Wind Energy Simulation Toolkit (WEST): A wind mapping system for use by wind energy industry

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ABSTRACT

A state-of-art wind mapping system, The Wind Energy Simulation Toolkit (WEST), was developed in the Meteorological Service of Canada (MSC) for use by the wind energy industry. WEST is based on a statistical-dynamical downscaling approach: a statistical analysis of climate data to determine the basic atmospheric states, and a dynamic adaptation of each basic state to high resolution terrain and surface roughness by using mesoscale and microscale models. WEST is applied to the Gaspé region of Canada. The mesoscale model is run at 5 km resolution, while the microscale model at 200 m. The simulation results are evaluated with tower observations at a height of 40 meters above ground level. The under-estimation of wind speed is about 6% if only meso-component of WEST is used, and about 1% if both meso- and micro-components are used. The correlation coefficient is improved from 0.5 with meso-component alone to 0.7 with full WEST.

1 INTRODUCTION

The wind resource assessment is a key and first step towards the installation of wind turbines for electricity generation. Traditionally, this is done by interpolating and/or extrapolating the observation data, mainly from sparse meteorological stations (hundreds kilometers apart), and by installing a (or some) special observation mast(s) at the potential sites to do wind monitoring for a period of one or two years. This process is time consuming and expensive particularly for the remote regions and under harsh weather conditions. The temporal and spatial extent of the validity of these measurements depends strongly on the climate regime and the terrain complexity of the region.

Efforts were made in development of physical model to simulate the surface boundary-layer flow in complex terrain to overcome the limitations of simple interpolation/extrapolation of observation data. (Walmsley et al., 1986) and WAsP (Wind Atlas Analysis and Application program, Troen and Petersen, 1989) are among the most popular microscale models used in wind mapping. Both models are derived from the two-dimensional theory of Jackson and Hunt (1975). Troen and Petersen (1989) described the procedure of wind resource assessment using microscale model. A regional uniform wind climate at about 1-km AGL is first established with a microscale model by scaling up the observed wind to that altitude for some standardized surface roughnesses. This regional wind climate is assumed to be valid for a horizontal extent of hundreds square kilometers. Then, the same microscale model is used to estimate the wind at a specific site by taking into account the local effects at this site and the regional wind climate established in the first step. This kind of microscale models can be applied efficiently to a horizontal domain of hundreds square kilometers at a grid-spacing of tenth kilometers due to their simplicity. However, mesoscale effects are ignored in these microscale models. As discussed in Frank and Landberg (1997), mesoscale models can be used to estimate the wind resource taking into account the mesoscale phenomena like channeling effect of wind by wide valley if the large-scale climatological forcing is correctly specified.

WEST was built to estimate wind resource taking into account the atmospheric forcing in wide range scale both in time (from decadal to diurnal variations) and in space (from synoptic large-scale to meso-/micro-scale). The paper begins with a detail description of the WEST system. This will be followed by an application of WEST in Gaspé region of Canada in section 3, and its validation in section 4. Conclusion and further developments will be discussed in section 5.

2 WIND ENERGY SIMULATION TOOLKIT (WEST)

WEST is founded on a statistical-dynamical downscaling approach (Frey-Buness et al., 1995). The basic assumption is that regional climate is associated with a specific frequency distribution of basic large-scale weather situations. The downscaling procedure is illustrated schematically in Figure 1, and can be summarized in the following major steps:

1) A set of basic weather situations (or classes hereafter) are defined using relevant meteorological parameters. In the wind energy application, geostrophic wind is used as the key parameter for classification. The frequency of each class is determined by applying a statistical analysis on long term gridded global dataset (e.g. the meteorological centers' re-analysis). The weather situation is simplified to a single profile of atmospheric state (temperature, wind, etc.) for the whole region. The size of the region should be large enough for a weather situation to be determined, but as small as possible for not allowing the development of transitional situation during the model simulation in step 2. A domain less than 1000 by 1000 km^2 seems to be reasonable for this kind of application.

2) For each class determined in the first step, a mesoscale model simulation will be initialized with the corresponding atmospheric profile, while the lateral boundary conditions are kept constant in time. The simulation time should be long enough for the atmosphere to reach a steady state, but as short as possible for not allowing the development of transitional weather situation. The convergence of the model towards the

steady state depends mainly on the air stability, model resolution and the initial state at which the model starts.

3) The mesoscale wind climate is obtained by weighting the simulation results of each class with its occurrence frequency. The frequency distribution of wind by direction sector and wind speed interval (bivariate frequency distribution) is also established. This is a key input for microscale modeling.

4) A series of microscale simulations are then performed to further refine the mesoscale results. The microscale model computes a speed-up over hills. The input of the model includes high resolution terrain elevation, land use, and bivariate frequency distribution table established in step 3.

The global long term dataset used in WEST is the NCEP/NCAR (National Centers for Environmental Prediction / National Center for Atmospheric Research, by Kalnay et al., 1996) reanalysis. The mesoscale model is based on the Canadian Mesoscale Compressible Community Model (Tanguay et al., 1990, Thomas et al., 1998) with the modification in the model's initialization. MsMicro (Walmsley et al., 1986) is used for microscale modeling. The following sub-sections describe, in detail, the main components of WEST.

2.1 Classification scheme

The NCEP/NCAR reanalysis is chosen to be the long term global dataset for time series analysis due to its relatively uniform quality both in space and time, and its free access to the public. The reanalysis used in this study covers a period of 43 years (1958-2000) with a time sampling of every 6 hours. The dataset is in latitude-longitude grid (2.5 degrees of grid spacing) at 17 pressure levels in vertical (from 1000 to 10 mb).

The parameters used for classifying large-scale weather situation depend on the application. For wind energy study, only the wind within the first hundreds meters AGL is of interest. In mid-latitudes, it is mainly influenced by the pressure gradient, air stability, terrain shape (elevation and orientation), and surface roughness. The geostrophic wind turns to be the prime parameter since it is linked to the large-scale pressure gradient through geostrophic balance in mid-latitudes, and its vertical variation is related to the horizontal variation of potential temperature.

The atmospheric state is simply defined at 4 heights above sea level (ASL): 0, 1500, 3000, and 5500 m, since only the near surface wind is of interest. The interpolation/extrapolation (simply referred as interpolation hereafter) of meterological parameters from 4 pressure levels (1000, 850, 700, 500 mb) is done in two steps. The pressure value at the above mentioned 4 heights is obtained through interpolation using hydrostatic approximation. The temperature and humidity at pressure levels are then interpolated to the pressure values (obtained from the first step) corresponding to the 4 height levels. The geostrophic wind is then calculated at the 4 height levels using the interpolated pressure, temperature, and humidity.

The weather situations are classified into equiangular direction sectors and non-uniform speed intervals (Frank and Landberg, 1997). The number of classes is chosen as a compromise of accurate description of regional climate and computational effort. In this study, the geostrophic wind direction is classified into 16 sectors, and each sector is divided into 14 speed classes (with class limits as: 2, 4, 6, 8, 10, 12, 14, 16, 18, 22, 26, 30, 34 m/s and above). The vertical shear of geostrophic wind (or wind speed difference between 1500 and 0 m) is also considered in the classification scheme. Each class of a sector and speed interval is then divided into two classes according to the sign (positive or negative) of shear, except for the lowest wind speed interval. In this demonstration study, seasonal variation is not considered in the classification scheme (although it can be important) to minimize the computational requirement. There are maximum 432 possible classes.

2.2 Mesoscale model

The Canadian Mesoscale Compressible Community Model (MC2) is used for mesoscale modeling. MC2 (Tanguay et al., 1990, Thomas et al., 1998, Girard et al., 2005) is a compressible non-hydrostatic limited area model. It was developed for mesoscale modeling research and operational weather forecasting. Benoit et al. (2002) documented the performance of MC2 in real time high resolution forecast over complex terrain. This paper will present only the changes made in the model to accommodate the downscaling procedure. As discussed in section 2.1, the classification procedure outputs the occurrence frequency of a class (one vertical profile of meteorological parameters) for the entire mesoscale model domain. The vertical profile is set at the center of model domain as initial condition. The initial condition for the rest of the model grid points is obtained by using hydrostatic and geostrophic approximation (discussed in the following paragraph). The model will start with this initial condition and with the boundary conditions kept constant in time, as opposed to the usual NWP application, in which the model is fed with three-dimensional meteorological data and with time dependent lateral boundary conditions provided by the driving model.

The construction of three-dimensional meteorological data is done with the assumption of hydrostatic and geostrophic balance. Under this assumption, the three components of the momentum equation in a conformal projection of the spherical earth and with geometric-height as the coordinate reduce to:

$$RT\frac{\partial q}{\partial X} = fV - K\frac{\partial S}{\partial X} \tag{1}$$

$$RT\frac{\partial q}{\partial Y} = -fU - K\frac{\partial S}{\partial Y} \tag{2}$$

$$RT\frac{\partial q}{\partial z} = -g \tag{3}$$

where R is the gas constant for dry air (287 J kg^{-1} K^{-1}); T air temperature; $q = ln(p)$ with p the air pressure; f the Coriolis parameter ($f = 2\ \Omega\ sin\ \phi$, with Ω the angular velocity of the earth's rotation, and ϕ the latitude); U and V the components of horizontal wind along

X and Y; $K = (U^2+V^2) / 2$ the kinetic energy; S the square of map scale factor m; and g the effective gravitational acceleration (9.8 m/s).

MC2 is built in generalized terrain-following height coordinate. In WEST application though, model terrain heights are initially set at sea level (or 0 m). This setting simplifies the construction of three-dimensional initial conditions since $\delta z = \delta Z$ for terrain height at sea level. During a first phase of the model integration, terrain heights are then made to grow at a preset rate to eventually reach values characteristic of the region and suitable for the model resolution considered. Thus meteorological fields adjust dynamically to orographic forcing.

In the model, thermodynamic variables are decomposed into a basic state and perturbation components, $T = T^* + T'$ and $q = q^* + q'$. When this basic state, representing a stationary isothermal atmosphere in hydrostatic equilibrium, $\left[\partial q^* / \partial z = -g / RT^*\right]$, is subtracted from equations (1) – (3), they become:

$$R(T^* + T')\frac{\partial q'}{\partial X} = fV - K\frac{\partial S}{\partial X} \tag{4}$$

$$R(T^* + T')\frac{\partial q'}{\partial Y} = -fU - K\frac{\partial S}{\partial Y} \tag{5}$$

$$R(T^* + T')\frac{\partial q'}{\partial z} = -g\frac{T'}{T^*} \tag{6}$$

Finally, new variables are defined: generalized pressure $P = RT^*q'$ and buoyancy $b = gT'/T^*$. With this change of variables, equations (4)-(6) become:

$$(1+\frac{b}{g})\frac{\partial P}{\partial X} = fV - K\frac{\partial S}{\partial X} \tag{7}$$

$$(1+\frac{b}{g})\frac{\partial P}{\partial Y} = -fU - K\frac{\partial S}{\partial Y} \tag{8}$$

$$(1+\frac{b}{g})\frac{\partial P}{\partial z}=-b \qquad (9)$$

To initialize the model, vertical profiles of temperature and geostrophic wind from classification (at 4 heights: 0, 1500, 3000, 5500 m) are set at the center of the model domain. They are interpolated to the model levels (28 levels) using cubic interpolation up to 5500 m. Above, the profiles are kept constant. Using the temperature (buoyancy *b*) profile at the center of domain, a generalized pressure *P* profile is calculated by numerically integrating (9). The full distribution of pressure is then determined by numerically integrating equations (7) and (8) in the *X*- and *Y*-direction respectively starting from the center towards the edges of the domain and, of course, assuming uniformity of the geostrophic wind throughout. Finally, temperature profiles away from the center profile are obtained through iteration using Eq. (9) again. We note here that the temperature profiles after this step can no longer be identical to the original ones obtained from the classification except at the center since it is impossible to maintain strictly both hydrostatic and geostrophic balances in the large numerical model domain with uniform temperature and geostrophic wind profiles. The temperature profiles calculated with iteration, though slightly different from the original ones, offer the advantage of satisfying the geostrophic balance in the model.

The geostrophic balance is a valid first order approximation for the free atmosphere but not in the planetary boundary layer where the air flow is ageostrophic under the influence of friction originating from the surface. In this study, the geostrophic wind is adjusted to ageostrophic wind through model physics parameterization in the model computation domain. In the nesting zone where no model computation is applied, however, the friction effect is simply parameterized with a reduction of wind speed by 40% and a derivation of the wind direction by 40 degrees to its left facing downstream.

The three-dimensional atmospheric state is then established and ready for the model integration. As mentioned earlier, the model mountain is set at sea level (0 m ASL) and starts to grow at the first time step. The ground temperature will be adjusted to that of air in immediate contact with the ground. When the mountain reaches its steady state, the ground temperature will be kept constant in time to make sure a better stability and shorter integration time for the model to reach the steady state of the atmosphere. Radiation is then turned off in the model. However, the sea/lake breeze and mountain/valley circulation cannot be simulated with this setting. The atmosphere is considered to be dry (no humidity) since the condensation effect on the surface wind is relatively small. Experiments for various regions show a six-hour physical simulation time would be enough for most of classes to reach a steady state. In practice, a simulation of 9 hours is made for all the classes.

2.3 Statistic module

The simulation results for each class are weighted with its occurrence frequency to build a database of statistics. This database includes characteristics of the mean properties of simulated winds. As each mean is weighted by the frequency of geostrophic wind classes, it represents wind climate for the entire analyzed period (43 years). The statistics can be calculated for any height near surface by assuming a logarithmic profile of surface wind with which the wind speed is interpolated from model vertical levels to the height at which the statistics are calculated.

All variables, available within the database, are identified in table 1. Among them are mean values of wind speed and wind power, and different frequency distributions with respect to wind speed, direction and wind power classes. Note that the mean wind power ($0.5\rho v^3$ in Watts/m^2, with ρ the air density and v wind speed) is also called kinetic energy flux density (Frank et al., 2001). The air density is assumed to be unit to simply the computation of energy.

To generate categorical statistics, the wind speed, wind direction and wind power are classified into different categories. There are 27 wind speed classes with an increment of 1 m/s between the classes, except classes 0, 1 and 26. Class 0 denotes wind speeds between 0 and 0.2 m/s, class 1 between 0.2 and 1 m/s, class 2 between 1 and 2 m/s, and finally class 26 wind speeds of 25 m/s and above. Wind direction classes are referred to as sectors. There are 12 equiangular sectors centered at 0, 30, 60… and 330 degrees. Sector 360 contains a sum of all other sectors' values. For the variable UHR the sum is in sector 360 and class 26.

Eight wind power classes (used for EH and EC variables) are defined by using the following thresholds: 0, 200, 300, 400, 500, 600, 800 and 1000 W/m^2. Class 1 indicates wind power between 0 and 200 W/m^2, class 2 between 200 and 300 W/m^2, and finally class 8 - wind power equal to or higher than 1000 W/m^2. The eight cumulative frequency classes are defined for wind power equal or higher than a threshold value.

Three variables (ERN, UR and UHR) are worth to be mentioned. They constitute an input for microscale model to further downscale wind to a higher resolution. All three variables are averaged over the point and its eight closest neighbours on the grid. ERN is the frequency distribution of the mean wind direction, UR is the mean wind speed distribution by sector and UHR is the bivariate frequency distribution of mean wind by sector and wind speed class. This bivariate table is a key input for the microscale model because it allows the determination of mean wind speed and mean wind power from the microscale winds.

2.4 Microscale model and its coupling with mesoscale model

The theory of Jackson and Hunt (1975) provided a basis for numerical modeling of two-dimensional steady state of turbulent flow over a low hill. In their theory, the surface Rossby and Reynolds numbers are assumed high enough for the wind profile in most part of boundary-layer to be logarithmic. The air flow is separated into inner and outer regions. The governing momentum equations are linearized with the aid of scale analysis and assumptions of uniform rough surface with small slope of a hill. The inner flow is under the balance of perturbation stress, inertia stress and pressure gradient, while the outer flow is characterized by a pressure gradient driven irrotational and invicid flow. Application of this theory to the wind energy study led a development of two most popular microscale modeling softwares: WAsP (Troen and Petersen, 1989) and MsMicro (Walmsley et al. 1990). The later is used as the microscale modeling tool in WEST.

MsMicro undergoes several steps of development. It is based on Mason and Sykes' model (1979), which is an extension of the 2D-theory of Jackson and Hunt to three-dimensional topography. Walmsley et al. (1982) introduced a height-dependent pressure forcing and made a first application of MsMicro to real terrain. A variable roughness was later implemented by Walmsley et al. (1986). Their results compare reasonably well with the in situ observations for small slope (<0.3) terrain. Note that error can be large over a steep terrain, and in particular if the separation of the flow occurs.

In the context of WEST, a mesoscale domain (about 875x875 km^2) is decomposed into hundreds, or even thousands overlapped sub-domains (or tiles) depending on the resolution of MsMicro used for the application. The tiles are spread out along the mesoscale grid with the center of the tiles co-locating with the corresponding mesoscale grid point (Fig. 2). The inputs to the MsMicro are cautiously prepared to avoid double accounting of effects, like the speedup over hills. The perturbation of the terrain (difference between terrain elevation at micro-model resolution and that at meso-model resolution) is used as terrain elevation in the microscale. For the same reason, the upstream roughness length used in meso-model is also taken into account in the micro-model simulation. The bivariate frequency distribution (BFD) of mean wind speed from the statistic module is also a key input to MsMicro. The BFD is chosen at a level higher than the microscale target level. With these inputs, MsMicro is run for each individual microscale domain. The final results, mean wind speed and wind power, are merged together with a space weight function.

3 APPLICATION OF WEST AND ITS VALIDATION

WEST is applied to Gaspé region, in Quebec province of Canada. The NCEP/NCAR global reanalysis (43 years of data from 1958 to 2000) is used for weather situation classification. In total, 366 classes are determined for this region. Figure 3 shows the frequency distribution of geostrophic wind (GW) as function of speed (top panel), and as function of wind direction sectors (bottom panel). The frequency curve of GW follows approximately Weibull distribution. Note here that the second peak (in top panel) centered at 20 m/s is an artifact, due to a change in the wind speed interval from 2 to 4 m/s for GW larger than 18 m/s. The mean GW for that region is about 10.6 m/s, plotted in dotted line. Gaspé is in the Westerlies as shown in the bottom panel.

MC2 is set up at a grid spacing of 5 km covering Gaspé region (Figure 4). There are 175 x 175 grid-points and 28 vertical levels non-uniformly distributed from surface to 20 km ASL (with 10 levels within the first 1.5 km). The first wind level is about 50 m AGL. MC2's parameter settings are listed in Table 2. Typical wall clock time for this size of domain is about 2.5 hours per simulation on a Pentium-4 2.4 GHz. The simulation for all the 366 classes will be done in about one month using a single PC, or within 4 days by using 10 similar PCs.

A total of 24336 microscale model domains are set up with an overlap ratio of 0.6 to cover the entire mesoscale model domain (about 608400 km^2) at a resolution of about 200 m. MsMicro's parameter settings are also listed in Table 2. For the size of domain (128x128 grid points) listed in the table, it takes about 2 second for a Pentium-4 PC to do one simulation, and 14 hours (or 1.4 hours for 10 PCs) for all the 24336 simulations.

4 WIND MEASUREMENTS AND VALIDATION AGAINST MODEL

The measured wind speed data used for the comparison are from 29 out of 44 stations that were offered by the Ministère des Ressources naturelles du Québec for the study in the Gaspé Region. The 29 stations were located as shown in Figure 4 which is centered on the St Laurence river. Most of the stations were located near the shoreline of the Gaspé Peninsula. The colors on the map represent wind speeds (m/s) at 40 m AGL from simulations with both meso- and micro-components of WEST (WEST hereafter), while the red contours are the wind speeds from the meso-component only (MC2 hereafter). The contouring of wind speed is similar between these two, but more details can be seen in WEST simulations. It is apparent from this map that the higher wind speeds are either out on the river away from land, in coastal land or at higher elevations as shown in the upper left corner of the map.

Better details of the high resolution simulation ca be seen in Figure 5 which shows a zoom-in of the areas with labels (A, B, C, D) in figure 4. In general, the MC2 produces a relatively smooth wind speed distribution (in contours), while WEST gives more details (in color shadings) due to the higher resolution terrain and simulation grid. In Figs 5A, 5B, and 5C, the contours are almost parallel to the shoreline. The speedup over hills is almost missed in MC2 simulations, but well simulated with WEST (the observed 7.1 m/s versus the WEST 7.8 m/s in Fig. 5B; 6.9 m/s versus 6.1 m/s in Fig. 5C; and 9.1 m/s versus 7.7 m/s in Fig. 5D).

Of the 44 stations, the stations that were rejected in this study had either too short of a monitoring period, in some cases only 0.4 years, were missing data at 40 m AGL, or were out of the domain range. The period of measurements for the 29 stations averages about 1.2 years. The shortest period is 0.8 and the longest is 2.4 years. The wind data was sampled every second and averaged at 10-minute intervals. Errors due to periodic variability from the long-term mean wind speed are considered here because of the short measurement periods. For all of these stations the long-term mean is unknown and so two nearby long-term stations are analyzed for such periodic variability. The Atlantic Wind Test Site (AWTS) is located at the north end of Prince Edward Island and is about 210 km south of the town of Gaspé. The tower at the AWTS is 50 m AGL, the data was collected on 10-minute intervals and averaged to monthly means spanning 17 years. The 17-year mean wind for this station is 8.3 m/s. The other station, the Caribou upper air station is located 180 km south of Rimouski. The long-term wind speed of 6.1 m/s is interpolated to 110 m AGL and is calculated from 12-hour samples spanning 17 years to match the AWTS station and 43 years to match the 1958-2000 period of data used in the input analysis.

Figure 6 depicts the 1^{st} and 99^{th} percentile variation of mean wind speed from the moving average of seven different period lengths from the long-term mean of the two stations. The graph shows a decreasing variability with long term average as the measurement period is increased. Generally the one-month means vary by about ±30% (1^{st} and 99^{th} percentile) from the long-term mean and reduce to ±10% or less for periods of one year and longer. The 17-year analysis of the Caribou station compares relatively well with the AWTS station for the periods one year and longer; both have variability errors of about ±7% at one year, increase slightly at 1.5 year, and then decrease to about ±2% at five years. The 43-year variability at Caribou is slightly larger than the 17-year analysis showing a variation of +4% and -6% at five years. The variability errors for the Caribou 43-years analysis that are shown as the thick black line labels in Figure 6 are used here to calculate the error in the measurements at each of the Gaspé stations. No other errors are considered in this analysis.

The simulation results as produced by WEST are compared to the measured wind speeds and are shown in the scatter plot of Figure 7. The horizontal error bars are derived from interpolating the Caribou variability error (from the 43-year analysis) in relation to period monitoring length and applying them to each of the 29 stations based on their monitoring length. The error bars show that most of the stations could conceivably match the simulation with great accuracy.

The measurements are compared to both the MC2 and the WEST simulations. The wind speeds of the MC2 simulation under-predicts those of the measurements with a mean MC2-to-measurement ratio of 0.94, which means that on average the MC2's wind speeds are about 6% lower than the measurements. The correlation coefficient is about 0.5. The WEST produces better results with the model now under-predicting the measurements by an average of only 1% (WEST-to-measurement ratio of 0.99). The simulated wind speeds are on average about 0.15 m/s lower than those of the measurements. The correlation is also improved considerably to 0.7. The improvement of WEST results over MC2 alone is mainly due to the resolution enhancement of surface properties, terrain height and land use particularly in coastal regions.

5 CONCLUSIONS AND DISCUSSIONS ON FURTHER DEVELOPMENTS

This paper documented the WEST system, and showed a demonstration run over Gaspé, a region of Quebec, Canada. The results compare well with the mast observations. The under-estimation of mean wind speed is about 6% with meso-component alone, and only 1% with both meso- and micro-components (i.e. 0.15 m/s). The correlation coefficient is also improved from 0.5 with meso-component to 0.7 with both meso- and micro-components. The WEST system was also used to create the Canadian wind atlas at a resolution of 5 km (with meso-component only), the first digital atlas for such a large country. The atlas is accessible in both graphical and digital format at www.windatlas.ca.

WEST is designed for both research and industry use, even with modest computation facility. For instance, a high quality map of long term (over last 50 years) wind climatology for an area of 875 x 875 km^2 at a resolution of hundreds of metres can be established in about one month with a stand alone PC (Pentium-4, CPU 2.4GHz with 1 GB RAM), or in about 4 days with 10 similar PCs. The WEST code is ported to Windows operating system. The Window based version of WEST is licensed for commercial applications. Users can run it with single Windows PC, or dispatch the simulations to a pool of PCs (Windows or Linux) through the frontal Windows PC to shorten the simulation time. Since the most intensive computation is in meso-component of the WEST and has been completed for the Canadian territory, users can download the output of meso-component at the atlas web site and feed it directly into the micro-component of WEST. In this way, users can produce a wind map for an area of about 875 x 875 km^2 at a resolution of hundreds meters within a day.

In this study, the classification of weather situations is done at 4 heights (0, 1500, 3000, and 5500 m ASL). This implies an extrapolation of global climate data over land towards the sea level. Errors can be large in high land like Rocky-mountains. Classification at average terrain height as surface level may be an alternative to minimize the errors.

MC2 has a varying topography capability in the first integration hours, that is, the topography varies from coarse resolution (at time zero) to model's resolution (in about one hour). In WEST, the coarse resolution terrain is set to 0 m ASL (in fact, no terrain). This creates too large a slope in the nesting zone, and affects the model's solution inside of the model domain. In future application, an averaged terrain height (say, smoothed over 8 neighboring grid-points) can be used as coarse resolution topography to initialize MC2.

Surface heat flux is turned off (by keeping the ground temperature the same as that of air in immediate contact) in this version of WEST to ensure a final steady solution in mesoscale modeling. This simplification prevents the model from simulating the thermo-circulation, like lake-land breeze. Further study is needed to include more physical parameterizations in the mesoscale modeling.

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REFERENCES

Benoit, R., C. Schar, P. Binder, S. Chamberland, H.C. Davies, M. Desgagné, C. Girard, C. Keil, N. Kouwen, D. Luthi, D. Maric, E. Muller, P. Pellerin, J. Schmidli, F. Schubiger, C. Schwierz, M. Sprenger, A. Walser, S. Willemse, W. Yu, and E. Zala, 2002: The Real-Time Ultrafinescale Forecast Support during the Special Observation Period of the MAP, Bull. Amer. Meteor. Soc., 81, 2953-2962.

Frank, H.P. and L. Landberg, 1997: Modelling the Wind Climate of Ireland, Boundary-Layer Meteorol. 85, 359-378.

Frank, H.P., O. Rathmann, N.G. Mortensen, and L. Landberg, 2001: The Numerical Wind Atlas – The KAMM/WAsP method, Riso-R-1252(EN), Published by Riso National Laboratory, Roskilde, Denmark.

Frey-Buness, A., D. Heimann, and R. Sausen, 1995: A statistical-dynamical downscaling procedure for global climate simulation. Thoer. Appl. Climatol. 50, 117-131.

Girard, C., R. Benoit and M. Desgagné, 2005: Finescale Topography and the MC2 Dynamics Kernel, Mon. Wea. Rew., Vol. 133, 6, 1463-1477.

Jackson, P.S. and J.C.R. Hunt, 1975: Turbulent Flow Over a Low Hill, Quart. J. Roy. Meteorol. Soc. 101, 929-955.

Kalnay, E, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, Roy Jenne and Dennis Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project., Bull. Amer. Meteor. Soc., Vol. 77, No. 3, 1996, pp. 437-471.

Mason, P.J. and R.I. Sykes, 1979: Flow Over an Isolated Hill of Moderate Slope, Quart. J. Roy. Meteorol. Soc., 105, 383-395.

Tanguay, M., A. Robert, and R. Laprise, 1990: A semi-implicit semi-Lagrangian fully compressible regional forecast model, Mon. Wea. Rev. 118, 1970-1980.

Thomas, S., C. Girard, R. Benoit, M. Desgagné, and P. Pellerin, 1998: A new adiabatic kernel for the MC2 model. Atmos.-Ocean, 36, 241-270.

Troen, I. and E.L. Petersen, 1989: European Wind Atlas. Published by Riso National Laboratory, Roskilde, Denmark, ISBN 87-550-1482-8. 656p.

Walmsley, J.L., J.R. Salmon, and P.A. Taylor, 1982: On the Application of a Model of Boundary-Layer Flow Over low hills to Real Terrain, Boundary-Layer Meteorol. 23, 17-46.

Walmsley, J.L., P.A. Taylor, and T. Keith, 1986: A Simple Model of Neutrally Stratified Boundary-Layer Flow Over Complex Terrain with Surface Roughness Modulations (MS3DJH/3R), Boundary-Layer Meteorol. 36, 157-186.

Walmsley, J.L., I.B. Troen, D.P. Lalas, and P.J. Mason, 1990: Surface-Layer Flow in Complex Terrain: Comparison of Models and Full-Scale Observations, Boundary-Layer Meteorol. 52, 259-281.

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Figure 3: Frequency distribution of geostrophic wind (GW) as function of speed (top panel), and as function of wind direction sectors (bottom panel). The second peak (in top panel) centered at 20 m/s is an artifact, due to a change in the wind speed interval from 2 to 4 m/s for GW larger than 18 m/s. The mean GW is about 10.6 m/s, plotted in dotted line. Gaspé is in the Westerlies as shown in the bottom panel.

Figure 4: Mean wind speed produced with WEST is plotted in color shadings, and with MC2 in red contours. The observed wind speed from the 29 stations is also printed in black numbers with black circle-and-cross representing the station location. The relatively low spatial variability of wind speed (color shading) in the area surrounded by straight lines is an artifact due to the lack of high resolution terrain data along Canada-US border. The letters A, B, C, D indicate the areas in which detail map is plotted in Figure 5.

Figure 5: Same as Figure 4 but a zoom in the selected areas.

Figure 6: This graph shows the 1st and 99th percentile variation of mean wind speed from the moving average of seven different period lengths from the long-term mean of the two stations. The thick black line with the labels is a 43-year analysis while the thin line is a 17-year analysis of the Caribou station. The Caribou station is an upper air station located in Maine approximately 180 km south of Rimouski. The wind data is interpolated at 110 m AGL. The gray line is the

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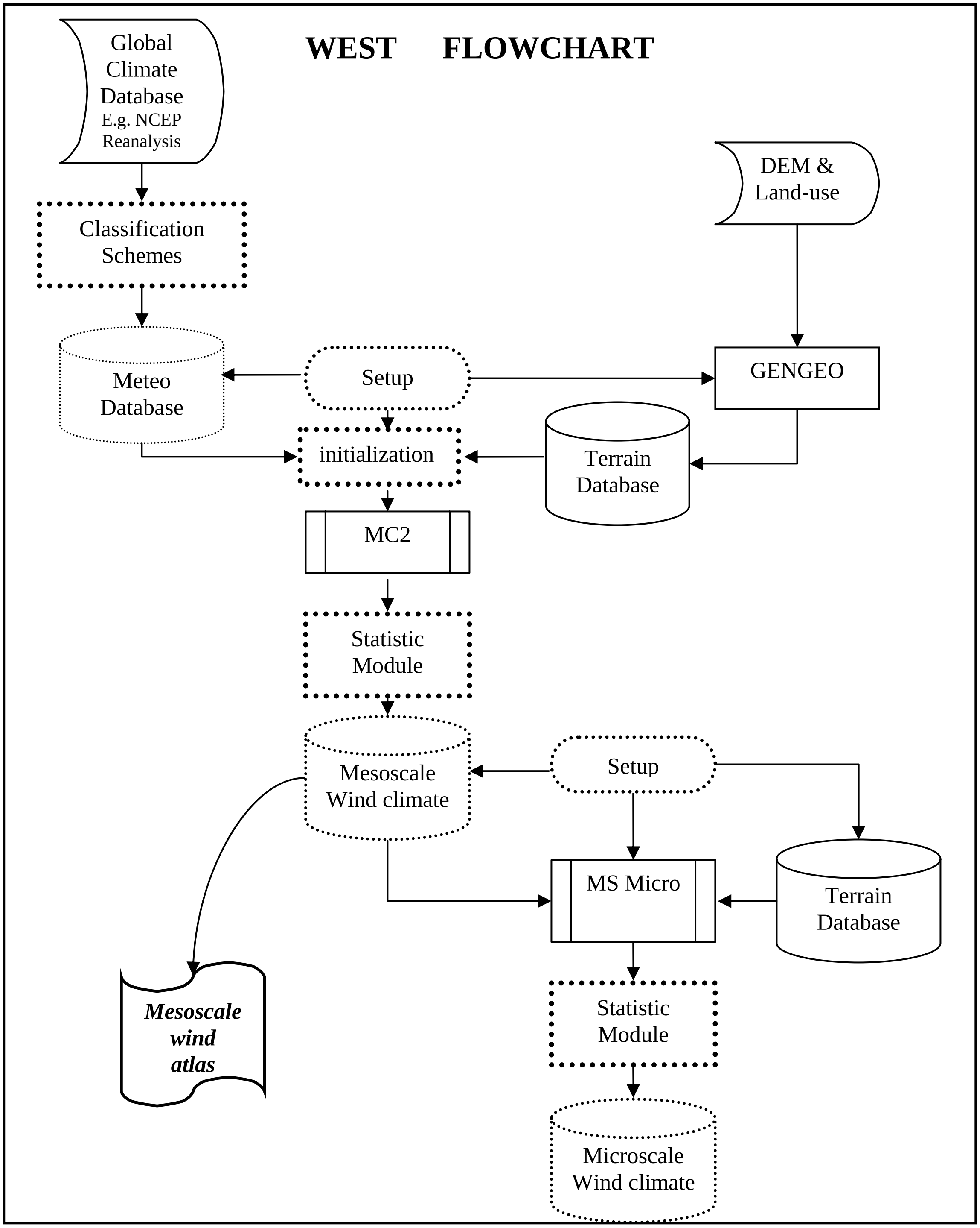

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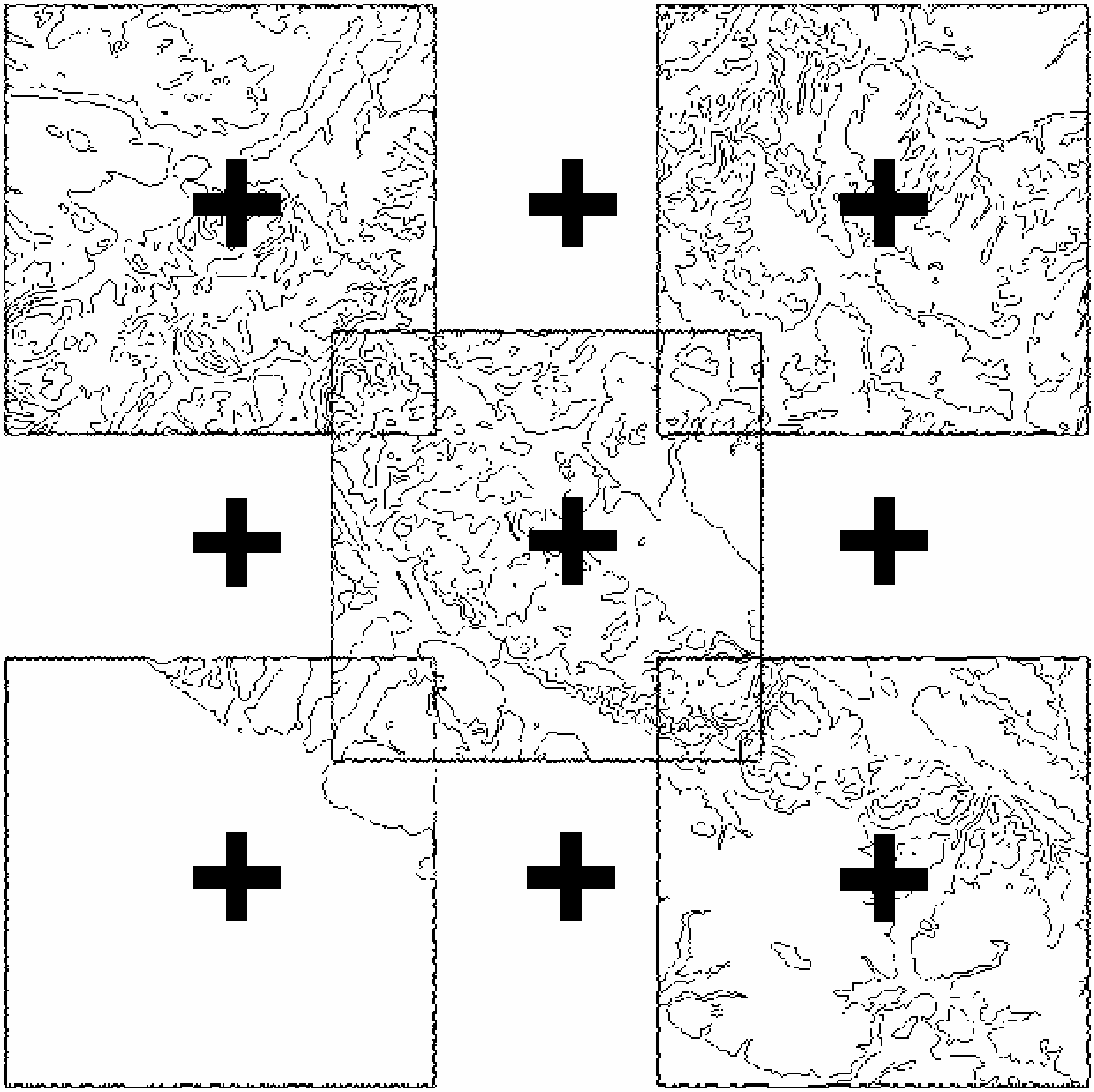

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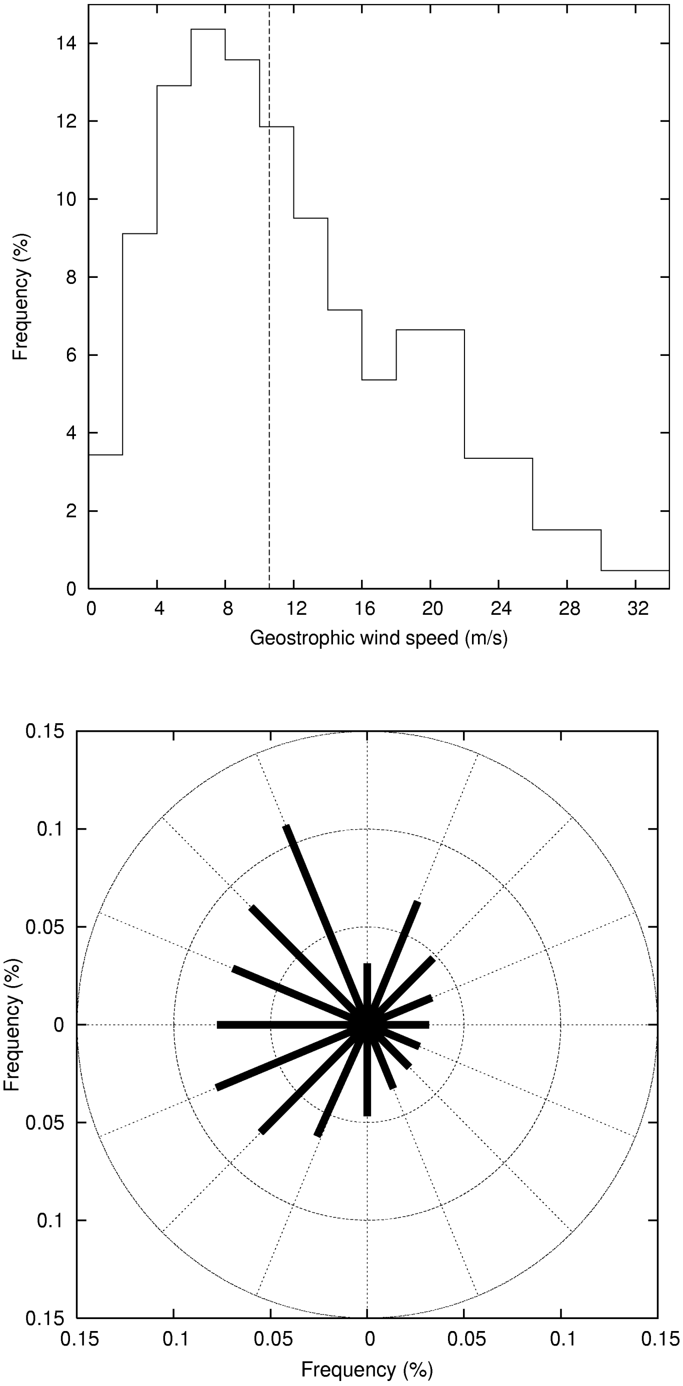

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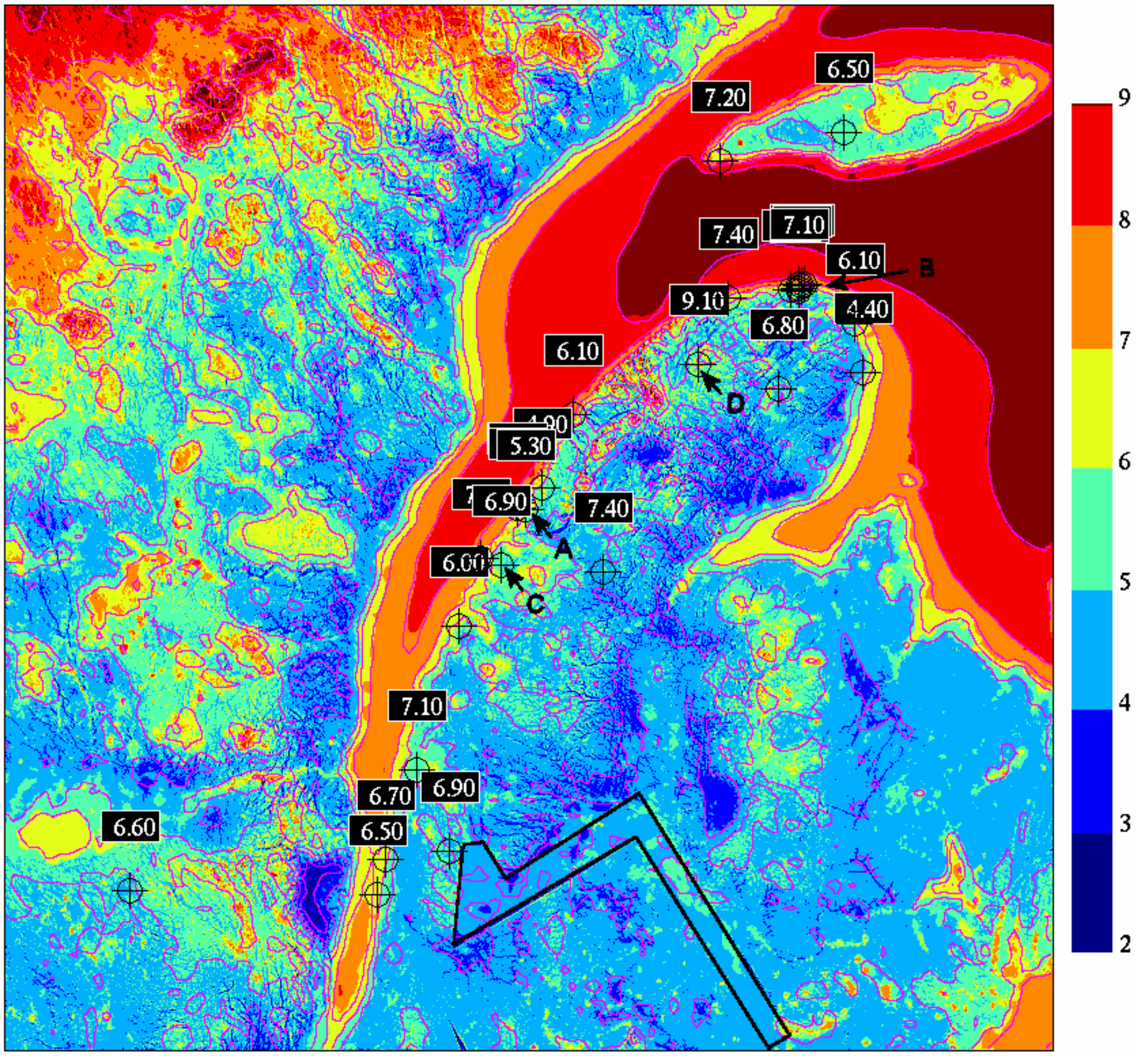

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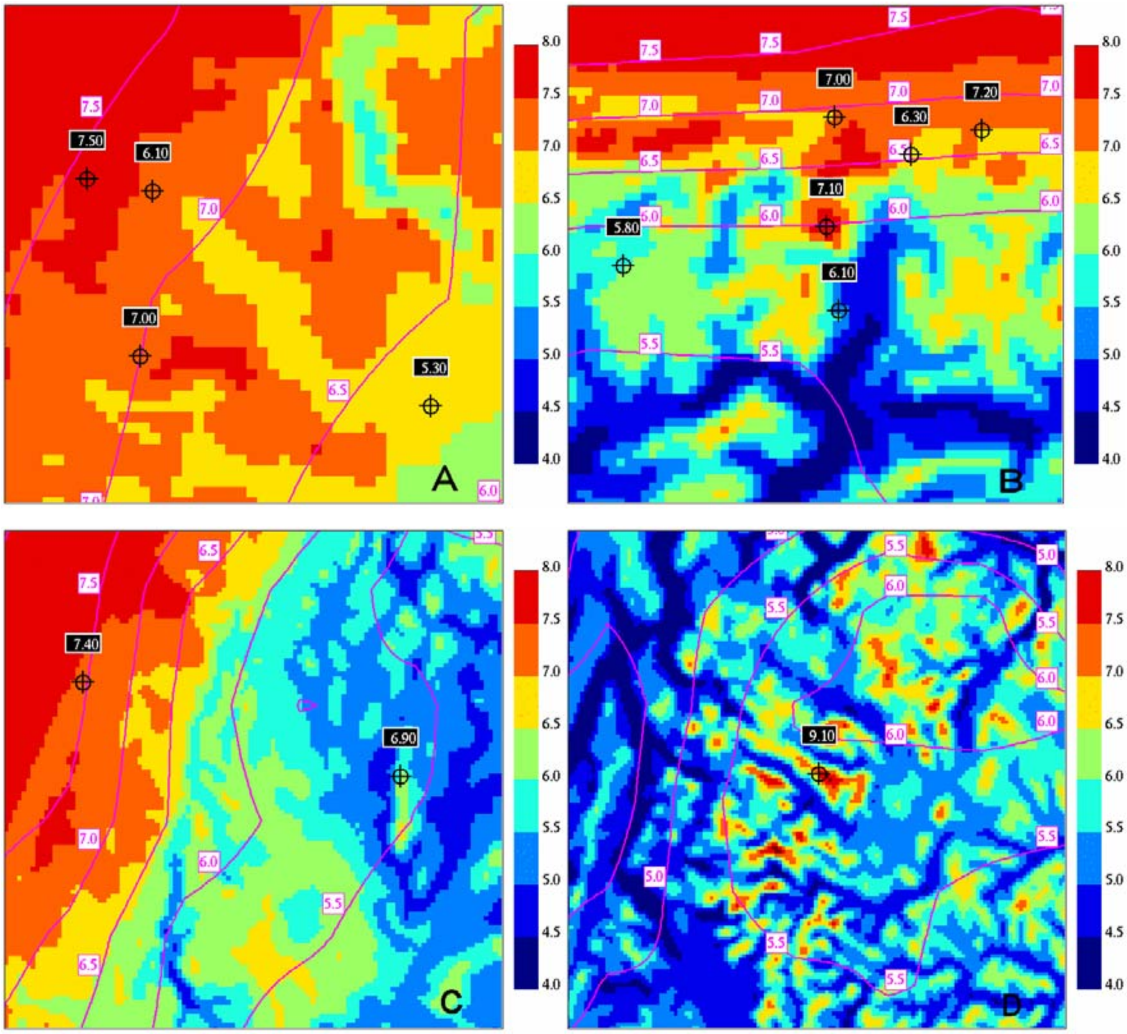

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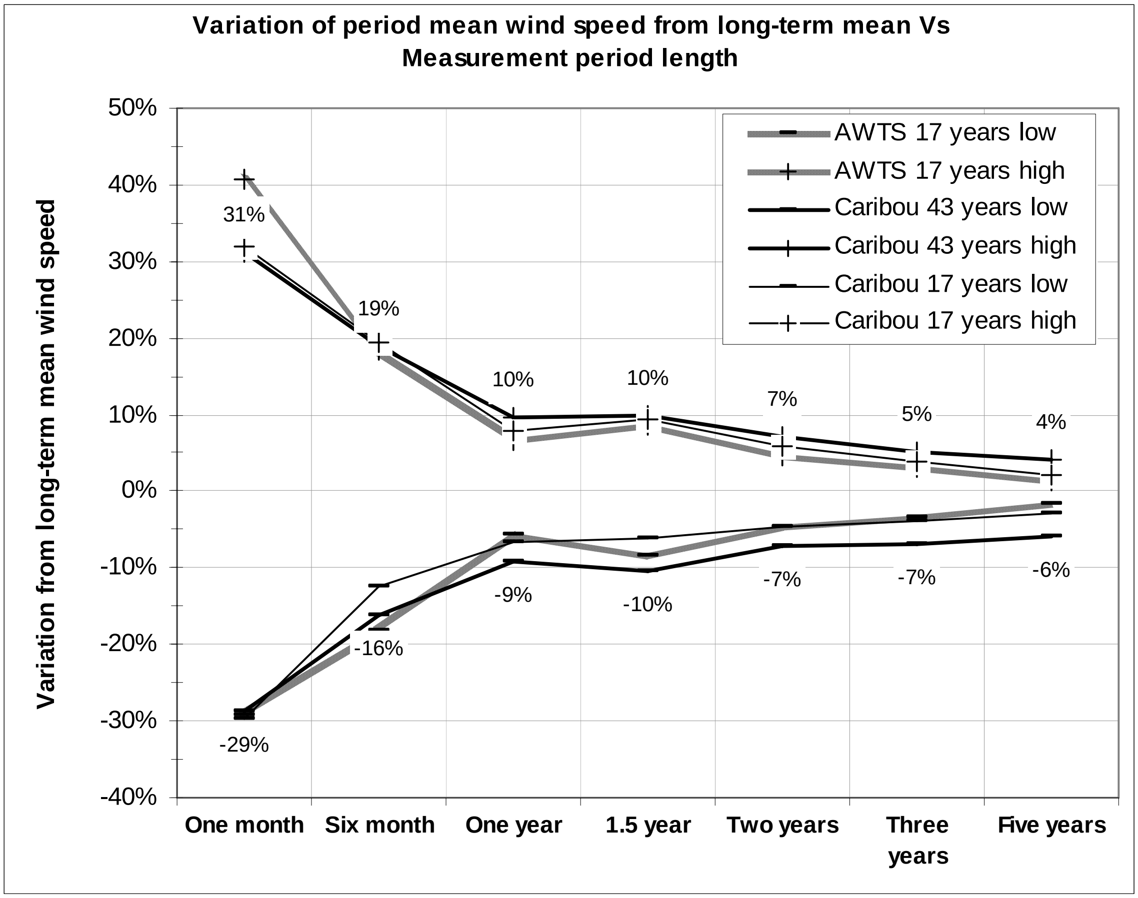

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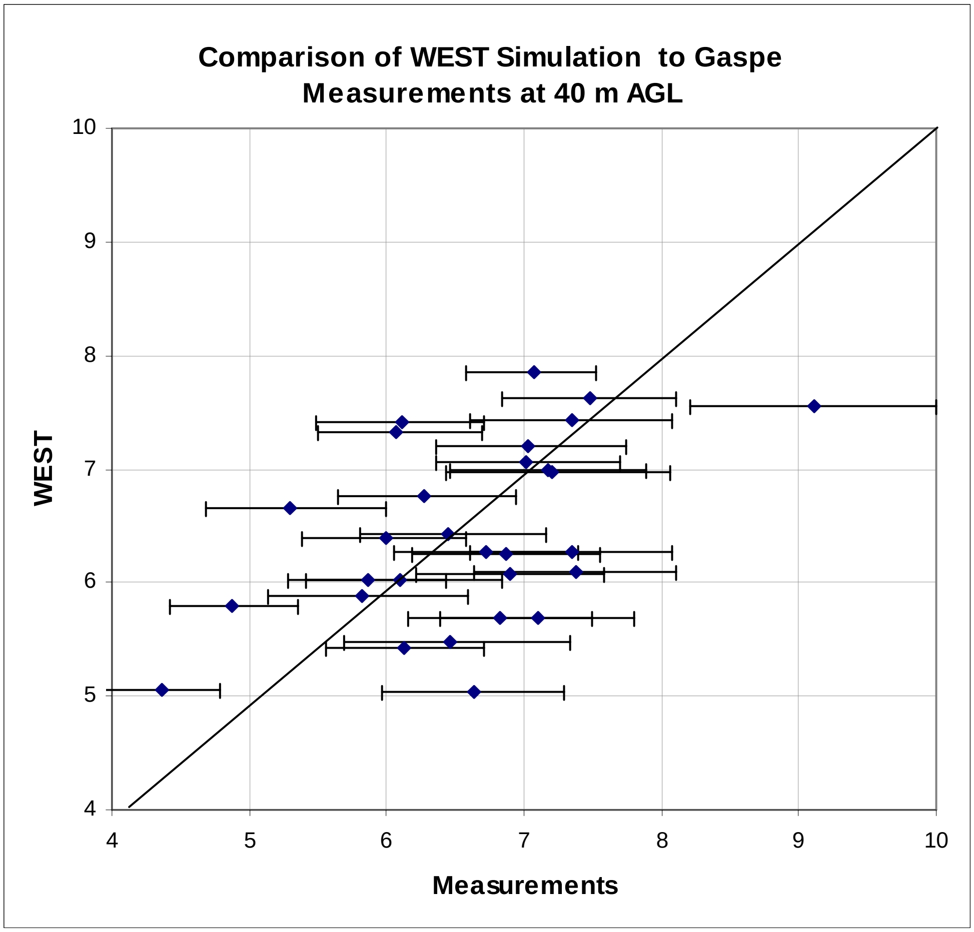

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Table 1: Variables calculated with the statistic module

Variable	Definition
EU (m/s)	Mean wind speed
EU2 (m/s)	Standard deviation of mean wind speed
UH (%)	Frequency distribution of mean wind speed
ER (%)	Frequency distribution of mean wind direction
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ERN (%)	Frequency distribution of mean wind direction, averaged over the point and its eight closest neighbors on the grid
UHR (%)	Bivariate frequency distribution of mean wind speed and direction, averaged over the point and its eight closest neighbors on the grid
UR (m/s)	Mean wind speed distribution by direction, averaged over the point and its eight closest neighbors on the grid
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UU (knots)	Mean wind along x axis
VV (knots)	Mean wind along y axis
……………….	……………………………………………………………………………………..
E1 (W/m2)	Mean wind power
E2 (W/m2)	Standard deviation of mean wind power
EH (%)	Frequency distribution of mean wind power
EC (%)	Cumulative frequency distribution of mean wind power

Table 2: Model parameters for both MC2 and MsMicro

MC2		
Parameters	Description	Value
Grd_dx	Horizontal resolution (m)	5 000
“Grd_ni” x “Grd_nj”	Horizontal grid points	175 x 175
Grdt	Timestep (seconds)	120
htop	Height of model lid (m)	20 000
Gnk	Number of vertical levels	28
gnnpbl	Number of levels in boundary layer (< 1500 m AGL)	10
vmh_ndt	Number of time steps during which mountains grow	29
MsMicro		
Parameters	Description	Value
Alpha	Stride on the coupled mesoscale model grid	1
Sigma	Overlap ration between 2 micro-domains	0.6
Nu	Grid points along X	128
Delta	Grid spacing of the coupled mesoscale model (m)	5000