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High-altitude wind velocity at Oukaimeden observatory

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ABSTRACT

This paper aims at studying the wind at 200 mbar over the Moroccan observatory Oukaimeden, as high-altitude winds have been adopted as a useful parameter for site characterization in terms of the suitability of a site for the development of some adaptive optics techniques. The data used come from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data base, which is widely acknowledged as being reliable. Statistical analyses of 200-mbar wind speed since 1983 are performed. Comparison with some of the main observatory sites worldwide qualifies Oukaimeden as one of the best observatory sites in terms of 200-mbar wind statistics. Our analysis of a record of seeing measurements during the years 2003 and 2004 concludes that while 200-mbar wind speed can be used as a parameter for ranking astronomical sites in term of their suitability for adaptive optics, it cannot be used for the whole atmospheric seeing prediction. A comparison of monthly values of the seeing parameter at Oukaimeden, La Silla and Paranal demonstrates the high seeing quality of Oukaimeden, as the seeing values measured were lower than those of La Silla and Paranal for most of the time during the comparison period. Furthermore, a statistical analysis of atmospheric stratified seeing, wavefront coherence time and isoplanatic angle measured with a Multi-Aperture Scintillation Sensor instrument over Paranal from 2004 to 2007 have been performed. We found good correlations between 200-mbar wind velocity and levels 4, 5 and 6 seeing, wavefront coherence time and isoplanatic angle, with corresponding correlation coefficients of 0.74, 0.79, 0.70, 0.97 and 0.78.

Key words: atmospheric effects – methods: data analysis – site testing.

1 INTRODUCTION

The degradation of astronomical images by inhomogeneities in the Earth's atmosphere is generally called 'seeing'. It represents the angular diameter of the stellar images as seen through a turbulent medium. Vernin (1986) revealed the great influence of the wind speed at the tropopause on the seeing, as he found a good correlation between the seeing and the 200-mbar wind speed at La Silla and Mauna Kea. Indeed, wind speed is weak near the ground and strong at high altitude. The 200-mbar pressure level is where the wind speed is fastest, whatever the latitude and the longitude. Zones of steep wind gradient give rise to mechanical turbulence that creates optical turbulence by mixing air masses of different temperatures and hence degrading astronomical observation quality. However, the seeing is not a sufficient parameter for the characterization of astronomical observatories. Other parameters relevant to adaptive optics systems are essential. These parameters depend on the vertical profile of the refractive-index constant structure C_N^2 and the wind velocity. The average velocity of the turbulence V_0 is a key parameter because other quantities relevant to adaptive optics are directly related to V_0 (Roddier, Gilli & Lund 1982). Thus, if it possible to obtain V_0 by independent and reliable means, the rest of the adaptive optics quantities can be estimated from V_0.

Sarazin & Tokovinin (2002) found for Paranal and Cerro Pachón an empirical relationship that relates the turbulence velocity V_0 measured *in situ* with the wind speed at 200 mbar, obtained by using data from the National Oceanic and Atmospheric Administration (NOAA) Global Gridded Upper Air data base (GGUAS): $V_0 = 0.4V_{200\,\mathrm{mbar}}$. They proposed a more general formula $V_0 = \max(V_{\mathrm{ground}}, 0.4V_{200\,\mathrm{mbar}})$: with moderate wind at ground level and at equal seeing quality, the existing and potential astronomical sites can be ranked in terms of suitability for adaptive optics simply by looking at the wind at 200 mbar. By comparing the turbulence velocity measurements obtained using the generalized SCIntillation Detection and Ranging (SCIDAR) of the Laboratoire Universitaire

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d'Astrophysique de Nice, France, with the wind speed at 200 mbar, Carrasco, Avila & Carramiñana (2005) found that San Pedro Mártir reproduces the empirical relationship found by Sarazin & Tokovinin (2002).

Masciadri & Egner (2006) calculated the wavefront coherence time τ_0 using an atmospheric model 'Meso-NH' over 80 nights uniformly distributed in 2001 above San Pedro Mártir. They found that the 12–13 km slab affects the trend in seasonal variation of τ_0 more than the 2.7–4.7 km slab, underlining the fact that the absolute value of τ_0 was mostly affected by the wind near the ground during the period studied. They found a correlation between the 200-mbar wind speed and the average turbulence velocity V_0, and then a good correlation between the τ_0 simulated with the model Meso-NH and $\tau_0 = 0.31 r_0 / 0.56 V_{200\,\mathrm{mbar}}$.

Carrasco & Sarazin (2003) compare for the first time wind velocity at 200 mbar from two different data sets provided by NOAA, the GGUAS and the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data bases. The authors analyse the monthly average wind speed for San Pedro Mártir and Mauna Kea and show that the two data sets follow the same seasonal trend but the instantaneous fluctuations are larger by more than a factor of 2 for GGUAS than for NCEP data. Chueca et al. (2004) tested the quality of the NCEP/NCAR reanalysis data by comparing them with radiosonde measurements from the Canary Islands, and the agreement was excellent. Carrasco et al. (2005) analyse the monthly average wind speed at 200 mbar for Sierra Negra, San Pedro Mártir (SPM), Mauna Kea, Paranal, La Silla, Maidanak and Gamsberg using the data provided by the NCEP/NCAR reanalysis data base. They find a yearly wind modulation for all the sites and they model it. In the case of SPM this result is consistent with the seeing seasonal evolution calculated in the [10–15] km slab by Masciadri & Egner (2004), simulated with an atmospheric model (Meso-NH) for 2001. Furthermore, Avila et al. (2006) compare the wind profiles obtained by the generalized SCIDAR in San Pedro Mártir with those obtained from the NCEP/NCAR model at different pressure levels, and the agreement is very good, showing that the model reproduces the empirical data. García-Lorenzo et al. (2005) also carried out a comparison of high-altitude wind statistics at some of the main observatories: La Palma, La Silla, Mauna Kea, Paranal and San Pedro Mártir. They used the NCEP/NCAR reanalysis data base. Therefore high-altitude wind speeds can be adopted as a parameter for astronomical site selection, owing to their suitability for adaptive optics.

In this paper we present a statistical analysis of the wind over the Moroccan observatory Oukaimeden, located at 2700 m above sea level (7°52′52″W, 31°12′32″N). Wind values come from the NCEP/NCAR reanalysis data base, which provides the wind in east–west (U-wind) and north–south (V-wind) directions. We found that the 200-mbar wind speed over Oukaimeden fits the model developed by Carrasco et al. (2005). A record of 2 yr seeing measurements is used to check whether there is any correlation between 200-mbar wind speeds and seeing values. We found that the annual trend of the seeing parameter and that of the 200-mbar wind speed are similar. Daily seeing values for the year 2003 correlate with daily wind speeds at 200 mbar with a correlation coefficient $R = 0.66$, whereas data related to the year 2004 give no specific relationship. Monthly values of differential image motion monitor (DIMM) seeing and wind speed at 200 mbar were analysed over La Silla and Paranal in order to check for any connections between seeing and 200-mbar wind speed. Multi-Aperture Scintillation Sensor (MASS) seeing data over Paranal consisting of the vertical profile of seeing, the wavefront coherence time and the isoplanatic angle were also analysed. A comparison between our seeing record and the monthly coincident values at La Silla and Paranal leads to the conclusion that Oukaimeden's observatory can be compared with the best sites.

2 OUKAIMEDEN CHARACTERIZATION

Oukaimeden observatory is located in the Atlas mountains and more specifically in the high Atlas plateau, at 2700 m above sea level. Oukaimeden is about 70 km easy access south of the town of Marrakech and 150 km inland from the Atlantic coast. The mountain is about 20 km north of Jbel Toubkal, the highest peak in the Atlas mountains, which is 4165 m high. The geographical coordinates of the observatory are longitude 7°52′52″W and latitude 31°12′32″N.

The procedure of the selection of the Oukaimeden as a potential site for astronomical observations was presented by Benkhaldoun et al. (1991) and Benkhaldoun (1994). The studies of photometric and meteorological qualifications have been reported in several publications (Benkhaldoun et al. 1993; Jabiri et al. 2000; Benkhaldoun 2002; Siher & Benkhaldoun 2004). The seeing-quality measurements were carried out for the first time with a Generalized Seeing Monitor (GSM) instrument (Ziad et al. 1999) and an in-house-made differential-image monitor called the Differential Image Motion Monitor of Marrakech (DIMMAR; Benkhaldoun et al. 2005). The seeing results showed that Oukaimeden observatory is comparable to the main ones.

2.1 Oukaimeden 200-mbar wind statistics

The wind data were taken from the NCEP/NCAR reanalysis data base. Through numerous bibliographies (Sarazin & Tokovinin 2002; Carrasco & Sarazin 2003; Chueca et al. 2004; Carrasco et al. 2005; García-Lorenzo et al. 2005; Avila et al. 2006) it has been shown that the NCEP/NCAR reanalysis wind data are robust, reliable and correlate very well with meteorological balloon measurements.

Fig. 1 shows the annual average 200-mbar wind speed over 24 yr from 1983 to 2006, and the corresponding wind direction. The error bars are the fluctuations with respect to the monthly mean value. The seasonal behaviour is clear, with a minimum value of 16 m s^{-1} in summer time and a maximum of 28 m s^{-1} in spring. The wind rose exhibits one predominant direction towards the east.

2.2 Oukaimeden seeing record

Seeing measurements have been carried out at Oukaimeden observatory with the DIMMAR seeing monitor constructed by the team of the astrophysics laboratory at Marrakech. This instrument monitors different parameters of the atmospheric turbulence, such as scintillation index, extinction coefficient and seeing. The seeing values vary on a daily basis from 0.4 to 2.7 arcsec and on a monthly basis from 0.6 to 1.23 arcsec. Table 1 shows the monthly statistics of seeing values measured during the years 2003 and 2004. The numbers of days of measurements is given along with the first, second and third quartiles. We can see from Table 1 that there is a median seeing value for all the 98 nights of 0.79, attesting to the good quality of astronomical observations at the Oukaimeden site.

Monthly values of 200-mbar wind speed averaged over a 24-yr period from 1983 to 2006 at La Silla, Paranal and Oukaimeden are shown in Fig. 2. We can clearly see that the 200-mbar wind characteristics at Oukaimeden are better, with a lower mean and amplitude considering the seasonal trend, which

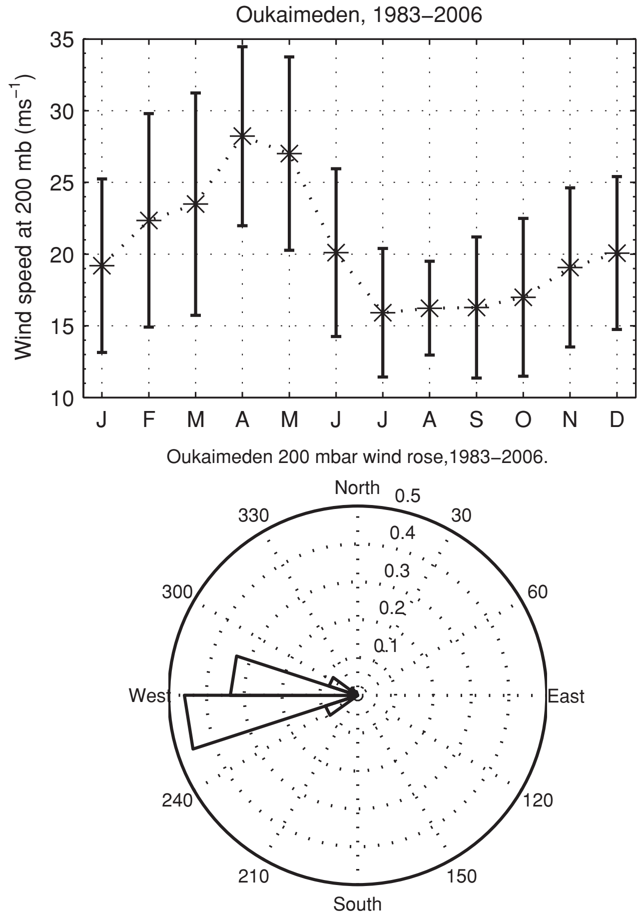

Figure 1. Top: wind behaviour at 200 mbar from 1983 to 2006. Monthly wind speed averaged for the 24-yr period with standard deviations. Bottom: histogram of wind direction in per cent of occurrence.

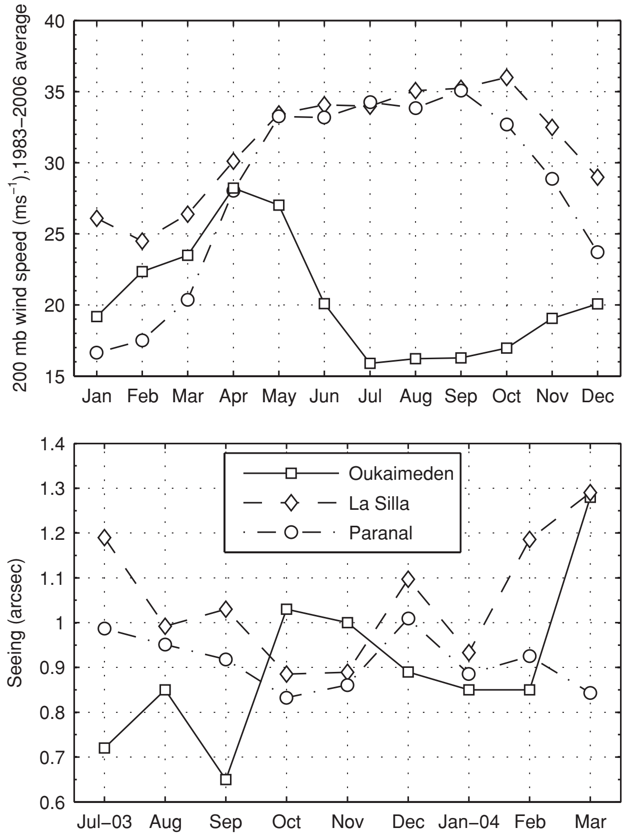

Figure 2. Comparison of monthly 200-mbar wind velocity averaged for a 24-yr period from 1983 to 2006, at Paranal, La Silla and Oukaimeden (top), and monthly average seeing values at Oukaimeden, La Silla and Paranal for the period 2003–2004 (bottom).

Table 1. Monthly statistics of the seeing at the Oukaimeden site for the period of 2003–2004. For each month, the number of days of measurements is given, along with the first, second and third quartiles (Benkhaldoun et al. 2005).

Months	N nights	1st quartile (arcsec)	Median (arcsec)	3rd quartile (arcsec)
2003 July	8	0.60	0.69	0.83
2003 August	13	0.66	0.79	1.00
2003 September	12	0.51	0.60	0.76
2003 October	5	0.65	0.79	1.15
2003 November	10	0.72	0.89	1.20
2003 December	18	0.70	0.85	1.03
2004 January	15	0.66	0.78	0.98
2004 February	7	0.65	0.81	0.98
2004 March	10	0.95	1.23	1.55
9 months	98	0.65	0.79	1.00

is shifted 6 months between the northern and southern sites, as reported by Carrasco et al. (2005). Fig. 2 shows the seeing monthly averages of the three sites for a 9-month period extending from 2003 July–2004 March. We can see that for 67 per cent of the time the seeing at Oukaimeden was lower than the seeing at Paranal and La Silla. We conclude that Oukaimeden observatory is comparable to Paranal and La Silla during the period analysed.

The atmospheric time constant τ_0 and the isoplanatic angle are important parameters for all high-resolution adaptive optics techniques. The definition of the adaptive optics time constant τ_0 given by Roddier et al. (1982) is

$$\tau_0 = \frac{0.31 r_0}{V_0}, \tag{1}$$

where r_0 is the Fried parameter and V_0 the average velocity of the turbulence. V_0 is given by

$$V_0 = \left[\frac{\int_0^\infty V(h)^{5/3}\, C_N^2(h)\,\mathrm{d}h}{\int_0^\infty C_N^2(h)\,\mathrm{d}h} \right]^{3/5}, \tag{2}$$

where $C_N^2\,(h)$ is the vertical profile of the refractive index constant structure and $V(h)$ is the vertical profile of the modulus of the wind speed.

The isoplanatic angle θ_0 is defined by Roddier (1981) as follows:

$$\theta_0 = \frac{0.31 r_0}{H_0}, \tag{3}$$

where H_0 is given by equation (4):

$$H_0 = \left[\frac{\int_0^\infty h^{5/3} C_N^2(h)\,\mathrm{d}h}{\int_0^\infty C_N^2(h)\,\mathrm{d}h} \right]^{3/5}. \tag{4}$$

Measurements of the wavefront coherence time cannot be taken with a simple DIMM as is done for seeing: a vertical C_N^2 and wind speed profiler is needed. Since such measurements are not provided in our observatory, we made the assumption that the Sarazin &

Table 2. Seeing, isoplanatic angle and wavefront coherence time reported by Lawrence et al. (2004). For comparison, astroclimatic parameters related to Oukaimeden observatory are also reported; the median seeing measured with a DIMM instrument (Benkhaldoun et al. 2005), the isoplanatic angle measured with a GSM instrument (Ziad et al. 1999) and the wavefront coherence time estimated assuming the Sarazin & Tokovinin (2002) relationship between the 200-mbar wind velocity $V_{200\,\mathrm{mbar}}$ and the average turbulence V_0.

Site	ε_0 arcsec	θ_0 arcsec	τ_0 ms
Dome C	0.27	5.7	7.9
Paranal	0.80	2.6	3.3
La Palma	0.76	1.3	6.6
Mauna Kea	0.5–0.7	1.9	2.7
San Pedro Mártir	0.59	1.6	6.5
Oukaimeden	0.79	1.5	6

Tokovinin (2002) relation [$V_0 = \max(0.4 V_{200\,\mathrm{mbar}},\ V_{\mathrm{ground}})$] is valid. DIMM measures the Fried parameter r_0 related to the full seeing ε at wavelength λ:

$$\varepsilon = \frac{0.98\lambda}{r_0}. \qquad (5)$$

The wavefront coherence time varies on a monthly basis from 1.6–10 ms, with a 6-ms average for the period analysed. Ziad et al. (1999) measured the isoplanatic angle at Oukaimeden with a GSM during 10 nights in 1998 April. They found a log normal distribution of θ_0 with a median value of 1.5 arcsec.

As a comparison, Lawrence et al. (2004) reported median seeing, wavefront coherence time and isoplanatic angle at Dome C, Mauna Kea, San Pedro Mártir, Paranal and La Palma. The wavelength considered is $\lambda = 500\,\mathrm{nm}$. Campaign measurements were carried out either with microthermal balloon launches or with generalized SCIDAR apertures. Table 2 illustrates the values reported by Lawrence et al. (2004). We added in the table the median seeing at Oukaimeden, the isoplanatic angle and the wavefront coherence time.

2.3 Connections between seeing and 200-mbar wind velocity at Oukaimeden

Following the pioneering work by Vernin (1986), we looked for any connections between seeing and 200-mbar wind velocity over Oukaimeden. Our interest in this method is related to astronomical site pre-selection purposes. Indeed, if relations between $V_{200\,\mathrm{mbar}}$ and astroclimatic parameters are proven, then pre-selection of astronomical sites becomes easier: $V_{200\,\mathrm{mbar}}$ is easily estimated by meteorological analysis, while estimating astroclimatic parameters requires C_N^2 and wind profiler data. We suggest that the correlation with wind speed at 200 mbar is restricted to sites dominated by a jet stream, like mid-latitude ones. There is indeed a polar jet above Antarctica but the correlation with seeing has not been demonstrated yet. Fig. 3 shows monthly averages of 200-mbar wind speed and seeing during 2003 and 2004. We can notice from this figure that the shape of the variation of both seeing and wind speed at 200 mbar over Oukaimeden observatory is similar. The correlation coefficient between these two parameters is 0.55. We can therefore extend the analysis further and see what happen to daily values. The NCEP/NCAR reanalysis data base provides data four times per day, at 0000, 0600, 1200 and 1800 UT. For the analysis we consider the

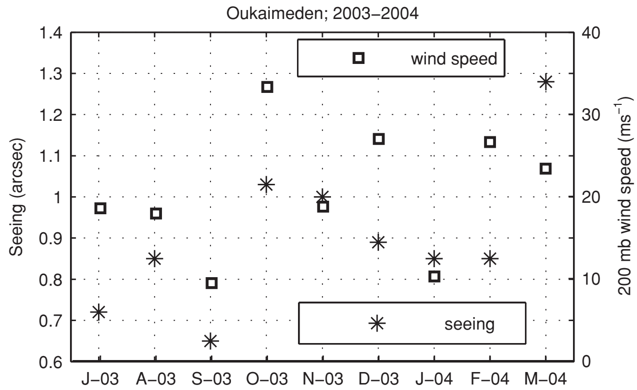

Figure 3. Monthly averages of 200-mbar wind speed and seeing at the Oukaimeden observatory.

wind velocity value at 0000 UT, as it corresponds to about midnight at Oukaimeden. We found a linear correlation between 200-mbar wind speed and seeing for the year 2003, the expression for which is

$$\mathrm{Seeing} = 0.023(\pm 0.0068)\, V_{200\,\mathrm{mbar}} + 0.42(\pm 0.32).$$

The corresponding correlation coefficient is $R = 0.66$. However, the daily seeing and 200-mbar wind speed values related to the year 2004 gave no specific relationship. One can ask the question of why there is correlation for 2003, even if it is a weak one, and yet no correlation for 2004? How often does this correlation happen? Attempts to answer the second question will be found in the next section concerning Paranal and La Silla, because a long-term data base of seeing is provided. In the next paragraph, we will try to answer the first question.

In order to compare our results with a long-term mean we plot in Fig. 4 the monthly average behaviour over 24 years, from 1983 to 2006 (dotted line), along with the monthly average of the years 2003 and 2004. It can be appreciated that the 200-mbar wind speed for 2004 behaves like the long-term average; however the 2003 profile looks completely different from the 24-year average, with a spring value even lower than the minimum fluctuation and a summer value higher than the maximum fluctuation. The year 2003 has many fluctuations with a low September mean ($9.4\,\mathrm{m\,s^{-1}}$ versus $16.3 \pm 4.9\,\mathrm{m\,s^{-1}}$ for the 24-year average) and a very high October one ($33.3\,\mathrm{m\,s^{-1}}$ versus $17 \pm 5.5\,\mathrm{m\,s^{-1}}$ for the 24-year average). The 200-mbar wind roses of the years 2003 and 2004 exhibit a predominant direction from the west, like the 24-year average (Fig. 1), leading to the conclusion that the 200-mbar wind direction did not play a role in the connection between the seeing and the 200-mbar wind velocity.

Following the analysis by García-Lorenzo et al. (2005), we calculate the correlation coefficient between the wind speed at 200 mbar and the wind speed at different pressure levels, ranging from 700 to 70 mbar for 2003 and 2004. We can see from Fig. 5 that the correlation coefficients for wind speed at lower altitudes are higher for 2003 than for 2004. In general, 2003 exhibits better correlations between 200-mbar wind speed and wind speed at different pressure levels. This behaviour could explain why the seeing and the wind velocity at 200 mbar are better correlated for 2003 than for 2004, for which we could not find even a weak correlation. García-Lorenzo et al. (2005) found similar results for Paranal, where the wind speed at 200 mbar correlates most with the wind speed at different pressure levels and has the lowest seeing values for the years analysed.

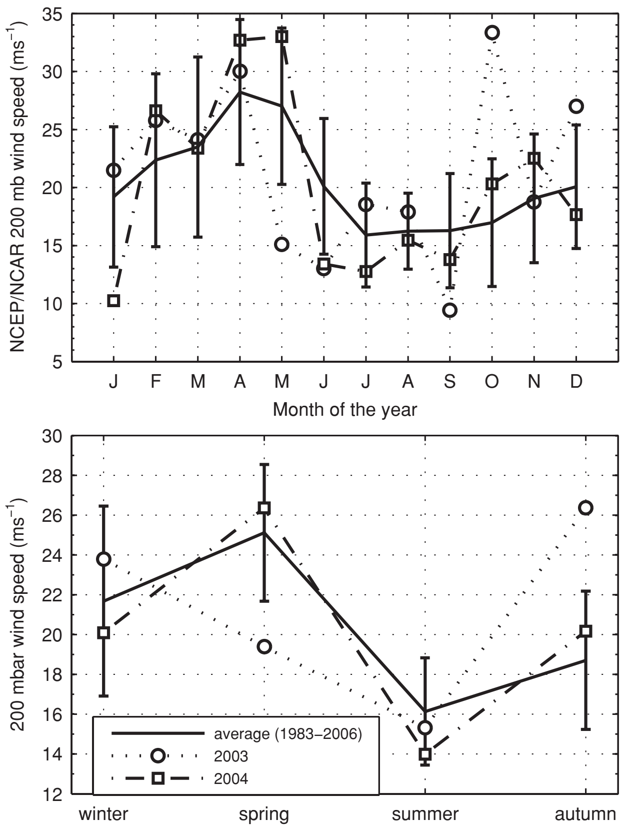

Figure 4. Comparison between monthly (top) and seasonal (bottom) values of wind speed at 200 mbar related to the years 2003 and 2004 with the 24-year average from 1983 to 2006; the standard deviations related to the 24-year average are given.

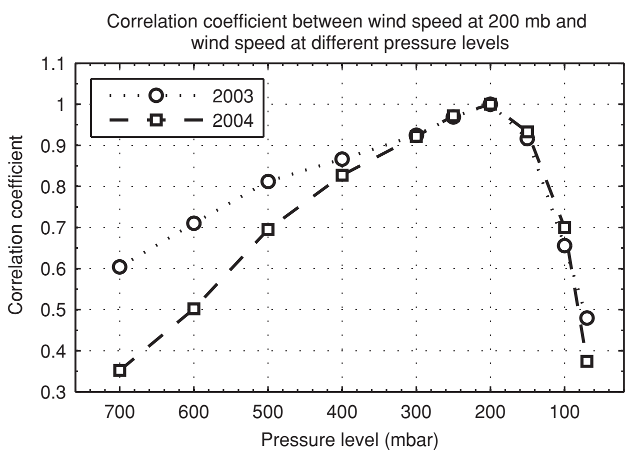

Figure 5. Correlation coefficient of the wind speed at 200 mbar in terms of the wind speed at different pressure levels, ranging from 700 to 70 mbar, related to the years 2003 and 2004 at Oukaimeden Observatory.

Finally, we should state as a conclusion that in the case of Oukaimeden observatory and for the period studied there is no correlation between the seeing and the 200-mbar wind velocity despite a slight correlation in 2003 due to its correlated wind speed profiles.

3 LA SILLA AND PARANAL RECORDS

In order to understand better the relation between the 200-mbar wind speed and the seeing, a long-term record of data is required. As our observatory has not such a long-term data base, we collected Paranal and La Silla data. We collected DIMM measurements over Paranal and La Silla from 1988 to 2005 and MASS measurements over Paranal from 2004 to 2007. MASS provides the stratified seeing at six atmospheric levels centred on 0.5, 1, 2, 4, 8 and 16 km. It also provides the seeing, the wavefront coherence time and the isoplanatic angle that would be obtained without the contribution of the first 500 m above the ground. A record of four years measurements at Paranal will be studied and compared with the 200-mbar wind velocity.

3.1 DIMM measurements

While the monthly values of seeing and 200-mbar wind velocity gave no specific relationship for both Paranal and La Silla, the seasonal trend of 200-mbar wind velocity and seeing are comparable for the period analysed. Fig. 6 shows the monthly values of the DIMM seeing and the 200-mbar wind speed averaged from 1987–2005 over Paranal (top) and La Silla (bottom). The long-term seeing record of almost twenty years provides a confident seeing shape. It can be appreciated that the general trend of seeing and 200-mbar wind velocity are similar in some periods of the year and different in others. At Paranal, for example, January and October break the relative linearity between seeing and 200-mbar wind speed. The correlation coefficient between seeing and 200-mbar wind speed is $R = 0.37$, and when we exclude January $R = 0.60$. At La Silla, the

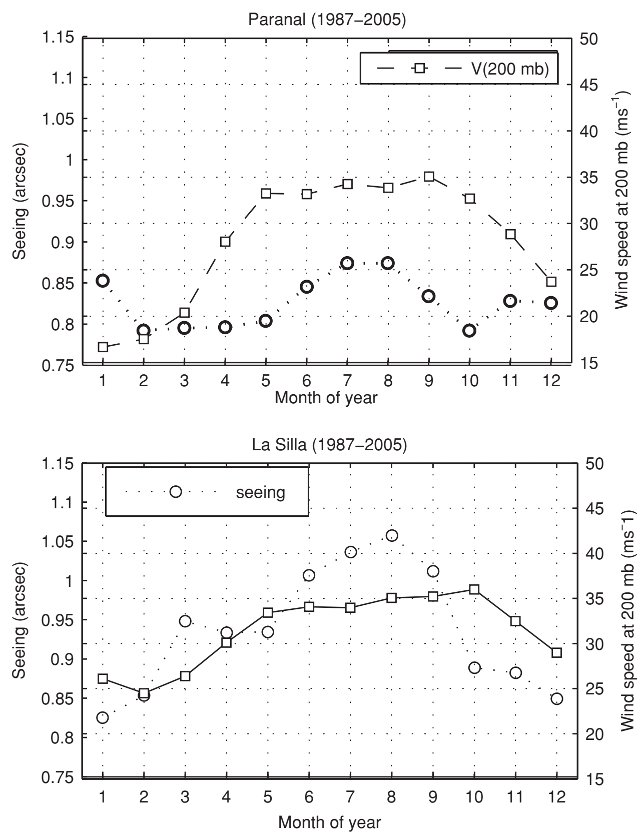

Figure 6. Annual average from 1987 to 2005 of DIMM seeing and 200-mbar wind speed at Paranal and La Silla.

Table 3. Correlation coefficients of monthly DIMM seeing and 200-mbar wind-speed parameters at La Silla and Paranal (from 1988 to 2005), on a year-by-year basis.

Year	Correlation coefficient Paranal	Correlation coefficient La Silla
1988	0.63	*
1989	0.45	0.18
1990	*	*
1991	*	*
1992	*	*
1993	*	0.58
1994	*	*
1995	0.44	0.37
1996	*	0.31
1997	0.63	*
1998	0.05	*
1999	0.04	0.30
2000	0.42	0.36
2001	0.20	0.37
2002	0.30	0.14
2003	0.40	0.27
2004	0.48	0.41
2005	0.15	0.37
All	0.37 (0.60 without January)	0.63

correlation coefficient between seeing and 200-mbar wind speed is $R = 0.63$. Table 3 shows the correlation coefficient between the monthly DIMM seeing and the 200-mbar wind velocity at Paranal and La Silla, on a yearly basis. For each observatory only twice is the correlation coefficient greater than 0.5. The correlation is not systematic and it randomly and rarely happens at both observatories. We can then draw the conclusion that 200-mbar wind speed is not a robust criterion for atmospheric columnar seeing prediction. This result is consistent with those obtained by other authors in shorter periods of time, like Carrasco et al. (2003) for Sierra Negra.

From the time evolution of seeing and 200-mbar wind velocity, we have noticed that the seeing over Paranal has an important increasing trend with increasing years, especially from 1997 to 2005, whereas both the velocity and the direction of the 200-mbar wind remain stable during the period analysed. Lombardi, Navarrete & Sarazin (2008) have demonstrated that the seeing trend over Paranal is affected by the ground layer and especially the first atmospheric layer centred on 47 m. They used a long-term recombined data base from DIMM, MASS and SLODAR for the period from 2005 January to 2007 June in order to study the evolution of both the turbulence profile and the seeing at Paranal observatory. They compared the trends of the total C_N^2 measured by DIMM with the C_N^2 of the ground layer (atmospheric layer extending from 0 to 375 m) and the free atmosphere (atmospheric layer extending from 375 m to 24 km). They demonstrated that the evolution of the free atmosphere was almost constant and that the increasing trend in the DIMM C_N^2 was driven by the increase of the ground layer. They also evaluated the contribution of the first layer (from 0 to 94 m) to the total ground layer and found that 78 per cent of the C_N^2 of the ground layer is concentrated in the first layer. They concluded that the turbulence driving the increase tendency is concentrated in the first 50 m above the ground, assuming the log-normal distribution of the turbulence of the first layer reported by Tokovinin & Travouillon (2006).

Therefore in the case of Paranal the wind velocity is not correlated with the seeing for the period analysed. Nevertheless, other astroclimatic parameters correlate with the wind speed at 200 mbar, as we discuss in the following sections.

3.2 MASS measurements over Paranal

Current techniques for turbulence profiling include in situ sounding with balloon microthermals and remote optical sounding by generalized SCIDAR and MASS instruments. MASS is the only instrument that can be used for routine measurements during the selection process of new astronomical sites, because it is portable and operates under less constrained conditions than SCIDAR. However, MASS has low vertical resolution, $\Delta h/h = 0.5$ where h is the altitude from the ground, and MASS is not sensitive to turbulence in the first 500 m above the ground. MASS measures the turbulence profile from the scintillation of single stars (Tokovinin & Korlinov 2001; Korlinov et al. 2002). The light flux of a single star collected by a small telescope (14 cm) is received by four concentric ring apertures with diameters of 2, 3.7, 7.0 and 13 cm and detected by 1-ms time-sampling photomultipliers. 10 scintillation indices corresponding to four individual apertures and six pairwise combinations are fitted by a model of six thin turbulent layers at pre-defined altitudes of 0.5, 1, 2, 4, 8 and 16 km above the site (Tokovinin et al. 2003). Another model of three layers at altitudes not pre-defined is fitted as well, in order to detect the altitudes of the strong turbulent layers.

Each layer represents an integral of turbulence J_i:

$$J_i = \int_{\text{layer}} C_N^2\, w(h)\, \mathrm{d}h, \tag{6}$$

measured in $\mathrm{m}^{1/3}$, where C_N^2 (h) is the refractive index structure constant in $\mathrm{m}^{-2/3}$ and $\omega(h)$ is the dimensionless response function of MASS. MASS response functions are nearly triangular (Tokovinin et al. 2003), going to zero at the altitudes of adjacent layers, and are equal to unity at the given altitude layer. The sum of all response functions is constant (within 10 per cent) at altitudes above 500 m.

The atmospheric seeing ε_l produced by a turbulent layer is computed from the intensity J_l:

$$\varepsilon_l = \left(\frac{J_l}{6.8 \times 10^{-13}}\right)^{\frac{3}{5}} \tag{7}$$

for ε_l in arcsec at $\lambda = 500\,\mathrm{nm}$.

The seeing obtained without the contribution of the turbulence of the first 500 m above ground is the free-atmosphere seeing ϵ_{f}.

As the MASS measurements provide an important set of astroclimatic parameters, we will generalize our objective and look for any relationships between these astroclimatic parameters and the 200-mbar wind velocity. The reason for this is that if any relationships are proven at Paranal, there is a chance this could be the case at other observatories. Parameters relevant to adaptive optics techniques are the seeing, the atmospheric time constant and the isoplanatic angle. The definitions of the seeing, the time constant and the isoplanatic angle are given by equations (1), (3), (5) and (7).

Fig. 7 illustrates the correlations found between astroclimatic parameters provided by the MASS instrument and the 200-mbar wind velocity at Paranal. All nightly median values are considered with their corresponding 200-mbar wind velocities at 0000 UT, which corresponds to about 2000 h at Paranal. Fig. 8 shows the seasonal shapes of the 200-mbar wind together with the seeing of levels 4–6 (top left), wavefront coherence time (bottom left) and isoplanatic angle (bottom right). Fig. 9 illustrates the vertical profile of the seeing in winter, spring, summer and autumn. Levels 1, 2 and 3 do not correlate with the 200-mbar wind velocity. We should mention

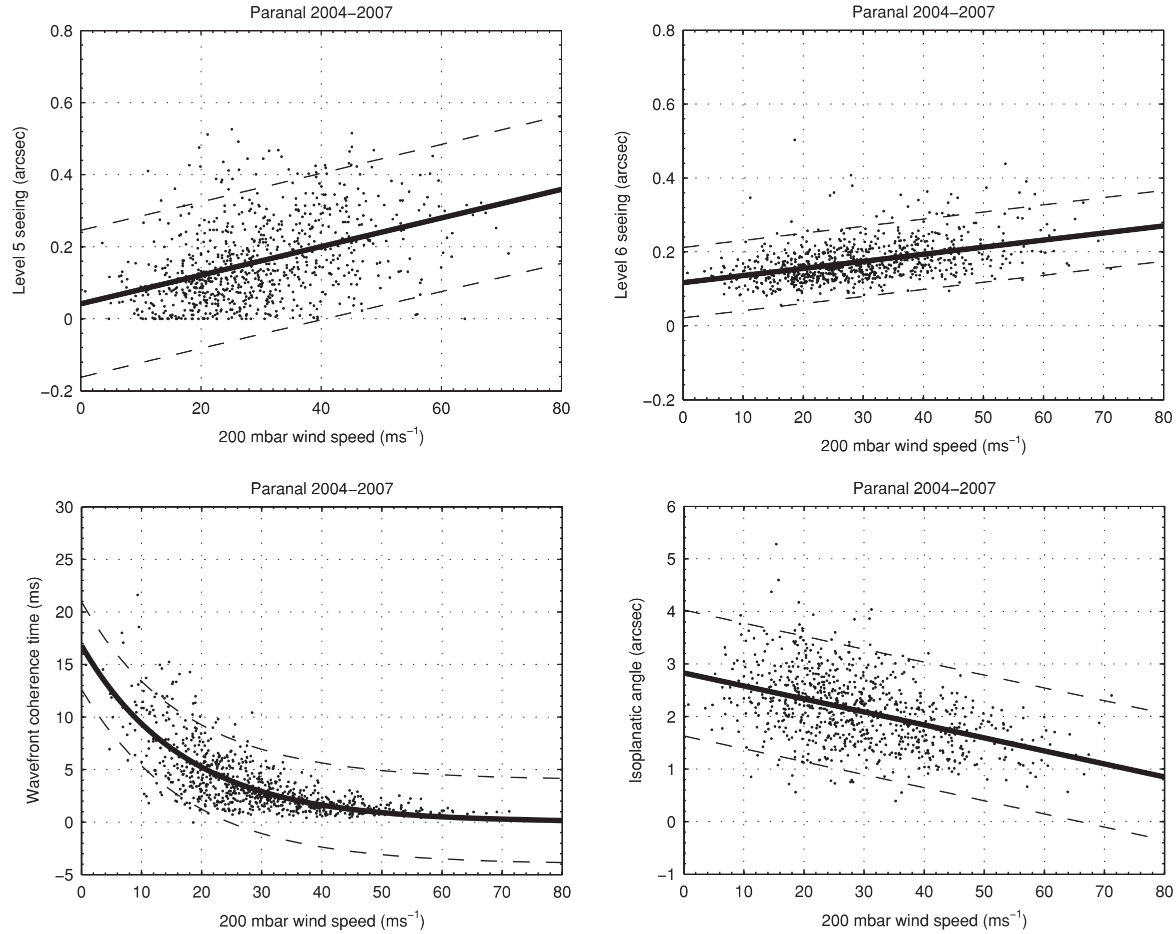

Figure 7. Correlation between median nightly values of astroclimatic parameters and the 200-mbar wind velocity at 0000 UT collected from the NCEP/NCAR reanalysis data base. The parameters considered are the MASS measured seeing of atmospheric levels 4, 5 and 6, the wavefront coherence time and the isoplanatic angle. The period studied extends from 2004 September to 2007 April. The fitting functions are given within 95 per cent confidence limits.

Table 4. Correlation coefficients between the monthly 200-mbar wind velocities averaged for the period 2004–2007 and the median seeing at different atmospheric levels, averaged for the period 2004–2007.

Correlation of 200-mbar wind velocity and astroclimatic parameters	*R* Nightly medians	*R* Monthly averages	*R* Averaged monthly averages
Level 4 seeing	0.28	0.48	0.74
Level 5 seeing	0.43	0.69	0.79
Level 6 seeing	0.44	0.59	0.70
Free-atmosphere seeing	0.19	0.27	0.45
Wavefront coherence time	0.68	0.89	0.97
Wavefront coherence time (exp fit)	0.76	0.92	0.98
Isoplanatic angle	0.45	0.59	0.78

that these levels did not correlate with the wind speed of lower atmospheric levels: 700, 600 and 500 mbar. The vertical gradient of the potential temperature may contribute to this lack of correlation between the seeing level and the corresponding wind speed.

Clear tendencies are visible for levels 5 and 6, the wavefront coherence time and the isoplanatic angle (Fig. 7). Table 4 illustrates the correlation coefficients related to these data sets compared with the 200-mbar wind velocity. The first column concerns the nightly median values of the astroclimatic parameters and 200-mbar wind velocity at 0000 h. In the second column, the nightly values averaged to obtain monthly averages are considered. In the statistics of the 200-mbar wind velocity, we considered only the nights where MASS data are provided. The last column is related to averaged monthly averages, providing the seasonal shape. Linear correlations between 200-mbar wind speed and nightly seeing data never exceed 0.5. The highest values reached are about 0.44 for levels 5 and 6. Even if it is a low correlation coefficient, it is a very important feature when related to nightly medians. Starting with these values, we can expect higher correlation coefficients for the data sets of monthly averages and even higher for averaged monthly averages. Fig. 10 shows the wind speed in terms of geopotential heights averaged for the 2004–2007 period. The points indicated correspond to the altitudes of the MASS levels. The highest values of the wind speed are reached at 200 mbar, which corresponds to an altitude of

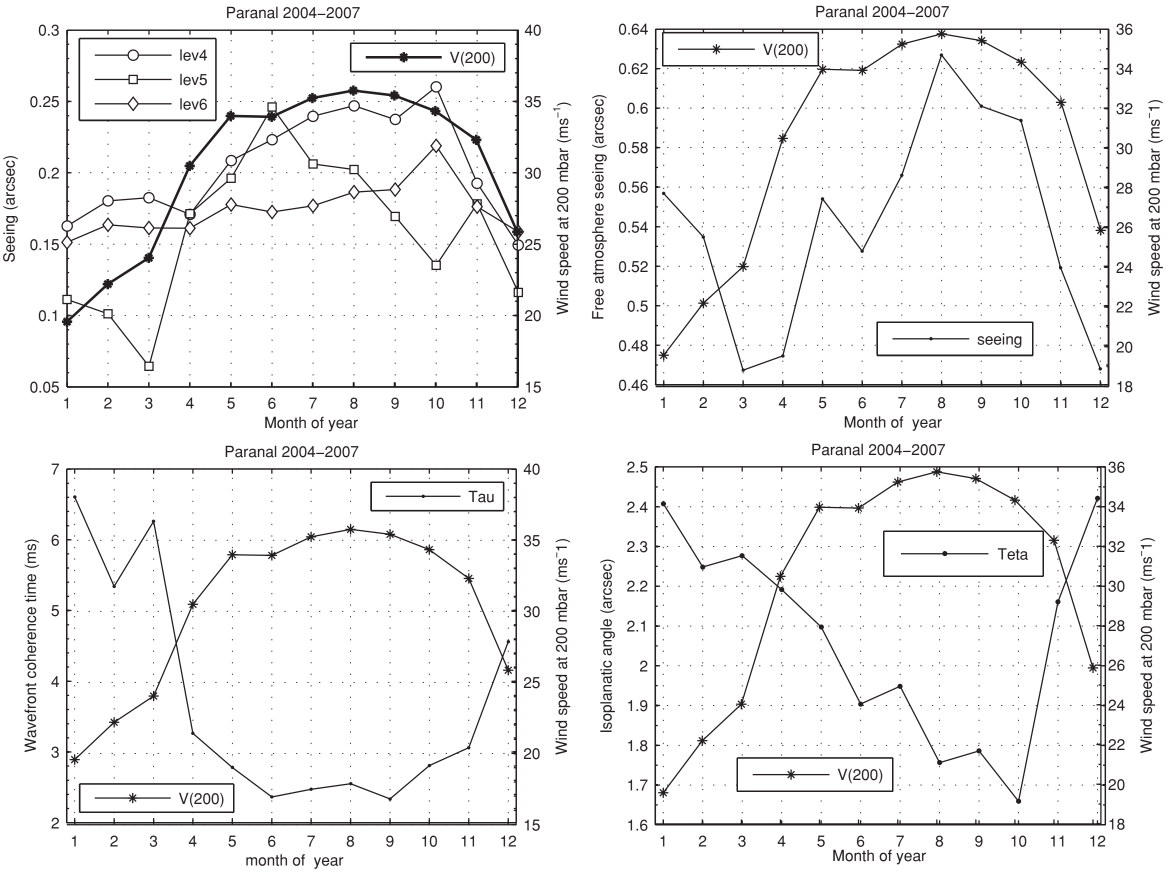

Figure 8. Seasonal shape of the 200-mbar wind velocity and astroclimatic parameters: seeing of levels 4, 5 and 6, free-atmosphere seeing, atmospheric time constant and isoplanatic angle.

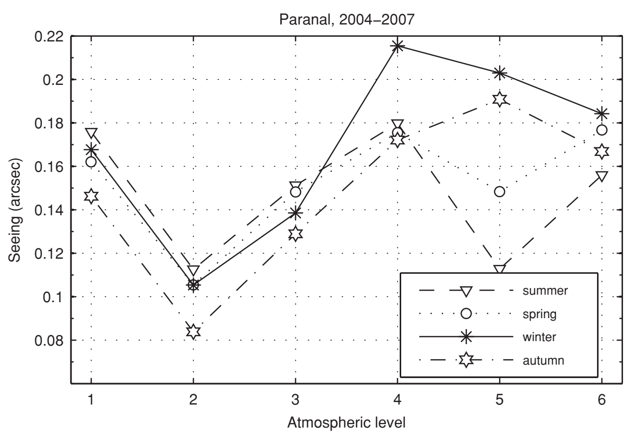

Figure 9. Atmospheric seeing seasonal behaviour. July, August and September accounts for winter, October, November and December for spring, January, February and March for summer and April, May and June for autumn.

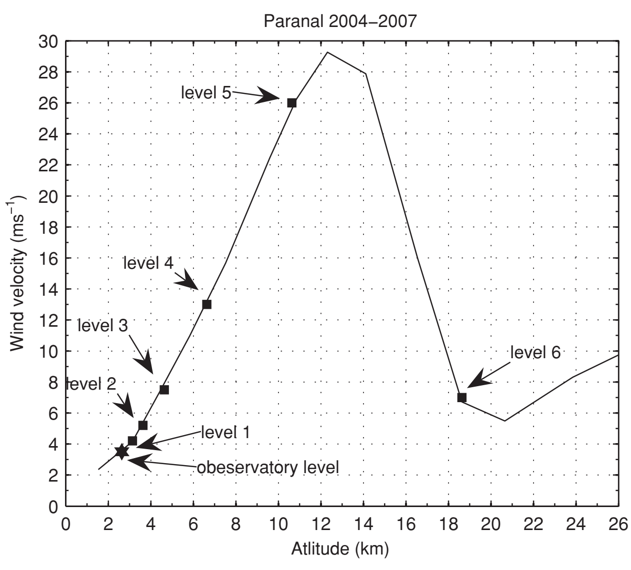

Figure 10. Wind velocity profile in terms of geopotential heights, averaged for the period 2004–2007, at Paranal observatory. Wind data are provided by the NCEP/NCAR reanalysis data base. The altitudes and corresponding wind velocities of the MASS levels are given.

12 km above sea level. The contribution of the 200-mbar wind is accounted for in both levels 5 and 6. This is the reason why the correlations are higher between 200-mbar wind speed and the seeing of levels 5 and 6 compared with other levels. It is surprising that layer 6 of the MASS has a tighter correlation to the 200-mbar wind speed than level 5 (Fig. 7), considering that level 5 is close to the peak wind speed (Fig. 10). The level 5 seeing has a very broad histogram with wide monthly and seasonal variations (Figs 9 and 10), whereas the level 6 seeing has a very narrow histogram with slight monthly and seasonal variations. The corresponding linear relationships illustrated in Fig. 7 between 200-mbar wind velocity and levels 5 and 6 seeing are given by the following formulae expressed

within 95 per cent confidence limits:

$$\varepsilon_{\mathrm{level5}} = 0.0040(\pm 0.0012)\, V_{200} + 0.042(\pm 0.037), \quad (8)$$

$$\varepsilon_{\mathrm{level6}} = 0.0019(\pm 0.0005)\, V_{200} + 0.117(\pm 0.017). \quad (9)$$

32 months contribute to the monthly statistics. The correlation coefficient is 0.69 for level 5 and 0.59 for level 6. For the data set constituting the seasonal shape, $R = 0.79$ for level 5, $R = 0.70$ for level 6 and $R = 0.74$ for level 4. Given the fact that level 4 is close to level 5, and that the wind speed of close atmospheric levels correlate well in general, the seasonal shape of the level 4 seeing is mostly driven by the 200-mbar wind velocity. Paranal observatory is where the correlations between the wind speed of all atmospheric levels and the wind speed at 200 mbar correspond the most, compared with other observatories (García-Lorenzo et al. 2005). The average free-atmosphere seeing is 0.53 arcsec.

The wavefront coherence time decreases with increasing 200-mbar wind velocity. The tendency seems exponential. In fact the correlation coefficient is $R = 0.68$ for a linear polynomial fit and $R = 0.76$ for an exponential fit. The correlations are very high considering the fact that they are related to nightly data. The exponential tendency illustrated in Fig. 7 is given within 95 per cent confidence limits by the following relation:

$$\tau_0 = 16.8(\pm 2.4)\, \exp[-0.058(\pm 0.007)\, V_{200}. \quad (10)$$

For the monthly data set $R_{\mathrm{linear}} = 0.89$ and $R_{\mathrm{exponential}} = 0.92$ and for averaged monthly averages $R_{\mathrm{linear}} = 0.97$ and $R_{\mathrm{exponential}} = 0.98$. Currently, we have no explanation for the exponential tendency of the MASS atmospheric time constant in terms of the 200-mbar wind velocity. We will work on that in a forthcoming paper. The average wavefront coherence time measured by the MASS instrument at Paranal is 3.8 ms.

However, we should mention that we expect the coherence time to be a function of $C_{\mathrm{st}}/V_{200\,\mathrm{mbar}}$, where C_{st} is a constant. Such a fit gives a very poor correlation: $R^2 = -0.18$. Given the fact that $\tau_0 = 0.31 r_0/V_0$ and that the Fried parameter r_0 is not a constant, such a correlation between $V_{200\,\mathrm{mbar}}$ and τ_0 is very poor. When we consider the variable $t = r_0/V_{200\,\mathrm{mbar}}$, then the function expressed within 95 per cent confidence limits, $\tau_0 = 0.352(\pm 0.011)\, t$, gives a correlation coefficient $R = 0.77$. This is representative of the correlation between τ_0 measured by the MASS instrument and the wavefront coherence time obtained by the Sarazin & Tokovinin (2002) relation, $\tau^* = (0.31 r_0)/(0.4 V_{200\,\mathrm{mbar}})$, if we suppose that the nights with high-atmospheric-level turbulence dominate, which is generally the case over Paranal observatory.

We can then point out the great influence of the 200-mbar wind speed on the wavefront coherence time measured by the MASS instrument at Paranal during the period studied.

Concerning the isoplanatic angle, there is an anti-correlation with the 200-mbar wind speed. The correlation coefficient $R = 0.45$ for nightly data and $R = 0.59$ and 0.78 for averaged monthly data. The average isoplanatic angle at Paranal for the period studied is 2 arcsec. The relationship of the anti-correlation illustrated in Fig. 7, between the isoplanatic angle and the 200-mbar wind speed, is given within 95 per cent confidence limits by the following expression:

$$\theta_0 = -0.025(\pm 0.007)\, V_{200} + 2.83(\pm 0.22). \quad (11)$$

The turbulence characteristic altitude $\overline{H} = 0.31 r_0/\theta_0$ is about 7242 m above the observatory level, which corresponds to about 10 km above sea level, close to the nominal altitude of the jet stream. This is the reason for the anti-correlation between θ_0 and V_{200}.

We can then underline the importance of studying the 200-mbar wind in pre-selection processes, as it drives most of the seasonal shapes of the astroclimatic parameters as evidenced in Fig. 8. This is confirmed by the results illustrated in Table 4. We can see a good anti-correlation between the seasonal shapes of wavefront coherence time and isoplanatic angle compared with that of the 200-mbar wind speed. Good correlations are also observed for levels 4, 5 and 6. One other reason to consider the wind speed at 200 mbar as an important parameter having a great influence on seeing is visible in Fig. 9. Here the seasonal behaviour of the vertical profile of the seeing is illustrated. Upper atmospheric levels dominate the influence on the seeing during the south hemisphere winter and spring.

4 COMPARISON OF OUKAIMEDEN RECORDS WITH OTHER OBSERVATORIES

Carrasco et al. (2005) studied the 200-mbar wind speed, from 1980 to 1995, at Costa Rica (10°N, 85°W), Sierra Negra (18.98°N, 97.31°W), San Pedro Mártir (31°.05N, 115°.49W), Mauna Kea (19°.83N, 155°.47W), Paranal (24°.63S, 70°.40W), La Silla (29°.25S, 70°.73W), Gamsberg (23°.34S, 16°.23W) and Maidanak (38°.68N, 66°.90E). Costa Rica was included as a tropical location that has no jet stream and was taken as a reference. The authors found that the monthly wind velocity at 200 mbar for the sites considered was best fitted by the following function $V(t)$, given by the relation

$$V(t) = C_{\mathrm{s}} - B \cos[2\pi(t - t_0)/1\,\mathrm{yr}], \quad (12)$$

with three fitting parameters: C_{s} is the average wind speed; B the amplitude of the wind-speed modulation and t_0 the time of the year of minimum wind speed. We found that this model fits our 200-mbar wind speed data. Fig. 11 shows the monthly values of 200-mbar wind speed averaged over the same 16-year period, from 1980–1995, at Oukaimeden observatory, fitted by

$$V(t) = 19.9 - 5.31 \cos\left[\frac{2\pi}{12}(t - 9.8)\right]. \quad (13)$$

Table 5 shows the characteristics of modulated 200-mbar wind speed over a 16-year period from 1980–1995. The sites studied in Carrasco et al. (2005) are shown, as well as our results concerning Oukaimeden observatory. We can see that Sierra Negra has the lowest mean 200-mbar wind speed ($C_{\mathrm{s}} = 17.37$), followed by Oukaimeden ($C_{\mathrm{s}} = 19.9$), Gamsberg ($C_{\mathrm{s}} = 23.09$), Mauna Kea

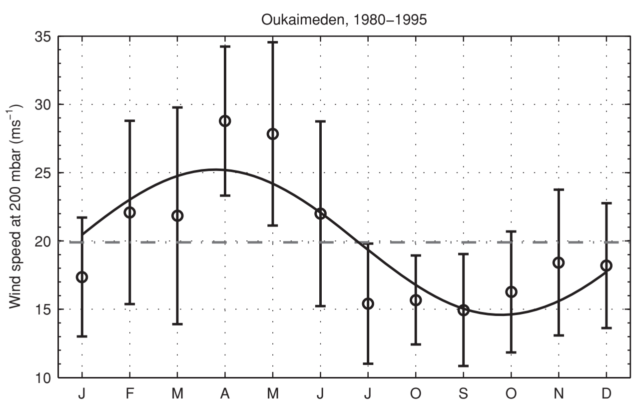

Figure 11. Monthly wind speed at Oukaimeden averaged for a 16-year period from 1980–1995, with standard deviations. The solid line indicates the best fit of a yearly modulated wind speed, $v(t) = C_{\mathrm{s}} - B \cos[2\pi(t - t_0)/1\,\mathrm{yr}]$. The dash–dotted line indicates the average.

Table 5. Characteristics of modulated 200-mbar wind speed: $v(t) = C_s - B\cos[2\pi(t - t_0)/1\,\mathrm{yr}]$, over a 16-year period from 1980–1995 (Carrasco et al. 2005).

Site	C_s ($\mathrm{m\,s^{-1}}$)	$2B$ ($\mathrm{m\,s^{-1}}$)	t_0 (month)
Costa Rica	9.67	4.21	6.82
Sierra Negra	17.37	21.47	8.00
Oukaimeden	19.9	10.62	9.8
Gamsberg	23.09	18.39	1.12
Mauna Kea	24.34	16.56	8.43
San Pedro Mártir	25.36	24.46	7.51
Mainanak	29.30	5.83	7.29
Paranal	29.75	21.23	1.66
La Silla	32.65	12.32	2.14

Table 6. 200-mbar wind statistics for the period 1980–2006 (27 years) at different astronomical sites. $\langle V_{200}\rangle$ is the 200-mbar wind-speed global average, amplitude is the difference of maximum and minimum statistical winds and $\langle std\rangle$ is the average standard deviation for 1980–2006. These statistics are computed from monthly means.

Site	$\langle V_{200}\rangle$ ($\mathrm{m\,s^{-1}}$)	Amplitude ($\mathrm{m\,s^{-1}}$)	$\langle std\rangle$ ($\mathrm{m\,s^{-1}}$)
Costa Rica	7.686	9.261	2.855
Sierra Negra	18.323	27.793	4.028
Oukaimeden	20.331	13.061	5.649
La Palma	20.831	20.928	5.490
Mauna Kea	20.973	17.303	5.512
Gamsberg	21.662	21.208	3.986
Aklim	22.618	21.486	5.635
San Pedro Mártir	22.902	27.101	6.30
Mainanak	25.907	6.694	5.160
Paranal	28.054	17.716	4.871
La Silla	31.235	12.173	5.462

($C_s = 24.34$), San Pedro Mártir ($C_s = 25.36$), Maidanak ($C_s = 29.3$), Paranal ($C_s = 29.75$) and La Silla ($C_s = 32.65$). Concerning the amplitude of the modulating sinusoidal function, Maidanak has the lowest value ($2B = 7.29$), followed by Oukaimeden ($2B = 10.62$), La Silla ($2B = 12.32$), Mauna Kea ($2B = 16.56$), Gamsberg ($2B = 18.39$), Paranal ($2B = 21.23$), Sierra Negra ($2B = 21.47$) and San Pedro Mártir ($2B = 24.46$). Even if Sierra Negra has an average 200-mbar wind velocity lower than Oukaimeden's, its amplitude is higher by a factor of two (21.47 versus 10.62 for Oukaimeden). However, Sierra Negra 200-mbar monthly averages are lower than Oukaimeden's, with the exception of January, February, March and December. Concerning the amplitude, although the amplitude is lower for Maidanak ($5.83\,\mathrm{m\,s^{-1}}$ versus $10.62\,\mathrm{m\,s^{-1}}$ for Oukaimeden), the average wind speed is higher ($29.3\,\mathrm{m\,s^{-1}}$ versus $19.9\,\mathrm{m\,s^{-1}}$ for Oukaimeden). Therefore we conclude that Oukaimeden observatory has good 200-mbar wind-speed characteristics for adaptive optics (low mean and amplitude).

Table 6 illustrates the 200-mbar wind velocity characteristics at different astronomical sites with the global mean 200-mbar wind velocity. The amplitude of the wind, which is the difference between maximum and minimum monthly averages, and the monthly standard deviations are given. 324 monthly 200-mbar wind velocities contributed to the statistics (27 years, 1980–2006) for every observatory. Aklim (latitude = 30°.13N, longitude = 8°.31W, altitude = 239 3 m) is a Moroccan candidate site for the Extremely Large Telescope project prospect. We can see good 200-mbar characteristics for Oukaimeden, with a small global mean ($20.3\,\mathrm{m\,s^{-1}}$), the second in the list after Sierra Negra ($18.3\,\mathrm{m\,s^{-1}}$), and a small amplitude ($13\,\mathrm{m\,s^{-1}}$), the third in the list after Maidanak ($6.7\,\mathrm{m\,s^{-1}}$) and La Silla ($12.2\,\mathrm{m\,s^{-1}}$).

5 CONCLUSIONS

In this work we have performed wind statistics over Oukaimeden observatory; we have shown that the 200-mbar wind speed has a seasonal behaviour, with a maximum in spring and a minimum in summer. The wind direction is predominantly towards the east.

We found a weak correlation between daily seeing values and 200-mbar wind speed for 2003 and no specific relation for 2004. We tried to understand the variability of the correlation by studying La Silla and Paranal DIMM seeing and 200-mbar wind velocity, because long-term data are available. We conclude that this correlation happens randomly and very rarely.

We have analysed the wind vertical profile for the years 2003 and 2004 in order to look for any connections between 200-mbar wind speed and other pressure-level velocities. We found that for 2003 the correlation coefficients between the 200-mbar wind velocity and the other pressure-level velocities are higher than the ones for 2004, especially at lower altitudes (0.60 versus 0.35 for the pressure level 700 mbar, 0.71 versus 0.50 for the pressure level 600 mbar, 0.81 versus 0.69 for the pressure level 500 mbar and 0.87 versus 0.81 for the pressure level 400 mbar). These correlations could explain why the seeing and the 200-mbar wind velocity exhibit a linear tendency for the year 2003. Even if the correlation coefficient between daily values of seeing and 200-mbar wind velocity is weak (0.66), it is exceptional.

The direction of the 200-mbar wind speed is stable during all the years analysed, with a predominant direction from the west, leading to the conclusion that only the magnitude of the 200-mbar wind speed affects the average velocity of the turbulence. The vertical profiling of the turbulence will be treated elsewhere.

Nevertheless, a large set of astroclimatic parameters provided by the MASS instrument at Paranal observatory during a period of four years has been also analysed. Stratified seeing measurements at six atmospheric levels (0.5, 1, 2, 4, 8 and 16 km), free-atmosphere seeing, wavefront coherence time and isoplanatic angle have been compared with the velocity of the 200-mbar wind. As a result, we found good correlations of the 200-mbar wind velocity with level 4, 5 and 6 seeing, wavefront coherence time and isoplanatic angle, with correlation coefficients of 0.74, 0.79, 0.70, 0.97 and 0.78 respectively. The free-atmosphere seeing exhibits only a slight tendency, with a correlation coefficient of 0.45. First, the jet-stream airmass accounted for in levels 5 and 6 leads to satisfying correlation coefficients when comparing their seeing with the 200-mbar wind velocity; secondly, the 200-mbar wind velocity must be comparable to lower-pressure-level wind speeds for the period analysed. With better vertical resolution, we expect an improved correlation coefficient between the 200-mbar wind velocity and the corresponding atmospheric seeing level.

We compared our results with those reported by Carrasco et al. (2005). They compared 200-mbar wind velocity statistics at Sierra Negra, Pedro Mártir, Mauna Kea, Paranal, La Silla, Gamsberg and Maidanak. We found that their model fits our data. Furthermore, by comparing our statistics with theirs, we found that Oukaimeden has one of the best characteristics for adaptive optics applications.

We also compared our statistics with those concerning Paranal, La Silla, La Palma, Mauna Kea, San Pedro Mártir, Maidanak, Gamsberg, Aklim and Sierra Negra for a period of 27 years extending from 1980–2006. In conclusion, in terms of 200-mbar wind statistics Oukaimeden observatory is classified as having very good characteristics, comparable to the best sites worldwide. The comparison between our seeing record of 2003 and 2004 and those of La Silla and Paranal measured over the same period leads to the result that 67 per cent of the time the seeing at Oukaimeden was lower than the seeing at La Silla and Paranal observatories.

We will continue monitoring the site for further studies of turbulence and meteorological data comparison. Moreover, we are also monitoring the Aklim site, as it is one of the candidates for the E-ELT programme, among three others: ORM in the Canary Islands, Ventarones in Chile and Macon in Argentina. Four identical MASS–DIMM apertures have been set up in these observatories and are now collecting data. One interesting issue is to carry this study to these sites in order to compare their seeing qualifications and explore the connections between 200-mbar wind velocity and astroclimatic parameters in a large area.

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