Astronomical site ranking based on tropospheric wind statistics

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ABSTRACT

High-altitude wind speeds have been adopted as a parameter for astronomical site selection based on the relationship found at the Paranal and Cerro Pachón sites between the average velocity of the turbulence (\(V_0\)) and winds at the 200-mbar pressure level (\(V_{200}\)). Although this relationship has not been checked at any other site in the world and a connection between image quality and \(V_{200}\) has not been proven anywhere, high-altitude wind speed (\(V_{200}\)) is a parameter for checking the suitability of sites for adaptive optics and surveying potential sites for extremely large telescopes.

We present comprehensive and reliable statistics of high-altitude wind speeds and the tropospheric flows at the location of five important astronomical observatories. We have used the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data base to collect wind data at nine tropospheric pressure levels for the five selected sites. For comparison and validation of the data from the climate diagnostic model, we have also obtained wind profiles from radiosonde stations. The degrees of correlation found indicate a high level of significance between NCEP/NCAR Reanalysis and balloon data bases, pointing to NCEP/NCAR Reanalysis as a useful data base for site characterization.

Statistical analysis exclusively of high-altitude winds points to La Palma as the most suitable site for adaptive optics, with a mean value of 22.13 m s\(^{-1}\) at the 200-mbar pressure level. La Silla is at the bottom of the ranking, with the largest average value 200 mbar wind speed (33.35 m s\(^{-1}\)). We have found a clear annual periodicity of high-altitude winds for the five sites under study.

We have also explored the connection of high- to low-altitude atmospheric winds as a first approach of the linear relationship between the average velocity of the turbulence and high-altitude winds. We may conclude that high- and low-altitude winds show good linear relationships at the five selected sites. The highest correlation coefficients correspond to Paranal and San Pedro Mártir, while La Palma and La Silla show similar high- to low-altitude wind connection. Mauna Kea shows the smallest degree of correlation, which suggests a weaker linear relationship. Our results support the idea of high-altitude winds as a parameter for ranking astronomical sites in terms of their suitability for adaptive optics, although we have no evidence for adopting the same linear coefficient at different sites. The final value of this linear coefficient at a particular site could drastically change the interpretation of high-altitude wind speeds as a direct parameter for site characterization.

Key words: turbulence – instrumentation: adaptive optics – site testing.

1 INTRODUCTION

Ground-based astronomical observations are drastically affected by the presence of atmospheric turbulence. The theoretical angular resolution of a telescope, determined by its diameter, is usually severely degraded because of atmospheric turbulence. Adaptive optics techniques have been developed to compensate for the effects of the atmosphere on astronomical images and to reach the diffraction limit of our telescopes. However, the design and operation of adaptive optics systems are complex and difficult because the turbulence above astronomical sites is still insufficiently well characterized. In spite of partial information on the turbulence behaviour above existing astronomical observatories, it is obvious that a site with low and

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stable turbulence should be better suited for the implementation of adaptive optics than one with a turbulent and chaotic atmosphere. The requirements for excellent image quality of current large and future very large telescopes demand a proper knowledge of atmospheric turbulence, and several projects are already pursuing this aim. Moreover, the precise characterization of the turbulence above a particular site requires long-term monitoring. To counter the lack of long-term information on turbulence, high-altitude winds (in particular winds at the 200-mbar pressure level – hereafter $V_{200}$) have been proposed (Sarazin & Tokovinin 2002) as a parameter for estimating the total turbulence at a particular site, because records of this parameter exist from several sources. This proposal is based on the idea that the greatest source for turbulence generation is related to the highest peak in the vertical wind profile, which is located at the 200-mbar pressure level globally. Also, Sarazin & Tokovinin (2002) find a good correlation between the average velocity of the turbulence, $V_0$, and $V_{200}$ of the form $V_0 = 0.4V_{200}$ at the Cerro Pachón and Paranal Observatories in Chile. Although the $V_0 \propto V_{200}$ relationship has not been tested at other sites, its validity would simplify the calculation of key parameters for adaptive optics, such as the coherence time. Furthermore, $V_{200}$ statistics could be used as a parameter for ranking the suitability of different observing sites for adaptive optics. However, such a relationship never indicates a connection between the total turbulence at the ground level (seeing) and wind speed at the 200-mbar pressure level. Indeed, Sarazin & Tokovinin (2002) have also studied this option but a connection has not been found. Despite this, a false idea of a connection between image quality and high-altitude wind speed is increasingly widespread among those in the astronomical community interested in adaptive optics.

Some studies centred on $V_{200}$ statistics values have been published recently (Sarazin 2002; Carrasco & Sarazin 2003), and a detailed statistical analysis of $V_{200}$ for Roque de los Muchachos Observatory (ORM) on the island of La Palma (Spain) have been performed by Chueca et al. (2004). While the linear $V_0 \propto V_{200}$ relationship (Sarazin & Tokovinin 2002) is confirmed at other sites, a first approach to connecting high-altitude winds to turbulence at ground level can be carried out by studying the wind vertical profile and the relation of high- to low-altitude winds. Previous studies have also reported a connection of ground layer winds to image quality (Muñoz-Tuñón, Varela & Mahoney 1998; Varela, Muñoz-Tuñón & Gurtubai 2001).

In this paper we present a detailed statistical analysis of $V_{200}$ for different observing sites in the two hemispheres. For the first time, we study the connection of high- to low-altitude winds and we present the statistical analysis of the wind vertical profile at five astronomical sites: the ORM, Mauna Kea and San Pedro Martir in the north, and Paranal and La Silla in the south (Table 1). We also discuss the suitability for adaptive optics of the five summits analysed on the basis of the wind vertical profile statistics.

2 THE DATA

We have selected five existing sites spread all over the globe to study the behaviour of $V_{200}$ and the vertical wind profile. Table 1 lists the astronomical observatories considered, their location and altitude. We used the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data base to collect wind speeds at different pressure levels for the five sites. The Reanalysis data were obtained as six-hourly and daily $U$-wind and $V$-wind components from the beginning of 1980 to the end of 2002. Wind speeds in this data base are considered as one of the most reliably analysed fields (see Kalnay et al. 1996 and Kistler et al. 2001 for a detailed description) and they are heavily constrained by observational data. We obtained the six-hourly and daily wind speed module from $U$-wind and $V$-wind six-hourly and daily components (more than 33 600 data for each component and location).

For comparison and validation of the data from the climate diagnostic model, we have obtained winds from radiosonde stations. The main criteria in selecting radiosonde stations were the year range for available data and the distance from the observing sites. Table 2 shows information about the final selected stations.

In both data bases we have selected the simultaneous data for the period 1980–2002 to derive the mean monthly wind at the different common pressure levels. We found a good correlation between the balloon and NCEP/NCAR data statistics in the sites studied. Fig. 1 shows the linear Pearson correlation coefficient of the mean monthly $V_{200}$ time series from the two data bases at different pressure levels. The degrees of correlation found indicate a high level of significance between the NCEP/NCAR Reanalysis and balloon data bases at the five selected locations and for any altitude considered, thereby

### Table 1. Location of selected observing sites (from http://www.seds.org/billa/bigeyes.html).

| Station         | Place                  | Latitude  | Longitude | Available range | Close to site | Distance to site (km) |
|-----------------|------------------------|-----------|-----------|-----------------|---------------|----------------------|
| ORM (La Palma)  | La Palma               | 28.46 N   | 16.25 W   | 1960–2001       | La Palma      | 163                  |
| 600200          | Santa Cruz de Tenerife (Spain) | 28.467 N | 16.25 W   | 1960–2001       | La Palma      | 163                  |
| 855430          | Quintero (Chile)       | 32.780 S  | 71.517 W  | 1957–1999       | La Silla      | 400                  |
| 912850          | Hilo (Hawaii, USA)     | 19.716 N  | 185.06 W  | 1950–2002       | Mauna Kea     | 44.5                 |
| 854420          | Antofagasta (Chile)    | 23.410 S  | 70.467 W  | 1957–2001       | Paranal       | 136                  |
| 722930          | California (USA)       | 32.867 N  | 117.15 W  | 1972–2001       | San Pedro Martir | 260                |

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revealing NCEP/NCAR Reanalysis as a useful data base for the site characterization approach. The detailed analysis of winds in the following sections will be performed only with the NCEP/NCAR Reanalysis data at each site. This data base provides better temporal coverage and resolution than the balloon measurements and has no gaps in the time series.

3 ANALYSIS

Sarazin & Tokovinin (2002) have suggested that the suitability of a site for adaptive optics is related to winds at the pressure level of 200 mbar. The average altitude of this pressure level at the Earth’s poles is about 1 km lower than at the equator. Moreover, the 200-mbar pressure level presents a slightly seasonal altitude dependency, being about 400 m lower in altitude in winter than in summer time. All other pressure levels show a similar behaviour. Assuming an International Civil Aviation Organization (ICAO) standard atmosphere (see http://www.pdas.com/coesa.htm for an exact definition), we shall consider hereafter a mean altitude of 12 170 m for the 200-mbar pressure level at any site. In the same way, we adopt the same mean altitude for any of the pressure levels considered in this paper at any site. Therefore, the height axis of the figures can only be taken as an approximate value.

3.1 $V_{200}$ statistics and seasonal behaviour

We have derived the monthly average, $V_{200}$, for the period 1980–2002 for the five selected sites, and the resulting monthly statistics are shown in Fig. 2(a). There is a seasonal trend in the high-altitude wind behaviour. In the Northern hemisphere, the highest $V_{200}$ occurs during spring and the lowest in summer. La Silla and Paranal in the Southern hemisphere show high $V_{200}$ values during the southern winter and spring.

In the Northern hemisphere, San Pedro Mártir shows the lowest $V_{200}$ during the summer, while the lowest $V_{200}$ in winter corresponds to La Palma. In autumn, Mauna Kea and La Palma show similar values of $V_{200}$. The differences in $V_{200}$ are small for the three northern observatories during the spring. We define $V_N$ as the ratio of the monthly average wind velocity at 200 mbar to the $V_{200}$ mean over the full period (Table 3) ($V_N = V_{200\text{monthly}}/V_{200\text{global mean}}$). This ratio has the same seasonal behaviour as $V_{200}$ at each observatory but magnitudes are related to the same reference level, the $V_N$ mean, which is always equal to unity. If $S_{200}$ is the monthly standard deviation of $V_{200}$, the $V_N$ to $S_{200}$ ratio gives a view of the stability of high-altitude winds, as shown in Fig. 2(b). The $V_N/S_{200}$ ratios at
any site are directly comparable, with higher \( V_{200}/S_{200} \) values indicating more stable \( V_{200} \) regimes. According to the defined stability parameter, \( V_{200}/S_{200} \), San Pedro Mártir presents the least stable high-altitude winds of the three northern sites. La Palma shows a similar stability parameter throughout the year, with the more stable \( V_{200} \) during May and June. Mauna Kea presents a seasonal behaviour of the stability parameter, with highest values in February and March and lowest during May and June. Although the high-altitude winds at Mauna Kea are more stable than at La Palma from January to March, \( V_{200} \) is higher in Mauna Kea during these months. Only September and October show a better behaviour at Mauna Kea than at La Palma, with similar \( V_{200} \) values but high stability at Mauna Kea.

In the Southern hemisphere, Paranal has more stable high-altitude winds than La Silla except in January. At Paranal, November is the most stable month in terms of \( V_{200} \). Table 3 lists the \( V_{200} \) mean, median, standard deviation and rms values for the period 1980–2002 for the five observatories studied.

In terms of \( V_{200} \), La Palma is the best site of the five studied, with a mean value of 22.13 m s\(^{-1}\), the smallest standard deviation (Table 3) and showing the most stable high-altitude winds. In contrast, La Silla shows the highest average value, with a mean \( V_{200} \) of 33.35 m s\(^{-1}\), although the amplitude in Table 3 (the difference between minimum and maximum) at this site is only 12.46 m s\(^{-1}\), the lowest of the five observatories studied. The statistical \( V_{200} \) amplitudes for Paranal and Mauna Kea are quite similar, while the value for San Pedro Mártir is approximately twice the \( V_{200} \) amplitude at La Silla or La Palma. According to the relationship connecting \( V_{200} \) and \( V_{200} \) at Mauna Kea, the linear relationship of 150 and 200 mbar for La Palma, La Silla, Paranal and San Pedro Mártir. For Mauna Kea, the 700-mbar pressure level is always below the altitude of the observatory. The connection between the boundary layer and high-altitude winds is the subject of a forthcoming study (Varela et al., in preparation).

In order to determine any dominant temporal variation of \( V_{200} \) over the observatories in question, we have performed a wavelet analysis (see Torrence & Compo 1998 for a practical step-by-step description of wavelet analysis) of the time series obtained from NCEP/NCAR data bases for the five selected observatories. We used a Morlet function as wavelet mother. Fig. 3 shows the time series (plots a), the local wavelet power spectrum (plots b) and the time average power spectrum (plots c) corresponding to the wavelet analysis of each of the five observatories in study. A table of the reconstruction time series accuracy for each site is shown in Fig. 3(F). The wavelet analysis of \( V_{200} \) for the La Palma site has already been discussed by Chueca et al. (2004), and is in good agreement with the present results.

The annual periodicity of \( V_{200} \) remains significant for all the five sites studied. Except for Mauna Kea, a 0.5-yr period appears in the global power spectrum for the other four selected sites, although only for La Palma is this peak still significant in the local wavelet power. For La Palma and La Silla, a 2.3-yr period is also significant in the local power spectrum, but they are less than significant globally. A 4-yr period appears for the five observatories in study, but only in San Pedro Mártir does it remain significant in the global power spectrum.

Atmospheric conditions at the Paranal site have changed considerably from the site testing period in the early 1990s to the present (Sarazin 2000). The increase in the average seeing from 1998 onwards at Paranal has been identified with El Niño/La Niña events in South America (Beniston, Casals & Sarazin 2002). However, we have found no similar discrepancy between high-altitude winds before and after 1998 at Paranal. The temporal evolution of the annual periodicity of \( V_{200} \) remains quasi-constant from 1990 (Fig. 3D). The mean and standard deviation of \( V_{200} \) for the period 1990–1994 are 29.19 and 7.66 m s\(^{-1}\), respectively. These values are slightly lower than those obtained for the period 1998–2002 (30.77 and 8.31 m s\(^{-1}\) for the mean and standard deviation of \( V_{200} \), respectively) but they are still in agreement. Therefore, the influence of events affecting the atmospheric conditions at the Paranal site at low altitude has no counterpart to winds at high altitude.

### Table 3. Statistical results of 200-mbar wind speed (m s\(^{-1}\)) by using the data from the NCEP/NCAR Reanalysis data base for the period 1980–2002 at different astronomical sites. Amplitude is the difference of maximum and minimum statistical winds.

| Site          | Amplitude (m s\(^{-1}\)) | Mean (m s\(^{-1}\)) | Median (m s\(^{-1}\)) | Standard deviation (m s\(^{-1}\)) | rms (m s\(^{-1}\)) |
|--------------|--------------------------|---------------------|-----------------------|----------------------------------|-------------------|
| La Palma     | 13.69                    | 22.13               | 20.79                 | 11.67                            | 0.06              |
| La Silla     | 12.46                    | 33.35               | 32.77                 | 12.94                            | 0.07              |
| Mauna Kea    | 18.00                    | 24.33               | 22.81                 | 12.30                            | 0.07              |
| Paranal      | 18.47                    | 30.05               | 28.63                 | 13.01                            | 0.07              |
| San Pedro    | 26.49                    | 26.55               | 24.57                 | 15.39                            | 0.08              |
Figure 3. Wavelet analysis results for the mean monthly 200-mbar wind velocity at: (A) ORM (La Palma), Spain; (B) La Silla, Chile; (C) Mauna Kea, Hawaii, USA; (D) Paranal, Chile; (E) San Pedro Martir, Mexico. In these panels, (a) is the time series used for the wavelet analysis, and (b) is the local wavelet power spectrum of the time series obtained from the Morlet wavelet. The colour scale at the bottom indicates the power spectrum intensity of the full range; (c) is the average power spectrum. The dashed line is the 95 per cent confidence level. Panel (F) shows the results comparing the reconstruction time series from the wavelet analysis and the input time series.
Figure 4. Linear Pearson correlation coefficient obtained comparing the wind data at each pressure level to the wind measurements at any other level at (a) La Palma, (b) La Silla, (c) Mauna Kea, (d) Paranal and (e) San Pedro Mártil. The comparison level is indicated by a different line type or symbol according to the table at the bottom right. The value equal to 1 also indicates the comparison pressure level.

tropopause. In other words, wind measurements at 100 mbar could correspond to tropospheric, tropopausal or mesospheric winds, depending on the season.

Table 4 shows the mean values of winds at different levels, derived by averaging the individual Pearson coefficients obtained from comparing a particular level to any other (Fig. 4) and the standard deviation of these coefficients ($\sigma_m$). We have not considered the comparison of any level to itself (Pearson coefficient of 1 in Fig. 4).

Table 4 also includes the mean covariance (Cov.) and its standard deviation ($\sigma_{cov}$) as an indicator of the strongest of the linear relationships. Although the largest mean correlation coefficients correspond to 400 mbar above La Palma, La Silla and San Pedro Mártil, and 300 mbar for Mauna Kea and Paranal, the maximum mean covariance corresponds to a level of around 200 mbar.

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Combining Fig. 4 and the results of Table 4, we may conclude that high-altitude winds show good relationships to low-altitude winds.

The highest correlation corresponds to Paranal and San Pedro Mártir. La Palma and La Silla show a similar behaviour in this regard, while Mauna Kea shows a worse correlation between high to low winds. On the basis of these results, we deduce that the relationship $V_0 \propto V_{200}$ (Sarazin & Tokovinin 2002) should be worse for Mauna Kea than for any of the other sites considered in this paper. The topographical influence seems to be slightly greater at the sites on islands than at the continental sites.

### 3.3 Wind profile statistics and seasonal behaviour

Fig. 5 shows the monthly average wind for the period 1980–2002 at different pressure levels for the five observatories. Wind statistics at the different pressure levels follow a similar seasonal behaviour to that of $V_{200}$ (Section 3.1), $V_{200}$ being the highest winds at any month and site. Only Mauna Kea shows slightly stronger mean winds at 150 mbar than $V_{200}$ during May. The monthly average winds at 100 mbar show the largest differences from the statistics of all the others at the pressure levels considered, perhaps because the 100-mbar level can be above or below the tropopause. The observatories studied seem to be statistically stable in the sense that they show the worst and best wind measurements for the same epoch at any of the pressure levels considered. Only Mauna Kea shows the strongest winds in levels at different months: while the statistical $V_{200}$ peak corresponds to March, the strongest winds for 150 and 250 mbar occur in April and February, respectively. The monthly average wind behaviour shown in Fig. 5 for Mauna Kea confirms the results of the previous section, showing that the connection between high- and low-altitude winds is not clear for the Mauna Kea site.

Table 5 shows the annual statistical results of the wind profiles for the five observatories. Vertical wind gradients are larger in winter than in summer, indicating more stable and hence less turbulent atmospheres in summer for all the observatories studied.

### 4 DISCUSSION AND CONCLUSION

The connection between $V_{200}$ and the average velocity of the turbulence, $V_0$, found by Sarazin & Tokovinin (2002) at Paranal and Cerro Pachón has been accepted as a parameter for tackling astronomical site suitability for adaptive optics. The linear relationship between $V_0$ and the vertical wind profile, $V(h)$, is established by the definition of $V_0$

$$V_0 = \frac{\int_0^\infty C_2^V(h)V(h) \, dh}{\int_0^\infty C_2^V \, dh},$$

where $C_2^V(h)$ is the turbulence vertical profile. The high level of agreement between winds at any altitude demonstrated in Section 3.2 therefore suggests a relationship between $V_0$ and $V_{200}$ at any of the observing sites studied. However, we have only demonstrated a connection of high- and low-altitude winds, not a connection of high-altitude winds and the average velocity of the turbulence. Even if such a connection were valid worldwide, it could be either linear or non-linear. In the mean time, we consider a linear relationship at the sites studied similar to that found at Paranal and Cerro Pachón. Our results support the idea of considering $V_{200}$ as a parameter for ranking astronomical sites with regard to their suitability for adaptive optics in spite of the lack of information on $C_2^V(h)$. However, the importance of deriving atmospheric turbulence profiles is still
essential. $C_2^{Nh}(h)$ determines the coefficient of the linear fit connecting $V_0$ and $V_{200}$ ($A$ hereafter, $V_0 = AV_{200}$). For Paranal and Cerro Pachón, this coefficient is $A = 0.4$ (Sarazin & Tokovinin 2002), but there are still no measurements for any other site. According to the results of this paper, we do not have any evidence for adopting the same coefficient at the different sites. Even in the hypothetical case of similar $C_2^{Nh}(h)$ at different summits (which is less than probable), the connection between high- to low-altitude winds reveals several differences at different sites, suggesting a different $A$ coefficient in the linear fit. The final value of the linear coefficient at a particular site could drastically change the interpretation of $V_{200}$ as a direct parameter for site characterization. If we consider a site with $V_{200}$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{wind velocidad.png}
\caption{The monthly average wind velocity for the period 1980–2002 at the pressure levels indicated in the table at the bottom right for the selected sites.}
\end{figure}
Table 5. Statistical results of wind speed profile (m s\(^{-1}\)) by using the data from the NCEP/NCAR Reanalysis data base for the period 1980–2002 at different astronomical sites. Amplitude is the difference of maximum and minimum statistical winds at each pressure level.

| Site       | Level (mbar) | Amplitude (m s\(^{-1}\)) | Mean (m s\(^{-1}\)) | Median (m s\(^{-1}\)) | Standard deviation (m s\(^{-1}\)) | rms (m s\(^{-1}\)) |
|------------|--------------|---------------------------|---------------------|------------------------|-----------------------------------|-------------------|
| La Palma   | 100          | 14.55                     | 13.69               | 12.69                  | 7.72                              | 0.04              |
|            | 150          | 14.39                     | 20.51               | 19.43                  | 10.24                             | 0.06              |
|            | 250          | 12.61                     | 20.66               | 19.04                  | 11.49                             | 0.06              |
|            | 300          | 11.30                     | 18.23               | 16.56                  | 10.49                             | 0.06              |
|            | 400          | 8.53                      | 14.18               | 12.71                  | 8.44                              | 0.05              |
|            | 500          | 5.29                      | 11.64               | 10.42                  | 6.86                              | 0.04              |
|            | 600          | 3.09                      | 9.78                | 8.79                   | 5.63                              | 0.03              |
|            | 700          | 3.02                      | 8.27                | 7.52                   | 4.64                              | 0.03              |
|            | 100          | 11.17                     | 20.58               | 20.37                  | 7.73                              | 0.04              |
|            | 150          | 10.68                     | 31.09               | 30.74                  | 10.93                             | 0.06              |
|            | 250          | 12.42                     | 31.04               | 30.23                  | 13.05                             | 0.07              |
| La Silla   | 300          | 12.06                     | 27.52               | 26.70                  | 12.20                             | 0.07              |
|            | 400          | 10.92                     | 20.45               | 19.48                  | 10.01                             | 0.05              |
|            | 500          | 9.32                      | 14.80               | 13.73                  | 7.96                              | 0.04              |
|            | 600          | 7.50                      | 10.46               | 9.35                   | 6.27                              | 0.03              |
|            | 700          | 5.18                      | 7.20                | 6.16                   | 4.68                              | 0.03              |
|            | 100          | 14.14                     | 12.76               | 10.85                  | 8.35                              | 0.05              |
|            | 150          | 16.81                     | 22.22               | 20.54                  | 11.53                             | 0.06              |
|            | 250          | 16.98                     | 21.39               | 19.77                  | 11.35                             | 0.06              |
| Mauna Kea  | 300          | 15.83                     | 17.41               | 15.73                  | 9.83                              | 0.05              |
|            | 400          | 11.88                     | 11.27               | 9.75                   | 7.12                              | 0.04              |
|            | 500          | 8.09                      | 8.00                | 6.85                   | 5.25                              | 0.03              |
|            | 600          | 4.93                      | 6.24                | 5.46                   | 3.99                              | 0.02              |
|            | 100          | 15.45                     | 18.05               | 17.83                  | 8.35                              | 0.05              |
|            | 150          | 18.09                     | 28.58               | 27.99                  | 11.73                             | 0.06              |
|            | 250          | 17.29                     | 27.38               | 25.76                  | 12.66                             | 0.07              |
| Paranal    | 300          | 15.46                     | 23.85               | 22.29                  | 11.54                             | 0.06              |
|            | 400          | 12.41                     | 17.13               | 15.70                  | 9.29                              | 0.05              |
|            | 500          | 10.34                     | 12.12               | 10.66                  | 7.30                              | 0.04              |
|            | 600          | 7.67                      | 8.39                | 7.20                   | 5.31                              | 0.03              |
|            | 700          | 3.98                      | 5.43                | 4.80                   | 3.31                              | 0.02              |
|            | 100          | 19.49                     | 15.45               | 14.27                  | 9.59                              | 0.05              |
|            | 150          | 26.01                     | 23.94               | 22.77                  | 13.54                             | 0.07              |
|            | 250          | 24.07                     | 24.62               | 22.24                  | 14.87                             | 0.08              |
| San Pedro  | 300          | 21.15                     | 21.44               | 18.88                  | 13.45                             | 0.07              |
|            | 400          | 16.22                     | 16.22               | 13.88                  | 10.77                             | 0.06              |
|            | 500          | 12.32                     | 12.83               | 10.82                  | 8.63                              | 0.05              |
|            | 600          | 8.45                      | 10.26               | 8.71                   | 6.52                              | 0.04              |
|            | 700          | 5.40                      | 7.86                | 6.93                   | 4.67                              | 0.03              |

statistics similar to Paranal and A adopts larger values than 0.4 at that particular site, we obtain larger \( V_0 \) values than for Paranal. In contrast, a smaller A value will indicate less atmospheric turbulence at that hypothetical site than at Paranal.

Another important point is the seasonal behaviour of \( V_{200} \). Changes in \( V_{200} \) regimes in different seasons could have an important influence on the value of \( A \), taking into account that we have presented here only the statistics of wind modules, and that we have not considered the wind direction, which could point to changing wind regimes with season. We could obtain different A values for different months, i.e. A could also present seasonal behaviour. To have the best parametrization of the average wind turbulence, \( V_0 \), in terms of \( V_{200} \) seems to be mandatory in any study of the seasonal behaviour of the linear coefficient A. Unfortunately, our information about A is very poor, with measurements only at Paranal and Cerro Pachón (Sarazin & Tokovinin 2002). If A were a constant coefficient and had a similar value to that found for Paranal and Cerro Pachón, \( V_0 \) would present a similar seasonal behaviour to that of \( V_{200} \). In this hypothetical case, the statistical results obtained here for \( V_{200} \) would indicate that La Palma is at the top of the suitability ranking list for adaptive optics, while La Silla is at the bottom.

Atmospheric stability, in the sense of similar behaviour and good correlation of winds at different altitudes, is also an important point in establishing \( V_{200} \) as a direct parameter for site characterization and adaptive optics suitability. Our results show that Paranal and San Pedro Mártir present statistically more stable atmospheres than the other three sites considered. The stability results are found to be...
similar for La Silla and La Palma. Mauna Kea shows the worst results with regard to high- to low-altitude winds. Taking into account the behaviour of $V_{200}$ and its connection to low-altitude winds, Mauna Kea should present unstable average wind turbulence compared to the other sites. However, the stability of winds at different altitudes is not a guarantee of stable turbulence behaviour. If $C_{nl}^2(h)$ is stable enough at a site with unstable wind behaviour at altitude, it should be a similar or better site for adaptive optics than a site with stable winds and unstable $C_{nl}^2(h)$ behaviour. A more stable atmosphere, in the sense established in this paper, suggests a better relationship between $V_0$ and $V_{200}$ and better accuracy of the determination of the $A$ coefficient than sites with unstable atmospheres.

Although a correlation between seeing and winds at the 200-mbar pressure level has not been found at any site (Sarazin & Tokovinin 2002; Carrasco & Sarazin 2003) the mistaken idea of identifying high-altitude winds with turbulence has become increasingly popular among the astronomical community. If there is indeed a relationship between $V_0$ and $V_{200}$ at the different sites, this does not mean that the level of turbulence depends on $V_{200}$ but only that the coherence time will vary with $V_{200}$ behaviour. We wish to alert the astronomical community concerning this false interpretation of $V_{200}$ as a parameter related to turbulence.

5 SUMMARY AND CONCLUSIONS

We have analysed the wind vertical profiles for the period 1980–2002 using the NCEP/NCAR Reanalysis archive at five astronomical sites. We have verified the consistency of the statistical results derived from these data bases and balloon measurements. Our main results and conclusions may be summarized as follows.

(i) The excellent statistical correlation between NCEP/NCAR Reanalysis data and balloon measurements reveals the NCEP/NCAR Reanalysis archive to be a useful source of meteorological data for site characterization.

(ii) In terms of high-altitude wind speed ($V_{200}$) statistics, La Palma is the best of the five sites studied, with a mean value of 22.13 m s$^{-1}$, the lowest standard deviation and the most stable $V_{200}$ behaviour. La Silla is at the bottom of the ranking with a mean $V_{200}$ of 33.35 m s$^{-1}$, although the seasonal $V_{200}$ amplitude is the lowest of the five cases, with a statistical value of 12.46 m s$^{-1}$.

(iii) We have found a clear annual periodicity of $V_{200}$ at the five observatories.

(iv) We have found a good level of correlation between high- and low-altitude winds, supporting a linear relationship between $V_{200}$ and the average velocity of the turbulence at any of the sites. However, the proportional coefficient of this relationship may differ from site to site as a result of the clear seasonal behaviour of winds and the large differences of wind vertical profile behaviour at the sites.

The results in this paper do not confirm a relationship between $V_0$ and $V_{200}$ at the studied sites, but only a connection between high- and low-altitude winds. $V_0$ strongly depends on turbulence structure, and therefore its connection to high-altitude winds could only be established with a proper turbulence characterization. We alert the astronomical community to the wrong idea of identifying high-altitude winds and turbulence at ground level, which is becoming more and more popular in recent meetings. If a relationship between $V_0$ and $V_{200}$ were valid elsewhere, we could connect coherence time and high-altitude winds, but never image quality.

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