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Mesoscale optical turbulence simulations at Dome C: refinements

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ABSTRACT

In a recent paper, the authors presented an extended study aimed at simulating the classical meteorological parameters and optical turbulence at Dome C during the winter with the atmospheric mesoscale model Meso-NH. The goal of that paper was to validate the model above Dome C with the support of measurements and to use it afterwards above the Internal Antarctic Plateau to discriminate between the qualities of different potential astronomical sites on the plateau. A statistical analysis has been presented and the conclusions of that paper were very promising. Wind speed and temperature fields (important for the computations of the optical turbulence parameters) were revealed to be reconstructed very well by the Meso-NH model, with better performances than achieved with the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, especially near the surface. All results were revealed to be resolution-dependent and it has been proved that a grid-nesting configuration (three domains) with a high horizontal resolution ($\Delta X = 1$ km) for the innermost domain is necessary to reconstruct all the optical turbulence features with a good correlation to measurements. High-resolution simulations provided an averaged surface-layer thickness just $\sim$14 m higher than estimated by measurements, and the seeing in the free atmosphere showed a dispersion from the observed one of just a few hundredths of an arcsec ($\Delta\varepsilon \sim 0.05$ arcsec). The unique limitation of the previous study was that the optical turbulence in the surface layer appeared to be overestimated by the model in both low- and high-resolution modes. In this study we present the results obtained with an improved numerical configuration. The same 15 nights have been simulated, and we show that the model results now match the observations almost perfectly in all their features: the surface thickness, the seeing in the free atmosphere and in the surface layer. This result now permits us to investigate other Antarctic sites using a robust numerical model well adapted to the extreme polar conditions (Meso-NH).

Key words: turbulence – atmospheric effects – site testing.

1 INTRODUCTION

The ability of the Meso-NH model to forecast the evolution of the atmosphere and the optical turbulence above the Antarctic Plateau has been extensively discussed in a previous paper by our team (Lascaux et al. 2009). In that paper, all the 15 winter nights for which measurements of C_N^2 were available (Trinquet et al. 2008) above Dome C were simulated with Meso-NH. The main conclusion of Lascaux et al. (2009) was that Meso-NH was able to reconstruct the optical turbulence in a region with extreme meteorological conditions such as Dome C. However, a mono-domain configuration with low resolution (100 km) is not suitable for providing optical turbulence features well correlated to measurements, while a grid-nesting configuration constructed with three domains (horizontal resolutions of 25, 5 and 1 km) can do this. More precisely, the mean simulated surface-layer thickness $h_{\rm sl,mnh-high} = 48.9 \pm 7.6$ m was only 14 m higher than the observed one ($h_{\rm sl,obs} = 35.3 \pm 5.1$ m). The median simulated free-atmosphere seeing ($\varepsilon_{\rm mnh,FA} = 0.35 \pm 0.24$ arcsec) was very well correlated with the observed one ($\varepsilon_{\rm obs,FA} = 0.3 \pm 0.2$ arcsec). However, the model tended to overestimate the intensity of the optical turbulence in the surface layer, thus generating too strong a median total seeing ($\varepsilon_{\rm mnh,TOT} = 2.29 \pm 0.38$ arcsec) compared with the observed one ($\varepsilon_{\rm obs,TOT} = 1.6 \pm 0.2$ arcsec). This paper presents the updated results for the same set of winter nights with an improved numerical configuration for the Meso-NH model.

2 IMPROVEMENTS IN THE NUMERICAL CONFIGURATION

We refer readers to Lascaux et al. (2009) for a complete overview of the numerical configurations of the mesoscale simulations. Here we

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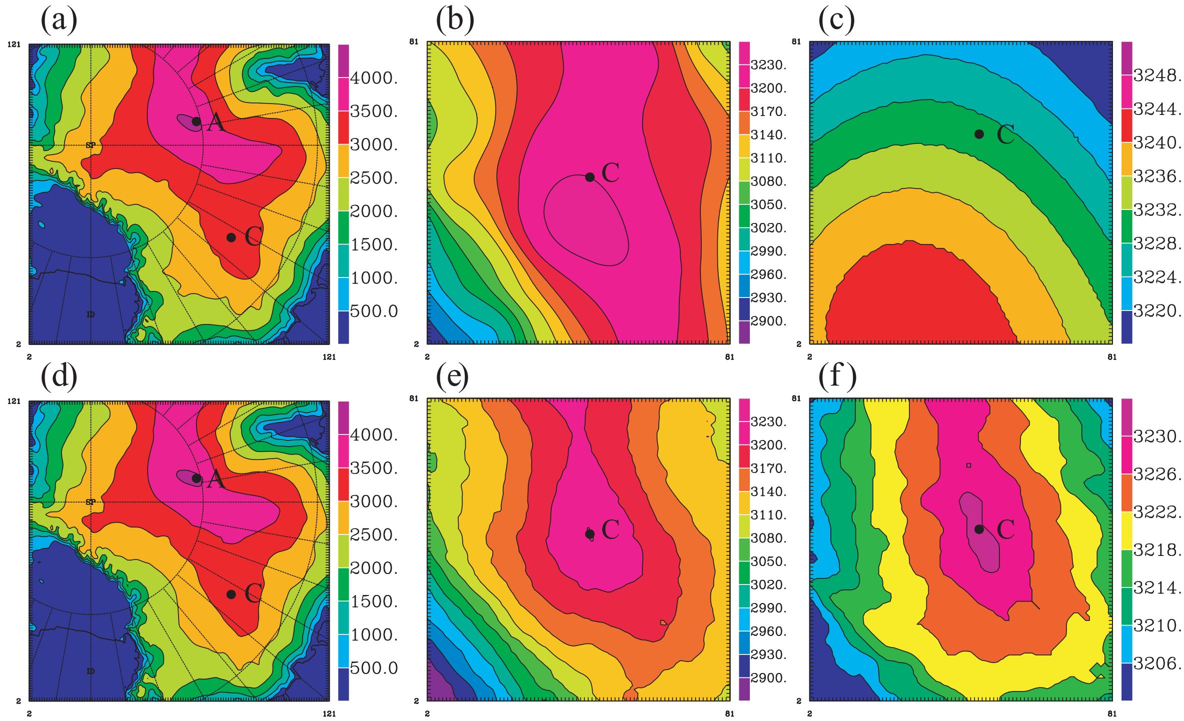

Figure 1. Orography of Antarctica as seen by the Meso-NH model (polar stereographic projection, grid-nesting configuration). (a), (b) and (c) show the original orography (GTOPO30) with horizontal resolution of 25, 5 and 1 km, respectively. (d), (e) and (f) show the orography obtained with the new digital elevation model (RAMPDEMv2) with horizontal resolution of 25, 5 and 1 km, respectively. The dot labelled 'C' indicates the Concordia Station. The dot labelled 'A' indicates Dome A. The altitude is expressed in metres (m).

briefly describe the differences in the numerical set-up with respect to the Lascaux et al. (2009) paper.

(1) A different digital elevation model (DEM), the so-called Radarsat Antarctic Mapping Project Digital Elevation Model, version 2 (RAMPDEMv2: Liu et al 2001) has been used instead of the GTOPO30 DEM from the US Geological Survey used in Lascaux et al. (2009). The improvement in the description of the orography is shown in Fig. 1. The best description of the Dome C area is obtained with RAMPDEMv2, and is especially visible at horizontal resolutions below 5 km. At $\Delta X = 5$ km (Figs 1b and e, with GTOPO30 and RAMPDEMv2 orographic models respectively), one can see that the Concordia Station (labelled C on the figure) is located on the local summit with RAMPDEMv2 and is not with GTOPO30. This is even more evident inside the innermost domain ($\Delta X = 1$ km, Figs 1c and f).

(2) The surface scheme of Meso-NH, the so-called Interaction Soil Biosphere Atmosphere (ISBA) scheme, has been optimized for Antarctic conditions: the thermal coefficient of the soil has been optimized for polar conditions and a climatological underground temperature T_c has been introduced (Le Moigne et al. 2009). We briefly summarize the main concepts of that study. Our ability in reconstructing the surface temperature T_s is related to our ability in reconstructing the sensible heat flux H that is responsible for the buoyancy-driven turbulence in the surface layer. The Meso-NH surface scheme is based on the force-restore method, which consists of two equations that control the temporal evolution of the surface temperature T_s and the deep temperature T_2 at a few tens of centimetres underground. The equation of the temporal evolution of the deep temperature has been modified by adding a term depending on two free parameters: a climatological temperature T_c and a relaxation term called γ. The two equations previously mentioned were forced by a one-year set of measurements of solar direct and long-wavelength radiation, the temperature T, wind speed V, pressure p and specific humidity q of the air above the ground. The simulated T_s and T_2 were compared with the observed ones (i.e. the temperature measured at -5 cm and -30 cm from the ground) to minimize the dispersion. This permitted us to determine the two free parameters T_c and γ. Such a study permitted us to optimize the surface scheme ISBA for applications of the Meso-NH model to polar conditions.

Coming back to our study, both mono-domain (low-resolution) and grid-nesting (high-resolution) configurations have been employed in Lascaux et al. (2009). In this paper we could have restricted the study to the grid-nesting configuration (with high horizontal resolution), as it was the one giving the best results. However we decided also to present the results of the low-horizontal-resolution configuration to confirm the previous conclusions of Lascaux et al. (2009) regarding the horizontal resolution necessary to be used for obtaining reliable forecasts.

3 OPTICAL TURBULENCE FORECAST

We focus our attention on the prediction of the three-dimensional maps of C_N^2 obtained with the Astro-Meso-NH package implemented by our team in the Meso-NH mesoscale model (Masciadri, Vernin & Bougeault 1999a; Masciadri, Vernin & Bougeault 1999b) and validated in successive phases above different astronomical sites (among the most important validations are Masciadri & Jabouille 2001, Masciadri, Avila & Sanchez 2004 and Masciadri & Egner 2006). The model is employed here with the new configuration mentioned in the previous section. We look especially at three different features that mainly characterize the optical turbulence, already discussed in Lascaux et al. (2009):

(i) the surface-layer thickness;
(ii) the median free-atmosphere seeing;
(iii) the median total seeing (from the ground up to 10 km above ground level).

The study is performed for the same set of 15 winter nights used in Lascaux et al. (2009) and employing the same analysis. We first present the results of prediction of the surface-layer thickness and then we present the forecasting of the free-atmosphere seeing $\varepsilon_{\rm FA}$ and the total seeing $\varepsilon_{\rm TOT}$.

3.1 Surface-layer thickness ($h_{\rm sl}$)

The same method used in Lascaux et al. (2009) is employed to determine the surface-layer thickness for each night. We highlight that this is not the only way to define the surface layer, but we are forced to use this method, employed by Trinquet et al. (2008), to be able to compare simulations with measurements. The thickness $h_{\rm sl}$ is defined as the vertical slab containing 90 per cent of the optical turbulence developed in the first kilometre:

$$\frac{\int_{8\,\rm m}^{h_{\rm sl}} C_N^2(h)\,{\rm d}h}{\int_{8\,\rm m}^{1\,\rm km} C_N^2(h)\,{\rm d}h} < 0.90, \qquad (1)$$

where C_N^2 is the refractive-index structure parameter.

We report in Table 1 the values of the observed surface-layer thicknesses and the corresponding mean and standard deviation (σ) and statistical error ($\sigma/\sqrt{N}$) for the 15 nights. The simulated $h_{\rm sl}$ for both the mono-domain configuration (i.e. low horizontal resolution) and grid-nesting configuration (i.e. high horizontal resolution) are summarized in Table 2. The values related to each night as well as the mean $h_{\rm sl,mnh-low}$ and $h_{\rm sl,mnh-high}$ are computed. A careful examination of the night of 2005 September 5 (for which the computed $h_{\rm sl,mnh-high}$ was 338.4 m) highlighted the fact that the value of the surface layer retrieved with the criterion reported in equation (1) was not exploitable for this night. Indeed, a look at the temporal evolution of the C_N^2 profile during that night (not shown here) clearly indicates a very weak turbulent night, with maxima of C_N^2 concentrated well below 30 m. Using the criterion expressed by equation (1), it follows that $h_{\rm sl}$ necessarily has to be large to achieve 90 per cent of turbulence developed in the first kilometre in this night. We therefore decided to remove this night from the mean computation in the high-resolution case in order to have a more representative $h_{\rm sl,mnh-high}$. This removal does not affect the qualitative conclusions inferred from the comparison between the observed and the computed mean values.

The high-resolution configuration gives a mean surface-layer thickness $h_{\rm sl,mnh-high} = 44.2 \pm 6.6$ m (with $\sigma = 24.6$ m) and the low-resolution configuration $h_{\rm sl,mnh-low} = 68.4 \pm 6.8$ m (with $\sigma = 26.5$ m). We confirm, therefore, the same conclusion obtained in Lascaux et al. (2009): the surface-layer thickness computed in grid-nested mode is closer to the observed one ($h_{\rm sl,obs} = 35.3 \pm 5.1$ m). Fig. 2 shows the correlation between observed and simulated surface-layer thicknesses with the associated intrinsic dispersion (error bar) equal to the σ values. This figure confirms the tendency of the high-resolution simulations to give $h_{\rm sl}$ values closer to the observed ones from a statistical point of view. One can see that the dispersions of the simulated values ($\sigma_{\rm mnh-high} = 24.6$ m and $\sigma_{\rm mnh-low} = 26.5$ m) are just slightly higher than the observed $\sigma_{\rm obs} = 19.9$ m. The dispersion of the surface-layer thicknesses is, therefore, reasonably well reconstructed by the model. If we take into account the statistical error in the high-resolution case ($\sigma/\sqrt{N}$), we conclude that the mesoscale model provides, for this statistical sample, a typical surface-layer thickness just ∼3 m higher than the observed one. We have therefore an excellent estimated mean, almost within the statistical uncertainty.

Table 1. Surface-layer thickness $h_{\rm sl}$ for 15 winter nights (Trinquet et al. 2008). The mean value is reported with the associated standard deviation (σ) and statistical error ($\sigma/\sqrt{N}$), where N is the number of independent estimates that are independent nights. Units in metres (m).

Date	Observed surface-layer thickness	Date	Observed surface-layer thickness
04/07/05	30	12/08/05	22
07/07/05	21	29/08/05	47
11/07/05	98	02/09/05	41
18/07/05	26	05/09/05	20
21/07/05	47	07/09/05	39
25/07/05	22	16/09/05	24
01/08/05	40	21/09/05	22
08/08/05	30		
	Mean	35.3	
	σ	19.9	
	$\sigma/\sqrt{N}$	5.1	

Table 2. Mean surface-layer thickness $h_{\rm sl}$ for the same 15 winter nights that are reported in Table 1, deduced from Meso-NH computations using the criterion in equation (1) in the temporal range 1200–1600 UTC. The mean value is reported with the associated statistical error $\sigma/\sqrt{N}$. Units in metres (m).

Date	Surface-layer thickness Meso-NH grid-nesting	Surface-layer thickness Meso-NH mono-domain
04/07/05	30.4	55.3
07/07/05	35.4	37.2
11/07/05	80.0	108.3
18/07/05	49.7	82.2
21/07/05	66.7	94.9
25/07/05	27.4	36.7
01/08/05	22.6	39.6
08/08/05	34.2	71.9
12/08/05	16.7	43.9
29/08/05	91.4	106.1
02/09/05	70.9	89.5
05/09/05	338.4	79.6
07/09/05	52.5	92.5
16/09/05	19.4	41.0
21/09/05	21.0	47.8
Mean	44.2*	68.4
σ	24.6*	26.5
$\sigma/\sqrt{N}$	6.6*	6.8

* These values are computed without taking into account the night of 2005 September 5 (see text for further explanations).

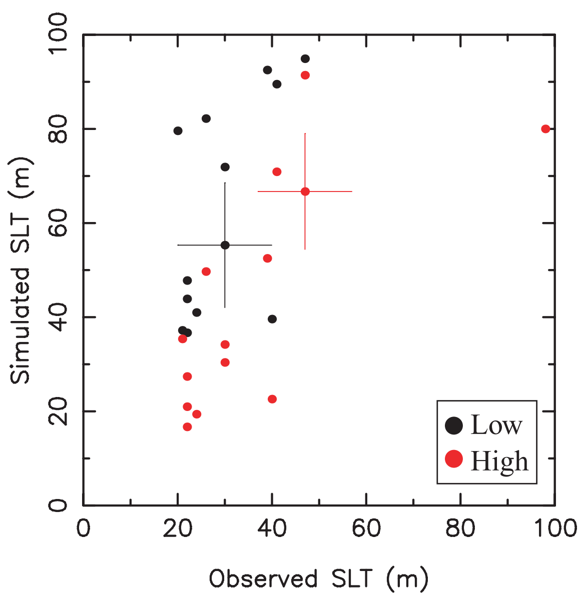

Figure 2. Correlation plot between measured and simulated surface-layer thicknesses (black: mono-domain configuration; red: grid-nested configuration). For the simulated values only the mean values between 1200 UTC and 1600 UTC are considered. For each configuration of the simulation (high and low horizontal resolution) the error bars are reported for one point only (and are equal to σ). Units are in metres (m).

3.2 Optical turbulence vertical distribution: seeing in the free atmosphere and in the whole atmosphere

Table 3 reproduces the observed and simulated total seeing ($\varepsilon_{\rm TOT}$) and free-atmosphere seeing ($\varepsilon_{\rm FA}$) for each night. The median values, with the respective standard deviation (σ) and statistical error ($\sigma/\sqrt{N}$), are reported for the low- and high-resolution cases. One can see that the median total seeing calculated with the low-resolution mode ($\varepsilon_{\rm TOT,mnh-low} = 2.05 \pm 0.21$ arcsec) still remains larger than the observed one ($\epsilon_{\rm TOT,obs} = 1.6 \pm 0.2$ arcsec), as was observed in Lascaux et al. (2009). However, the median forecasted seeing in the high-resolution mode matches the observations almost perfectly ($\varepsilon_{\rm TOT,mnh-high} = 1.7 \pm 0.21$ arcsec). The same can be stated for the median free-atmosphere seeing reconstructed by the model ($\varepsilon_{\rm FA,mnh-high} = 0.30 \pm 0.17$ arcsec), which is very well correlated to the observed one ($\epsilon_{\rm FA,obs} = 0.30 \pm 0.20$ arcsec). Fig. 3 shows the correlation plots for the total and free-atmosphere seeing, for each of the 15 investigated winter nights. This figure confirms the good agreement between model and observation from a statistical point of view. How do the modifications implemented in the Meso-NH model change the the vertical distribution of the optical turbulence (C_N^2 profiles)? Fig. 4 shows the vertical profiles of the observed and simulated C_N^2 obtained with the low- and high-resolution modes. We can observe that, similarly to the results of Lascaux et al. (2009), near the ground the high-resolution model provides a sharper decrease in the optical turbulence than the low-resolution mode. However, with this new model configuration the shape of the C_N^2 profile is better correlated to measurements in the first 60 m than with the previous configuration. We finally observe that, in both cases, there is still space for future improvements in some vertical slabs. We expressly avoid more complex calibration specific for a particular site, such as presented in Masciadri et al. (2004), because we intend to use the same model to discriminate between the quality of other sites above the internal plateau.

Table 3. Total seeing $\varepsilon_{\rm TOT} = \varepsilon_{[8\,{\rm m},h_{\rm top}]}$ and seeing in the free atmosphere $\varepsilon_{\rm FA} = \varepsilon_{[h_{\rm sl},h_{\rm top}]}$, calculated for the 15 nights and averaged in the temporal range 1200–1600 UTC. See the text for the definition of $h_{\rm sl}$ and $h_{\rm top}$. In the second column the observed values are reported, and in the third and fourth columns the simulated values obtained with high and low horizontal resolution respectively. Units in arcsec.

Date	Obs. $\varepsilon_{\rm FA}/\varepsilon_{\rm TOT}$ ($h_{\rm sl} = 33$ m)	MESO-NH HIGH $\varepsilon_{\rm FA}/\varepsilon_{\rm TOT}$ ($h_{\rm sl} = 44.2$ m)	MESO-NH LOW $\varepsilon_{\rm FA}/\varepsilon_{\rm TOT}$ ($h_{\rm sl} = 62.4$ m)
04/07/05	0.3/1.6	0.22/2.28	0.35/2.13
07/07/05	0.2/1.5	0.28/1.91	0.24/1.49
11/07/05	1.4/1.7	1.61/1.81	1.57/2.08
18/07/05	0.3/2.0	0.80/1.94	1.98/2.20
21/07/05	0.7/1.1	0.86/1.27	0.41/1.02
25/07/05	0.3/1.0	0.25/0.85	0.23/2.03
01/08/05	0.8/1.6	0.22/2.27	0.22/2.05
08/08/05	0.5/2.3	0.35/1.70	0.31/1.00
12/08/05	0.2/1.5	0.23/0.99	0.28/2.49
29/08/05	2.5/3.6	2.29/2.47	2.12/2.78
02/09/05	0.9/1.9	1.16/1.54	0.92/1.77
05/09/05	0.3/1.0	0.30/0.52	0.27/0.73
07/09/05	1.4/2.8	1.69/3.73	1.88/3.69
16/09/05	0.2/1.5	0.21/1.57	0.20/2.25
21/09/05	0.2/1.7	0.26/1.63	0.22/0.75
Median	0.3/1.6	0.30/1.70	0.31/2.05
σ	0.7/0.7	0.67/0.77	0.66/0.81
$\sigma/\sqrt{N}$	0.2/0.2	0.17/0.21	0.17/0.21

4 CONCLUSIONS

In this paper, simulations of the C_N^2 profiles related to all 15 nights for which measurements made at Dome C in winter are available have been compared with measurements. We conclude, that, in the present configuration, the Meso-NH model with the 'Astro-Meso-NH' package provides excellent estimates of the optical turbulence at Dome C, from a qualitative as well as quantitative point of view, if used in the high-resolution mode. All the conclusions achieved in Lascaux et al. (2009) remain unchanged. However we clearly find evidence, in this paper, of the positive impact of the new numerical configuration of the model Meso-NH on the forecast of the optical turbulence, especially for the surface-layer thickness and the total and free-atmosphere seeing. In synthesis, the Meso-NH model provides the following:

(1) a simulated mean surface-layer thickness $h_{\rm sl,mnh-high} = 44.2 \pm 6.6$ m, versus the observed $h_{\rm sl,obs} = 35.3 \pm 5.1$ m;

(2) a simulated median total seeing $\varepsilon_{\rm TOT,mnh-high} = 1.7 \pm 0.21$ arcsec, versus the observed $\varepsilon_{\rm TOT,obs} = 1.6 \pm 0.2$;

(3) a simulated median free-atmosphere seeing $\varepsilon_{\rm FA,mnh-high} = 0.30 \pm 0.17$ arcsec, versus the observed $\varepsilon_{\rm FA,obs} = 0.30 \pm 0.20$.

We are now ready to apply this model to other Antarctic regions and to explore the optical turbulence features of other potential interesting sites such as Dome A, South Pole or even Ridge A, in order to perform site intercomparisons and identify the best location for astronomical applications.

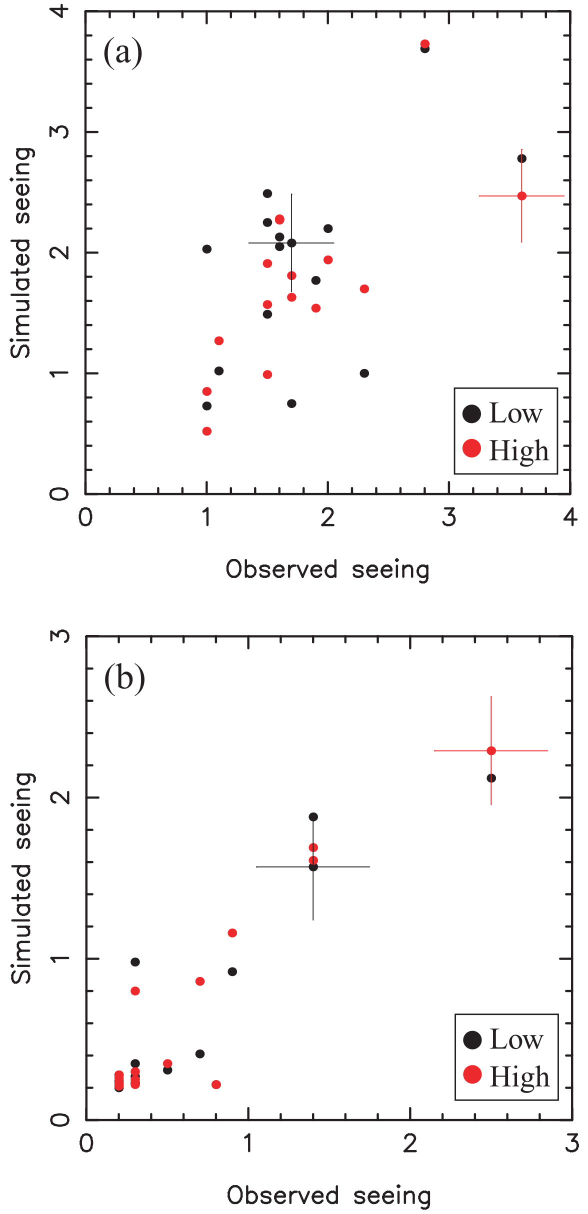

Figure 3. Correlation plot between measured and simulated (a) total seeing and (b) free-atmosphere seeing. Black dots: low resolution; red dots: high resolution. The error bars for simulations and observations are reported for one point only (and are equal to σ). Units are in arcsec.

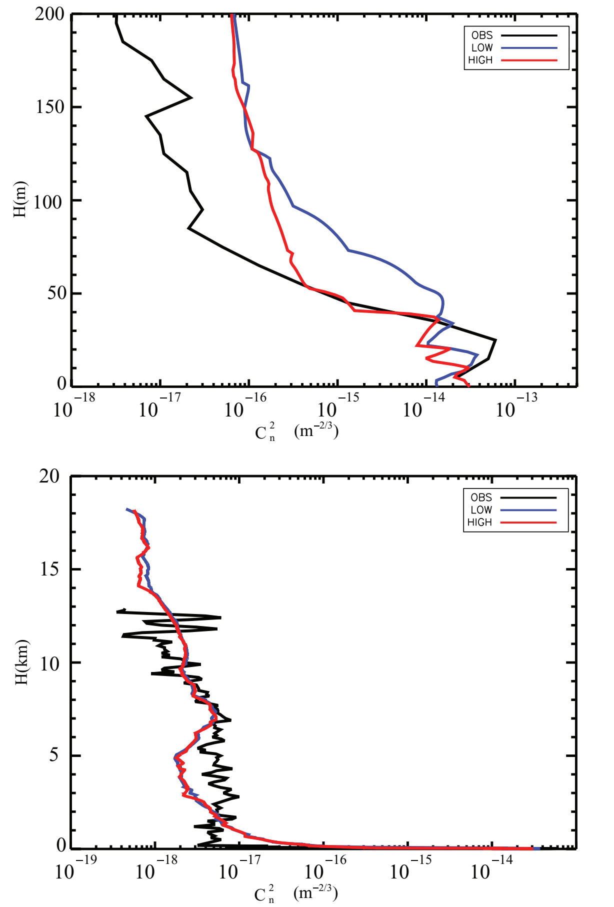

Figure 4. Median C_N^2 profile measured (black line) with microthermal sensors mounted on balloons (from Trinquet et al. 2008) and simulated with the Meso-NH mesoscale model with low horizontal resolution (blue line) and high horizontal resolution (red line), computed over the 15 nights. Upper: from the ground up to 200 m. Lower: from the ground up to 20 km. Simulations are considered in the temporal range 1200–1600 UTC. Units are in $m^{-2/3}$.

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