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# Influence of the UTLS region on the astrolabes solar signal measurement

C. Badache-Damiani,<sup>1</sup>★ J. P. Rozelot,<sup>2</sup> K. Coughlin<sup>3</sup> and N. Kilifarska<sup>4</sup>

<sup>1</sup>*Observatoire de Paris, LESIA (Bt 8), 5 place Jules Janssen, 92195 Meudon Cedex, France*

<sup>2</sup>*Observatoire de la Côte d'Azur, OCA-FIZEAU, Avenue Copernic, 06130 Grasse, France*

<sup>3</sup>*University of Reading, Department of Meteorology, Earley Gate, PO Box 243, Reading RG6 6BB*

<sup>4</sup>*Geophysical Institute, ul. Acad. G. Bonchev, bl3, Sofia 1113, Bulgaria*

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## ABSTRACT

Regular measurements of the Sun's diameter have been obtained by means of solar astrolabes for several decades. However, the variations found from those measurements are still very controversial, and the results implying changes in the solar radius are not conclusive. Since the quality of the measurements cannot be doubted, it is necessary to wonder what they are actually observing. We show here that some refraction effects, neglected so far, must be taken into account. Then, if the lower atmospheric layers merely add high-frequency noise (validated by the measured Fried parameter), we show here that the mid- to long-term variations take root in the upper troposphere – lower stratosphere region. Hence, the annual means of the Sun's apparent radius, measured at Calern (France) and Santiago (Chile), are linearly correlated with the geopotential height at 50–100 mb with correlation coefficients of  $-0.66$  and  $0.62$ , respectively, the opposite signs being the signature of the symmetry of the two hemispheres, North and South. In addition, the measurement dispersion is correlated with the variance of the wind speed above each observatory. Thus, it appears that the solar signal is amplified by the mechanisms dwelling in this interface zone between the lower stratosphere and the upper troposphere. Because these amplification mechanisms are unknown, it is difficult to extract pure solar information from the astrolabe signals, especially in sites where the seeing is less than 14–16 cm.

**Key words:** atmospheric effects – Sun: general.

## 1 INTRODUCTION

An absolute measurement of the solar diameter has been wanted since antiquity. Despite the constant improvement of the different techniques, this value is still unknown. The value of 959.63 arcsec, which is adopted by the ephemerids, was determined in 1859. It has only recently been questioned with the development of helioseismology. We speak today of a 'seismic radius', which differs from the 'photospheric radius' by about 500 km.<sup>1</sup> At a time where the very large telescope interferometer (VLTI) allows the measurement of stellar diameter with an unprecedented accuracy, it seems paradoxical that the solar diameter should be so badly estimated (Lefebvre et al. 2005). During the sixties, a program was started to accurately determine the ephemerids using a high-performance instrument, the

impersonal Danjon astrolabe. In the set of equations establishing the links between the various variables, the solar radius (that we will note  $\delta r$ ) is an unknown that appeared to be easily assessed. As time went by and observations went on,  $\delta r$  should have remained constant, but it did not. The astonishing temporal variability of the solar radius, rather simply obtained by measuring the time between two successive contacts of the solar limb with a circle of height, soon raised a great interest. 20 yr after the first results and more than five years after several solar astrolabes throughout the world have come into operation, in France, Chile, Brazil and Turkey, the question of solar diameter variability is still debated. Identical instruments, or at least instruments designed on the same principle, by means of similar data reductions, should yield the same value of  $\delta r$ . Yet they do not, in terms of absolute value as well as for the amplitude of the modulation and the phase of the temporal signal  $\delta r(t)$ . Finally, the values obtained by means of the solar astrolabes are not consistent with those obtained by other means. However, the network of astrolabes keeps growing: an astrolabe of the same type as the French one will soon come into operation in Algeria, and the Observatory of San Fernando, in Spain, equipped with a slightly different

\*E-mail: cilia.damiani@obspm.fr (CBD); jean-pierre.rozelot@obs-azur.fr (JPR); k.coughlin@reading.ac.uk (KC); natalka@geophys.bas.bg (NK)

<sup>1</sup> See 'Astrophysical Quantities', Allen (1976)  $R_{\odot} = 695\,997$  km and 2000 edition,  $R_{\odot} = 695\,508$  km.

**Table 1.** Values of the solar radius determined with the astrolabes in different sites. Those estimates have been taken from published papers mentioned in column (Reference). Standard deviation  $\sigma$ ; fried parameter  $r_0$ .

Reference	Measurement series	$\delta r$ (arcsec)	error (arcsec)	$\sigma$ (arcsec)	Scattering (arcsec)	$r_0$ (mm)
Delmas (2003)	OCA-Calern station (F) (CCD)	959.509	$\pm 0.014$	0.490	1.	$40.0 \pm 4.5$
Delmas (2003)	OCA-Calern station (F) (visual)	959.51	$\pm 0.01$	0.27	1.2	
	Tubitak National Observatory (T)					
Golbasi et al. (2001)	Years: 1999–2000 (CCD)	959.03	$\pm 0.07$	0.40	2	
Kiliç et al. (2005)	Years: 2001–2003 (CCD)	959.091	$\pm 0.014$	0.326	1.5	$47.0 \pm 6.6$
Andrei et al. (2001)	Observatório de Rio de Janeiro (B)	959.190	$\pm 0.013$	0.580	1.5	$36.7 \pm 3.2$
Noël (2003)	Observatorio Astronómico National, Santiago (C) (visual)	963.33	$\pm 0.01$	0.352	1.5	$\approx 40$

**Table 2.** Amplitude and phase deduced from the astrolabe series compared to the 11-yr solar activity cycle.

Site	Amplitude (mas)	Phase compared to solar activity	Reference
Chile (Santiago)	600	+	Noël (2003), p. 189
France (Calern)	200	–	Delmas (2003), p. 201
Brazil (Rio de Janeiro)	70	–	Andrei et al. (2001), p. 78
Turkey (Antalaya)	50	–	Kiliç et al. (2005), p. 10
		See note <sup>a</sup>	Data length insufficient

<sup>a</sup>The semidiameter of the Sun increases with an amplitude of 0.017 arcsec per year in opposite phase with solar cycle 23.

astrolabe (using an optical set square instead of the prism) has joined the R2S3<sup>2</sup> network. Moreover, the measurements have been greatly discredited by the lack of a solar physics theory allowing a variability of  $\delta r$  which compares to those observed. The following question thus arises: if we cannot doubt the meticulousness of the observers, what are we measuring with the astrolabes? We will answer this question without ambiguity (but limiting ourselves to the astrolabes only), and bring elements of a theoretical explanation.

## 2 ASTROLABE MEASUREMENTS OF $\delta r$

There is an overwhelming number of papers available on the subject as each annual measurement series is regularly published by the different teams. Since original measurements have been continuously re-evaluated by various signal analysis methods resulting in various interpretations of the same measurements, it is difficult to gain a clear picture from the literature. We will only mention here two synthesis papers, Andrei's (Andrei et al. 2004) and Damiani's (Badache-Damiani & Rozelot 2006), the latter being extracted from a more comprehensive report treating the subject (Badache-Damiani 2005). Despite the fact that Chile is not a

member of the R2S3 network, it is also integrated into this study because the observations and the results cannot be a priori discarded. As an example, Tables 1 and 2 give some  $\delta r$  values and related quantities found in the literature for the four observatories above mentioned.

Such results do not seem to agree, yet it has been concluded by the R2S3 network that the observed solar signal shows an 11-yr cycle. In the case of the Calern, it is in antiphase with the solar activity cycle. Although their series is just a few years long, the observers of Antalaya reach the same conclusions. For Rio's observers, the conclusions are not as definitive and the determined amplitude is clearly smaller than it is for the other studies, but the authors agree that their results indicate an antiphase. Santiago's measurement alone is in phase with the solar cycle, thus the observers of the R2S3 network have discarded them for their studies.

In return, and surprisingly enough, when the measured radii are ordered and averaged out by heliographic latitude bins (hence time independent), every series agree with a global shape of the figure of the Sun. This common shape shows a slight equatorial bulge, followed by a faint slump above the royal zones (between around 10° to 30° of latitude).

We are thus facing two facts. On one hand, if we take the temporal evolution into account, the conclusions deduced from the observations with the astrolabes does not seem to be consistent. Besides, the amplitude of the various modulations do not directly compare to space measurements. Last, no physical theory can explain the amplitude of the 11-yr cycle found with the astrolabes, if it is purely of solar origin. On the other hand, those measurements become consistent when the temporal criterion disappears and rotating fluid body physics can explain the static figure found (Rozelot, Lefebvre & Kosovichev 2007). The observers have thus concluded the validity

<sup>2</sup>Réseau de Suivi au Sol du Rayon Solaire, initiated by C. Delmas from the OCA. The 'R2S3' team is composed of the following observatories: OCA-GEMINI (France) – F. Laclare, P. Bourget, B. Chauvineau, C. Delmas, S. Lefebvre, F. Morand and J.P. Rozelot – Tubitak National Observatory (Turkey) – O. Golbasi, H. Kiliç and A. Kilcik – Observatorio Nacional (Brazil) – A. H. Andrei, J. L. Penna, E. Reis Neto and E. G. Jilinski – Bouzareah Observatory (Algeria) – A. Berdjia, M. Fodil, A. Irbah and A. Toufik – San Fernando (Spain) – F. Gomez, J. L. Muñoz and Vicente.

of their data, neglecting the discrepancy by a factor of 10 found in the asphericities (see Section 3.3).

These conclusions are contradictory and demand clarification. We present here the study we lead in order to understand why those measurements appear so discrepant.

### 3 TEMPORAL MODULATIONS

#### 3.1 Statistical analysis

The statistical analysis of the four time series has shown their robustness (Badache-Damiani & Rozelot 2006). With a good significance level, they pass various tests that show that the samples can be considered as matched-pairs and present a persisting behaviour. Each series follows a Gaussian law, typical of that kind of measurement and shows the absence of any systematical bias. However, it is not possible to join the four series to the same statistical law with classical tests nor it is possible to find a significant correlation coefficient when taken as pairs. They none the less present an interesting behaviour since the analysis reveals a positive correlation coefficient between data coming from the same hemisphere and negative for opposite hemispheres. The geostatistical methods could not find a common estimator for the four series and the variograms do not fit the inversion models that we knew of, except for a very strong ‘nuggets’ effect, typical of a highly disorganized phenomenon. Moreover, the variographic analysis does reveal clear features at various time-scales (deduced from all the variograms, thus objective). For a time-scale inferior to 40 d, the data show the behaviour of white noise. At larger scales, the signal is smooth, which justifies *a posteriori* the treatment used with the French data (by bins of 40 d, numbers were found empirically) and that leads to the extraction of a temporal modulation. At larger scales, an annual periodicity is also found. Lastly, for a time-scale larger than 6 yr, the faint trace of an 11-yr cycle can be seen but without information on the phase. As a conclusion to this study, it appears that the astrolabe time series do carry common information, but the origin of it still needs to be found. Even if it is clear that the four time series show similarities, their lack of correlation and the mean and especially the variance discrepancies, require explanations. With these varying results, is it still possible to unify the various results into a single interpretation?

#### 3.2 Refraction

One of the major problems experienced by ground-based measurements is the atmospheric refraction. The one-year periodicity mentioned above has already been found before (Ribes et al. 1991) and it has been shown by Wittman (Wittman & Débarbat 1990) that it is the result of an omitted effect in the computation of correction for the refraction. The solar astrolabe observers point out that refraction is not a major matter, for it reduces to zero, at least to the first order, between the passing of the limb (direct and reflected) at the almucantar. This only regards the differential refraction between the two limbs, none the less, the measurements need to be corrected for the value of the angle of refraction that corresponds to the height above the horizon that defines the circle of height. Besides, this supposes that the turbulence is frozen between the two times at which the measurement is taken, which is not strictly the case, even if the time-span is very short (of the order of a few tenth of a second).

The refraction corrections for the astrolabe measurements are detailed in Chollet (Chollet 1981) and are valid in the frame of certain known approximations. Those approximations are not rigorous

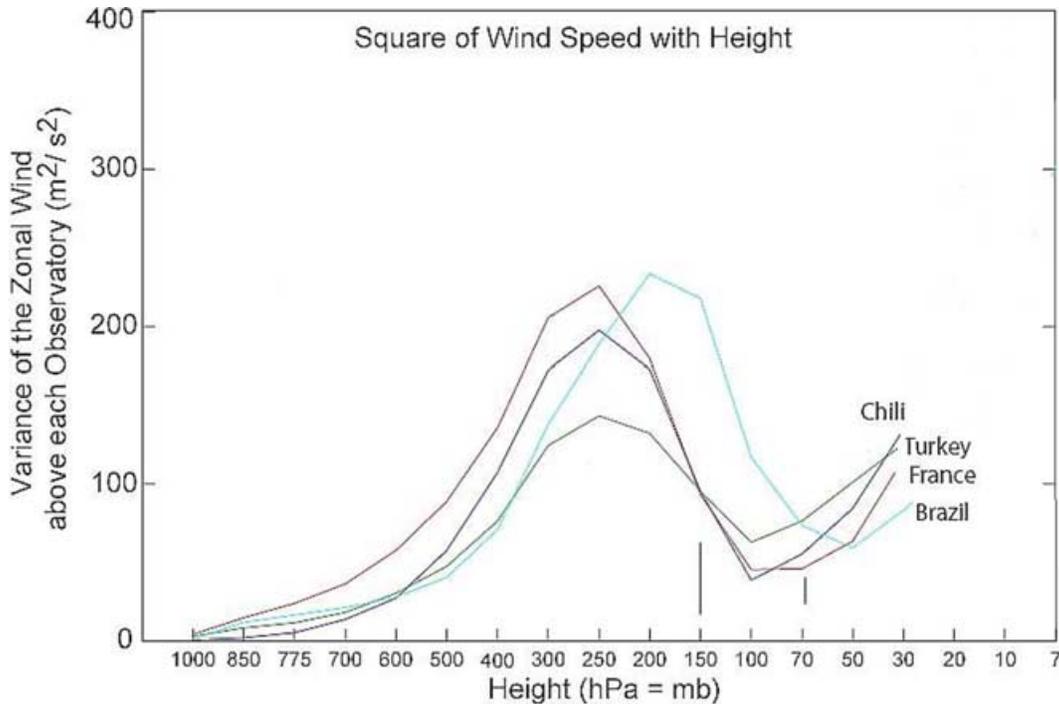
enough nowadays because the order of magnitude of the searched effects, about a few milliarcseconds, demand that we take into account the recent developments in atmospheric models, especially regarding the periodicities of the pressure and the temperature gradients. Regarding this matter, we will briefly recall the two-component nature of the refraction, one symmetric-radial and the other asymmetric. The theory of the radial-symmetric refraction relies on a spherical density distribution of the atmosphere (Teleki 1979). This type of refraction also called ‘pure’ or ‘normal’, only depends on the zenithal distance of the object and is independent of the azimuth. This refraction disappears when the Sun is at the zenith, following a  $\sec(z)$  dependence, and that is why it is common practice to determine the parameters of this law and correct the data. This is done within the visual measurements of the Calern observatory by means of a least-mean-square method or concerning the CCD measurements by extrapolating the value of the Fried parameter towards infinity (i.e.  $1/r_0 \rightarrow 0$ , see e.g. Fig. 1; Kiliç, Golbasi & Chollet 2005, which is rather daring.). The asymmetric refraction, also called abnormal refraction, refers to the part that cannot be explained by the former models (Teleki 1979). Contrary to symmetric-radial refraction, abnormal refraction is dependent on both zenithal distance and azimuth. Chollet (Chollet 1981), in a study that stands as a corner stone for later works, denotes that it is not necessary to account for it. This is, however, a major point where the accuracy of the desired measurement matters, as improperly corrected measurements will carry the effects of abnormal refraction throughout the calculations to the end result. The propagation of these effects will severely damaged the accuracy of the results.

As a second point, the curvature of the rays in the atmosphere is a consequence of temperature and pressure gradients changing the index of refraction through which the ray is travelling. Yet, these changes fluctuate with time. It has been assessed (Sugawa & Kikuchi 1979) that the refraction angle is affected by seasonal effects of an order of magnitude of 0.01 arcsec. Finally, local gradient of temperature, that can be strong at the sea-land border or above steep ground (which is the condition of the observatories considered in this study), can considerably affect the measurements. The amplitude of abnormal refraction is typically about 0.1 arcsec (Bretterbauer 1965) but can fluctuate between 0.05 and 0.2 arcsec as shown by Hirt’s recent studies (Hirt 2006). This amplitude can be compared to what is found in astrolabe measurements (fig. 1 in Hirt’s paper shows a striking analogy with charts showing the raw values of the solar radius in time) showing that major part of the variability of the measurement must come from improperly corrected refraction effects. It is clear that Chollet does not take this effect into account (see Chollet 1981, annexe C). The value of abnormal refraction is underestimated by two to three orders of magnitude.

From this study, can we conclude altogether that only refraction effects are at stake? It is known that the principal source of noise is the atmospheric disturbance, mainly in the lower layers of the atmosphere. But what is the influence of the higher layers, where indeed the atmospheric parameters evolve periodically?

##### 3.2.1 Solar signal in the atmosphere

Quasi-decadal variability found in many atmospheric parameters (temperature, geopotential height, winds, chemical compositions, etc.) have been reported by many authors (Labitzke 1987; Labitzke & van Loon 1997; Chandra, Ziemke & Stewart 1999; Larkin, Haigh & Djavidnia 2000; Zerefos et al. 2001; Coughlin & Tung 2003). There are many hypotheses related to the amplification of the



**Figure 1.** Interannual variability (i.e. departure of the annual temperatures from the mean period 1961–1975), in millidegrees Celsius (from Sterin 2001), in the UTLS region versus the mean annual solar radius observed at Santiago (Chile), on the left-hand side, and at Calern (France), on the right-hand side, values taken out from Delmas (2003) and Noël (2003).

solar signal by different mechanisms but all of them explain only partially the observed quasi-decadal variability of the lower atmosphere. Based on the statistically robust result that Upper Troposphere – Lower Stratosphere (UTLS) region is warmer (by about 1 K) in solar maxima comparing to solar minima, and the Lower Stratosphere during west Quasi-Biennial zonal wind Oscillation (QBO) phase being warmer (by about 1.5 K) than during east QBO phase, Kilifarska and Mukhtarov (Kilifarska & Muhtarov 2006; Kilifarska & Mukhtarov 2007) present a new explanation of the comprehensive interactive influence of solar-QBO signals on the lower atmosphere. They supposed that the solar influence from below (through redistribution of solar heating from the tropical UTLS towards the poles and corresponding changes in mean meridional circulation) may be sufficiently effective in changing conditions for planetary wave propagation in this region.

Other studies treating notably of the chemistry of the atmospheric components (Law et al. 2006) show the importance of this zone, the role of which being underestimated so far.<sup>3</sup>

It is possible that the UTLS region might be the place where solar effects have the strongest influence on climatic parameters and their variations. As a consequence, the 11-yr period found in the astrolabe solar radius measurements might not be constitutive of a phenomenon of solar origin, but could be the result of an amplification of the signal modulated by solar irradiance via some mechanism in the UTLS region. Latitudinal distributions of temperature and pressure produced by those phenomena would then explain the difference in amplitude and phase found in the different data sets. As an illustration, we can compare the various physical parameters

in this zone to the observed values of the radius, as detailed in the following sections.

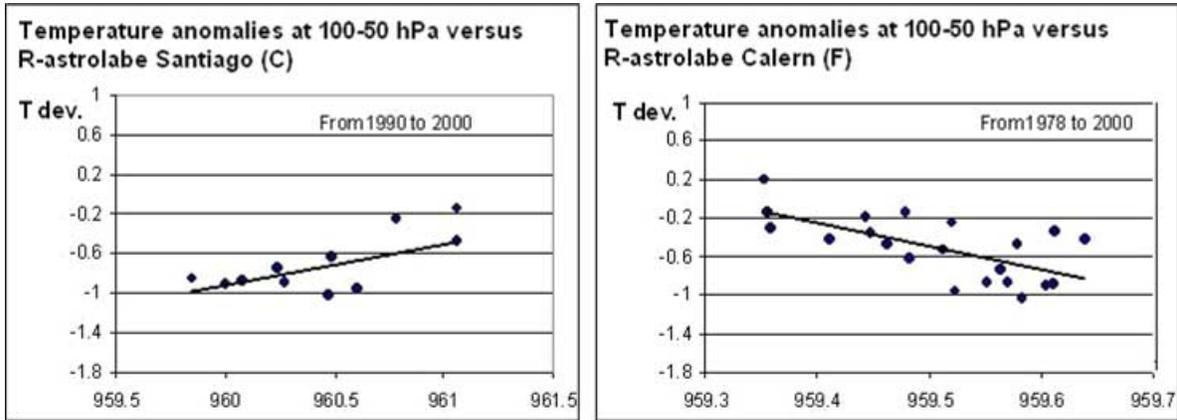
### 3.2.2 Interannual temperature variability in the UTLS region versus $\delta(r)$

Fig. 1 only displays result for French and Chilean observatories, because they are the only ones for which we have a long enough observational record using the visual detection of the limb. It shows a linear regression between interannual temperature variability in the zone between 50 and 100 mb – the lower stratosphere – and the annual mean of the observed diameter. The correlation coefficient is reasonably high, respectively  $-0.66$  for France and  $+0.62$  for Chile, and we note that opposite hemispheres have opposite signs of the slopes of the trend.

### 3.2.3 Zonal wind speed variance in the UTLS region

An other point supporting our view is given by the study of the zonal wind speed variance in the UTLS region above each observatory. Fig. 2 displays the variance of the winds above each observatory as a function of atmospheric height. Note that all the curves have similar behaviours departing only by their respective values, except for Brazil which seems to have an offset in altitude. This is due to the fact that the Brazilian station is closest to the equator, where the tropopause level is higher than for the other stations. We observe in the UTLS region, that is, between 150 and 90 mb, a relation of order in the wind speed variance. So, in increasing order we have Chile, France, Brazil and Turkey. This result should be compared to those presented in Table 2, and we notice that it matches the decreasing order of amplitudes of the 11-yr cycle found in the radius measurements. It would be dangerous to establish a law of causality

<sup>3</sup> A direct radiative forcing of about  $0.1 \text{ W m}^{-2}$  yields significant variations of  $O_3$  density [Intergovernmental Panel on Climate Change (IPCC) <http://www.ipcc.ch/activity/act.htm>].



**Figure 2.** Variance of the zonal wind speed above each observatory. In the UTLS region (between 150 and 70 mb), a relation of order is preserved: by ascending order, Chile, France, Brazil and Turkey. This may explain the dispersion deduced from measurements, which are in the same amplitude order. Note that the Brazil station shows an offset in altitude (the tropopause level is higher over this country).

between the magnitude of the wind speed in the UTLS region over a particular location and the observed radius data directly. But we know that the wind speed is related to pressure and temperature, which does influence the refractive index of air. Given this, we feel there is at least some evidence on which to base our hypothesis.

### 3.3 Theoretical framework

A solar cycle variability ranging from about  $0.07\text{--}0.6 \text{ arcsec}^2$  in amplitude, as reported in astrolabe measurement literature, is not supported by any physical theory to this day. And when searching for astrophysical consequences induced by such a modulation, for example, using lunar libration (Rozelot & Bois 1997) or the Mercury perihelion advance (Pireaux & Rozelot 2003), it appears that values obtained by means of the astrolabes yield absurd results.

Sofia et al. (2005) have recently tried to explain the amplitude of the solar radius temporal modulation by introducing subsurface magnetic effects. Regrettably, their model is strongly contradictory with  $f$ -modes observations (Lefebvre, Kosovichev & Rozelot 2007). Moreover, the gravitational study of layers of the Sun just below the surface, which supports the helioseismic analysis of the  $f$ -modes, show that Lefebvre, Kosovichev & Rozelot (2006):

(i) A temporal variability of the solar radius is depth dependent (at least for the very first layers below the surface). The diameter should vary in phase with solar activity in the layers between  $0.97$  and  $0.99 R_{\odot}$  and in antiphase beyond this zone (i.e.  $0.99 - 1 R_{\odot}$ ); the maximum amplitude between 1996 and 2005 does not exceed 40 km (Lefebvre et al. 2007).

(ii) Asphericities do exist, but without exceeding a deviation of 10 mas from the reference sphere (helioid) (Lefebvre & Rozelot 2004).

Lastly, temporal variability of the radius as observed from space is inferior to 7 mas during one cycle (Kuhn et al. 2004; Emilio & Leister 2005).

Such orders of magnitude are not compatible with solar astrolabe measurements, they can only be seen from the ground where seeing quality is especially good.

## 4 CONCLUSION

The UTLS region is a key-layer in the understanding of climatic phenomena. Changing chemistry in this region has lead us to better

unravelling the dynamical feedback that can occur here. Undoubtedly, dynamical feedback in conjunction with the solar irradiance changes can influence the interannual variability of temperature in this zone.

We have shown here that the discrepancy of ground-based solar measurements may be explained in terms of atmospheric variations. The short-scale noise comes from the lower layers of the atmosphere, but the longer time-scales, wind speed amplitude above each observatory is correlated with the amplitude of the solar radius variations. The significant correlation found between astrolabe measurements, and the temperature height in the UTLS region allows us to say that the solar signal is influenced (and maybe amplified) within this zone, at the interface between the troposphere and the stratosphere.

Our results provide an answer for the apparent contradictions denoted to this day among various observatories. As far as we are concerned, they put to an end the controversy about the scattering of the measurement, and the amplitude and phase of the modulation. Solar astrolabes have proven to be of a very important use, and the scientific criticism of the measurements reveals the necessity to further explore changes in the UTLS region that might play a part in the physics of the atmosphere; specifically, the changes in the index of refraction. Astrolabes are wonderful instruments, not for the direct measurement of solar radius and its variability, but for the sounding of the UTLS region. The potential use of astrolabes for climatic research in the tropopause should be further explored but it is useless to try to extract information from these measurements for purely solar related ends, especially at location where the seeing is inferior to about 14–16 cm.

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