ESTIMATING WIND RESOURCE USING MESOSCALE MODELING

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Summary

The expansion of wind energy to new markets poses a challenge into estimating this resource on larger scales. An accurate climatic description relies on a comprehensive regional observation network, characteristic often not available on Latin American markets. In these cases the use of Mesoscale modeling can provide a large-scale analysis with regional features. Considering existing limitations, this approach can be used to support an initial ranking and selection of sites for wind farm projects.

Initial large-scale conditions are obtained from the Reanalysis database, which contains global meteorological observations. A consequent initial analysis is conducted to determine the years that best describe the average conditions in most of the locations across a desired area, providing the input for a regional simulation.

The simulation of the regional wind climate is conducted using the Weather Research and Forecasting system (WRF). This state of the art Mesoscale modeling system calculates the dynamics and thermodynamics of the atmosphere in limited areas, and is currently developed and employed at several universities and research centers worldwide. Through the process of downscaling the Reanalysis data is used to describe the initial conditions for the desired area, allowing the WRF to calculate in great detail the effects of local features over the large-scale conditions.

In order to assess the limitations and advantages of this approach several validation efforts were conducted in Portugal, Romania, Texas (U.S.) and Northern Mexico, providing an overview of the benefits of this methodology for wind energy estimation.

Introduction

The current and future [1] expansion of wind energy markets poses a challenge into determining the most appropriate sites for energy exploration. Due to the limited amount of data available in emerging markets and remote areas, initial assessments are often carried out using statistical techniques in order to extrapolate the available data to the desired location, or large-scale climatic descriptions [2]. While these approaches offer an overview of the available resource, in most cases regional features of the terrain will modify the wind pattern, therefore hindering an accurate description of the resource.

In order to determine the regional climate it is proposed the usage of a global meteorological dataset as input data to a regional numerical model, in order to estimate the effects of local features from large-scale atmospheric conditions. Coupled with an analysis of the climatic representation of the global input data, this solution aims to represent the regional climate of the wind on a limited area.

The product generated from such method can be used to represent the wind resource distribution over an area of interest for a wind farm project, and data points can be obtained in order to represent time-series and vertical profiles for a specific area. However, as with any numerical simulation, the limitations of this approach should be carefully considered on a case-per-case analysis, and its results should be used as an additional aid to initial studies and green-field procurement.

Methodology

Input data

A key element for estimating wind resource is reliable meteorological data including, but not limited to, surface observations and upper-air conditions. The U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) maintains the Reanalysis project [3], which aims to provide a consistent source of meteorological observations for the entire world, with data obtained from several sources over the past decades.

The Reanalysis project uses a dynamic data assimilation system to ingest locally observed and remote sensing data to create a regular grid with 208km (2.5°) spatial resolution, from a T62/28 global spectral model with refined levels on the boundary layer and terrain following sigma vertical coordinates. The variables from this dataset are classified according to their reliability to the original source, being the “A” type variables most influenced by the actual observations, which includes the zonal and meridional wind (U and V) variables, among others. The output frequency follows standard WMO (World Meteorological Organization) definitions for surface (synoptic) stations, with data at 00, 06, 12 and 18 hours GMT (Greenwich Mean Time).

This dataset is routinely used as a climatic database, offering the means to promote analysis at spatial resolutions above the horizontal resolution of the dataset (208km). Due to this limitation, this dataset alone cannot be used to determine the wind resource on a regional scale, since any local feature smaller than 208km will not be represented. In order to circumvent this limitation it is proposed the usage of a dynamical downscaling technique applying a mesoscale numerical model.

Land characteristics are provided by the USGS 30-second Global Elevation Data (United States Geological Survey and University Corporation for Atmospheric Research). This dataset is a Digital Elevation Model (DEM) that provides terrain elevation information in a horizontal grid of 30 arc seconds (approximately 1 km), derived from several raster and vector sources of topographic information [4]. Land cover data is provided by the Global Land Cover Characteristics Data Base (USGS, National Center for Earth Resources Observation and Science – EROS, Joint Research Centre of the European Commission). It consists of a 1 km resolution global land cover characteristics dataset, conceived to be used in a wide range of environment research and modeling applications, and derived from global observations acquired between April 1992 and

March 1993 from the Advanced High Resolution Radiometer, located aboard the NOAA series satellites [5,6,7].

Numerical modeling

A dynamical downscaling can be shortly described as a the process of initialization of a limited area model (LAM) by using mass, momentum and thermodynamic data from a general circulation model (GCM) or another LAM with greater area, and by providing lateral boundaries conditions during the numerical integration of the LAM. This technique offers the advantage of enhancing the simulation of regional features due to the increase in the horizontal resolution (and the consequent refinement of lower boundary discretization) and by allowing the representation (as opposed to parametrization) of dynamical features such as deep convection, for instance.

The LAM used in this project is the Weather Research and Forecasting (WRF) model [8]. This model consists of several modules created to ingest observational data and simulate atmospheric conditions, describing the dynamics and thermodynamics of the atmospheric flow in limited areas. The numerical integrator consists of a fully compressible, Eulerian and nonhydrostatic equation set, employing a terrain-following, hydrostatic-pressure vertical coordinate being the top of the model a constant pressure surface, in a Arakawa-C horizontal grid. A third-order Runge-Kuttan time integration scheme with a 2nd to 6th order spatial discretization is used during the integration. This model is under active development mostly by an association between the NCAR, National Oceanic and Atmospheric Administration (NOAA), U.S. Air Force Weather Agency (AFWA), Naval Research Laboratory, Oklahoma University and Federal Aviation Administration (FAA). As a community-driven initiative [9], it also receives constant collaborations from various researches and users. This model has been chosen due to its collaboratory organization, fact that brings the improvements from the latest research developments in rapid deployment cycles.

Climatic data definition

Initialization data used to describe the climate regime is extracted from the NCEP/NCAR Reanalysis project dataset. A 30 years data range is classified per year according to the pattern behavior of the available kinetic energy [10], as defined by the equation

$$K = \frac{1}{2}\sqrt{u^2 + v^2}$$

where U and V are the magnitudes of the zonal and meridian components of the wind speed, respectively, at the lowest level. The available kinetic energy pattern can also be described by analyzing the horizontal wind speed at the same level.

This analysis is used to determine the years which best describes the climate regime of the wind speed at a certain area within the Reanalysis horizontal resolution (approximately a square with 208km sides).

Due to the nature of the Reanalysis dataset, secondary procedures are used when ranking the data series. It is considered within the years that have a 10% deviation from the 30 years average value the most recent year, unless the best year is within the latest 15 years. This criteria is only applied on developing countries, where meteorological stations are less prone to error due to an increased use of automated stations and generally more observations, and due to better remote sensing techniques observed in the past 15 years. Whenever a Reanalysis area has its center in an ocean it is used a linear interpolation with the nearest point on land in order to reduce the effects caused by the varying surface roughness; in all other cases no interpolation is applied to the Reanalysis data.

Afterwards the selected data range is used as initial condition to a WRF simulation.

WRF Simulation

The numerical simulation on WRF is setup on a 2-way nested (telescoping) grid configuration, with the outer grid covering an area with at least 170,000 km^2, thus using at least 4 Reanalysis data points as input data, and an inner grid with a horizontal resolution between 6km and 1km, depending on the complexity of the terrain, and 42 vertical levels, with the lowest ones at 10m, 30m, 45m, 60m and 100m above ground level (a.g.l.). The parameterization settings are defined on a case-per-case analysis.

Results

In order to establish the model capability and limitations of describing the climate conditions of a region, different validation experiments were undertaken. Four distinct regions, ranging from a low complexity coastal terrain to complex sites, located in different countries and climates, are presented. The data obtained from such simulations were compared against different meteorological stations, with wind speed and direction records mostly at 60m a.g.l.

Coastal terrain experiment

This experiment takes place with a grid over a coastal area in the center of Portugal, with the following approximate grid placement (Table 1, Figure 1):

Table 1: Grid Placement

Parameter	Outer Grid	Inner Grid
Center	LAT 41.28°, LON -8.64°	LAT 41.27°, LON -8,88°
Number of points (x,y)	52 x 52	52 x 52
Horizontal Resolution	9000 m	3000 m
Vertical Levels	42	42

Figure 1: Grid placement, outer grid in white, inner grid shaded blue

The meteorological station is located approximately 3km from the shore line, however due to data usage restrictions its exact location cannot be disclosed, and center values for the grids were truncated. Data collected during January 2007 is then compared with the results from the nearest point in the model domain to the measurement station at 60m a.g.l., with a distance from the model point to the station of approximately 250m. No interpolation takes place.

Average wind speed recorded at the station for January is 4.8 m/s, while in WRF is 5.1m/s, thus with a deviation of 5.88%. However the model simulates winds in general weaker than the measured data (Figure 2). The wind rose shows a stronger South contribution on WRF, with a consequent reduction in the East and North sectors (Figure 3). The general wind distribution averaged for January (Figure 4) illustrates the decay of speed with the increase in terrain roughness over mainland and due to regional features.

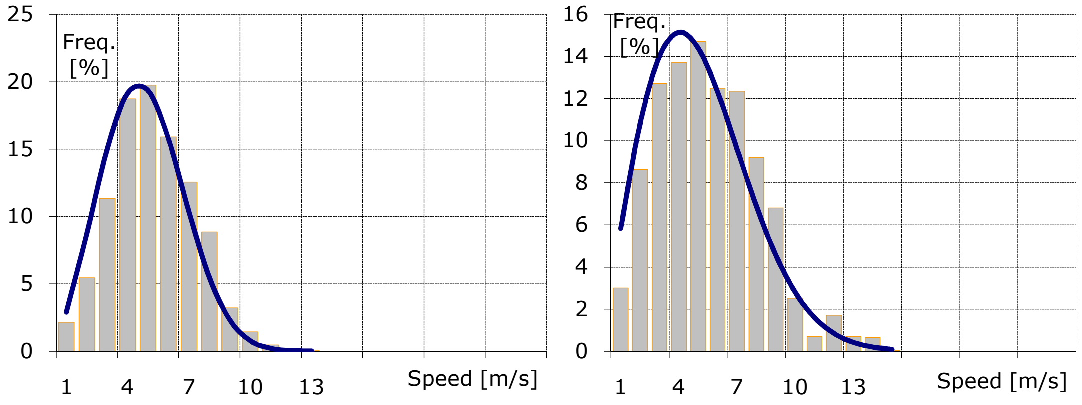

Figure 2: Wind Speed Histogram, station (left), WRF (right)

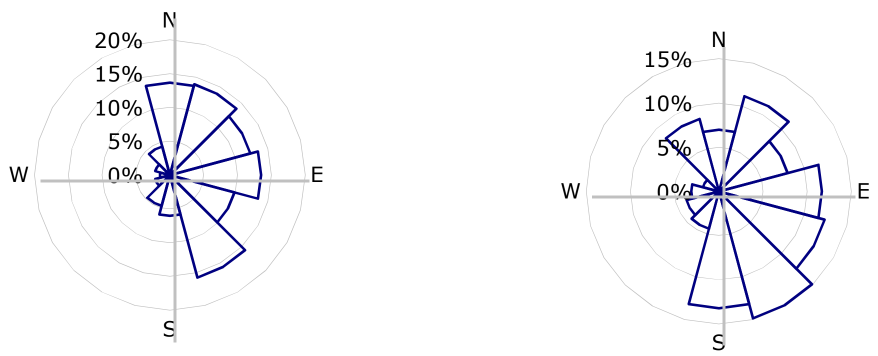

Figure 3: Wind Rose, station (left), WRF (right)

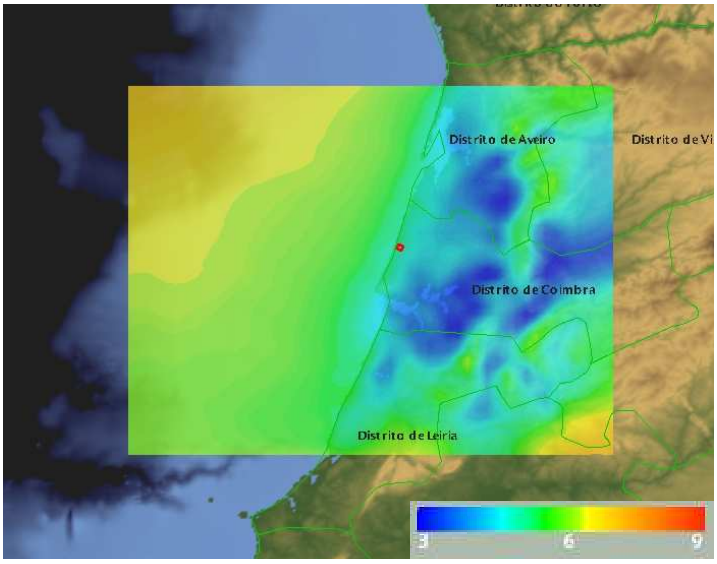

Figure 4: Wind speed (m/s) - spatial distribution

Southern Texas / Northern Mexico

This experiment takes place with two grids over a coastal area (Grid 1) and an inland area of moderate complexity (Grid 2), located in the Southern Texas / Mexican border, with the following approximate grid placement (Table 2, Figure 5):

Table 2: Grid Placement

Parameter	Grid 1	Grid 2
Center	LAT 25.88°, LON -97.4°	LAT 28.25°, LON -97.7°
Number of points (x,y)	61 x 61	49 x 49
Horizontal Resolution	3000 m	3000 m
Vertical Levels	42	42

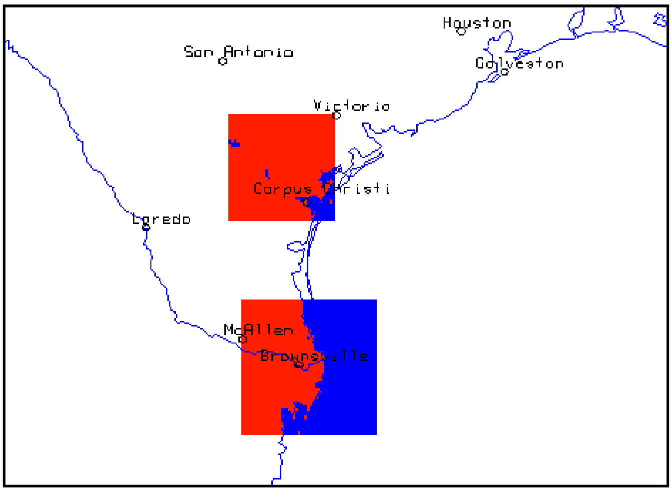

Figure 5: Grid placement, Grid 1 bottom, Grid 2 top

Grid 1 Analysis

The meteorological station is located approximately 7km from the shore line, however due to data usage restrictions its exact location cannot be disclosed, and center values for the grids were truncated. Data collected during June 2008 is then compared with the results from the nearest point in the model domain to the measurement station at 60m a.g.l., with a distance from the model point to the station of approximately 15m. No interpolation takes place.

Average wind speed recorded at the station for June is 7.4 m/s, while in WRF is 6.9m/s, thus with a deviation of 6.75%. The numerically simulated winds occur in general on a narrower range than the measured data (Figure 6). The wind rose shows a remarkable resemblance with observed data, with very little deviation (Figure 7).

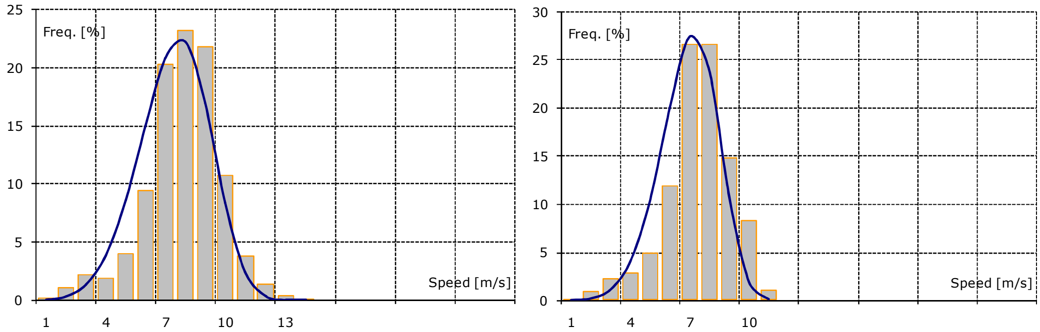

Figure 6: Wind Speed Histogram, station (left), WRF (right)

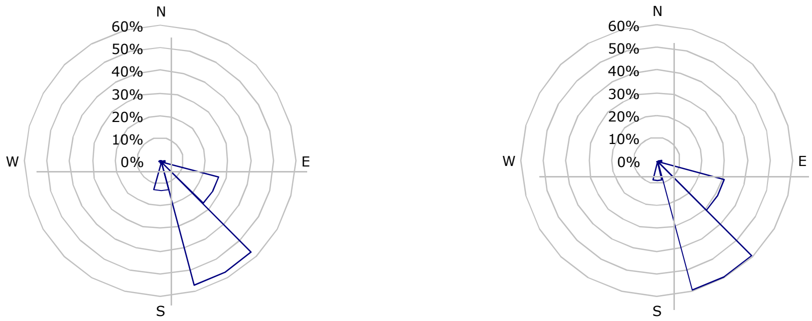

Figure 7: Wind Rose, station (left), WRF (right)

Grid 2 Analysis

The meteorological station is located between several water bodies, having a minimum distance of 4km from the closest water body, however due to data usage restrictions its exact location cannot be disclosed, and center values for the grids were truncated. Data collected during June 2008 is then compared with the results from the nearest point in the model domain to the measurement station at 60m a.g.l., with a distance from the model point to the station of approximately 40m. No interpolation takes place. It should be noted that this station has an anemometer at 65m a.g.l., and is located in an area with surrounds prone to seasonal flooding.

Average wind speed recorded at the station for June is 7.4 m/s, while in WRF is 7.1m/s, thus with a deviation of 4.05%. Similarly, the numerically simulated winds occur in general on a narrower range than the measured data, but having a better fit with the weibull curve (Figure 8). The wind rose shows a stronger South contribution on the observed data, whereas the model tends more to Southwest (Figure 9).

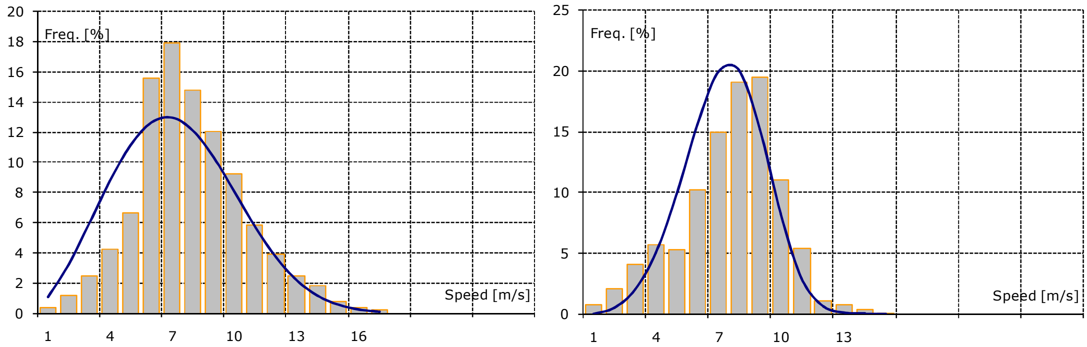

Figure 8: Wind Speed Histogram, station (left), WRF (right)

Figure 9: Wind Rose, station (left), WRF (right)

Romania

This experiment takes place with two telescoping grids over a coastal area near the Black Sea, located in Eastern Romania, with the following approximate grid placement (Table 3, Figure 10):

Table 3: Grid Placement

Parameter	Outer Grid	Inner Grid
Center	LAT 44.6°, LON 28.8°	LAT 44.6°, LON 28.8°
Number of points (x,y)	70 x 70	91 x 91
Horizontal Resolution	18000 m	6000 m
Vertical Levels	42	42

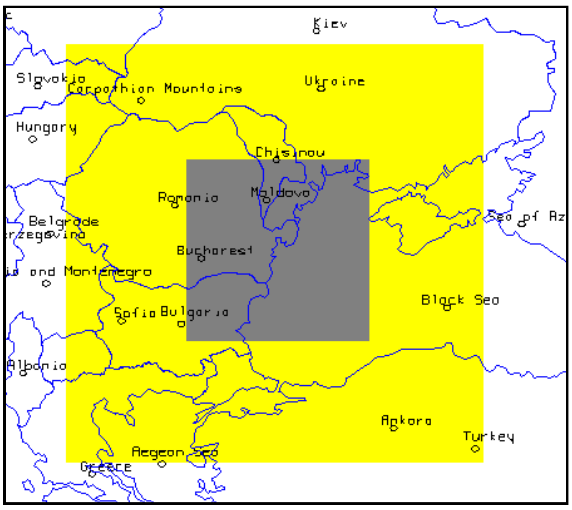

Figure 10: Grid placement, outer grid shaded yellow, inner grid shaded gray

The meteorological station is located on mostly flat terrain, with low complexity, distant approximately 25km from the Black Sea, however due to data usage restrictions its exact location cannot be disclosed, and center values for the grids were truncated. Data collected during June 2007 is then compared with the results from the nearest point in the model domain to the measurement station at 60m a.g.l., with a distance from the model point to the station of approximately 320m. No interpolation takes place.

Average wind speed recorded at the station for June is 5.6m/s, while in WRF is 5.3m/s, thus with a deviation of 5.35%. Similarly, the numerically simulated winds occur in general on a narrower range than the measured data (Figure 11). The wind rose shows a stronger North contribution on the observed data, whereas the model tends generally more to Western sectors (Figure 12).

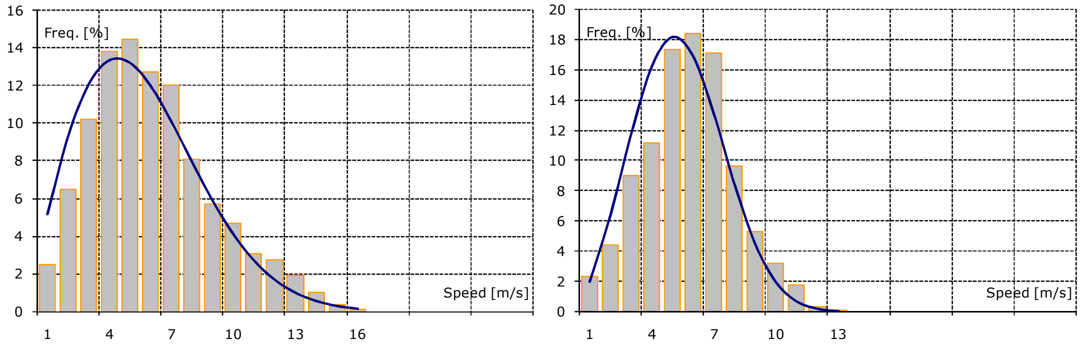

Figure 11: Wind Speed Histogram, station (left), WRF (right)

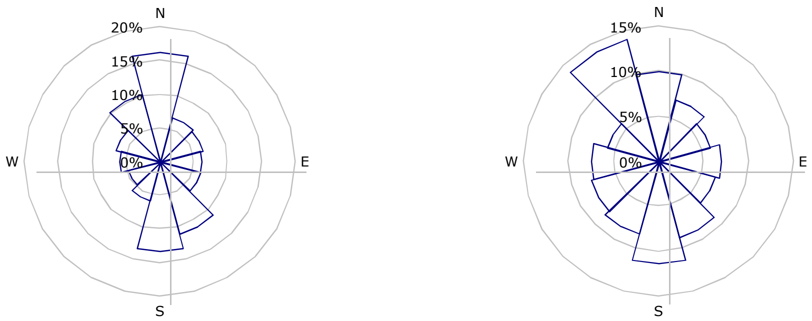

Figure 12: Wind Rose, station (left), WRF (right)

Conclusions

The undertaken experiments demonstrate that the model is capable of determining the monthly average wind speed with a deviation from observed data generally around 5%. As the methodology aims into obtaining a climatic description for a limited area, such values are well within the range of its purposed use.

However, as the data suggests, the intra-daily values present deviations from the observed records, reflecting on the frequency distribution, which tends to narrower on modeled results. Such behavior is expected due to the low temporal and spatial resolution of the input data, and illustrates a limitation with this approach.

A concurrent analysis of the wind direction results also exemplifies a deviation in some sectors, indicating an intrinsic limitation existing in any grid-based numerical model. Such models perform an adjustment of the lower boundary data in order to adapt it to its horizontal resolution, vertical resolution and projection. Sub-grid features will be smoothed in order to adjust it to the model native grid, leading to different results.

Nevertheless, it is important to assert that while these results are encouraging, they are not a substitute to locally acquired data, since several sub-grid features are not well represented by the existing parametrizations. A mesoscale approach is an important factor in initial studies, and its usage in microscale models can overcome limitations in the lower boundary discretization.

References

1 . U.S. Department of Energy. 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply. *http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf* . Accessed March 18, 2009.
2. Schwartz M., George R., Elliott D. The Use of Reanalysis Data for Wind Resource Assessment at the National Renewable Energy Laboratory. *European Wind Energy Conference,* 1999.
3. Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D.. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, 1996, v. 77, n 3, 437 – 470.
4. Anderson, J.R., Hardy, E.E., Roach J.T., and Witmer R.E., A land use and land cover classification system for use with remote sensor data: U.S. *Geological Survey Professional Paper* 1976, 964, 28 p.
5. Olson, J.S., , Global ecosystem framework-definitions: *USGS EROS Data Center Internal Report*, Sioux Falls, SD, 1994a, 37 p.
6. Sellers, P.J., Mintz, Y., Sud, Y.C., and Dalcher A., A simple biosphere model (SiB) for use within general circulation models: *Journal of Atmospheric Science* , 1996, v. 43, p. 505-531.
7. Verdin, K.L., and Greenlee, S.K.,. Development of continental scale digital elevation models and extraction of hydrographic features. In: Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, January 21-26, 1996. National Center for Geographic Information and Analysis, Santa Barbara, California.
8. Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, A description of the Advanced Research WRF Version 2. *NCAR Tech Notes* 2005 468+STR
9. Holland G., The WRF Modeling System: A Successful Community Activity. AMS Commission on Weather and Climate Enterprise.
http://www.ametsoc.org/boardpges/cwce/docs/2006/WRF_Overview.pdf. Accessed on March 15 2009.
10. Paiva L., Ferreira A., Chagas G., Silva R.. Determination of Wind Farms for the Bahia State Using Numerical Simulation of the Atmospheric Flow. *International Conference on Southern Hemisphere Meteorology and Oceanography,* 2006, Foz do Iguassu, Brazil.