and semidiurnal tides (up to about 20 K) have been efficiently suppressed.

Naturally, simply averaging over the data blocks would not eliminate the seasonal variation. The seasonal variation can be quite well determined from the good seasonal coverage of our data, and the interannual reproducibility, since 1998. For each parameter, and for a complete year, we obtain daily values of the seasonal mean, by using a 29 day running mean over the seasonally arranged nocturnal means. The details of the observed seasonal variation are too complex to treat here, and will be published elsewhere (for frequently updated graphics, see <http://www.iafe.uba.ar/aeronomia/io2.html>). The corresponding standard deviations that include not only the annual and semiannual components, but also other higher harmonics, are 3.2 K (3.6 K) for OH (O_2) temperature, and 18% (20%) for OH (O_2) intensity.

Therefore, we can free the block averages from this seasonal variation by subtracting the seasonal mean from each individual nocturnal mean. This procedure implies the assumption that the seasonal variation was the same before 1998, when the seasonal data coverage was insufficient. That this assumption is not too far-fetched is suggested by the reasonably good agreement of the (pre-1997) campaign nocturnal means with the post-1997 seasonal intensity variations (Scheer and Reisin, 2000).

Note that the seasonal variation may also contain a contribution from the *reproducible part* of the seasonal variation of the diurnal tide, but such a tidal contamination is also eliminated by the subtraction.

Planetary waves have quite variable amplitudes that are difficult to quantify. The effect of planetary waves is greatly reduced by averaging over a block. However, it is not eliminated completely, and still leads to fluctuations with standard deviations of about 1.7 K (2 K) for OH (O_2) temperature, and 5.3% (7.2%) for OH (O_2) intensity. These numbers also include a contribution from the *variability* of the diurnal tide, which is not likely to cancel in these night-only data. Exceptionally, cancellation of long-period planetary waves has been poor, as will be shown below.

3. Results

3.1. O_2 band

The seasonally corrected block averages are shown versus time in Fig. 1, for temperature and intensity of the O_2 emission layer at 95 km. The intensity scale has been normalized by the long-term mean. Error bars are not shown for all points, for legibility, but are applicable with similar size, everywhere. Those shown are equal to the mean standard deviations of the sets of points and are essentially due to planetary waves.

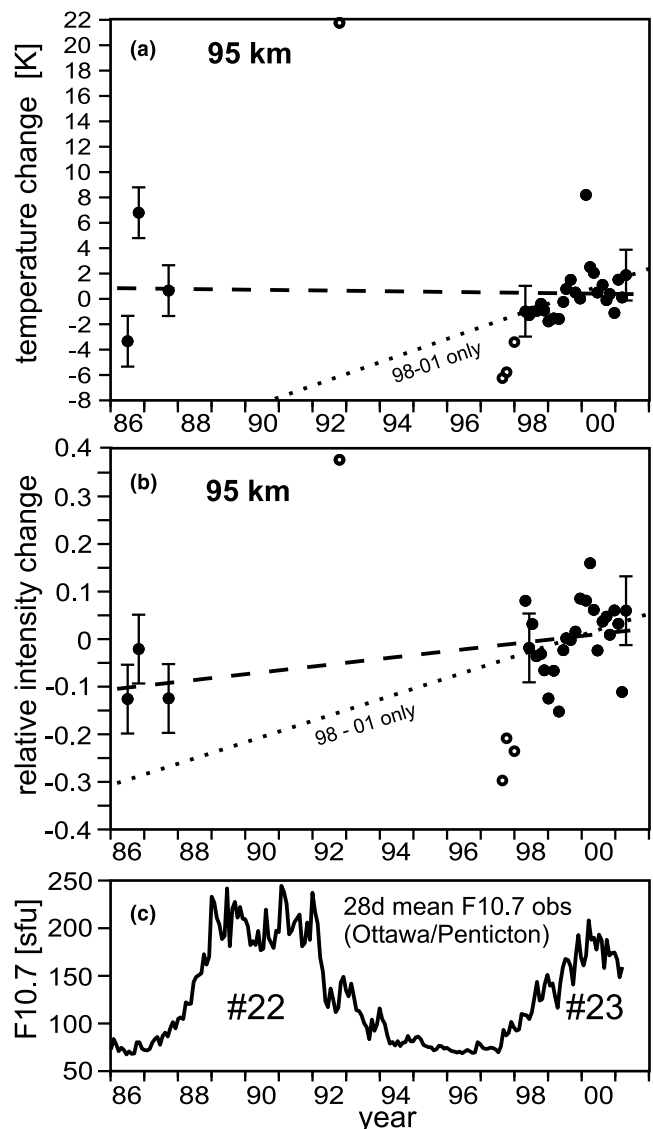


Fig. 1. Block averages minus seasonal mean for O_2 emission (95 km) at El Leoncito, 1986–2001. Temperature (a) and intensity ((b); normalized by long-term average). Data excluded from the trend analysis are marked as hollow circles. Only sample error bars are shown. Dashed line represents linear fit through all black points, dotted line only through 1998–2001 data. Solar activity variation (cycle 22 and 23) is shown for comparison (c).

Points affected by episodic geophysical anomalies must be identified and excluded from the trend analysis. In Fig. 1(b), the 1997 data exhibit extremely low intensities that have previously been attributed to the strong El Niño Southern Oscillation (ENSO) event (Scheer and Reisin, 2000). From this figure, we can now conclude that the seasonal anomaly was 20–30% below the long-term mean. Fig. 1(a) suggests that temperatures also have been affected. Here, the seasonal anomaly reached about -6 K. Therefore, these data will not be used in the present context.

Other points that look anomalous are the temperature and intensity averages for the 1992 campaign. They are much higher than the rest. Part of this may be a solar activity effect, but this would contradict the small solar activity correlation visible in the present solar cycle (see below). The unusually high-planetary wave activity during this campaign may also have played a role. However, there is also the possibility of an instrumental artifact, if the filter deterioration mentioned above had already started, then. An increase in filter halfwidth would be consistent with the high-observed values for O₂, but would not cause problems for OH, where the rotational components are resolved. This is the only campaign subject to this suspicion, until the filter was changed and the new calibration took effect.

Before looking for a long-term temperature trend, we examine the behaviour of the continuous data subset, since 1998 (Fig. 1(a)). During these three years, there is no conspicuous quasi-periodic pattern suggesting inter-annual variations like the quasi-biennial oscillation (this is also true for the other parameters, see also Fig. 1(b), and Fig. 2). A linear regression fit reveals a temperature trend of $+0.92 \pm 0.41$ K/year. The error given here implies that the trend is positive at a significance level of

98.8%, assuming a normal distribution. However, the true distribution cannot be expected to be so simple. For example, the +8 K temperature outlier (by about four standard deviations) for January–March 2000 seems to be due to the perturbation by an uncancelled planetary wave that also happened to be much stronger than average. Fortunately, because of its closeness to the middle of the data subset, this point has very little effect on the derived trend, so that it is not necessary to exclude it explicitly from the analysis.

Tentatively, we might interpret this recent trend in terms of a solar cycle effect. As can be seen in Fig. 1(c), the time since 1998 corresponds to the rise of solar cycle #23. Activity levels (in terms of Penticton observed F10.7 flux) increase from about 100 solar flux units (sfu) to slightly more than 200 sfu, in mid-March 2000 (208 sfu), followed by a decline towards 150 sfu, in early 2001. One would derive a solar activity effect between 0.017 and 0.056 K/sfu, depending on how one deals with the apparent anticorrelation during the last year. However, this effect, if real, is much smaller than previously reported; for example, Lübken and von Zahn (1991) have reported 0.15 K/sfu, above 80 km, for a high-latitude site. Therefore, a solar activity correction would have little impact on the trend analysis. On the other hand, such a correction cannot bring the 1992 point back into alignment with the other data.

If we neglect the solar cycle effect, and without including the 1992 point (nor the 1997 data, as mentioned), we arrive at a regression line for the 15 year data interval with a slope of -0.03 ± 0.11 K/year, consistent with no temperature trend, at all. This result is completely independent of the exclusion of the 1997 data. The slope would become slightly smaller, if the solar cycle effect is accounted for. Since the first campaigns and the beginning of the recent data correspond to the same solar cycle phase, we can easily estimate the impact of the solar cycle effect on the resulting slope by eliminating the recent trend. This gives a correction of -0.10 K/year, which would still leave our result consistent with zero. We can simply allow for this by defining asymmetric error margins of $+0.11$ or -0.21 K/year, while maintaining the mean value cited above.

Also for O₂ intensities, we find a positive trend during the last three years, of $+2.2 \pm 1.5\%$ /year (Fig. 1(b)). With the same reasoning as for O₂ temperature, we arrive at an estimate for the solar cycle effect between $+0.04\%$ /sfu and 0.13% /sfu. Again, this is nearly negligible for the trend analysis, and means that the 1992 deviation cannot be explained by the solar cycle (we ignore this data block). Such a small solar activity effect is also consistent with the absence of any serious contamination from low-latitude aurora.

So, with the same data selection as for temperatures, the 15 year O₂ intensity trend is $+0.8 \pm 0.33\%$ /year. If we take the solar activity effect at face value, this result is

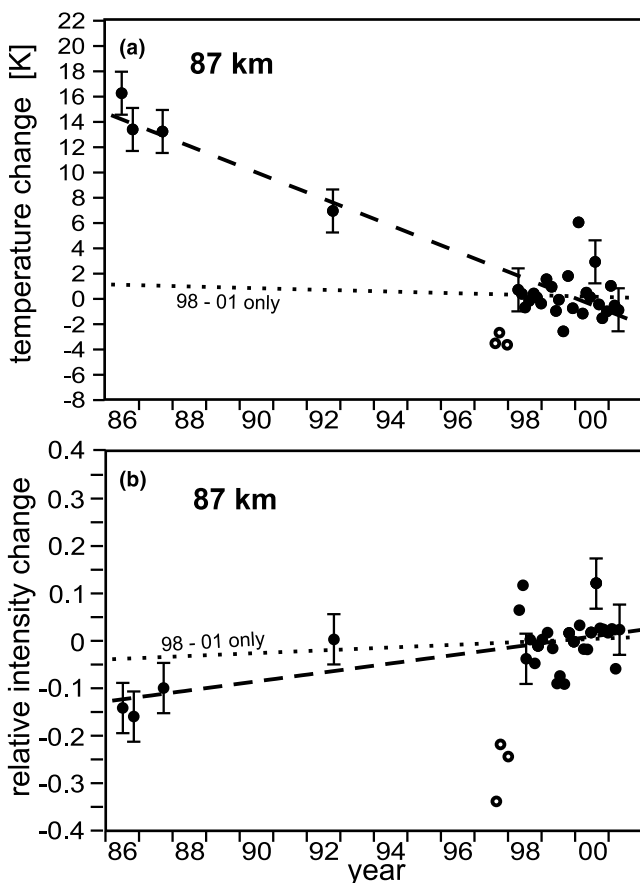


Fig. 2. As Fig. 1(a) and (b), but for OH emission (87 km).

Table 2
Derived trends

Nominal height (km)	Parameter	Only recent data 1998–2001	Complete 1986–2001 “long-term trend”
95	Temperature	$+0.92 \pm 0.41$ K/year	$-0.03 + 0.11$ K/year -0.21 K/year
95	Intensity O ₂	$+2.2 \pm 1.5\%$ /year	$+0.8 + 0.33\%$ /year -0.58% /year
87	Temperature	-0.07 ± 0.37 K/year	-1.05 ± 0.08 K/year
87	Intensity OH	$+0.3 \pm 1.2\%$ /year	$+1.03 \pm 0.24\%$ /year

diminished by 0.25%/year, in the same way as for O₂ temperature.

3.2. OH band

Fig. 2 shows the situation for OH, that is, corresponding to an altitude of 87 km. As for O₂, the OH intensity data for 1997 are affected by ENSO (Scheer and Reisin, 2000). The seasonal intensity anomaly according to Fig. 2(b) was 23–35% below the long-term mean. Fig. 2(a) also shows a well-defined temperature effect of about 3.5 K below the seasonal level. This again justifies the exclusion of the 1997 data from the trend analysis.

In contrast to O₂, the OH data for the 1992 campaign do not look anomalous, so there is no reason to discard them. As signalled above, this is consistent with the small instrument halfwidth sensitivity of OH.

The OH temperature trend for the three most recent years is -0.07 ± 0.37 K/year, that is, practically zero (Fig. 2(a)). This allows us to assume (only for the purpose of the present analysis, but also consistent with the behaviour in 1992) the absence of any solar cycle effect. The existence of a +6 K outlier for the same January–March 2000 data block as for O₂ supports its interpretation as a planetary wave perturbation.

Including all the data except those for 1997, we obtain a significantly negative long-term trend of -1.05 ± 0.08 K/year. As shown in Fig. 2(a), the individual campaigns are much more consistent with the linear regression, than in the case of O₂ temperature.

For OH intensities (Fig. 2(b)), and similar to the behaviour of OH temperatures, there is no recent trend, since 1998: we find a slope of $+0.3 \pm 1.2\%$ /year.

The long-term OH intensity trend is definitely positive: $+1.03 \pm 0.24\%$ /year. As with O₂, these trends are practically not changed by including the 1997 data. All the trend results are summarized in Table 2.

4. Discussion

The principal conclusion is a very pronounced negative long-term temperature trend at the (nominal) altitude of 87 km (see Table 2). This result is rather robust

because of the small statistical error margin, the absence of a noticeable solar activity effect, and the uncritical dependence of OH temperature on spurious changes in instrument bandwidth.

Similar trends have been reported, before (see Fig. 3, left panel): Golitsyn et al. (1996) obtained OH temperature trends from measurements at Abastumani (44°N, 43°E) and Zvenigorod (56°N, 37°E) of about -0.7 K/year. The value derived by Semenov (2000), for winter conditions, based on the Abastumani and Zvenigorod data and some of the data from Wuppertal (51°N, 7°E) is even closer to ours (Fig. 3). Note that a complete analysis of the Wuppertal data alone, by Bittner et al. (2002) shows no clear long-term trend. A systematic comparison with available observations at different sites would be necessary to draw conclusions about a possible relation to global change. Such a comparison is an objective of the data compilation in the context of this special issue of *Physics and Chemistry of the Earth*, and so need not be treated here.

In contrast to the negative trend at 87 km, we find a zero temperature trend at 95 km. This is not inconsistent

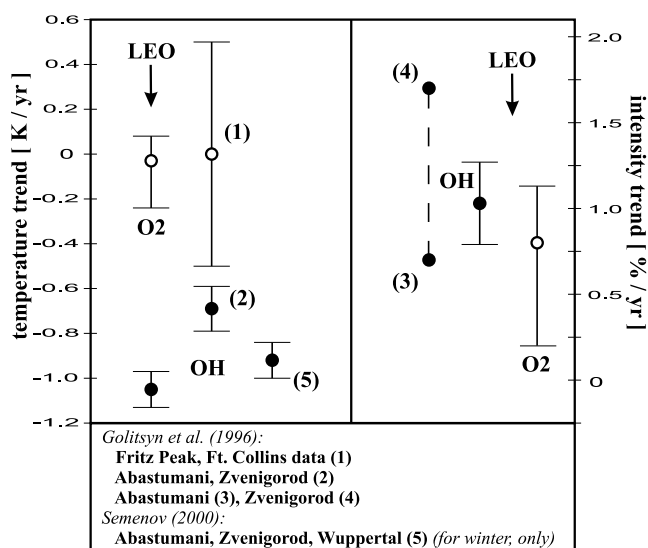


Fig. 3. Long-term (15 year) trends derived for El Leoncito (LEO) observations, and comparison with results from other sites. Black circles are for the OH emission (87 km), hollow circles for O₂ (95 km) and other data from similar altitude.

with previous findings. Golitsyn et al. (1996) also found a vanishing temperature trend for 97 km by combining green-line Doppler temperatures at Fritz Peak (40°N, 106°W; by Hernandez and Killeen (1988)) with more recent sodium lidar temperatures at Ft. Collins (41°N, 105°W; by She et al. (1993)). Our result has considerably smaller error margins than Golitsyn et al.'s (see Fig. 3).

We find positive intensity trends for both emissions. Our result for OH lies within the range of intensity trends observed at Abastumani and Zvenigorod (see Fig. 3, right panel). From the data shown in Golitsyn et al. (1996, their Fig. 3), we infer trends, with emphasis on the more recent years, of about 0.7%/year, at Abastumani, and about 1.7%/year, at Zvenigorod (the numerical value of 9.8 kR/year given by Golitsyn et al., corresponding to approximately 1%/year, includes the data before 1965, and so, the comparison could be misleading).

Our trend result for the O₂ intensity, not much smaller than for OH, stands here without comparison to other observations, because we are not aware of any previous publication.

A subsidence scenario as discussed by Golitsyn et al. (1996) and Semenov (2000) could be at least qualitatively consistent with the observed temperature trends, as well as the airglow intensity trends. This scenario consists of the idea that cooling of the middle atmosphere – consequence of the greenhouse effect – leads to a “shrinking” of the upper atmosphere. Let us assume for simplicity that, in the mesopause region, subsidence is equivalent to a downward shift of otherwise unmodified vertical temperature and density profiles. If the airglow layers participated in this subsidence, no observable trend effect would result.

If, on the other hand, we admit the (rather artificial) assumption that the airglow altitudes remain unchanged, this simple scheme would reproduce the observed features: there would be no temperature trend near the mesopause level (close to 95 km), and a negative trend below the mesopause, because of the negative temperature gradient, there. The positive airglow intensity trend for both altitudes would also result from the corresponding downward drift of the atomic oxygen profile, because of the strongly positive mixing ratio gradient, in this altitude range.

The observed and modelled mesopause region subsidence rates reviewed by Semenov (2000) all range between 30 and 100 m/year. Therefore, temperature gradients of only –1 or –2 K/km as contemplated in model atmospheres like CIRA 86 are insufficient to account for the size of the trend at 87 km. At any rate, a realistic model that also contemplates possible changes in airglow layers is necessary to account for the quantitative details, but this is outside the scope of the present paper.

Of course, the same trend results would be produced in an otherwise constant atmosphere, if both airglow layers moved upwards. However, this alternative does not seem plausible.

As another possibility, a long-term drift in the mean tidal phase could also create a trend, as suggested by Clemesha et al. (1997) for their sodium lidar observations. The non-cancellation of the diurnal tide (as mentioned) makes our (nocturnal) data susceptible to such an effect. The great difference in the temperature trends at 87 and 95 km would in principle be not incompatible with this view, because of the variation of the tidal phase with height (consistent with about 30 km vertical wavelength, typical of the diurnal tide). However, there would be a restriction on tidal phase: in order to be able to produce a maximum trend at 87 km, and nearly none, at 95 km, the mean tide at 87 km would have to pass through zero around local midnight. Moreover, this scheme would only work, if the seasonal variations of phase are small. Also, with realistic amplitudes for the mean diurnal tide – hardly more than 5 K have been observed, at our latitude (for the migrating component; Khattatov et al., 1997) – it appears impossible to explain more than a small part of the 15 K trend at 87 km.

The differences between the short-term (1998–2001) and long-term trends (except for OH intensity) may signal a real tendency towards more positive trends, or just be a short-term fluctuation (whether related to solar activity, or not). Future data are required to resolve this issue.

5. Summary

While attempting to extract information on long-term trends from our data set of mesopause region temperatures and airglow intensities, we have put some emphasis on the problems that arise from the geophysical variability at different time scales, and of non-periodic episodic perturbations. These problems must be addressed to permit the detection of trends, with the data available. The different complicating factors are listed in Table 3.

We find a negative long-term temperature trend at 87 km, but no trend at 95 km. Also, there are positive airglow intensity trends for the OH and O₂ emissions, at these respective altitudes, which may signal increments in atomic oxygen concentration. For the numerical values, the reader is referred to Table 2. The different long-term trends may be consistent with subsidence due to middle atmospheric cooling. The sparsity of our data before 1997 does not allow to distinguish trends for different seasons.

As a useful by-product of the present analysis, we obtain quantitative estimates of the temperature anomaly during 1997 (see Table 3), that complement previous

Table 3
Factors influencing observed variability

Variability source	Temperatures	Intensities
<i>Statistical error (incl. geophysical variability)</i>		
Individual night	0.4–0.8 K	
Each campaign/block	0.2 K	0.3–0.4%
<i>5 min–12 h oscillations (gravity waves, tides)</i>		
Amplitudes	Several K (GW), $\lesssim 20$ K (tides) suppressed by block averaging	suppressed by block averaging
<i>Planetary and tidal waves not cancelled in block means</i>		
Remaining S.D.	1.7 K (OH), 2 K (O ₂)	5.3% (OH), 7.2% (O ₂)
Peak deviations	+6 K (OH), +8 K (O ₂) ^a	$\pm 15\%$
<i>Seasonal variation, S.D.</i>		
	3.2 K (OH), 3.6 K (O ₂) No influence on variability ^b	18% (OH), 20% (O ₂) No influence on variability ^b
<i>Interannual variability</i>		
	Already included in empirical S.D.	Already included in empirical S.D.
<i>Solar activity effects</i>		
Present, upper limit	0.02–0.06 K/sfu (O ₂)	0.04–0.13%/sfu (O ₂)
<i>Episodic anomalies</i>		
1997 ENSO event (excluded from analysis)	–3.5 K (OH), –6 K (O ₂)	–23% to –35% (OH) –20% to –30% (O ₂)
<i>Perturbations originating at other altitudes</i>		
Auroral contamination	No problem in our data ^c	No problem in our data ^c
<i>Instrumental artifacts</i>		
	Avoided by data processing ^d	Avoided by data processing ^d

^a One temperature outlier (4 standard deviations) due to stronger-than-average planetary wave, but not excluded from analysis.

^b Reproducible part of seasonal variation of diurnal tide is already removed by subtracting seasonal mean.

^c Auroral OH contamination (OI 844.8 nm) outside spectral range. No evidence of O₂ effect (low geomagnetic latitude).

^d No moonlight bias (spectral background correction). All data from same instrument, uniform processing. Only O₂ data for 1992 may be affected by filter deterioration.

findings for airglow intensities (Scheer and Reisin, 2000), probably related to the strong ENSO event.

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