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MOSE: MESO-SCALE PREDICTION OF NEAR-GROUND METEOROLOGICAL PARAMETERS AT ESO SITES (CERRO PARANAL AND CERRO ARMAZONES)

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Abstract. In the framework of the MOSE project we present, in this contribution, a detailed analysis of the results obtained by comparisons between Meso-NH numerical model simulations and measurements from in situ instruments. The important amount of meteorological data came from in situ measurements from masts (distributed from the ground up to 30 m) and automatic weather stations (AWS). The parameters analyzed are the wind speed, the wind direction and the temperature at both sites. Different numerical set-up have been tested, with the highest model horizontal resolution having a grid size equal to 100 m. A sample of 20 nights in 2007 have been simulated. Model outputs have been compared to the in situ measurements from masts and AWS. The Meso-NH model succeeded very well in reproducing the meteorological parameters near the surface. We obtained excellent results for both wind and temperature parameters. These very encouraging results proved that the model could be used in operational mode at ESO E-ELT site to forecast wind speed, wind direction and temperature with a good level of accuracy, for application to the telescope management. Among the most important applications we cite the near-ground temperature forecast fundamental for the thermalization of the dome and the wind forecast extremely useful to evaluate telescope and secondary mirror vibrations.

1 Introduction

The work presented in this paper was done in the framework of the MOSE project, a general study about the feasibility of the forecast of meteorological parameters and optical turbulence at ESO sites (Cerro Paranal and Cerro Armazones). The MOSE project, is presented in [1]. The reader con refer to this paper to have more details about MOSE. We only recall here that the MOSE (Modeling at ESO sites) project aims at proving the feasibility of the forecast of all the most relevant classical atmospherical parameters for astronomical applications (wind speed intensity and direction, temperature, relative humidity) and the optical turbulence OT (C_N^2 profiles) with the integrated astro-climatic parameters derived from the C_N^2 i.e. the seeing (ε), the isoplanatic angle (θ_0), the wavefront coherence time (τ_0) above the two ESO sites of Cerro Paranal (site of the Very Large Telescope - VLT) and Cerro Armazones (site selected for the European Extremely Large Telescope - E-ELT). The final outcome of the project is to investigate the opportunity to implement an automatic system for the forecast of these parameters at the VLT Observatory and at the E-ELT Observatory.

The Meso-Nh model has already successfully been used to investigate some atmospherical parameters above sites of interest for the astronomy: at Roque de los Muchachos (near ground temperature, [2]); at San Pedro Martir (wind speed profiles, [3]); at Cerro Paranal in Chile and Maidanak in Uzbekistan (near ground wind speed, [4]); in Antarctica (wind speed and temper-

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ature profiles at Dome C, [5]); at Mount Graham, Arizona (wind speed vertical distribution, [6] and use of the Meso-Nh wind speed for wavefront coherence time reconstruction, [7]).

In the present study, we have analyzed the performances of the Meso-NH model in reconstructing the meteorological parameters near the surface, at Cerro Paranal and Cerro Armazones. We used data from masts and weather stations, from 2 m to 30 m above the ground, from 20 nights in November and December 2007. In Section 2, we present the model configuration. In Section 3, the observations data-set is described, together with the statistical tools used in the study. In Section 4, the performances of the model are discussed. Finally, conclusions are drawn in Section 5.

2 Model configuration

All the numerical simulations of the nights presented in this study have been performed with the mesoscale numerical weather model Meso-NH[1] [8]. The model has been developed by the Centre National des Recherches Météorologiques (CNRM) and Laboratoire d'Aéreologie (LA) at Toulouse (France). The Meso-NH model can simulate the temporal evolution of three-dimensional meteorological parameters over a selected finite area of the globe. The general numerical set-up and the physical packages employed in the simulations (coordinates system, vertical grid, temporal scheme, turbulence scheme, etc.) are already described in [1] and [9].

The grid-nesting technique [10], employed in this study, consists of using different imbricated domains of the Digital Elevation Models (DEM i.e orography) extended on smaller and smaller surfaces, with increasing horizontal resolution but with the same vertical grid. Here the first grid-nesting configuration employed three domains (Table 1) and the innermost resolution is ΔX = 500 m. The second configuration is made of five imbricated domains, the first same three as the previous configuration, and other two centered at both sites, with a horizontal resolution of ΔX = 100 m (all domains of Table 1).

Table 1. Meso-NH model configurations. In the second column the horizontal resolution ΔX, in the third column the number of grid points and in the fourth column the horizontal surface covered by the model domain. Domain 1, 2 and 3 include both Cerro Paranal and Cerro Armazones.

Domain	ΔX (km)	Grid Points	Domain size (km)
Domain 1	10	80×80	800×800
Domain 2	2.5	64×64	160×160
Domain 3	0.5	150×100	75×50
Domain 4 (C. Paranal)	0.1	100×100	10×10
Domain 5 (C. Armazones)	0.1	100×100	10×10

3 Observation data-set and statistics

During the MOSE project, our team have studied data from 20 nights of the PAR2007 campaign [11], which have been used for the model calibration of the optical turbulence (results will be

[1] *http://mesonh.aero.obs-mip.fr/mesonh/*

presented in a forthcoming paper). We decided to use these nights also for the meteorological forecast validation. However, not all the nights of the PAR2007 campaign have meteorological measurements available at both sites contemporaneously, so we completed the data sample with other nights during the same period (November-December 2007) for which observations were available at Cerro Paranal and Cerro Armazones. At Cerro Paranal, observations of meteorological parameters near the surface come from an automated weather station (AWS) and a 30 m high mast including a number of sensors at different heights. Both instruments are part of the VLT Astronomical Site Monitor [12]. Absolute temperature data are available at 2 m and 30 m above the ground. Wind speed data are available at 10 m and 30 m above the ground. At Cerro Armazones, observations of the meteorological parameters near the ground come from the Site Testing Database [13], more precisely from an AWS and a 30 m tower (with temperature sensors and sonic anemometers). Data on temperature and wind speed are available at 2 m, 11 m, 20 m and 28 m above the ground. At 2 m (Armazones) temperature measurements from the AWS and the sonic anemometers are both available but we considered only those from the tower [14]. Those from the AWS are not reliable because of some drift effects (T. Travouillon, private communication). Wind speed observations are taken from the AWS (at 2 m) and from the sonic anemometers of the tower (at 11 m, 20 m and 28 m). The outputs are sampled with a temporal frequency of 1 minute.

To estimate the statistical model reliability in reconstructing the main meteorological parameters we used the averaged values plus two statistical operators: the bias and the root mean square error (RMSE).

$$BIAS = \sum_{i=1}^{N} \frac{(\Delta_i)}{N} \tag{1}$$

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(\Delta_i)^2}{N}} \tag{2}$$

with $\Delta_i = Y_i - X_i$ where X_i are the individual observations, Y_i the individual simulations parameters calculated at the same time and N is the number of times for which a couple (X_i, Y_i) is available with both X_i and Y_i different from zero. Because the wind direction is a circular variable, we define Δ_i for the wind direction as:

$$\Delta_i = \{Y_i - X_i \ if \ |Y_i - X_i| \leq 180°; Y_i - X_i - 360° \ if \ Y_i - X_i > 180°; Y_i - X_i + 360° \ if \ Y_i - X_i < -180°\} \tag{3}$$

At the same time, due to the fact that we are interested in investigating the model ability in forecasting a parameter and not only in characterizing it, it is important to investigate also the correlation observations/simulations calculated night by night and not only in statistical terms. We also report in every scattered plot the slope of a regression line passing by the origin.

4 Model statistical performances

In this section we present some of the most important results for the three following meteorological parameters, at Cerro Paranal and Cerro Armazones: temperature, wind speed, and wind direction in the [0-30] m a.g.l. slb. A more extended and complete treatment can be found in [9]. For all the three parameters, we computed bias and RMSE (1) from the whole sample and (2) from the cumulative distributions of the individual nights. These statistical parameters allow us to evaluate the performances of the model in reconstructing the state of the atmosphere near the surface (from the ground up to 30 m a. g. l.). Please note that, when no indication on the configuration of the model is specified, it means that the reference ΔX = 500 m configuration has been used. In all the computations, we only take into account the values of the parameters during the night (between 00:00 UT and 09:00 UT).

4.1 Overall statistics

Here we consider the whole sample, combining all the 20 nights together. We have averaged every parameters (from both observations and model) over a 30 minutes interval. We have then computed the bias and RMSE. We present in Fig. 1 the scattered plots at every levels and for both sites (Cerro Paranal and Cerro Armazones) for the absolute temperature (observed vs. modeled). The reader can refer to [9] for similar plots with the wind speed and the wind direction. We present here only the main considerations about bias and RMSE. An extended study and a deeper analysis are presented in [9].
The results in terms of absolute temperature are particularly impressive. Considering both sites, and every levels, the bias is very small and remains below 0.8 °C. Even the RMSE is always inferior to 1.1 °C, which is very satisfying.

For the wind speed we report here just the results. We refer the reader to [9] for a detailed analysis. We analyse here the results for the wind speed only with the ΔX = 100 m configuration, because we need the high horizontal resolution to reconstruct in a satisfactory way the wind speed near the ground. Indeed, a too smooth orography leads to an underestimation of the wind velocity near the ground in the mountainous regions because the local peaks appear lower and smoother in the model than in reality [9]. The results are very satisfactory, with a bias always inferior to 1.5 $m \cdot s^{-1}$. The RMSE is around 2.5 $m \cdot s^{-1}$ at every level and at both sites.

Looking at the wind direction reconstruction, here again the results are very satisfactory. The bias, at every level, is in the interval [0.1 - 10 °], which is impressive. More over, the RMSE is around 45-50 ° , which also means that in other words we have a RMSE always smaller than a quadrant. In [9], we show that these values can be improved if we filter the weakest winds from the bias and RMSE computations, and that the RMSE decreases to around 30-40°.

4.2 Individual nights statistics

In this section we present the results of the analysis done on the model performances in reconstructing the atmospheric parameters, night by night. We computed for every single night the bias and RMSE between model and observations, for both sites and at every level near the surface where observations were available, for the absolute temperature and the wind speed and direction. We calculate the cumulative distributions for each parameter (20 points, corresponding to the 20 nights). We have then deduced from these cumulative distribution the median, the first and the third quartiles, of the bias and the RMSE.

The very good model performances for the absolute temperature and for the wind direction deduced from the overall statistical analysis are confirmed. The largest median bias for the temperature is only ~0.6 °C at Cerro Armazones, at 2 m. The median RMSE is always good, with values always inferior to 1 °C. The wind direction has a median bias, at every level, almost null (the worst value is ~7°). The night median RMSE is around 40 °. For the wind speed, with

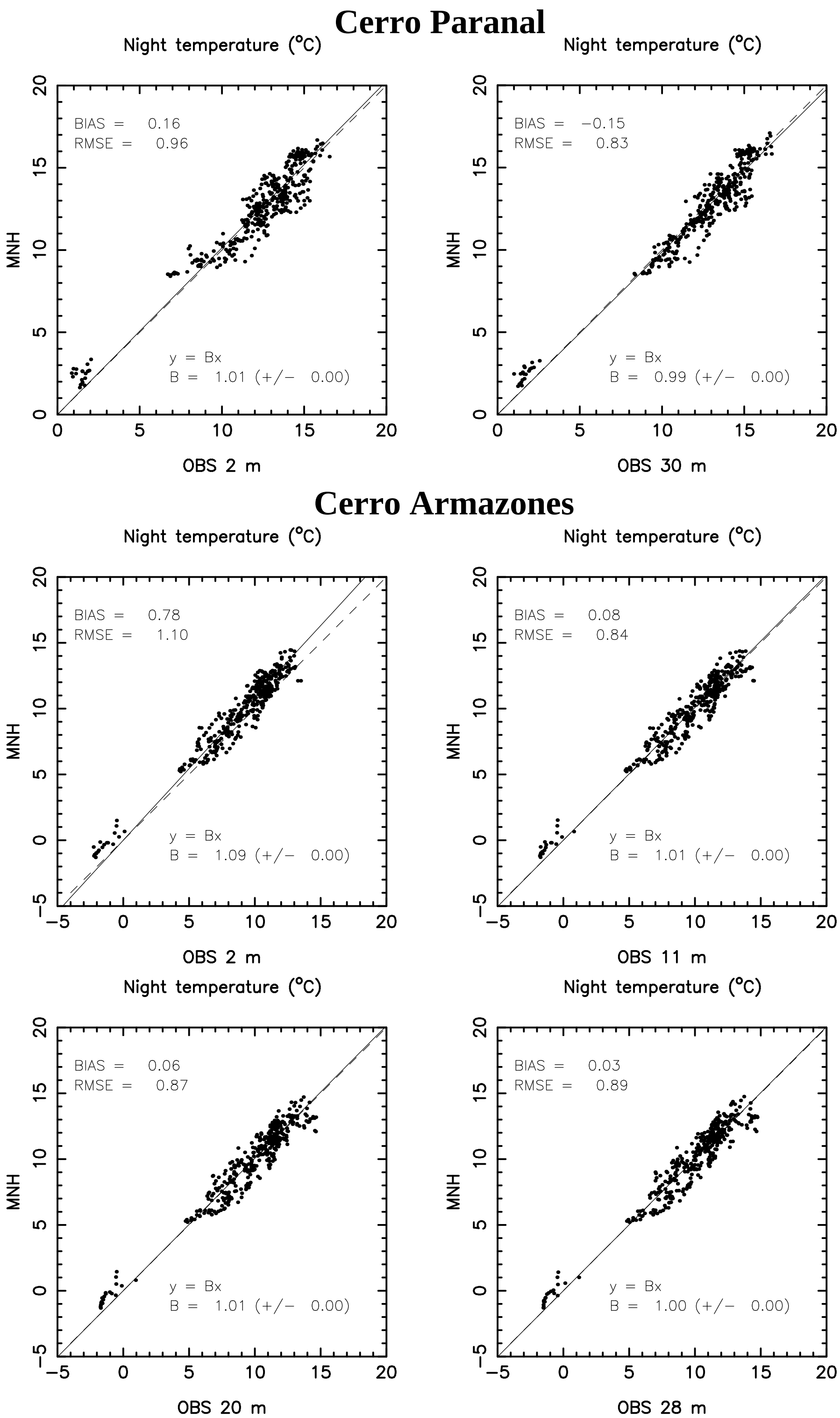

Fig. 1. Scattered plot of Meso-NH temperature against observations, at 2 m and 30 m at Cerro Paranal (top figures); at 2 m, 11 m, 20 m and 28 m at Cerro Armazones (central and bottom figures). Every point represents the average over an interval of 30 minutes.

the ΔX = 100 m configuration, the median bias oscillates between ~0.1m·s^{-1} and ~0.9 m·s^{-1} for every level. The median RMSE is around ~2 m·s^{-1}.

In general, the median bias and RMSE of the individual nights are slightly better than the one obtained with the whole sample.

4.3 Hit rates

The results of this section are prelminary results of a study that will be presented in a forthcoming paper.
One method to understand how the model succeeds in predicting the good values for the meteorological parameters is to construct the contingency tables (or multi-categories tables). In this section we present hit-rates tables for the wind speed and direction and for the temperature. From these tables, we compute three numbers G, N and B, that represents the percentage of times when the model makes a good prediction, the percentage of times when the model makes medium predictions, and the percentage of times when the model makes a bad prediction, respectively. A good forecast will be characterized by a high G and a low B. For 3×3 hit-rates tables (absolute temperature and wind speed), G, N and B are:

$$G_{3\times3} = \sum_{i=1}^{3}[i, i] \tag{4}$$

$$B_{3\times3} = [1, 3] + [3, 1] \tag{5}$$

$$N_{3\times3} = [1, 2] + [2, 1] + [2, 3] + [3, 2] \tag{6}$$

As a detailed example of hit-rates table, we show in Table 2, the results for the absolute temperature at 30 m at Cerro Paranal. In this case, the accuracy G is excellent (77.4%) and the bad predictions are inexistent (B=0%). Here we list some of the accuracy G and bad predictions B

Table 2. Hit rates table (3×3) for the absolute temperature during the night at Cerro Paranal at 30 m, obtained with the sample of 20 nights.

CERRO PARANAL		**OBS at 30 m T (°C)**		
		<12.33	[12.33,14.06]	>14.06
M-NH	<12.33	31.9%	7.5%	0.0%
M-NH	[12.33,14.06]	1.4%	21.9%	9.7%
M-NH	>14.06	0.0%	3.9%	23.6%

G=77.4% N=22.5% B=0.0%

obtained for the other parameters and for both sites. For the temperature, at Cerro Paranal at 2 m G=74.7% and B=0%. At Cerro Armazones G are equal to 51.3%, 79%, 78.9% and 76.7% at 2 m, 11 m, 20 m and 28 m, respectively; B are all inferior to 3.9%.

For the wind speed and with the ΔX = 100 m configuration, at Cerro Paranal G are equal to 41% and 54.5% at 10 m and 30 m; B are both inferior to 6.9%. At Cerro Armazones G are equal to 55.8%, 50%, 51.7% and 58.3% at 2 m, 11 m, 20 m and 28 m, respectively; B are all inferior to 8.9%. Since we have identified a negative bias in the forecast of the surface wind speed (the wind speed provided by the model is statistically underestimated of around 2 m·s^{-1}), we expect a better behavior when the modeled wind is corrected by the existing bias, and it will be the subject of a future study dedicated to the contingency tables.

For the wind direction, we used a 4×4 hit-rates table (with 4 intervals of 90 ° each), because of the circularity of the data. At Cerro Paranal, G are equal to 60.9% and 66.9% at 10 m and 30 m; B are all inferior to 7.2%. At Cerro Armazones G are equal to 62.2%, 59.4%, 62.2% and 65.3% at 2 m, 11 m, 20 m and 28 m, respectively; B are all inferior to 3.9%.

In general, G is satisfactory for all parameters (they are excellent for the temperature and the wind direction). More over, the bad prediction are all limited, demonstrating the robustness of the reconstruction of the meteorological parameters near the ground by the Meso-NH model.

5 Conclusions

In this study we have investigated the performances of the Meso-NH model in reconstructing some meteorological parameters near the ground at two ESO sites (Cerro Paranal and Cerro Armazones): the absolute temperature, the wind speed and the wind direction, from the ground to 30 m a. g. l. Only the main results were summarized in this paper, and the reader can refer to [9] to a complete study and statistical analysis. For the temperature, the results are excellent: the worst median value for the bias is ∼0.6 °, and the worst median RMSE is inferior to 1 °C. The results for the wind direction are good too: the worst median bias is ∼7 °, and the RMSE oscillates around 40 ° (all levels and both sites considered). For the wind speed, the bias is always inferior to ∼0.9 m·s^{-1} and the RMSE is ∼2 m·s^{-1} that provides, if consider the absolute values, a relative error within 20%.

The hit-rate tables analysis told us that the absolute temperature and the wind direction can be reconstructed by the model in a very efficient way. Preliminary results tell us that for the temperature the good hit-rate G is of the order of 73-78% at Paranal and 77-80% at Armazones with exception of the temperature at 2 m at Armazones where G=54%. For the wind direction G is of the order of 62-66% a Paranal and 63-65% at Armazones. For both parameters (temperature and wind direction) the bad hit-rate is very small (order of a few percents). For the wind speed reconstruction and when the highest horizontal resolution is 100 m the good hit-rate G is around of 50-55% at Cerro Paranal and Cerro Armazones. In a forthcoming paper, we will show how an improvement of these results is possible.

Model performances for the temperature providing a bias and a RMSE smaller than 1 °C let us think that the Meso-NH model could definitely contribute to solve the problem of the thermalization of the dome and the elimination of the dome seeing contribution (the most critical contribution in the total turbulence budget).

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