1. INTRODUCTION

The BSC-CNS is involved in the CALIOPE project (Baldasano et al., 2008), a national Spanish initiative that has as main objective to establish an air quality forecasting system for Spain coordinated by the Ministry of the Environment. The modeling system bases on the WRF-ARW model as meteorological driver (Figure 1). As is well known, air quality models are highly dependent on the quality of the meteorological inputs, and any improvement in meteorological fields should be maintained in chemistry models. Pérez et al. (2006) showed that an increase in 3°C of temperature can lead to an increase of 7.2 - 21.1 µg m⁻³ of ozone concentration in background areas. Moreover, moisture errors may impact in the formation of secondary organic aerosols and in the aqueous chemistry by modifying the OH radical concentrations, and an overestimation of wind speed will produce an increased mixing of pollutants within the boundary layer and a major advective effect, the result will be a simulation of lower background pollutant concentrations over the affected areas.

One major characteristic of WRF model is that it has the possibility to be configured with different dynamical cores. The need to analyze the performance of the system under different configurations is then demanded.

The main objective of the work is to analyze the skills of meteorological mesoscale models as drivers of air quality modeling system. For that purpose we planned to evaluate the 2 dynamical cores of the WRF modeling system, WRF-NMM (Janjic, 2003) and WRF-ARW (Skamarock and Klemp, 2008). WRF-NMM is currently the operational mesoscale meteorological model of NCEP and WRF-ARW is the research model of the NCAR.

To evaluate both models, we have performed an annual simulation of the year 2004 over an European domain at 12 km of horizontal resolution, and the results of the models have been evaluated against observations. We have focused on temperature, moisture, wind speed and direction; critical variables of the atmospheric photochemistry processes.

2. MODEL SETUP

A simulation of the year 2004 over Europe was designed. Both ARW and NMM dynamical cores of the WRF modeling system were used. The configuration of both systems is summarized in Table 1. The physical parameterizations selected for both dynamical cores were those widely used in research and operational applications. The domain of study was centered over central Europe and covers whole Europe. The horizontal resolution adopted was 12 km horizontal resolution and 38 vertical levels on the vertical up to 50 hPa for both systems. The initial and boundary conditions came from the 6 hourly 1-degree FNL analysis of 2004. The annual simulation was performed as 366 daily simulations with a cold start each day of 12 hours from FNL analysis initial conditions.
### Table 1. Setup of WRF-ARW and WRF-NMM runs.

<table>
<thead>
<tr>
<th></th>
<th>ARW</th>
<th>NMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics</td>
<td>ARW v2.2.1</td>
<td>NMM v2.2.1</td>
</tr>
<tr>
<td>PBL</td>
<td>YSU</td>
<td>MYJ</td>
</tr>
<tr>
<td>Cumulus</td>
<td>KF</td>
<td>BMJ</td>
</tr>
<tr>
<td>Radiation</td>
<td>RRTM, Dudhia</td>
<td>GFDL</td>
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<tr>
<td>LSM</td>
<td>Noah</td>
<td>NMM-LSM</td>
</tr>
<tr>
<td>Surface layer</td>
<td>Monin-Obukhov</td>
<td>Janjic</td>
</tr>
<tr>
<td>Microphysics</td>
<td>WSM-3</td>
<td>Ferrier</td>
</tr>
</tbody>
</table>

In the first stage of the evaluation, we identified some problems with NMM results during May month. Further analysis have to be done to understand the cause of the problems. Then, for the following evaluation, results from 29 April 2004 to 26 May 2004 are not taken into account.

### 3. VERIFICATION METHODOLOGY

A quantitative verification of the results was performed. The 2 m temperature, 2 m dewpoint temperature, 10 m wind speed and direction were evaluated as meteorological variables at surface level. The temperature, mixing ratio, wind speed and direction were also evaluated within the atmospheric boundary layer to complement the surface evaluation.

Several classical statistics were computed following Willmott et al. (1985): the mean absolute error (MAE), mean bias error (MBE), root mean square error (RMSE) and the systematic error (RMSEs). The definition of the systematic error is:

\[
RMSE_s = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (\hat{p}_j - o_j)^2}
\]  

(1)

- Systematic error:

\[
RMSE_u = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (\hat{p}_j - p_j)^2}
\]  

(2)

where \(\hat{p}_j\) is an ordinary least square estimate of \(p_j\) derived from the linear regression of \(P\) on \(O\):

\[
\hat{p}_j = a + b o_j
\]  

(3)

\(a\) being the y-intercept and \(b\) the slope of the linear regression line.

In order to evaluate the results of the models two observation datasets have been used: surface meteorological stations from the NCEP ADP Global Surface Observations archive, and for upper air evaluation, the European radiosoundings. From all the surface meteorological stations available for 2004 year, we selected those that had a coverage over 6000 hourly observations. On the other hand, the 00 and 12 UTC available soundings were used from the sounding database.

The model results were interpolated to the stations’ location, and then, the surface statistics were calculated. To complement this statistical analysis at surface levels, we have also computed the error of the vertical structure of the atmosphere within the atmospheric boundary layer. For that purpose, we used the European radiosoundings. The radiosounding observations were interpolated to model levels, and then, the statistics were computed as an integration of the different model layers from surface to 2000 m agl.

### 4. RESULTS

#### 4.1 Surface verification

We have computed the monthly mean and annual mean statistics. Figure 2 shows the annual evolution of the monthly mean RMSE. The results show a rather similar RMSE for temperature, dewpoint and wind direction in both models. The RMSE ranges around 2.5ºC for temperature, under 3ºC for dewpoint temperature, and around 60 degrees for wind direction. The wind speed error shows a seasonal behavior ranging around 2-3 m/s, with major differences between systems during wintertime, where NMM shows lower errors. The important differences appear in the MBE. Temperature and moisture are underpredicted for the whole year with ARW while NMM shows a slight overprediction in temperature and a more noticeable overestimation for dewpoint temperature. Spring is the season where ARW shows larger underestimation. In this sense, NMM has a more homogeneous performance.

To analyze the spatial distribution of the errors we have plotted the annual RMSE for the 2 m temperature for each station following a color legend. Lower errors are depicted in blue color and higher errors in red and violet color. Figure 3 shows the results of the annual RMSE for ARW (top panel) and NMM (bottom panel).
In general we can detect a good performance of both models over continental flat terrain areas, and major problems in complex terrain and complex coastal areas (Mediterranean coast). The larger errors observed over complex terrain is associated with a topography characterization problem, that would require higher resolution to better capture the temperature field. The results clearly identify the higher complexity to simulate the temperature over the Mediterranean region, and especially in the coastal Mediterranean areas. Those areas are characterized by a rough topography with mountain ranges at 10-50 km from the coast. It is also noticeable the lower errors observed with NMM in western and central Europe and the better performance in Eastern Europe of ARW.

The annual RMSE of dewpoint temperature shows similar errors for both models, with lower errors in the northern European coast, slight larger errors over continental flat terrain and the larger errors in complex terrain and Mediterranean coasts.

For wind speed, we do not see a clear pattern of the error, with distributed low and high errors across Europe. The total RMSE ranges from 1 to 3 m/s. It is important to notice that in complex terrain areas the error remains lower compared with the increased temperature statistic.

4.2 Boundary layer verification

The statistics have been computed for the atmospheric layer comprised between 0-2000 m. The MAE errors range around 2.5°C for ARW and 1.5°C for NMM during the whole 2004. It is important to note the larger underprediction of ARW for the temperature within the boundary
layer compared with NMM. For wind speed, both models have a clear tendency to overestimate the speed within the boundary layer. This overestimation decreases when we analyze upper layers (not shown). The MAE ranges from 2.5 to 3.5 m/s during 2004. The higher errors are produced in wintertime. The NMM performance in height is quite regular, while ARW shows a larger variability when we analyze upper layers.

If we compute the systematic RMSE (RMSEs), a clear difference appears between both systems (Figure 4). NMM results show a lower and constant systematic error for temperature that represents less than 1ºC of the total RMSE, while ARW has larger systematic errors. Coastal areas present the lower RMSEs, while inland zones and complex terrain regions are characterized by an increase of the systematic error. Differences in wind speed are not as noticeable as with temperature, however, NMM still shows lower systematic errors.

5. SUMMARY

An annual evaluation of the model WRF applied over Europe have been done. Two configurations of the WRF modeling system has been used for the study based on the ARW and NMM dynamical cores. The results have highlighted the skills of the models in different topographical regions. In coastal areas, the models present a good performance in northwestern European coasts during the whole year, while major problems appear in Mediterranean coasts. There is a clear difference in model skills between northern and southern Europe for temperature. The complex terrain regions as the Alps and Pyrenees mountain ranges are characterized by higher errors during the whole year for temperature, but reasonable wind results. The continental flat terrain areas show the overall best performance. The larger errors in these regions are related to meteorological conditions. It is important to note that the larger errors are produced over southern Europe and the Mediterranean region, and specially under high pressure or stagnant conditions. Finally, the WRF-ARW configuration has shown noticeable higher systematic errors than WRF-NMM configuration.

ACKNOWLEDGEMENTS

This work was funded by the project CALIOPE project 441/2006/3-12.1 and A357/200/2-12.1 of the Spanish Ministry of the Environment. The FNL analysis and verification data are provided by the NCAR’s Data Support Section. WRF-ARW and WRF-NMM simulations were performed with the Marenostrum supercomputer held by the Barcelona Supercomputing Center.

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