Meso- and Micro-scale Modelling in China: Application of Wind Atlas

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Meso- and Micro-scale Modelling in China: Application of Wind Atlas

Risø-I-Report

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Risø-I-3073(EN)
June 2010

Risø DTU
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Title: Meso- and Micro-scale Modelling in China: Application

Abstract (max. 2000 char.):

The report on Application of Wind Atlas is part of the "Meso-Scale and Micro-Scale Modelling in China" project, also known as the CMA Component or Component A of the Sino-Danish Wind Energy Development (WED) Programme.

This report seeks to provide an overview of the various elements and methods used to generate the data and wind atlases that can be applied as well as to collect the necessary information and instructions to any interested party to be able to apply these results of the "Meso-Scale and Micro-Scale Modelling in China" project. The report briefly describes the Wind Atlas Method, the application opportunities, how to apply the Numerical Wind Atlas for wind energy planning or wind farm project development, case studies for illustration and sums-up best practices and brief guidance with check lists.

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Introduction

1.1 Project A04 of the Component A of the WED Programme

Project A04 on Application is a part of the “Meso-Scale and Micro-Scale Modelling in China” project, also known as the CMA Component or the Component A of the Sino-Danish Wind Energy Development (WED) Programme.

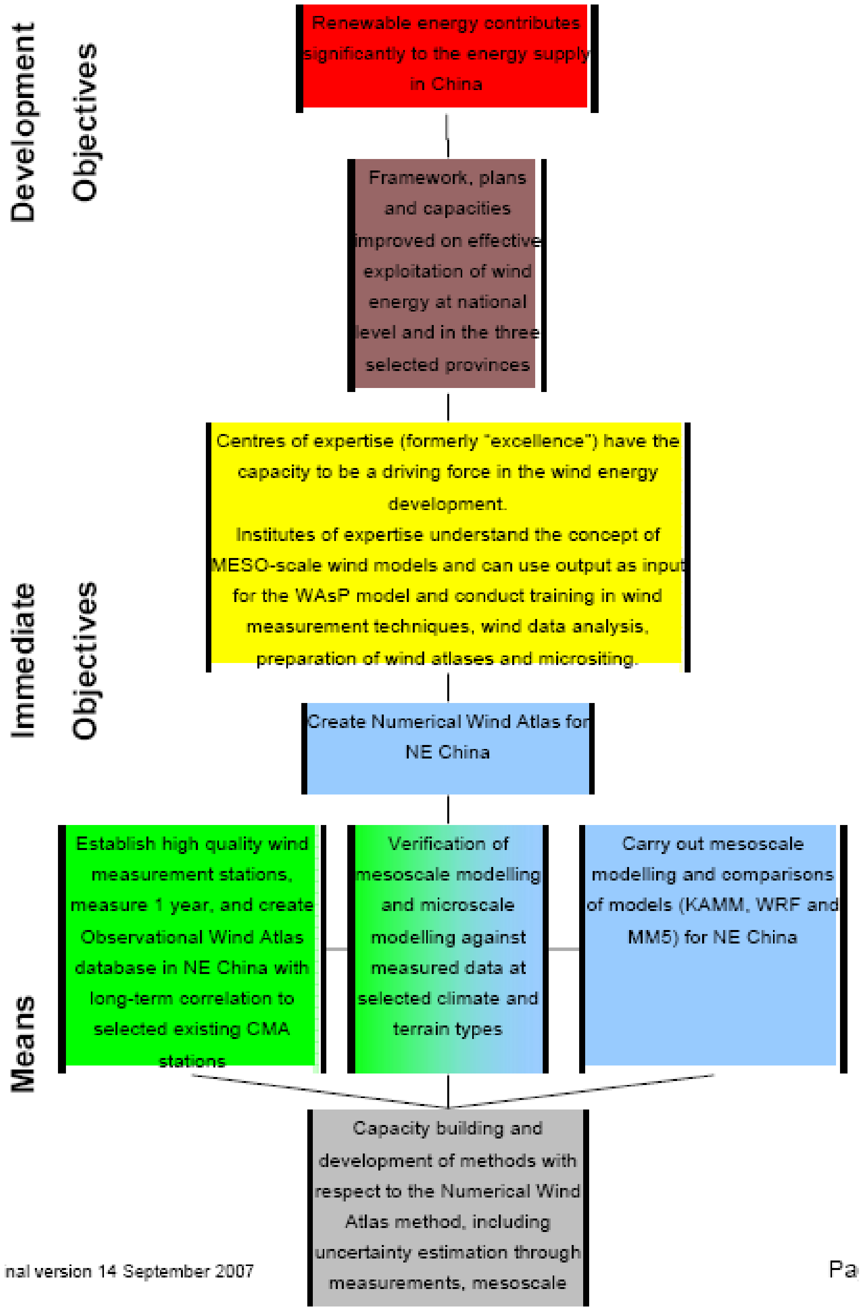


Figure 1. Objective tree of the Component A of the WED Programme as described by the Project Description Document.

In view of the objectives of the Component A of the WED Programme as shown in Figure 1, Component A should build expertise in mesoscale modelling, microscale modelling with WAsP as well as in measurement techniques, data analysis and preparation of wind atlases. This has all been achieved through Projects A01, A02 and A03. However, the use of results for actual applications has been referred to this Project A04 in order to provide a particular focus on this aspect for relevant parties other than the twinning partners developing the wind atlas – China Meteorological Administration and Risø DTU.

This report seeks to collect the necessary information and instructions to any interested party to be able to apply the results of the "Meso-Scale and Micro-Scale Modelling in China" project. The report will briefly describe

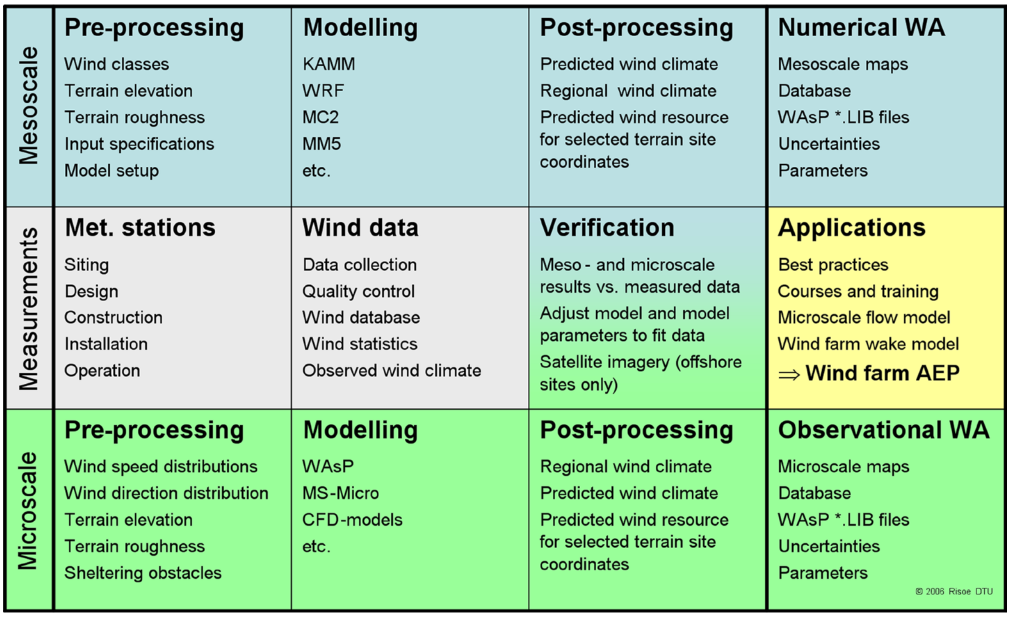
- the Wind Atlas Method – its history and how it has been used by the project to generate the Numerical Wind Atlas and the Observational Wind Atlases
- The application opportunities – who would be able to use the Numerical Wind Atlas and for what
- How to apply the Numerical Wind Atlas for wind energy planning or wind farm project development by employing the Wind Atlas Method and WAsP
- Case studies for illustration of possible ways of application of the Numerical Wind Atlas
- Summing-up best practices and brief guidance

2 Wind atlas methodology

2.1 Introduction

The wind atlas methodology was developed in the 80's and used initially for creation of the European Wind Atlas [1]. The wind resource assessment started the work to develop the microscale flow model, WAsP, conceived and developed at Risø National Laboratory [2]. WAsP did what we now call an observational wind atlas as described below. During the 90's techniques to employ mesoscale models were developed, which made it possible to model larger domains, mesoscale effects, and long-term wind climates [3]. Recently, the techniques have been combined for development of wind atlases in countries with scarcity of measurement stations and consistent verification against comparable values has proven effective. This section of the application report briefly describes the updated state-of-the-art of the wind atlas methodology as it is used in the "Meso-Scale and Micro-Scale Modelling in China" project. Figure 2 illustrates the elements in tabular form, showing the interfaces and process of

- Microscale modelling leading to Observational Wind Atlas
- Mesoscale modelling leading to Numerical Wind Atlas
- Measurements as inputs to Observational Wind Atlas and Verification
- Verification comparing Observational and Numerical Wind Atlases on Measurement locations
- Application of results



Mesoscale	**Pre-processing** Wind classes Terrain elevation Terrain roughness Input specifications Model setup	**Modelling** KAMM WRF MC2 MM5 etc.	**Post-processing** Predicted wind climate Regional wind climate Predicted wind resource for selected terrain site coordinates	**Numerical WA** Mesoscale maps Database WAsP *.LIB files Uncertainties Parameters
Measurements	**Met. stations** Siting Design Construction Installation Operation	**Wind data** Data collection Quality control Wind database Wind statistics Observed wind climate	**Verification** Meso - and microscale results vs. measured data Adjust model and model parameters to fit data Satellite imagery (offshore sites only)	**Applications** Best practices Courses and training Microscale flow model Wind farm wake model ⇒ **Wind farm AEP**
Microscale	**Pre-processing** Wind speed distributions Wind direction distribution Terrain elevation Terrain roughness Sheltering obstacles	**Modelling** WAsP MS-Micro CFD-models etc.	**Post-processing** Regional wind climate Predicted wind climate Predicted wind resource for selected terrain site coordinates	**Observational WA** Microscale maps Database WAsP *.LIB files Uncertainties Parameters

Figure 2. Wind atlas methodologies use wind measurements, as well as microscale and mesoscale modelling for wind resource assessment and siting.

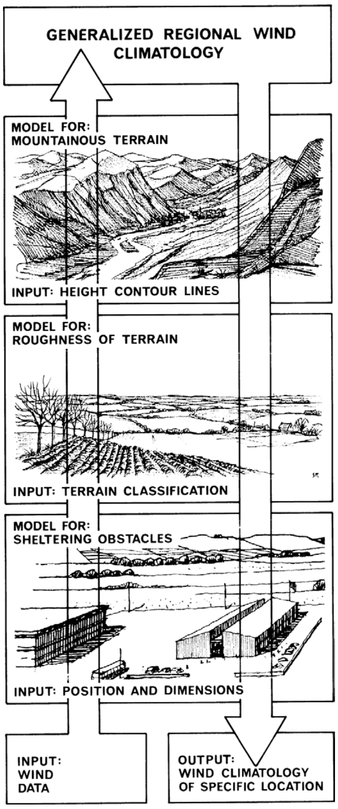
2.2 Microscale observational wind atlas

As the name implies, an *observational wind atlas* is based on observed wind climates from a dense network of meteorological stations or a wind atlas with limited geographical validity to the immediate surroundings of the mast or masts from which the observations for the wind atlas originates. The latter is the case in this project using 12 masts for verification of the mesoscale modelling (the Numerical Wind Atlas) that at the same time provide data for 12 discrete Observational Wind Atlases.

The observed wind climates contain the wind speed and direction distributions derived from long-term time-series of wind speed and direction measurements at the meteorological stations. The observed wind climates are thus representative for specific locations and heights above ground level, so in order to be able to predict the wind climate at a given wind turbine or wind farm site the observed wind climates must be transformed into generalised *regional wind climates*. This may be done using the wind atlas methodology of the European Wind Atlas [1], see Figure 3.

Employing detailed descriptions of terrain elevation, land-use and the occurrence of sheltering obstacles around each meteorological station, the observed wind climate is transformed into what would have been measured at the location of the station if the surroundings were completely flat, featureless and with a homogeneous surface and the measurements had been taken at 10, 25, 50, 100 and 200 m a.g.l. Through this transformation procedure, the observed wind climate is freed from the influence of local topography to become *regionally representative*.

The results in an observational wind atlas, given in the form of detailed statistics of the generalized wind speed and direction distributions for the locations of the meteorological stations. These data sets can then be used as inputs to the application process, whereby the same models are used in reverse to transform the regional wind climate to the *predicted wind climate* at any specific site and height near the station.



Inputs
- measured time-series of wind speed and direction – observed wind climate
- terrain topography – elevation, roughness and obstacles – digitised maps, SRTM, Google Earth

Outputs
- generalised *regional wind climate* for the specific location

Applications
- energy production estimate for wind farms in the region near the meteorological station

Figure 3. The wind atlas methodology will generate the Observational Wind Atlas (regional wind climate) for the location of the mast providing the wind data (observed wind climate).

2.3 Mesoscale numerical wind atlas

Numerical wind atlas methodologies have been devised to solve the issue of insufficient wind measurements, which render wind resource mapping efforts through observational methodologies problematic. Several so-called downscaling approaches exist, connecting the large-scale long-term global datasets via meso-scale modelling to small-scale local wind climate at a given location.

In this project two such methods have been applied.

a) the KAMM/WAsP method developed at Risø National Laboratory [3]. An approach called statistical-dynamical downscaling is used [4]. The basis for the method is that there is a robust relationship between meteorological situations at the large-scale and meteorological situations at the small-scale. Information about the large-scale meteorological situation is freely available from the NCEP/NCAR reanalysis data-set, see [5]. Figure 4 shows a schematic diagram illustrating how the mesoscale modelling results are combined to give regional wind climates in the numerical wind atlas system. The mesoscale model, KAMM, is used to create a wind map for N, typically 150, different wind classes, representing the climate of the region. The results are combined by taking into account the frequency of occurrence of each wind class to create the mesoscale wind resource. The mesoscale wind resource can be transformed to the generalised *regional wind climates,* thus arriving at a numerical wind atlas (e.g. with 5 km resolution) comparable to the observational wind atlas (where observations exist).

b) An adapted statistical-dynamical downscaling approach similar to the KAMM/WAsP method, however instead of KAMM using the mesoscale model WRF.

Both these methods are described in great detail in the dedicated reports regarding the meso-scale modelling part of the project.

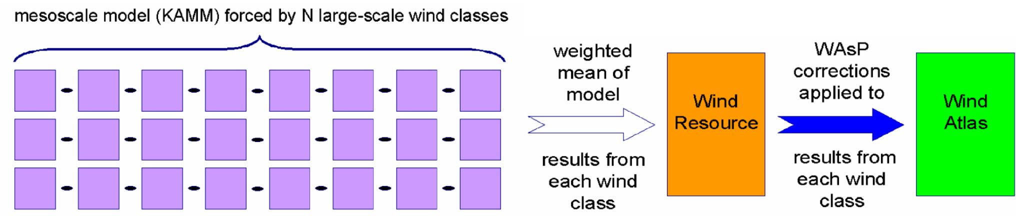


Figure 4: Schematic showing the numerical wind atlas methodology.

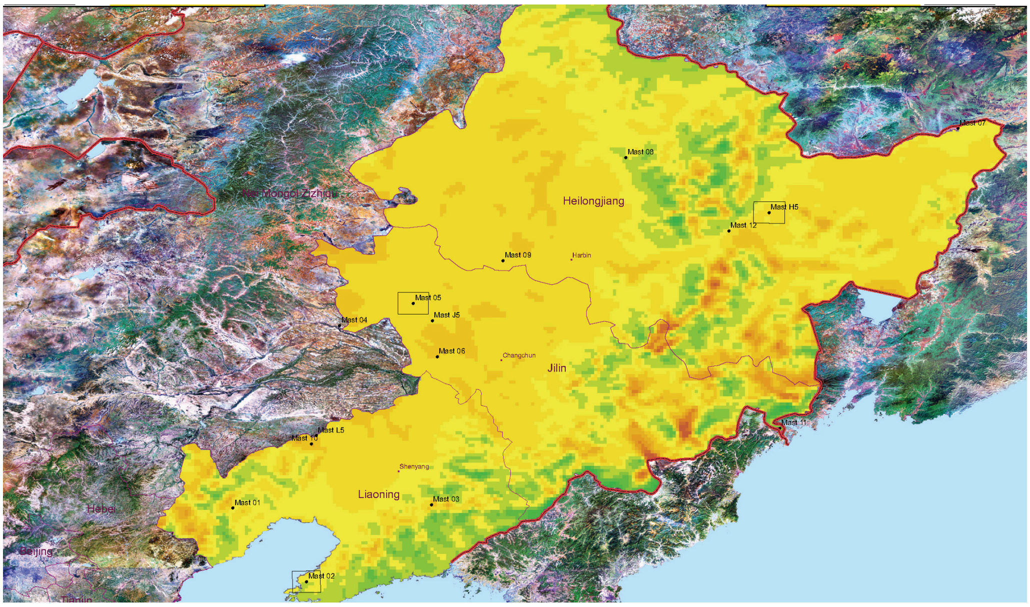


Figure 5: The wind resource map for N.E. China giving the wind at 100 m above ground level for land areas at 5 km resolution.

The results of the mesoscale numerical wind atlas can be given in the form of maps of wind climate for conditions as they are represented in the mesoscale modelling, and as maps of wind climate for generalized conditions - *regional wind climates*. For generalized conditions a conversion is carried out to give the wind for flat terrain and homogeneous roughness. Figure 5 shows the wind resource map for N.E China, taken from [9]. The results are also given in the form of detailed statistics giving the generalized wind speed and direction distributions for any location within the calculation domain for a set of standard heights above ground level. This information is given in a file format that is directly compatible with the WAsP software [2].

2.4 Measurements

Figure 6 shows the positions of project measurement sites in N.E. China. A total of 12 sites featuring 70 m masts and 3 sites featuring 100 m masts are part of the project measurement programme. The site selection was aimed at best possibly fulfilling criteria developed with the purpose of verification of the Numerical Wind Atlas. For details please see the dedicated Measurement Report [11] and the Site Inspection Report [12].

At 9 sites – M01, M02, M03, M04, M05, M06, M07, M08 and M09 – the 70m masts are all instrumented with both Risø DTU and CMA sensors. Another 3 masts of 70 m (ML5, MJ5 and MH5) with CMA instruments have been added in order to arrive at the planned density of stations for verification. The instrumentation of the 100 m masts with both Risø DTU and CMA sensors was completed Spring 2010, so recording of data at 100 m masts that will become useful for future projects has started.

For the purpose of verification of the Numerical Wind Atlas, the year 2009 was chosen. The data are available from the project database, and data will be available in the public domain through CMA. Permission to download data may be obtained from CMA subject to registration.

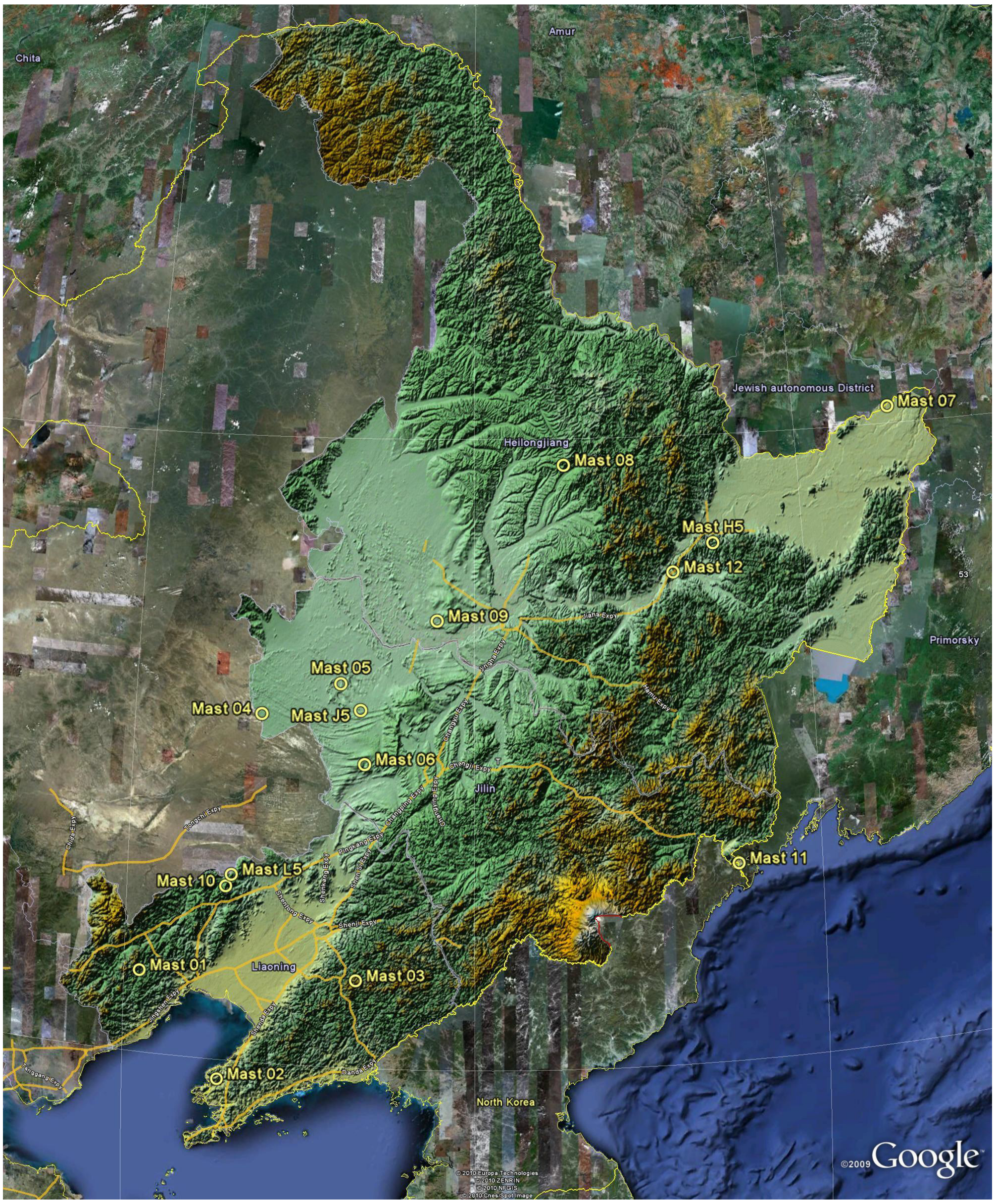


Figure 6. Overview map showing the location of the meteorological masts referred to in the text.

2.4.1 Mast positions

The positions of the meteorological masts were determined using a Garmin eTrex GPS receiver. Three readings were taken (corresponding approximately to the three legs of the mast) and subsequently averaged to find the position of the mast, see Table 1.

Table 1. Mast coordinates and elevations. The datum used is WGS 84; elevations are determined by the WAsP flow model from SRTM3 maps with 5-m height contours.

Province Mast ID	**Longitude** [°E]	**Latitude** [°N]	**Elevation** [m a.s.l.]	**Easting** [m]	**Northing** [m]	**UTM** zone
Liaoning						
01	120.27608	41.10905	342	271280	4554439	51
02	121.65722	39.73201	134	384932	4398875	51
03	123.99825	41.16924	1017	583740	4558025	51
L5	121.83645	42.46533	315	404342	4702100	51
Jilin						
04	122.27773	44.52714	168	442608	4930678	51
05	123.65746	44.94102	136	551871	4976609	51
06	124.10508	43.94166	185	588686	4865987	51
J5	124.01715	44.61596	155	580701	4940793	51
Heilongjiang						
07	133.87547	48.21450	40	416464	5340753	53
08	127.64503	47.66755	327	398278	5280240	52
09	125.34413	45.74241	147	215611	5071930	52
H5*	130.33285	46.64002	312	602009	5166025	52

* The position of Mast H5 has not been independently verified and is therefore considered preliminary.

2.4.2 Layout of wind measurement masts and sensor overview

The nine 70 m masts, M01-M09, instrumented with both Risø DTU and CMA sensors have been the main focus of the measurement programme and of the verification. The double instrumentation has been used for studies comparing sensor types and for obtaining maximum data recovery. The measurement equipment is described in detail in the dedicated Measurement Report [11. ML5, MJ5 and MH5 are the same type of 70 m masts instrumented with CMA measurement equipment in the same heights as M01-M09. The instrumentation in each height level is briefly listed in Table 2 and the layout is shown in Figure 7.

Table 2.: List of sensors and types used at each measurement station.

Sensor	Risø instrumentation		CMA instrumentation	
Cup anemometer	4	WindSensor P2546A	4	Tiajin Instruments EL15 - 1A
Wind vane	2	Vector Instruments W200P	2	Tiajin Instruments EL15-2D
Absolute temperature	1	Vaisala HMP45A	1	Unknown
Temperature gradient	1	Risø –DTU P2642A		
Barometric pressure	1	Setra 278		
Relative humidity	1	Vaisala HMP45A		

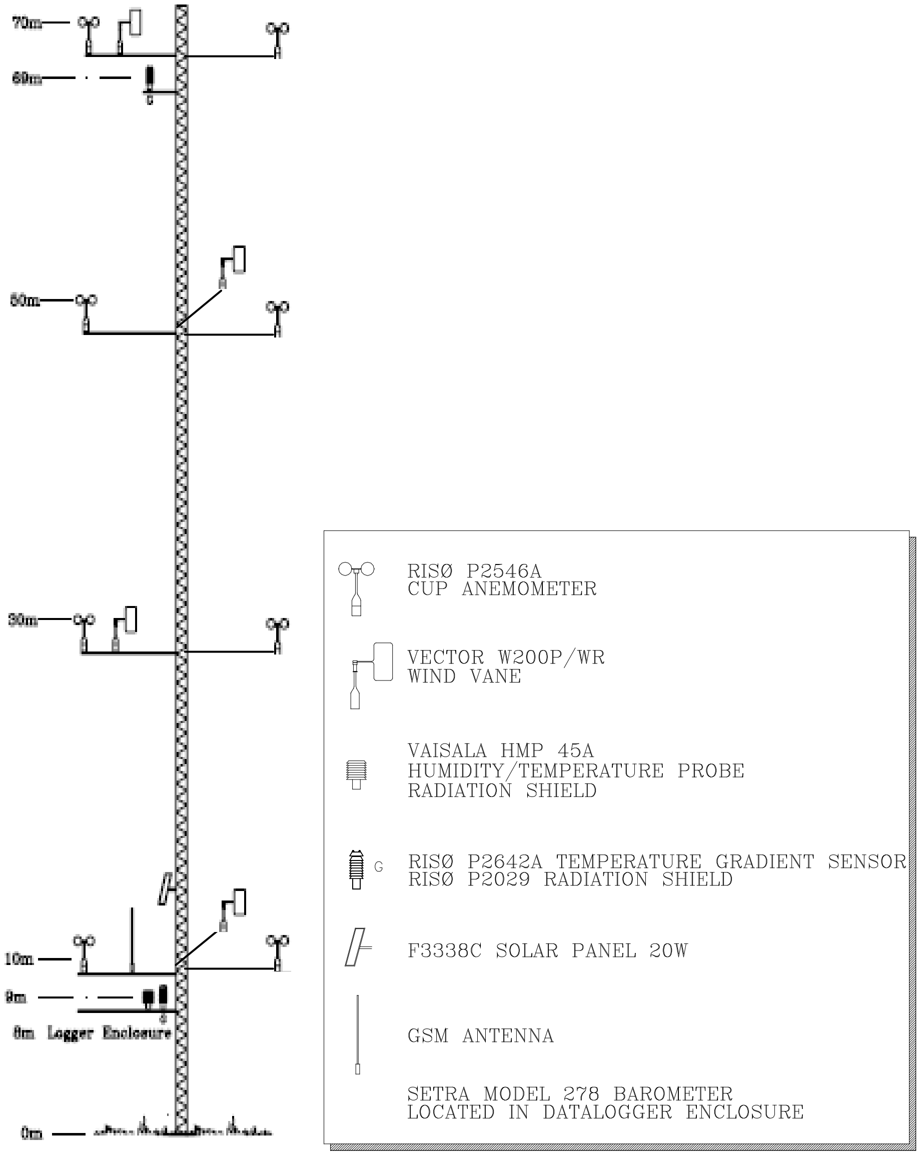


Figure 7: Drawing of mast layout and sensor equipment. The right hand side and the box describes the Risø instrumentation, the left hand side shows the CMA instrumentation.

2.4.3 Availability of wind measurements

Figure 8 shows the status of the meteorological measurements conducted with Risø DTU equipment at the time of writing.

CMA Component of WED: Status of Risø DTU measurements and data by 2010-06-15.

Station	Installed	Position	Data start	Data end	Raw data	CA project	Team site	In operation	Risø Rodeo	CMA
Liaoning							availability	% of 2009	database	database
Mast 01	Yes	Verified	2008-10-07	2010-01-31	Team site	Revision 1	481 d	100%	Yes	
Mast 02	Yes	Verified	2008-08-29	2010-02-10	Team site	Revision 1	541 d	100%	Yes	
Mast 03	Yes	Verified	2008-09-25	2010-01-31	Team site	Revision 1	491 d	100%	Yes	
Mast 10	No	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast L5	n/a	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Jilin										
Mast 04	Yes	Verified	2008-10-14	2010-03-24	Team site	Revision 1	526 d	100%	Yes	
Mast 05	Yes	Verified	2008-10-15	2010-03-25	Team site	Revision 1	526 d	100%	Yes	
Mast 06	Yes	Verified	2009-06-10	2010-03-26	Team site	Revision 1	289 d	56%	Yes	
Mast 11	No	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast J5	n/a	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Heilongjiang										
Mast 07	Yes	Verified	2008-09-04	2010-01-31	Team site	Revision 1	515 d	100%	Yes	
Mast 08	Yes	Verified	2008-10-12	2010-01-31	Team site	Revision 1	476 d	100%	Yes	
Mast 09	Yes	Verified	2008-10-10	2010-01-31	Team site	Revision 1	479 d	100%	Yes	
Mast 12	No	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast H5	n/a	Preliminary	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Total								95%		

Figure 8. Status of Risø DTU measurements as of 15 June 2010. The "% of 2009" column shows the potential availability of data rather than the actual data recovery rate.

Figure 9 shows the status of the meteorological measurements conducted with CMA equipment at the time of writing.

CMA Component of WED: Status of CMA measurements and data by 2010-06-15.

Station	Installed	Position	Data start	Data end	Raw data	CA project	Team site	In operation	Risø Rodeo	CMA
Liaoning							availability	% of 2009	database	database
Mast 01	Yes	Verified					0 d	0%		
Mast 02	Yes	Verified	2008-10-16	2009-11-10	Team site	Revision 1	390 d	63%	In progress	
Mast 03	Yes	Verified	2008-11-08	2009-10-16	Team site	Revision 1	342 d	74%	In progress	
Mast 10	Yes	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast L5	Yes	Verified	2008-11-12	2009-12-31	Team site	Final draft	414 d	100%	In progress	
Jilin										
Mast 04	Yes	Verified	2008-10-14	2010-03-24	Team site	Revision 1	526 d	100%	In progress	
Mast 05	Yes	Verified	2008-10-15	2009-06-23	Team site	Revision 1	251 d	48%	In progress	
Mast 06	Yes	Verified	2008-10-11	2010-03-26	Team site	Revision 1	531 d	100%	In progress	
Mast 11	Yes	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast J5	Yes	Verified	2008-10-10	2010-03-25	Team site	Revision 1	512 d	100%	In progress	
Heilongjiang										
Mast 07	Yes	Verified	2008-10-15	2009-11-04	Team site	Revision 1	385 d	84%	In progress	
Mast 08	Yes	Verified	2008-10-12	2009-11-06	Team site	Revision 1	390 d	85%	In progress	
Mast 09	Yes	Verified	2008-10-09	2009-07-13	Team site	Revision 1	277 d	53%	In progress	
Mast 12	Yes	Verified	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mast H5	Yes	Preliminary	2008-10-14	2009-11-03	Team site	Revision 1	385 d	84%	In progress	
Total								74%		

Figure 9. Status of CMA measurements as of 15 June 2010. The "% of 2009" column shows the potential availability of data rather than the actual data recovery rate

3 Uncertainties and sensitivities in wind resource assessment and production estimation

Wind resource assessment is known to be associated with numerous types of uncertainties many of which have been discussed in the literature for many years – see e.g. “Accuracy of Estimation of Energy Production from Wind Power Plants”, Wind Engineering, Vol. 16 No. 5 1992. This section contains some general comments to some of the main classical types of uncertainties.

As part of this project, the quantification of these uncertainties has been studied through carrying out a large number of sensitivity studies – reported in detail both in the Microscale Report [13] and in the Mesoscale Reports [8] and [9].

3.1 Uncertainties related to long-term and regional variations in wind climate

3.1.1 Climatic variability of the wind climate and Longer-term variations and climatic change

Any wind resource assessment exercise should attempt to make the necessary corrections for the measurement period relative to the long-term average wind climate. This may be done using data from wind atlas measurement stations, which can be found in the database.

Most of these stations have recorded the wind climate just 1 year and will therefore not be able to provide the necessary information. However, there are CMA and PMA station data available that have measured wind for long periods, although not necessarily with dedicated wind instrumentation or siting for wind energy purposes. Corrections using such data should be done with careful investigation of the history of the station.

Long-term wind data series are also available from the NCEP/NCAR reanalysis data set, but it is not yet clear whether these data can be used to estimate the long-term variations close to the ground in the N.E. China.

Little is known about climatic change in this region and the impact this may have on the power output from wind farms in the very long term – and it was not part of the project to investigate this aspect.

3.1.2 Large-scale effects on wind climate by large wind farms

The uncertainty due to large-scale effects on wind climate by large wind farms is very difficult to quantify and it is p.t. a subject for research in particular related to off-shore applications. However, results of this research will be relevant for large-scale land based applications in China as well.

It becomes necessary at large wind farms to do more than to run WAsP in its present version 10. The basic idea at present is at least to associate an upwind wind farm (outside the distance to which wake models have an impact on results) with an increased terrain surface roughness in both meso-scale and micro-scale models – KAMM, WRF and WAsP.

3.1.3 Gradients in wind climates

It can be seen from the mesoscale modeling results and the Numerical Wind Atlas that gradients in the wind climate can be significant.

For sites with a limited spatial extent, and where two or more measurement masts exist, it is possible to interpolate between these stations in order to get a reliable estimate of the AEP for a wind turbine or wind farm. A technique for interpolation between wind atlases may be considered. This method may be useful both in site selection studies as well as in the more detailed studies for optimization of the wind farm layout.

For sites with a large spatial extent or for sites far apart, it is not possible to use simple interpolation schemes. In such cases, one must 'interpolate' using a meso-scale model with a fine resolution in the grid. The KAMM and WRF results presented may be used for a qualitative analysis; however, these results are not reliable for obtaining accurate resource estimates for siting and layout optimization. Adaptation, test and development of such meso-scale models must be carried out in order to increase the accuracy of the model results.

3.2 Uncertainties related to flow modeling – WAsP, KAMM and WRF

The uncertainties associated with WAsP flow modeling in general have been identified and described in the Microscale Report [13]. Most of these uncertainties are well known uncertainties that also apply to the N.E. China. As it appears from the sensitivity studies, these uncertainties are not particularly pronounced in the large parts of N.E. China with relatively flat and homogeneous terrain and their sum will generally amount to less than 5-10%; if adhering to good engineering practices. Development of new or improved micro-scale models is not likely to improve significantly the reliability compared to WAsP-based resource estimates – at least in these types of terrain.

One point that deserves more attention in the future, though, is the extrapolation of wind climate estimates to larger heights (100-250 m above ground level) from measurements made at heights of 50-100 m a.g.l.

However, the largest uncertainties seem to be related to meso-scale modelling and the generation of the Numerical Wind Atlas – at least in parts of N.E. China. For details see the Mesoscale Reports [9] and [10].

A summary of the main impacts of the sensitivity tests is given in Table 3. Although it is difficult to quantity the sensitivities against each other, a qualitative impression of the sensitivity impacts can be obtained. For example, using more wind speed classes, but ignoring stability in wind class definitions, has a lesser effect than introducing stability classes in the wind class definitions. In most cases the tests exposed the possibility of large sensitivities at specific locations. The most sensitive regions can be stated generally as being in mountain/hill terrain and/or coastal regions.

From these sensitivity tests we can conjecture that the errors introduced in the each phase of the methodology within the wind class system selection, roughness assignment, model resolution limitations, and surface temperature configurations, will lead to a larger uncertainty and error in the mountain/hill terrain and/or coastal regions. This is reinforced in the results of the verification in Mesoscale Report [9] (Section 11 of Badger et al, 2010) and an indexing of the mesoscale terrain complexity in relation to numerical wind atlas error – see Mesoscale Report [9] (Section 12 of Badger et al, 2010).

Table 3. Summary of the KAMM/WAsP sensitivity test.

Sensitivity test	**Regional effect**	**Maximum effect**	**Locations of maximum effect**
Resolution	< 5%	~100 %	Mountain/hill terrain, ridges, gaps, coastal regions
Class definition location	< 2 %	< 33 %	Mountain/hill terrain, some coastal regions
Class definition height	< 2 %	< 38 %	Mountain/hill terrain, coastal regions
Number of stability classes	< 1 %	< 22 %	Slopes of mountain/hill terrain
Wind class number	< 1%	< 12 %	Most complex terrain areas, and their vicinity including offshore
Surface roughness	< 6 % < 2 %	< 25 % < 18 %	Coastal or lake coastal regions Coastal or lake coastal regions
Surface temperature	<13 %	< 82 %	Mountain/hill terrain and coastal regions

3.3 Uncertainties related to wind measurements

The different instrumentations have been compared at the masts with double-instrumentation, M01 – M09. The comparison has revealed some issues with the type of cup anemometers that the EL15-1A is and its mounting. It is recommended to use anemometer types like the P2546A cup anemometer as a primary sensor since it seems to be connected with a lower uncertainty. Methods for deriving correction formulas for the EL15-1A output has been derived and similar correction formulas may be derived for other anemometer types.

All data have been quality controlled in the WAsP climate analyzer. If a very low uncertainty in the data set is needed a further quality control can be performed by comparing the primary with the redundant sensor. Periods for which the measurements with the primary sensor are affected by tower or cup wakes can be replaced with corrected data from the redundant sensor, if available.

At several sites an expected specific pattern is observed in the comparison of the primary and the redundant sensor. At these sites the measurement uncertainty can be estimated from a traditional analysis based on the guidelines in the IEC standard [14], as in Figure 10. At locations where the comparison deviates from the expected pattern a specific uncertainty analysis has to be done – see [11].

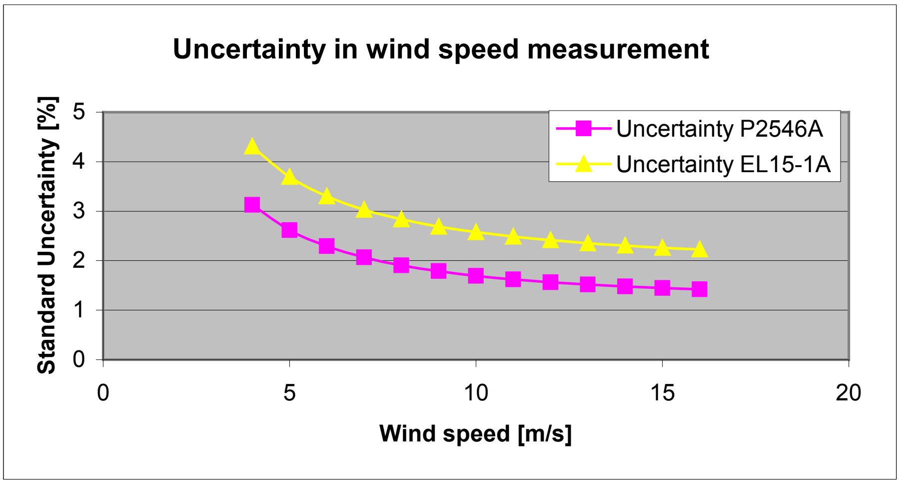


Figure 10: Standard uncertainty for the Risø and CMA cup anemometer measurement.

Recommendations on quality and accuracy requirements to limit uncertainties from meteorological stations and measurement equipment are given in [11] and [14].

3.4 Uncertainties related to topographic data

Topographic data is a significant source of uncertainty – e.g. regarding

- sourcing of good maps
- use of coordinate systems, projections, datum
- interpretation of terrain types
- major developments and their representation in maps

The sensitivity of wind resource assessment to the accuracy and detail of the topographical input data were studied in [13].

3.5 Uncertainties in wind turbine power performance

Uncertainty in wind turbine power performance is not studied in detail by this project. However, some parameters have been studied in the sensitivity studies in [13], including e.g. air density.

3.6 Uncertainties in wind farm array efficiency

Some limitations of the wake model implemented in the WAsP software should be mentioned:

- The distance between neighboring turbines in the farm should be larger than about four rotor diameters.
- For very large arrays there might be a larger reduction in power production than computed (see above under large-scale effects).
- The model is not able to properly handle major terrain speed-up in wakes, which may be important for wind farms in complex and mountainous terrain. The wake streamlines are supposed to follow the terrain surface of the landscape.
- It should be considered as well that wind turbine power output relative to the 10 minutes average hub height wind speed will vary as a function of turbulence intensity and vertical wind speed profile, and that appropriate corrections for the variations in air density should be made according to IEC 61400-12 (as mentioned above).

4 Verification of the Numerical Wind Atlas

The value of a wind atlas depends on the uncertainty of estimates made when applying it. It may vary for various applications like wind resource assessment, energy production estimates of a wind farm or design wind conditions or other uses. In any case a thorough verification against high quality measurements is essential for quantification of uncertainties. This may be achieved by comparison of wind speed and direction distributions derived from both numerical wind atlases and measurement. By comparing wind climates based on modelling and measurements for several wind measurement stations, an assessment of the uncertainty of the modelling based estimate can made.

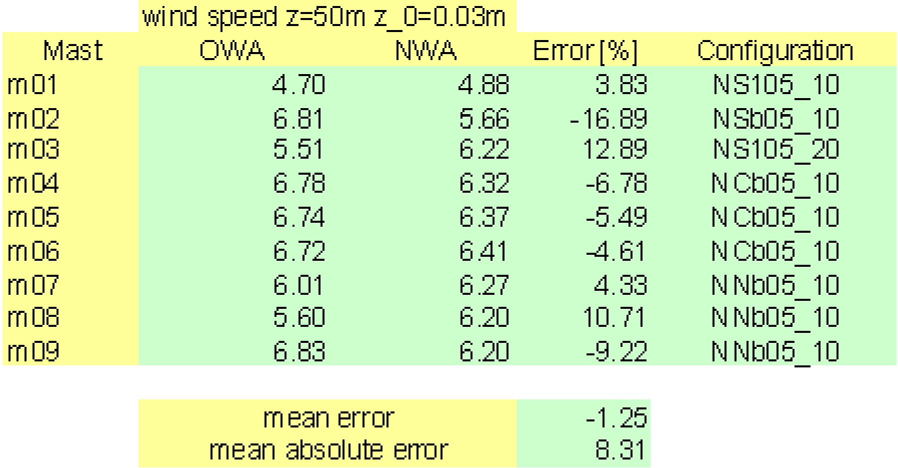
The process of verification aims to evaluate the uncertainty of an estimate of wind resource, whether based on the observational wind atlas or the mesoscale numerical wind atlas methodologies. Central to the verification process is the principle that a proper comparison of wind characteristics is being made. As examples: just as it makes little sense to compare a mean wind measured at 25 m a.g.l. with a mean wind measured at 80 m a.g.l., even at the same location, ***without*** accounting for a vertical wind profile, it makes little sense to compare a mean wind measured at a lakeside with a mean wind measured in a semi-urban area, ***without*** accounting for the effect of surface roughness. Similarly for measurements made on top of a hill the orographic speed up effects must be accounted for. Accounting for these kinds of effects is the backbone of the wind atlas methodology and the models within the WAsP software [2]. Therefore only wind climates transformed to standard conditions can be compared, i.e. winds at standard heights over flat terrain with a single homogenous surface roughness.

This principle ***must*** also be used when comparing mesoscale modelling results to measurements, because the spatial representation of the terrain in the model is impacted by the spatial resolution, even at high resolutions. Roughness conditions varying on a scale smaller than the grid scale will not be represented. Sharp or steep surface elevation features will tend to be smoothed and rounded by the grid scale representation. Therefore the wind climate given by a particular grid cell of a model cannot be directly compared to a measured wind in the vicinity of the same grid cell. The necessary step is to transform the mesoscale model winds to standard conditions to account for the effects of the roughness and orography as represented in the mesoscale model to provide the winds for generalised mean flat terrain with a single homogenous surface roughness.

A number of high quality and well distributed wind measurement stations as needed to validate the model output as described above have been established in the N.E. China geographical area for the “Meso-Scale and Micro-Scale Modelling in China” project. A chain of carefully executed and well documented activities are needed to provide these locally measured data. The same careful approach is needed regarding the use and interpretation of externally measured wind data.

Overall the qualitative agreement of the modelling and measured results is good as seen from Figure 11. The mesoscale modelling in terms of agreement of mean wind speed gives a performance that is comparable to that found in other studies (Frank, 2001 and Mortensen et al, 2005).

In most cases we also see that the direction distributions are in good agreement. Only M04 and M08 show some disagreement in the predominant wind direction sectors.



	wind speed z=50m z_0=0.03m			
Mast	OWA	NWA	Error [%]	Configuration
m01	4.70	4.88	3.83	NS105_10
m02	6.81	5.66	-16.89	NSb05_10
m03	5.51	6.22	12.89	NS105_20
m04	6.78	6.32	-6.78	NCb05_10
m05	6.74	6.37	-5.49	NCb05_10
m06	6.72	6.41	-4.61	NCb05_10
m07	6.01	6.27	4.33	NNb05_10
m08	5.60	6.20	10.71	NNb05_10
m09	6.83	6.20	-9.22	NNb05_10

mean error	-1.25
mean absolute error	8.31

Figure 11: Comparison of Observed Wind Atlas and Numerical Wind Atlas at the 9 mast locations – from the Mesoscale Report [9], Badger et al (2010).

Using the best modelling configuration for each station gives a mean error of -1.25 % (slight negative bias) and a mean absolute error for the 9 stations of 8 %. If we use just a single mesoscale model configuration for the entire region of interest the mean error is -4% and mean absolute error is 13%. This indicates that the region has a diversity of climate conditions. Further improvement of the wind resource modelling by KAMM/WAsP may be achieved through more specific configurations for smaller domains, as was performed from the Wind Atlas for Egypt study (Mortensen et al, 2005).

The mean wind speed agreement is poorest for station M02. However, for M02 a good agreement in the direction distributions was indicated. A similar behaviour is seen for M03, in which the wind direction distributions are captured fairly well, but the mean wind speed is overestimated. For M08, however, wind direction and mean wind speed together are more poorly captured. The NWA performance at the stations can be split with respect to agreement between modelled and measured wind resource in

a) better than average at M01, M04, M05, M06, and M07,

b) worse than average at M02, M03, M08, and M09.

From Figure 6 we can see that M04, M05, M06 and M07 are in rather simple terrain settings, whereas M01 appears to be in more complex terrain. Stations M03 and M08, are in more complex terrain settings, whereas M02 is in relative complex terrain and in a coastal region. Station M09 appears to have the least complex setting of all the stations with worse than average agreement.

On the whole the verification findings are in line with what was found in the sensitivity tests described in Section 7 of the Mesoscale Report [9], Badger et al (2010). Section 8 of [9] looks deeper into quantifying station terrain setting complexity.

Any user or application can establish their own mast and perform a verification at any other point in N.E. China and thereby confirm and quantify the usefulness and uncertainty levels associated with the application of the Numerical Wind Atlas in N.E. China.

5 Application of the wind atlases

5.1 Typical users and uses of the atlas

In very general terms, the typical use of a wind atlas may be categorised as listed in the table below. As it appears there is a very wide range of possible applications and therefore also a very big difference in needs and expectations regarding form and even accuracy of the result.

Authorities	Policies and regulations
Planners	Resource and development planning
Investors, owners and banks	Financial planning, risk assessment and decisions
Developers	Project development
Wind industry	Project design and implementation, Wind turbine design and development
Power sector	Power system planning, development and operation
Consultants	Independent expertise and tools development
Academic community	Research, methods and tools development

5.2 Applications of the numerical wind atlas

The use of a wind atlas is either related to planning or project development, each with a number of possible subtasks, like

- **Planning**
  National, Provincial and Local – physical, resource and power system planning
- **Project development**
  Wind farm siting and layout, energy production estimation, WTG design

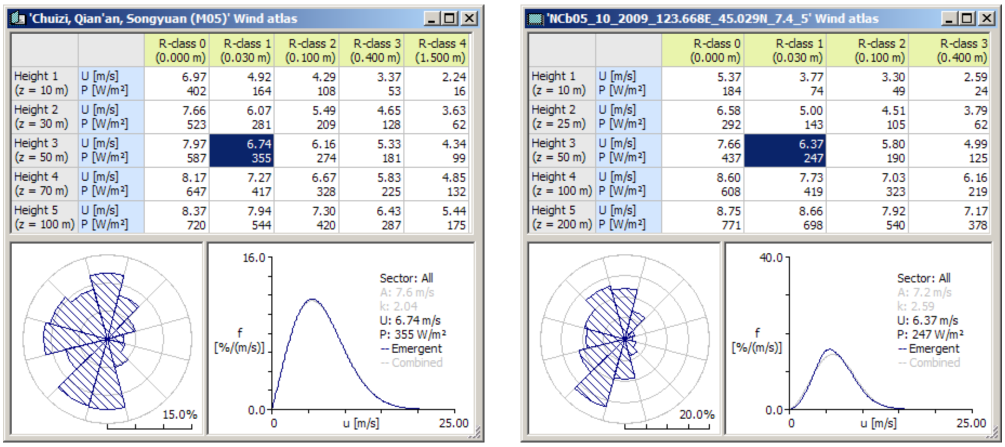
Useful input to these main types of tasks may be achieved through applying the wind atlas databases to one or more of these types of analyses.

1	Wind resource assessment and predicted wind climate (PWC) for a site or an area
2	Wind energy planning databases and graphics
3	Wind Farm Annual Energy Production (AEP) estimation
4	Wind turbine design conditions, e.g. as specified in IEC 61400-1

This may all be achieved by using the Wind Atlas database, i.e. by transformation of Regional Wind Climate (wind atlas *.LIB files) to Predicted Wind Climate, i.e. actual surface wind speed and direction distributions, using WAsP or similar micro-scale model.

5.3 Wind-climatological inputs

The wind-climatological inputs are treated extensively in the other Component A reports. The generalised wind climate data sets derived from the mesoscale modelling are described by Badger *et al.* (2010) and the data sets derived from the measurements by Lindelöw-Marsden and Enevoldsen (2010) and Mortensen *et al.* (2010). For application purposes – like the use of a wind atlas data set for estimation of the power production of a wind farm over the next 20 years or so – it should be borne in mind that these data sets represent very different time periods. The mesoscale data sets generally represent a 30-year period (1979-2008) whereas the data sets based on observations represent a 1-year period only (2009). It is essential in each project to evaluate how representative the chosen data set is for the long-term climatology of the site in question. Reliable wind index information is not readily available for NE China, so the predictions must be referenced to any or all long-term data sets available.



'Chuizi, Qian'an, Songyuan (M05)' Wind atlas

		R-class 0 (0.000 m)	R-class 1 (0.030 m)	R-class 2 (0.100 m)	R-class 3 (0.400 m)	R-class 4 (1.500 m)
Height 1 (z = 10 m)	U [m/s] P [W/m²]	6.97 402	4.92 164	4.29 108	3.37 53	2.24 16
Height 2 (z = 30 m)	U [m/s] P [W/m²]	7.66 523	6.07 281	5.49 209	4.65 128	3.63 62
Height 3 (z = 50 m)	U [m/s] P [W/m²]	7.97 587	6.74 355	6.16 274	5.33 181	4.34 99
Height 4 (z = 70 m)	U [m/s] P [W/m²]	8.17 647	7.27 417	6.67 328	5.83 225	4.85 132
Height 5 (z = 100 m)	U [m/s] P [W/m²]	8.37 720	7.94 544	7.30 420	6.43 287	5.44 175

'NCb05_10_2009_123.668E_45.029N_7.4_5' Wind atlas

		R-class 0 (0.000 m)	R-class 1 (0.030 m)	R-class 2 (0.100 m)	R-class 3 (0.400 m)
Height 1 (z = 10 m)	U [m/s] P [W/m²]	5.37 184	3.77 74	3.30 49	2.59 24
Height 2 (z = 25 m)	U [m/s] P [W/m²]	6.58 292	5.00 143	4.51 105	3.79 62
Height 3 (z = 50 m)	U [m/s] P [W/m²]	7.66 437	6.37 247	5.80 190	4.99 125
Height 4 (z = 100 m)	U [m/s] P [W/m²]	8.60 608	7.73 419	7.03 323	6.16 219
Height 5 (z = 200 m)	U [m/s] P [W/m²]	8.75 771	8.66 698	7.92 540	7.17 378

Figure 12. Sample wind atlas data sets for mast M05, Chuizi. Left-hand data set based on observations in 2009, right-hand data set based on mesoscale modelling for 2009.

5.4 Topographical inputs

The terrain features that influence the wind flow close to the ground – and thereby determine how the generalised wind climate is transformed into the site-specific wind resource – are often categorized in three broad classes:

- The geometry of the terrain surface (elevation, slope, ruggedness, etc.)
- The surface characteristics of the terrain (land use or roughness length)
- Near-by sheltering obstacles (houses, trees, shelter belts, etc.)

The coordinate systems used with these topographical inputs are described briefly at the end of this section.

5.4.1 Terrain surface elevation – height contour maps

An accurate description of the overall geometry of the terrain surface is a prerequisite for reliable modelling of the wind flow over the terrain. The most important feature is the elevation of the terrain surface above mean sea level.

The microscale model requires a digital height contour map for the flow modelling. This can be obtained by digitising the height contours from a standard topographical map; however, this is a labour-intensive and somewhat tedious process. Moreover, it may be impossible to find reliable and up-to-date maps for a given wind farm site.

Shuttle Radar Topography Mission (SRTM, 2005) elevation data (version 2.1) has recently become available. This data set consists of elevation values for the node points in a 3 arc-second (~93 m) grid, derived from radar measurements made from the space shuttle Endeavour. These data cover all of NE China. Figure 13 shows an example of elevation maps derived from the SRTM data set.

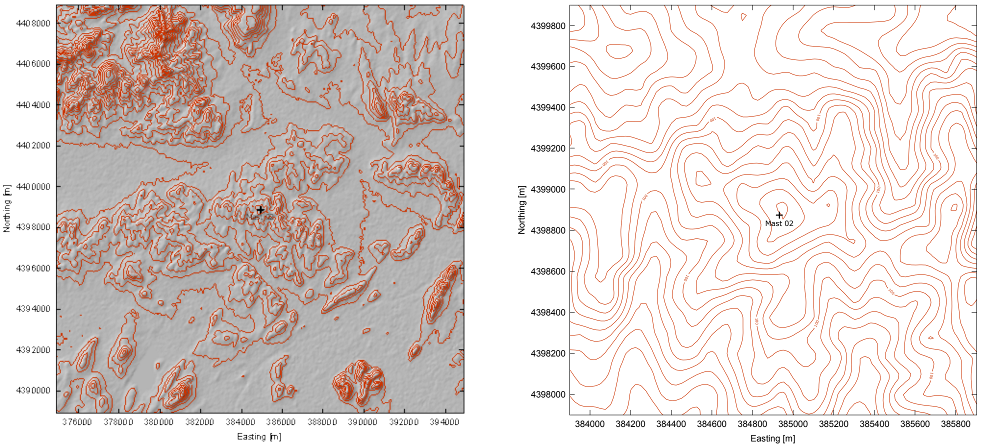


Figure 13. Elevation maps of the area around the meteorological mast M02. Left-hand map covers an area of 20×20 km^2 with 20-m height contours; right-hand map covers an area of 2×2 km^2 with 5-m height contours.

Investigations in NE China (Mortensen *et al.*, 2010) show that maps derived from SRTM data are often sufficiently detailed and accurate for most wind flow modelling purposes. However, the height contours should be compared to a reliable map of the area, if one exists – especially with respect to the height contours close to the site(s) of interest.

When it comes to actual planning and construction of a wind farm, more detailed maps may be required. These can be established by a number of other techniques; an example of a very detailed elevation map of a wind farm site in Egypt is given in Figure 14 (Mortensen et al., 2005).

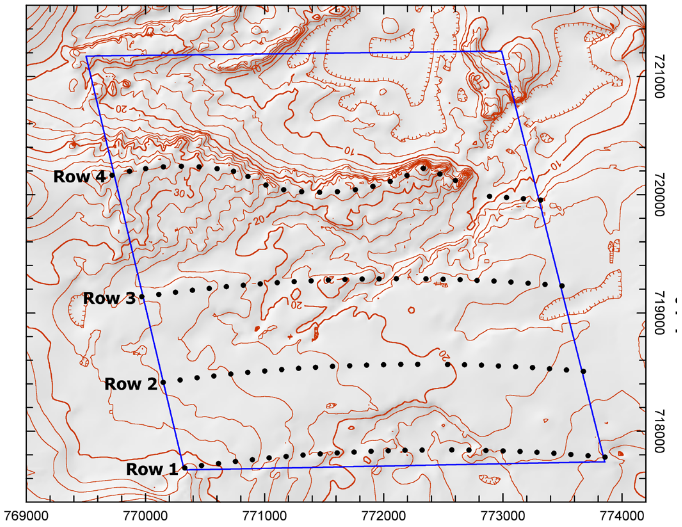


Figure 14. Elevation map of the Zafarana wind farm site in Egypt established by a site-specific survey employing kinematic GPS techniques. The height contour interval is 2 m. Four wind turbine groups, each of 25 600-kW wind turbines, are indicated by black dots.

In general, it is possible to establish digital maps with 10- or 5-m height contours in most of NE China. If spot heights from e.g. paper maps are considered as well, it may be possible to detail such maps in certain areas, but if a more detailed elevation description is needed, a site-specific survey of the terrain is required. How to make an elevation map from SRTM data is described in the Appendices.

The influence of the detail in the elevation description on the modelling of the wind flow – and thereby the estimation of the annual energy production – can be illustrated by using different maps of the same area; with different height contour intervals and detail. Examples are given by Mortensen *et al.* (2010) for the three case study sites M02, M05 and MH5, where AEP predictions have been made with maps derived from SRTM data only and maps improved by adding details from large-scale Chinese paper maps. The regional wind climate and wind turbine type used for the predictions are the same in both scenarios. The analysis shows that the AEP predictions are not very sensitive to the elevation map for the three case study areas; the maximum difference found is on the order of 1%.

5.4.2 Land-use and roughness length – roughness maps

An accurate description of the land use and roughness lengths of the terrain surface is another prerequisite for reliable modelling of the wind flow over the terrain. The most important land-use classes in NE China are: farmland, water surfaces, forests, mountains and built-up areas. The overall land-use pattern of a particular area can be established from topographical maps, aerial photographs or satellite imagery.

The most up-to-date and readily available information on the type and distribution of land-use classes stems from satellite imagery. An example is shown in Figure 15, where a satellite image is used to classify and digitize the land-use or roughness classes close to the anemometer at mast M02, Wafangdian. The coastline was obtained from the SRTM Water Body Data set.

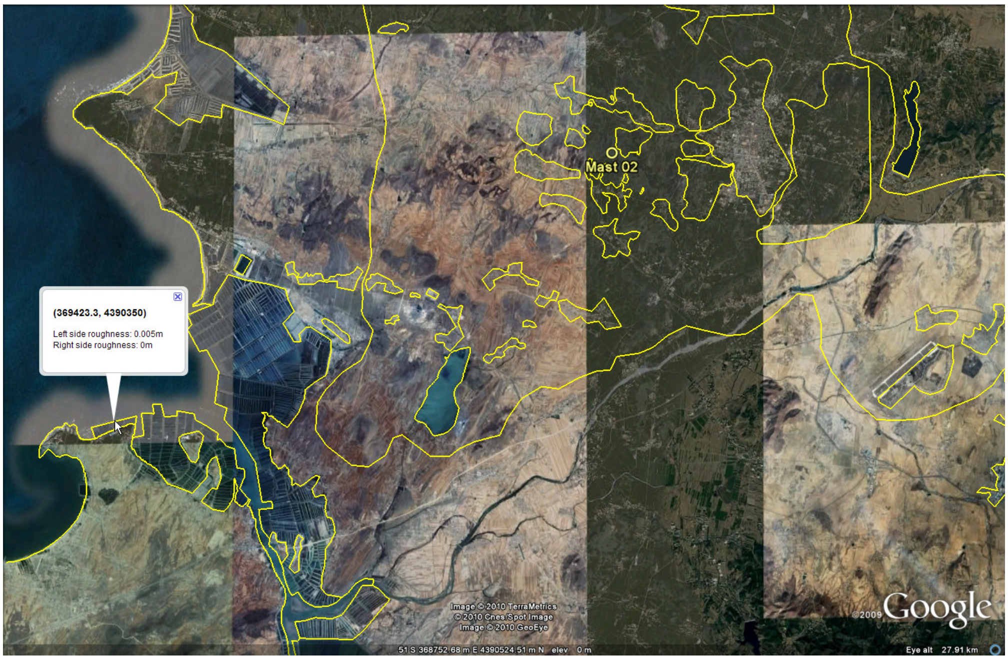


Figure 15. Classification and digitization of major roughness classes close to the meteorological station M02, Wafangdian. The classes identified here are: the sea, lakes,

built-up areas, airport runway area, rural areas and forest (© 2010 TerraMetrics, Cnes/Spot, GeoEye and Google Inc.).

Evidently, the terrain descriptions should correspond to the scenario one wants to model. So, if historical data from a standard meteorological station are analysed, the maps (especially the land-use) should correspond to the terrain at the time of the observations. Since the wind data analysed here were measured in 2009 and possible wind power projects will be built in the future, the elevation and land-use maps should correspond to present day conditions.

The most common land-use type, corresponding to the back-ground roughness length, consists of farmland. It may be difficult to estimate the roughness length of such surfaces; however, it should be borne in mind that this estimate is most critical if the meteorological mast is low and less critical the higher the mast. Preferably, the anemometer used for predicting the wind turbine production should be mounted at a height comparable to the hub height of the proposed wind turbine. The sensitivity of changing the background roughness length by a factor of two (both lower and higher) was investigated by Mortensen *et al.* (2010). For predictions of wind power production between 75 and 125 m a.g.l. from 70-m measurements, the sensitivity was found to be less than 2% in all three case studies.

5.4.3 Sheltering obstacles

Sheltering obstacles in NE China are man-made structures like houses, walls or fences. Shelter belts and rows of trees are also quite common. However, the height of typical obstacles and their distance to possible wind farm areas suggest that it will only rarely be necessary to model these structures as obstacles. Instead, the obstacles can usually be treated as adding to the roughness of the areas in question.

The following rule of thumb may serve as a guideline when deciding whether to include obstacles in the terrain as sheltering obstacles or as roughness elements:

- if the point of interest (anemometer or wind turbine hub) is closer than about 50 obstacle heights to the obstacle and closer than about three obstacle heights to the ground, the object should probably be included as a sheltering obstacle. In this case the obstacle should not at the same time be considered as adding to the roughness of the terrain.
- if the point of interest is further away than about 50 obstacle heights or higher than about three obstacle height, the object should most likely be included in the roughness description. In this case the obstacle should not at the same time be considered as a sheltering obstacle.

A wind turbine with a hub height of 50-100 m a.g.l. and sited well away from buildings will therefore rarely experience shelter effects. Conversely, the shelter effects may be quite severe for a meteorological station with a 10-m mast sited close to built-up areas.

5.4.4 Coordinate systems

Most of the information used in wind resource assessment and siting – and indeed much of the information needed for wind farm planning and development – is geo-referenced. The location of a given meteorological station, the elevation of the terrain, the extent and shape of significant land-use or roughness classes and the layout of a wind farm can only be described accurately by referring to the exact position or coordinates of the feature in question. Wind flow modelling requires accurate and reliable information on the coordinates of the inputs used. In WAsP, all coordinates must be given in the same Cartesian coordinate system.

Two coordinates systems (projections) are used in the reports of the present project: the common geographical coordinates (latitude, longitude) and the Cartesian Universal Transverse Mercator (UTM) system. Both systems are referenced to the World Geodetic System 1984 (WGS 84) datum.

Figure 16 shows the geographical coordinate system – lines of equal latitude and longitude – for NE China. This system is not Cartesian and therefore not suited for wind flow modelling or planning purposes. However, several input data are provided in this system, e.g. Google Earth images, other satellite images, Shuttle Radar Topography Mission elevation data, SRTM Water Body Data, Coastline Extractor data, etc.

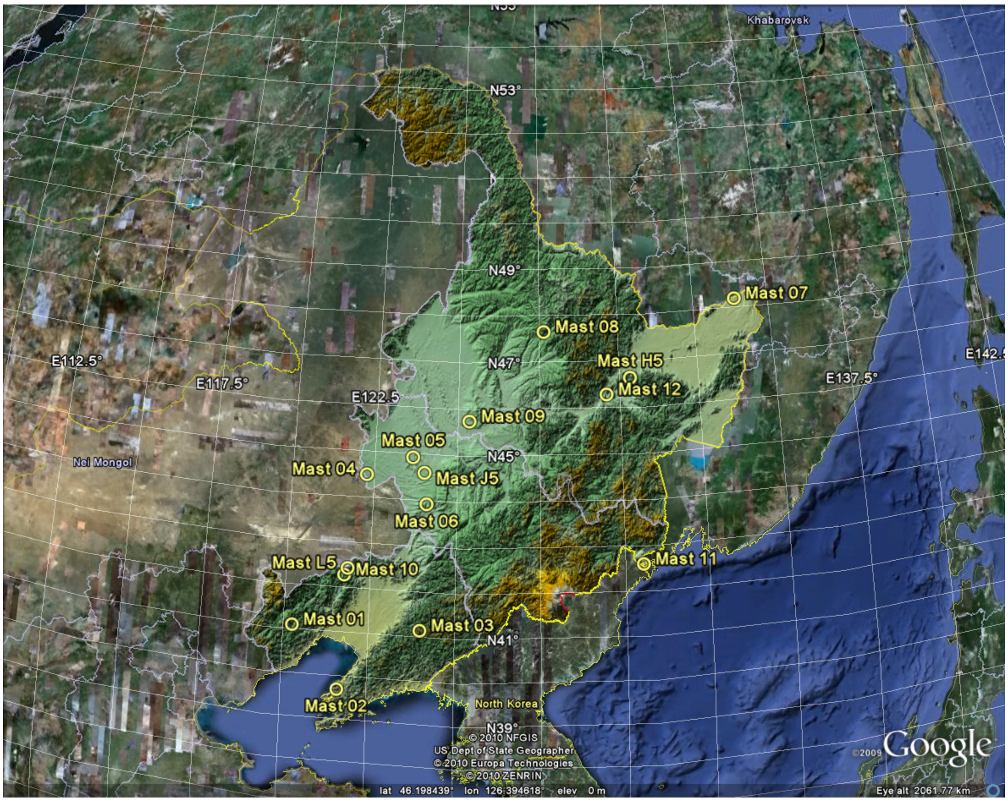


Figure 16. Elevation map of Dongbei showing the geographic coordinate grid – latitude and longitude lines in degrees north and degrees east, respectively.

Figure 17 shows the Cartesian UTM systems used. Because NE China spans more than 15 degrees of longitude, three different UTM zones must be used; these are shown by the grid lines in Figure 17. For the meteorological stations of NE China, it is necessary to use zones 51, 52 and 53.

Figure 17. Elevation map of Dongbei showing the three UTM zones covering NE China: 51, 52 and 53. Each zonal coordinate system is Cartesian and the coordinates can be given in [m] or [km].

Each zone has a local *x*-axis originating 500 km W of the central meridian of the zone. The *y*-axis originates at the Equator for all three zones. The meteorological station coordinates in NE China are referenced to either UTM zone 51, 52 or 53.

Ordinary topographical maps in China may be are drawn in entirely different systems, e.g. the System 42 (Peking 54) projection with Pulkowo-mean/Krassovsky 1940 datum. Transformation between different coordinate systems is quite complicated and must be performed using specialised software. The WAsP Map Editor and the Geo-Projection Transformer are two software packages that can transform single points, lists of points and entire WAsP map files – using several different map projections and almost 150 different map datums.

Global Positioning System (GPS) devices also refer to a specific coordinate system. The default system in most receivers is (latitude, longitude) referred to WGS84, but this can be changed in a set-up menu. Coordinates downloaded from the GPS using some software may be referenced to WGS84, regardless of the setting of the GPS.

5.5 Application in wind energy projects

Mesoscale and microscale models resolve different features of the terrain and how they are useful in the different phases of planning and project preparation. The mesoscale model output may not be used directly itself, since it represents an abstraction, namely the “mesoscale wind” in a mesoscale terrain, which has to be transformed to actual predicted surface wind by applying a microscale model. Application of mesoscale modelling for obtaining information about the predicted wind climate at a given location in N.E. China therefore will use a *.LIB file generated from the mesoscale modelling as input to a microscale model, WAsP, used according to recommendations.

However, mesoscale modelling has to be employed in order to enable assessment of the validity of the assumptions used for microscale modelling. The wind farm site may include an area with a large regional wind climate gradient, which would violate the microscale modelling assumption - constant regional wind climate over the microscale modelling domain. The mesoscale modelling may furthermore be used to identify locations with large gradients and thus locations where an extended measurement programme will be advisable in order to avoid gross errors in wind resource assessment.

The terrain features that influence the wind flow close to the ground – and thereby determine how the regional wind climate is transformed into the site-specific wind resource – are often categorized in three broad classes:

- The geometry of the terrain surface (elevation, slope, complexity, ruggedness, etc.)
- The surface characteristics of the terrain (land use or roughness length)
- Near-by sheltering obstacles (houses, trees, shelter belts, etc.)

As an example, the detail in the elevation description influences the modelling of the wind flow and thereby the estimation of the annual energy production (AEP). In microscale modelling an increase in height contour intervals from 2 to 10 m has been found to increase the contribution to uncertainties in AEP estimates by more than 5% - even in terrain with relatively little complexity or ruggedness. In more rugged, complex and mountainous terrain the uncertainty increases and the dependency on accuracy and resolution of terrain data increases. To test uncertainties associated with microscale and mesoscale flow modelling as well as with terrain data it is generally recommended to carry out

- model parameter studies and adaptation of models to local conditions
- sensitivity analyses, site calibration and verification against measurements

Other aspects to be considered are

- wind climate variability within the time-frame of the data collection and the planned projects
- inter-annual variations, long-term averages and climate change
- man-made large-scale effects on wind climate by changes in terrain and flow conditions due to the utilization of the land, especially building of new large wind farms and urbanisation

In general inter-annual variations relative to long-term averages are often seen to be of the order of 10% on mean wind speed. Wind climate variability differs however in different climate zones.

Longer-term wind data series that may be used to assess inter-annual variation and long-term averages are available from the NCEP/NCAR reanalysis data set, but any such dataset must be used with care in a wind power context. Global climate change modelling, rather than NCEP/NCAR reanalysis, may be valuable in the evaluation of impacts of global climate change on wind farm AEP – see e.g. [8].

Regarding man-made large-scale effects on wind climate, it should be noticed that the uncertainty due to any new large wind farm may be significant for its surroundings. Exact quantification is difficult, but up to 20% loss in energy production has been seen. This aspect will be relevant for all large wind farm projects and thereby also in planning phases when assessing the potential energy production from wind and the economics.

5.6 Wind farm calculations

The wind resource map is one of the basic inputs in the wind turbine siting procedure and in the determining the wind farm layout. Figure 18 shows a sample layout for a 48 MW wind farm at M02 as analysed in the case study. The wind farm layout should among other criteria that may be decided by the project developer, owner and authorities aim at maximising wind farm production, minimising wind farm wake losses and minimising the wind turbine structural loads – while at the same time also being aesthetically pleasing.

Once the wind farm layout and turbine type have been chosen, the wind atlas methodology (WAsP) can be used to estimate the actual annual energy production from the wind farm, including wake effects. For this calculation to be reliable, it is important to use site-specific power and thrust curves for the wind turbine in question. Information on the average annual air density at the site is required; this may be calculated from site measurements of atmospheric pressure and air temperature.

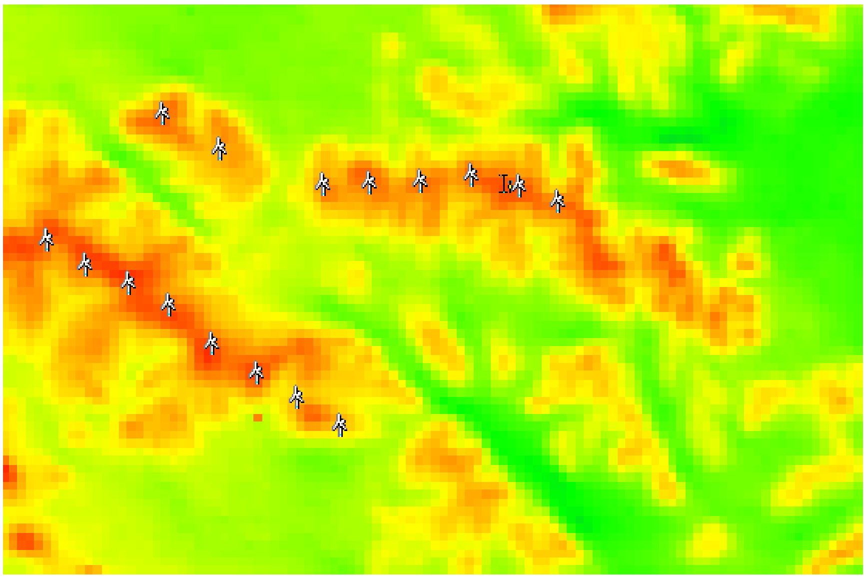


Figure 18. Sample layout for a 48-MW wind farm at M02 as analysed in the case study.

5.7 Wind resource mapping

For a given wind farm site, the regional wind climate derived from the numerical wind atlas or a near-by meteorological station can be used to map the wind resource over the site. Examples are given in the case studies, where the mean wind speeds at 80 m above ground level have been estimated by means of the WAsP model in grid points for 15 km × 15 km areas surrounding the masts. For wind farm sites located close to the masts the regional wind climate from the meteorological station may be used for the modelling as well as the regional wind climate files generated for the relevant mesoscale grid cells by the mesoscale modelling.

Even within fairly small and homogeneous sites, the estimated production easily varies by more than 20%, so for sites with ridges and other significant features, a very thorough site optimisation effort is essential.

Wind resource maps for any area in N.E. China can be established in the same manner by using the regional wind climate statistics from the numerical wind atlas.

5.8 Reliability of wind resource estimates

The reliability of wind farm calculations, wind resource mapping from Observational Wind Atlases as well as of the verification of the Numerical Wind Atlas depend first of all on the reliability of the data from the meteorological stations from which the wind statistics have been derived. The accuracy of the wind speed and direction measurements and the amount of data available has to be assessed. Secondly, it depends on the complexity of the terrain; at the meteorological station as well as around the sites of interest. Finally, the geographical variability of the wind resource will necessarily add to the uncertainty of the estimates.

The reliability of estimating the spatial variation of the wind resource and any extrapolation or interpolation depends on the performance of the mesoscale modelling and the generation of the Numerical Wind Atlas. Assessments in quite some detail from the results of the mesoscale modelling of N.E. China and the modelling domains are presented in [9], using the 9 measurement stations M01-M09 as verification points. These results may not be sufficiently detailed and accurate for micro-siting and bankable production calculations, but they provide a fairly reliable picture of the large-scale spatial variations of the wind resource, although considerably more accurate and reliable in the parts of N.E. China with less complicated terrain than in the parts with complex terrain.

5.8.1 The similarity principle

Current knowledge about the uncertainties in WAsP wind resource assessment may be summarised in the so-called *similarity principle*: Accurate predictions of wind climate and annual energy production based on observed wind climates require that the meteorological station (predictor) and the turbine site (predicted site) should be as similar as possible with respect to:

- Topographical setting
    - ruggedness (RIX index)
    - elevation and exposure
    - distance to significant roughness changes (coastline)
    - background roughness lengths
- Climatic conditions
    - regional wind climate (synoptic and mesoscale)
    - general forcing effects
    - atmospheric stability

With respect to WAsP, accurate predictions using the WAsP BZ-flow model – and indeed most other wind resource assessment and siting models – may be obtained (Bowen and Mortensen, 1996) provided:

- the meteorological station and wind turbine site are subject to the same overall weather regime, i.e. that mesoscale effects are not significant or, if present, the two sites are affected in the same way,
- the prevailing weather conditions are close to being neutrally stable, and
- the surrounding terrain (of both sites) is sufficiently gentle and smooth to ensure mostly attached flows.

The latter requirement in particular has a significant impact on the accuracy of WAsP predictions in complex terrain.

To what extent a similarity principle exists for the mesoscale modelling as well is not clear. Studies reported in the Mesoscale Report [9] indicate that a relation can be established between uncertainties and terrain complexity.

6 Design wind condition

In addition to the predicted wind climate – the distribution of wind directions (wind rose) and the sector-wise distributions of mean wind speed – other wind conditions may be important for the design of a wind farm. Some of these characteristics have been measured directly at the wind atlas stations; others must be estimated from the meteorological data.

6.1 A brief introduction to the IEC 61400-1 standard

The International Electrotechnical Commission provides the IEC 61400-1 standard for turbine safety (IEC 1999, 2005, 2009). The main principles are that manufacturers classify turbines and developers check that site conditions do not exceed the design limits of the class of the selected turbine.

Table 4. IEC 61400-1 turbine classification scheme.

Wind Turbine Class	I	II	III	S
V_{ref} (m/s)	50	42.5	37.5	Values specified by the designer
A I_{ref} (-)	16%			
B I_{ref} (-)	14%			
C I_{ref} (-)	12%			

6.1.1 Turbine classification according to IEC 61400-1

Edition 3 of IEC 61400-1 declares turbine classes I, II & III with a reference wind V_{ref} set to 50 m/s, 47.5 m/s and 37.5 m/s, respectively (IEC 2005). This reference wind is defined as a 10-min average wind speed at hub height. In addition, three turbulence categories A, B & C characterized by a reference turbulence intensity I_{ref} which is set to 16%, 14% and 12%, respectively[1]. The reference turbulence intensity is defined as the average turbulence intensity of the longitudinal velocity perturbations measured over random 10-min periods with a mean wind speed of 15m/s. A turbine is characterized by its wind class and turbulence category, e.g. a turbine for medium extreme wind and medium turbulence is classified as a class II_B turbine, see table MN1. There is an additional class S for which the manufacture specifies the reference wind and reference turbulence intensity. Class S is typically used for offshore turbines.

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[1] IEC 61400-1 Ed. 2 (IEC 1999) used a slightly different classification scheme.

To verify that a turbine is of a given class it must be proven that it can survive a list of design load cases. These load cases are defined by combinations of

- Turbine mode of operation – e.g. normal mode of production, normal start or stop, emergency stop, sudden grid failure, operation under yaw error etc.
- Load type - either ultimate load or fatigue load,
- Wind conditions – e.g. extreme wind, severe or normal turbulence, sever or normal wind shear or various gusts and wind direction changes.

The design wind conditions are specified by simple models which are parameterized by

- The reference wind speed V_{ref}
- The reference turbulence intensity I_{ref}
- The turbine hub height z_{hub}

An example of a load model is the normal turbulence model (NTM) which is applied for fatigue load simulations. In here the longitudinal velocity perturbations are modeled as

$$\sigma_1 = I_{\text{ref}} \left(\tfrac{3}{4} V_{\text{hub}} + 5.6\,\text{m/s} \right)$$

This model has wind-speed dependence and the intention is to model not the average turbulence level but the 90% percentile of a distribution of turbulence conditions. Reasons for such variation include variable atmospheric stability and trends in mean wind speed. The NTM turbulence is referred to as representative turbulence[2]. Another example is the normal wind profile (NWP) defined as

$$V(z) = V_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha}$$

The shear exponent α in this profile is set to 0.11 for extreme load test and 0.2 for fatigue loads. The standard defines several gust and wind-direction change load cases. These are specified by design models which all are parameterized by V_{ref}, I_{ref} and $z_{\text{hub.}}$

6.1.2 Site assessment according to IEC 61400-1

The general principle of IEC 61400-1 site assessment is that actual wind conditions must be less severe than assumed in the turbine design class. The following criteria apply[3]:

- The 50-year extreme wind must be lower than the reference wind of the turbine class;
- Flow-line inclination at hub height must be less than ±8° for all wind directions;
- The average wind-shear exponent α at hub height must be positive but less than 0.2. The reason to avoid excessive shear is the risk of enhanced fatigue damage and the reason to avoid negative shear is the risk of blade-tower interaction;
- The wind-speed distribution must be lower than the distribution used for turbine classification in a certain wind speed range. This range is either defined as 60% of rated wind speed to turbine cut-out wind speed or, in case the power curve is unknown, defined as 0.2 to 0.4 times the reference wind of the turbine class. More exposure in this wind-speed range would enhance fatigue damage;
- The effective TI, see below, must be lower than the applicable IEC model in a range from 0.6 times the rated velocity to the cut-out velocity. The applicable model is either characteristic or representative turbulence intensity depending on whether the turbine type is classified according to edition 2 or 3 of the standard.

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[2] IEC 61400-1 Ed. 2 defined a slightly different measure called characteristic turbulence intensity. It was based on mean plus standard deviation instead of the 90% level of Ed. 3.

[3] The design limits in this list can be changed in turbine class S.

These criteria apply to individual turbine sites. An additional rule states that turbulence must be scaled by a safety factor if the terrain is complex and the turbulence intensity has not been measured. The reason is that turbulent kinetic energy in complex terrain is redistributed among the three velocity components. Terrain complexity is evaluated by criteria based on terrain slopes in the area around each turbine site.

6.1.3 Effective turbulence intensity

Fatigue loads for turbine classification are simulated for a range of wind speeds using the representative turbulence intensity. However, due to non-uniform surface roughness the turbulence intensity will, however, often depend on wind direction. Turbulence from wakes of neighbour turbines in wind farms will contribute significantly to the directional variation of the turbulence intensity. IEC 61400-1 Ed. 3 has an Annex D suggesting an optional model for the effects of wake turbulence - see also the detailed description of Frandsen (2007). In this model an effective turbulence intensity is defined as constant turbulence intensity assumed to cause the same material damage as variable turbulence from all directions.

$$I_{\text{eff}}(u) = \left[\int_0^{2\pi} p(\theta|u) I^m(u,\theta)\, d\theta\right]^{1/m}$$

In this formula the Wöhler exponent m is a material constant, which is approximately m=10 for glass fibre. Annex D includes a simple model for the wake turbulence. Here, wake turbulence is modelled as a combination of background turbulence and added turbulence.

$$I_{\text{wake}} = \sqrt{I_{\text{ambient}}^2 + I_{\text{add}}^2}$$

The added turbulence intensity in the new IEC 61400-1/A1 amendment (IEC 2009) is modelled by

$$I_{\text{add}} = \frac{1}{1.5 + 0.8\,\Delta x/D\sqrt{C_T(u)}}$$

Here Δx is the distance to a neighbour turbine, with diameter D and thrust coefficient C_T at wind speed u.

6.2 Assessment of wind conditions

6.2.1 Extreme wind speed

An extreme wind is defined by an averaging period and a recurrence period. The latter period is the expected waiting time for an event, which exceeds the extreme wind level. The IEC standard refers to extreme winds with10-min averaging periods and 50-year recurrence periods. By fitting an extreme-wind model, typically a Gumbel distribution, to the observed extreme winds it is possible to extrapolate the statistics to the specified recurrence period, also when this is longer than the observation period. The accuracy of this extrapolation depends on the number of observation years and the slope parameter of the fitted Gumbel distribution. The IEC standard recommends a minimum of seven years. Furthermore, the Gumbel fit slope parameter is typically larger when modelling wind climates affected by tropical storms than when modelling continental or extra-tropical extreme wind climates. This leads to extra extreme-wind uncertainty.

According to the IEC standard, the extreme wind must be estimated at individual turbine sites. For this purpose we first use a micro-scale flow model to predict site-specific winds, then we fit local Gumbel distributions, and finally we extrapolate to local fifty-year extreme wind speeds. The reason for this procedure is that individual sites have different wind speed-up factors for winds coming from different wind directions.

Unfortunately, most wind energy projects do not have local wind data of sufficient duration for extreme wind prediction. An alternative, which is implemented in the WAsP Engineering program4, is to use the wind atlas method to transforms extreme wind climates at the reference site to the extreme wind climate for the wind energy project. The reference site should have a climate similar to that of the wind energy site. The procedure is to prepare two WAsP Engineering projects modelling the terrain around the reference mast and around the wind energy project, respectively. The first project is used to transform observed extreme wind climate to a regional extreme wind climate free of local effects. This regional extreme wind climate is stored on a file, which is loaded in the second project where it is used to predict extreme wind climates at individual turbine sites.

If no representative data of sufficient duration and quality can be found, the siting engineer may predict extreme wind climates by the high-end tails of the Weibull distributions in the WAsP mean wind climate. This method is, however, not very accurate.

6.2.2 Flow-line inclination

This can be calculated by a micro-scale flow model, e.g. that of WAsP Engineering. The IEC standard also allows use of terrain inclination instead of flow-line inclination as this is considered a conservative estimate.

6.2.3 Wind shear exponent

This can be evaluated by fitting a power law to micro-scale flow model results. WAsP Engineering calculates the shear exponent by the speed and its derivative at the hub height using the relation

$$\alpha = \frac{z_{\mathrm{hub}}}{u_{\mathrm{hub}}} \left.\frac{du}{dz}\right|_{\mathrm{hub}}$$

6.2.4 Wind speed distribution

This distribution is calculated by WAsP.

6.2.5 Effective turbulence intensity

Effective turbulence intensity can be calculated by the Windfarm Assessment Tool [5] (WAT), which is based on the Frandsen (2005) model and uses a combination of model results from WAsP and WAsP Engineering. The calculation includes the conditional wind rose, i.e. the wind direction distribution given the wind speed, which is estimated by a WAsP wind climate.

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4 See http://www.wasp.dk/Products/WEng.html

5 See http://www.wasp.dk/Products/wat/index.htm and Nielsen *et al.* (2009)

$$p(\theta|u) = \frac{p(u|\theta)p(\theta)}{p(u)} = \frac{p(u|A_j,k_j)fr_j}{\sum_{i=0}^{N-1} p(u|A_i,k_i)fr_i}$$

In this formula frequencies of occurrence fr_i are defined sectors with index i and the Weibull distributions in these sectors are

$$p(u|A_i,k_i) = (k_i/A_i)(u/A_i)^{k_i-1} \exp\left[-(u/A_i)^{k_i}\right]$$

A problem with estimating effective turbulence intensity in WAT is that the background turbulence intensity modelled by WAsP Engineering is valid only for steady flow and neutral atmospheric stability and it lacks random variation among 10-min periods. Thus, the WAsP Engineering turbulence prediction will typically be smaller than the representative turbulence intensity, which should be a measure of 90% percentile of a scattered distribution. We are currently developing a WAT method for correcting the WAsP Engineering predictions by observed turbulence intensity statistics based on data from a reference mast near the turbine sites.

6.2.6 Gust statistics

A gust is a sudden increase in wind speed, which should not be mistaken for an extreme wind, which is a term referring to average wind. The spatial scale of a gust relates to its duration, so the gusts which are considered significant for wind turbine design have durations on the order of 3 sec. Gusts are both important in the extreme wind situation and at moderate wind speeds where the turbine is operating. If turbulence is considered a Gaussian process, it is possible to calculate the most likely maximum gust in a 10-min periods. Extreme gusts will, however, typically deviate from the Gaussian model as they are associated with rare meteorological phenomena like downbursts of high-altitude winds inside a thundercloud.

The IEC 61400-1 site assessment rules do not include gust analysis. Even so, it might be a good idea to add gust detection to a field measurement system. This does not involve extra sensors only additional processing by the data acquisition system. The maximum and minimum excursion of a 3-sec moving average filtered cup anemometer signal from its mean value is of primary interest. Deviation from predictions by Gaussian theory could indicate flow separation from upwind terrain features. Analysis of pairs of signals are also of interest, e.g. wind shear detected by two vertically separated cup anemometers or wind veer detected by two wind vanes.

7 Case studies

7.1 Introduction

The application project has carried out three case studies in order to illustrate the application aspects, and also to be used for the application training courses.

The three case study areas are:

- Mast M02 in Liaoning – hilly site close to a coastline
- Mast M05 in Jilin – flat inland site where roughness changes are important
- Mast MH5 in Heilongjiang – hilly to complex inland site

For each case study site, an area of 15 × 15 km2 (corresponding to 9 grid cells of the mesoscale models) has been defined, at which the various case studies have been performed (see Figure 19), including

- Wind resource prediction (surface wind) from the mast measurements at a given height for a selected area inside each study area
- Wind farm calculations from the mast measurements assuming a given wind turbine – PWC and AEP
- Verification comparing measurements to Numerical Wind Atlas for nearest cell
- Wind resource prediction (surface wind) from the Numerical Wind Atlas the nearest grid cell *.LIB files at a given height for a selected area inside each study area
- Wind farm calculations from the Numerical Wind Atlas the nearest grid cell *.LIB files assuming a given wind turbine – PWC and AEP

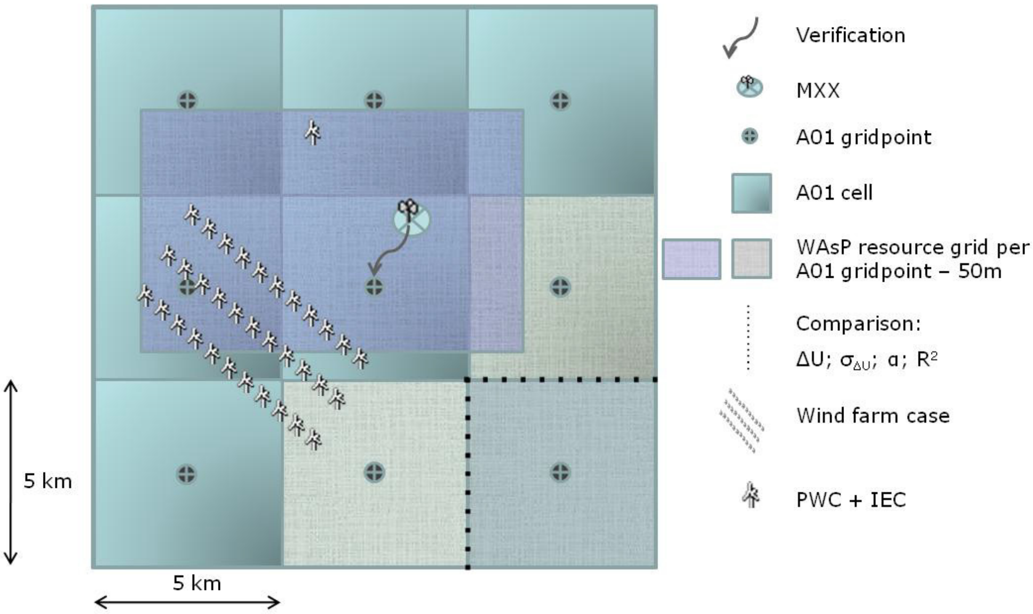


Figure 19. Sketch indicating the elements of each case study

The wind resource was modelled in detail. Inputs to the microscale flow modelling was the wind climate observed at the mast, as well as generalised wind climates derived from the mesoscale modelling – in the case of these case studies the Numerical Wind Atlas generated using the KAMM model was used. No long-term data from nearby met. stations have been available for correcting to long-term variations of the wind resource at the three sites, so it has been assumed based on the NCEP/NCAR data – as in the verification of the Numerical Wind Atlas – that the year 2009 was an average year. The colour scale for the mean wind speed in 80 m above ground level used for all case studies is the same to enable comparison between sites and methods (the last plot at M05 a second colour scale used for illustration of its small variations).

Topographical inputs (in addition to inputs already generated by Project A03 as a result of the Topographical Workshop) were made using the SRTM 3 elevation maps and Google Earth land-use / roughness maps. Hand digitised topography made in Project A03 at the Topographical Workshop is used for generation of Observational Wind Atlases from measurements at M02, M05 and MH5. Topography made by combining hand digitised topography data with SRTM data in expanded WAsP *.MAP files are used for generation of Numerical Wind Atlas, wind resource assessment, calculation of Predicted Wind Climate and for wind farm case studies at M02, M05 and MH5.

For the purpose of the case studies, a sample wind farm has been made in each case study area consisting of 16 × 3 MW wind turbines. The type of wind turbine is chosen at random and the wind farm layout is only for demonstration purposes, i.e. in no way to be understood as a proposal or an optimal wind farm for the area of the case study.

Figure 20 shows power curve and thrust coefficient curve for an air density of 1.24 kg/m^3 has been applied in all case studies – the closest standard value of air density for which power curve and thrust coefficient curve is available for the chosen 3 MW wind turbine.

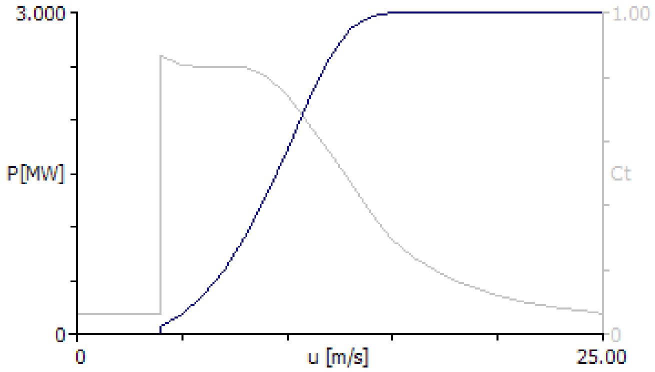


Figure 20. Power curve and Thrust coefficient curve for the 3 MW wind turbine chosen for the case studies at air density of 1.24 kg/m^3

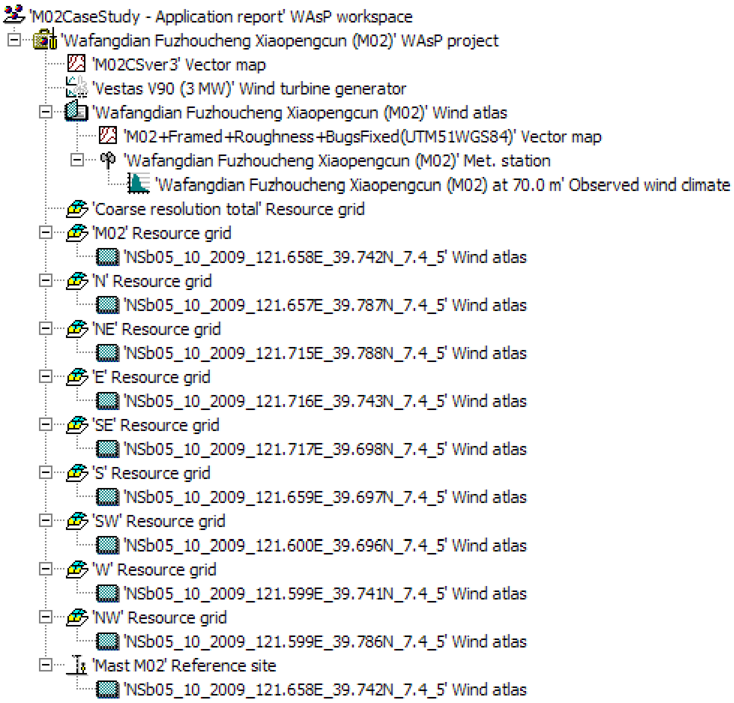
7.2 Liaoning (M02)

The Liaoning case study at mast M02 has been carried out applying the results of the “Meso-Scale and Micro-Scale Modelling in China” project in accordance with the recommendations of this report. The analyses have been done using WAsP, and the entire set of data and results are available in the WAsP workspace created for this study. Main results are reported below.

7.2.1 Setting up the WAsP workspace

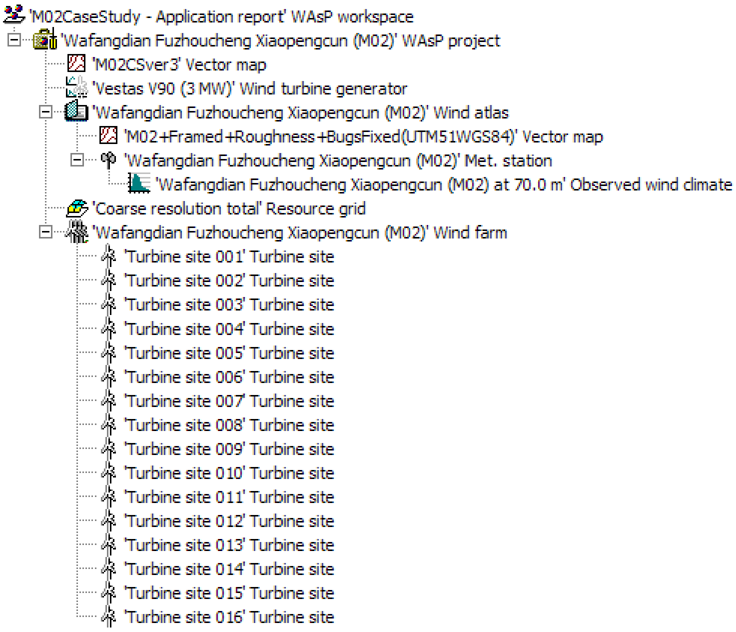
Figure 21, Figure 22 and Figure 23 show the WAsP workspaces set up for the case study

- Comparing wind resource maps from the Observational Wind Atlas (OWA) and Numerical Wind Atlas (NWA) as well as for verification and comparing predicted wind climate at the M02 location
- Wind farm calculations from OWA
- Wind farm calculation from NWA



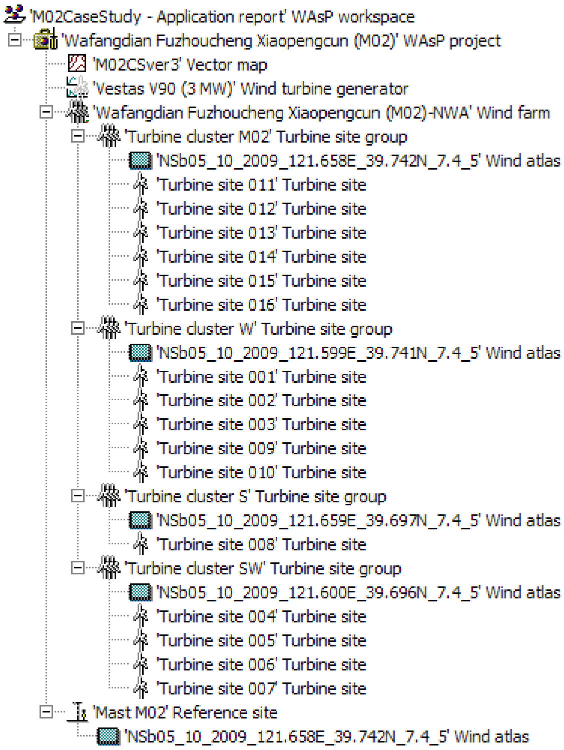
- 'M02CaseStudy - Application report' WAsP workspace
  - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' WAsP project
    - 'M02CSver3' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' Wind atlas
      - 'M02+Framed+Roughness+BugsFixed(UTM51WGS84)' Vector map
      - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' Met. station
        - 'Wafangdian Fuzhoucheng Xiaopengcun (M02) at 70.0 m' Observed wind climate
    - 'Coarse resolution total' Resource grid
    - 'M02' Resource grid
      - 'NSb05_10_2009_121.658E_39.742N_7.4_5' Wind atlas
    - 'N' Resource grid
      - 'NSb05_10_2009_121.657E_39.787N_7.4_5' Wind atlas
    - 'NE' Resource grid
      - 'NSb05_10_2009_121.715E_39.788N_7.4_5' Wind atlas
    - 'E' Resource grid
      - 'NSb05_10_2009_121.716E_39.743N_7.4_5' Wind atlas
    - 'SE' Resource grid
      - 'NSb05_10_2009_121.717E_39.698N_7.4_5' Wind atlas
    - 'S' Resource grid
      - 'NSb05_10_2009_121.659E_39.697N_7.4_5' Wind atlas
    - 'SW' Resource grid
      - 'NSb05_10_2009_121.600E_39.696N_7.4_5' Wind atlas
    - 'W' Resource grid
      - 'NSb05_10_2009_121.599E_39.741N_7.4_5' Wind atlas
    - 'NW' Resource grid
      - 'NSb05_10_2009_121.599E_39.786N_7.4_5' Wind atlas
    - 'Mast M02' Reference site
      - 'NSb05_10_2009_121.658E_39.742N_7.4_5' Wind atlas

Figure 21. M02 resource grids from OWA + NWA



- 'M02CaseStudy - Application report' WAsP workspace
  - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' WAsP project
    - 'M02CSver3' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' Wind atlas
      - 'M02+Framed+Roughness+BugsFixed(UTM51WGS84)' Vector map
      - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' Met. station
        - 'Wafangdian Fuzhoucheng Xiaopengcun (M02) at 70.0 m' Observed wind climate
    - 'Coarse resolution total' Resource grid
    - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' Wind farm
      - 'Turbine site 001' Turbine site
      - 'Turbine site 002' Turbine site
      - 'Turbine site 003' Turbine site
      - 'Turbine site 004' Turbine site
      - 'Turbine site 005' Turbine site
      - 'Turbine site 006' Turbine site
      - 'Turbine site 007' Turbine site
      - 'Turbine site 008' Turbine site
      - 'Turbine site 009' Turbine site
      - 'Turbine site 010' Turbine site
      - 'Turbine site 011' Turbine site
      - 'Turbine site 012' Turbine site
      - 'Turbine site 013' Turbine site
      - 'Turbine site 014' Turbine site
      - 'Turbine site 015' Turbine site
      - 'Turbine site 016' Turbine site

Figure 22. M02 wind farm + OWA



- 'M02CaseStudy - Application report' WAsP workspace
  - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)' WAsP project
    - 'M02CSver3' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Wafangdian Fuzhoucheng Xiaopengcun (M02)-NWA' Wind farm
      - 'Turbine cluster M02' Turbine site group
        - 'NSb05_10_2009_121.658E_39.742N_7.4_5' Wind atlas
        - 'Turbine site 011' Turbine site
        - 'Turbine site 012' Turbine site
        - 'Turbine site 013' Turbine site
        - 'Turbine site 014' Turbine site
        - 'Turbine site 015' Turbine site
        - 'Turbine site 016' Turbine site
      - 'Turbine cluster W' Turbine site group
        - 'NSb05_10_2009_121.599E_39.741N_7.4_5' Wind atlas
        - 'Turbine site 001' Turbine site
        - 'Turbine site 002' Turbine site
        - 'Turbine site 003' Turbine site
        - 'Turbine site 009' Turbine site
        - 'Turbine site 010' Turbine site
      - 'Turbine cluster S' Turbine site group
        - 'NSb05_10_2009_121.659E_39.697N_7.4_5' Wind atlas
        - 'Turbine site 008' Turbine site
      - 'Turbine cluster SW' Turbine site group
        - 'NSb05_10_2009_121.600E_39.696N_7.4_5' Wind atlas
        - 'Turbine site 004' Turbine site
        - 'Turbine site 005' Turbine site
        - 'Turbine site 006' Turbine site
        - 'Turbine site 007' Turbine site
    - 'Mast M02' Reference site
      - 'NSb05_10_2009_121.658E_39.742N_7.4_5' Wind atlas

Figure 23. M02 wind farm + NWA

7.2.2 Topographic data

Figure 24 and Figure 25 show the topography used for generation of Observational Wind Atlases from measurements at M02 and topography used for generation of Numerical Wind Atlas, wind resource assessment, calculation of Predicted Wind Climate and for wind farm case studies at M02, respectively. The map files represent adequately terrain up to 10 km away from any point of interest for the various elements of the study.

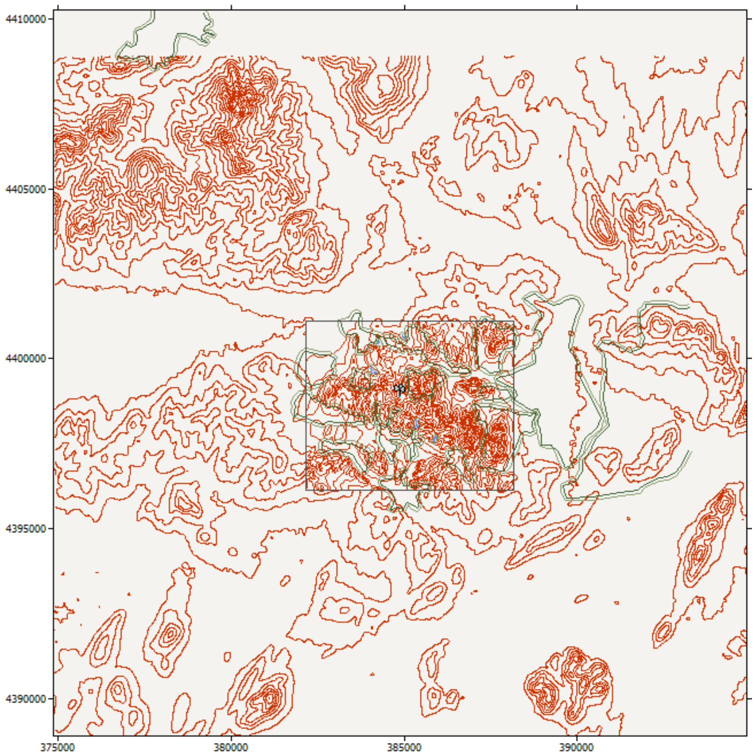


Figure 24. Hand digitised topography from paper maps used for generation of Observational Wind Atlas from measurements at M02.

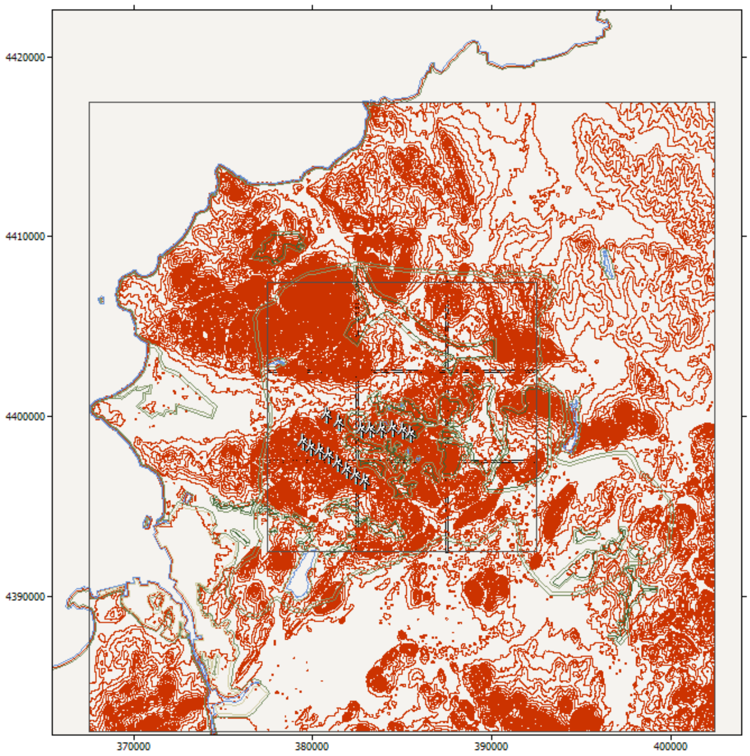


Figure 25. Topography used for generation of Numerical Wind Atlas, wind resource assessment and wind farm studies at M02.

7.2.3 Wind resource prediction from measurements

Mapping of wind resources near the M02 mast is possible – as shown in Figure 26.

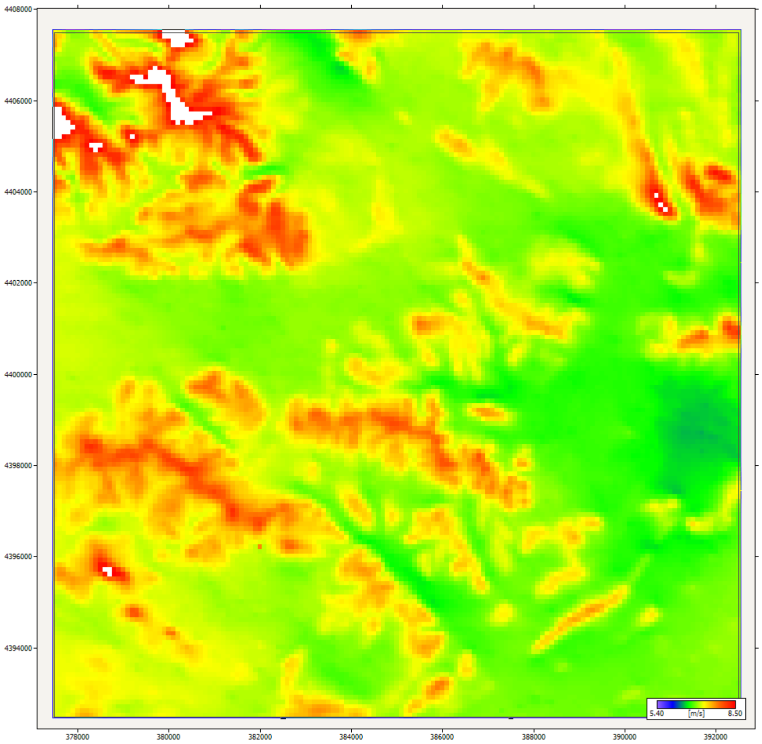


Figure 26. Predicted Wind Climate from Observational Wind Atlas shown as mean wind speed at 80 m a.g.l. in a 15 km × 15 km area around M02.

7.2.4 Wind farm calculations from measurements

Wind farm calculations for studying siting, layout and estimation of Annual Energy Production (AEP) may be performed based on the Observational Wind Atlas at M02 as shown in Table 5.Resulting AEP for the case study wind farm layout illustrated in Figure 27 and Figure 27. Case study wind farm layout illustrated on wind resource map at M02.

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Table 5.Resulting AEP for the case study wind farm layout illustrated in Figure 27

Parameter	Total	Average	Minimum	Maximum
Net AEP [GWh]	141.417	8.839	7.719	9.538
Gross AEP [GWh]	143.761	8.985	7.834	9.689
Wake loss [%]	1.63	-	-	-

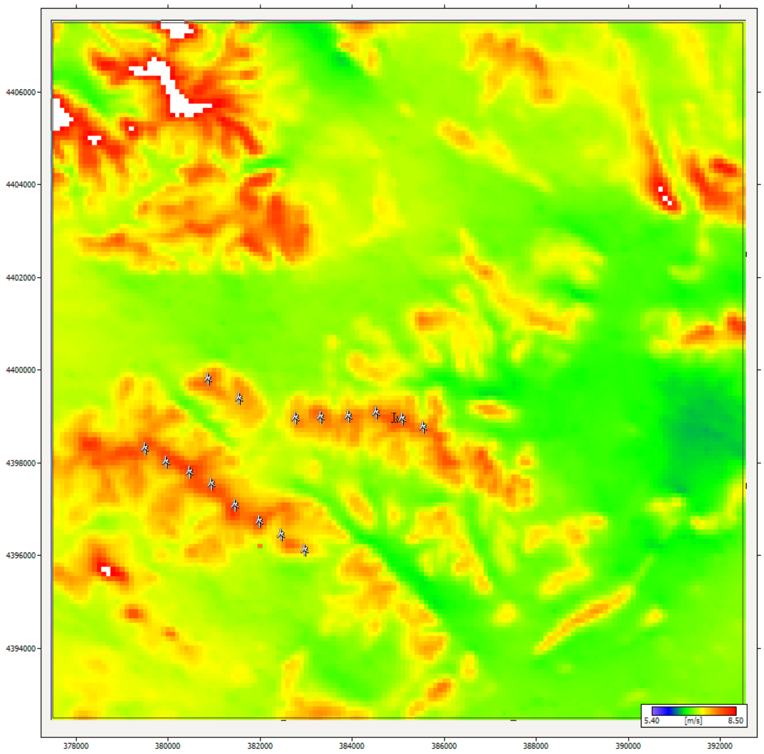


Figure 27. Case study wind farm layout illustrated on wind resource map at M02.

7.2.5 Comparing measurements to Numerical Wind Atlas for nearest cell

The self-prediction of the M02 measurements and the Predicted Wind Climate at M02 made by WAsP using the Numerical Wind Atlas are shown in Figure 28 and Figure 29 for comparison.

The M02 site coordinates are (384932, 4398875) at an elevation of 134 m above sea level. The height above ground level for which the comparison is made is 70 m.

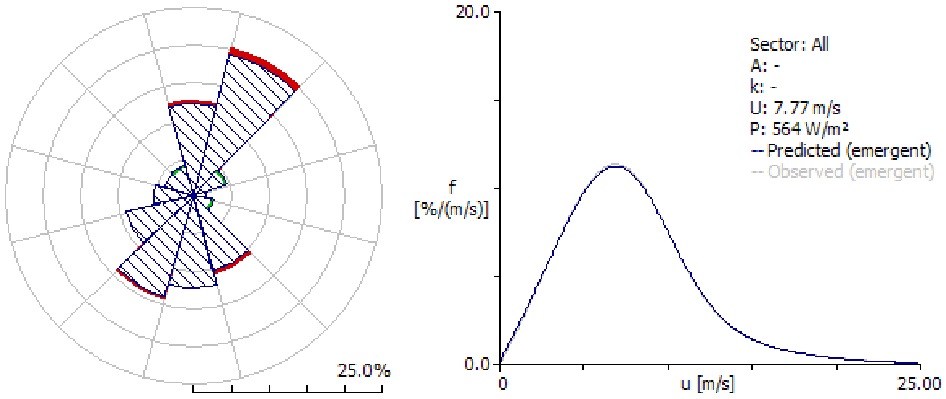


Figure 28 Measurements and self-prediction by WAsP using measured data

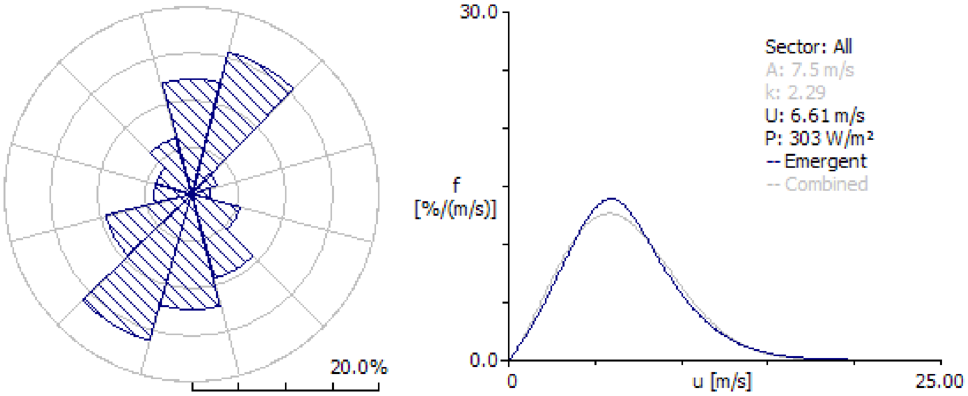


Figure 29 Predicted Wind Climate at M02 made by WAsP using the Numerical Wind Atlas

The Numerical Wind Atlas prediction of the annual average wind speed and the measurements differ by 1.16 m/s or 15%, which is a quite large difference as is also noted by the verification.

7.2.6 Wind resource prediction from the Numerical Wind Atlas

Mapping of wind resources near the M02 mast is possible using the Numerical Wind Atlas for the relevant grid cells as shown in Figure 30. Small discontinuities are seen at some of the overlapping boundaries between mesoscale grid cells as a consequence of the mesoscale effects in wind climate.

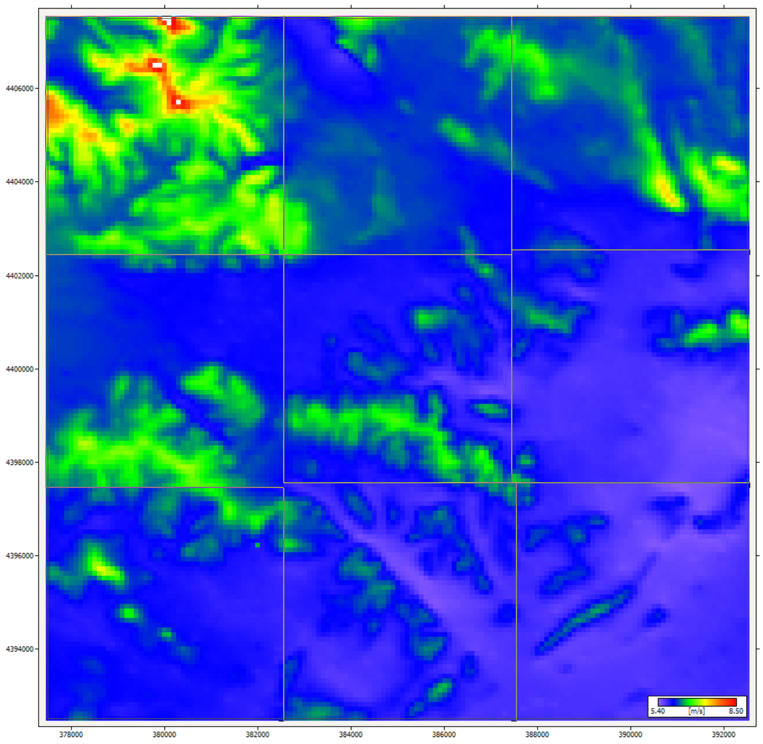


Figure 30. Predicted Wind Climate from Numerical Wind Atlas shown as mean wind speed at 80 m a.g.l. in a 15 km × 15 km area around M02 made from 9 mesoscale grid cells.

7.2.7 Wind farm calculations from the Numerical Wind Atlas

Wind farm calculations for studying siting, layout and estimation of Annual Energy Production (AEP) may be performed based on the Numerical Wind Atlas at M02 as shown in Table 6 and Figure 31. Case study wind farm layout illustrated on wind resource map at M02. .

Table 6.Resulting AEP for the case study wind farm layout illustrated in Figure 27

Parameter	Total	Average	Minimum	Maximum
Net AEP [GWh]	99.298	6.206	5.025	6.583
Gross AEP [GWh]	101.487	6.343	5.136	6.746
Wake loss [%]	2.16	-	-	-

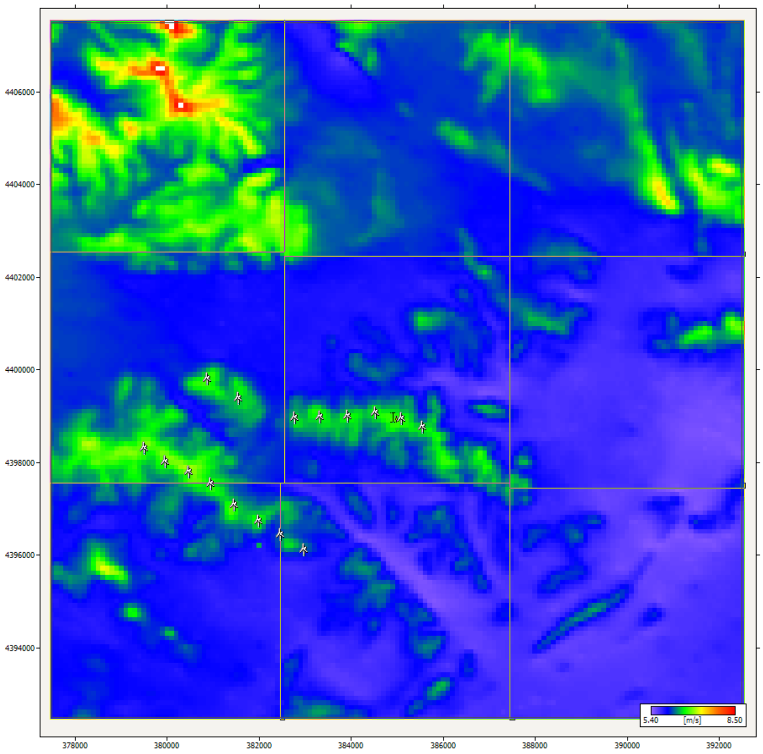


Figure 31. Case study wind farm layout illustrated on wind resource map at M02.

Differences of approximately 40% in AEP is found between applying the Observational and the Numerical Wind Atlases, which is a prohibitive difference for considering the Numerical Wind Atlas as a basis for project development in this area and maybe even for planning purposes. As discussed in the Verification (section 4) of this report and in more detail in [9], this finding is not yet fully understood. The hypothesis is that there seems to be a relation between terrain complexity and the performance of the mesoscale modelling, and that further refinement of modelling domains may lead to improved performance. For the time being the Numerical Wind Atlas in complex terrain types like at M02 should be used with extreme care.

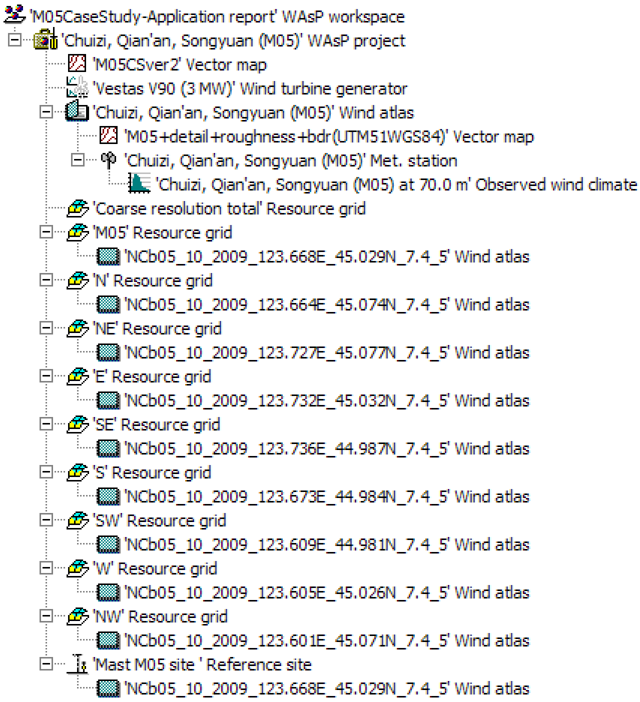
7.3 Jilin (M05)

The Jilin case study at mast M05 has been carried out applying the results of the “Meso-Scale and Micro-Scale Modelling in China” project in accordance with the recommendations of this report. The analyses have been done using WAsP, and the entire set of data and results are available in the WAsP workspace created for this study. Main results are reported below.

7.3.1 Setting up the WAsP workspace

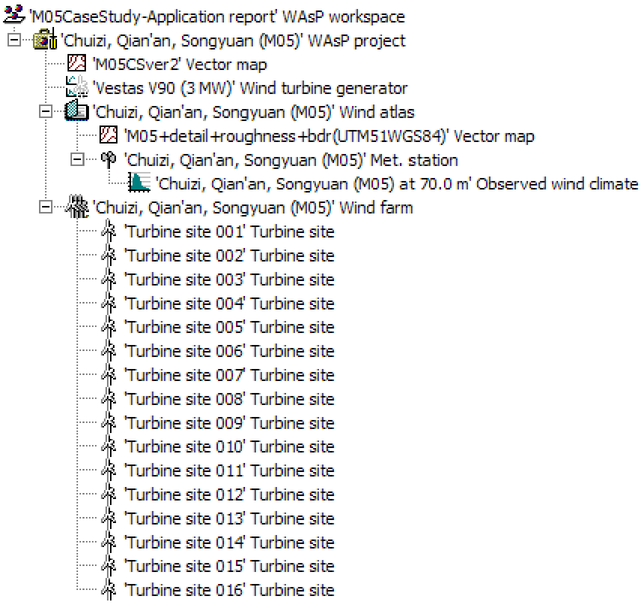
Figure 32, Figure 33 and Figure 34 show the WAsP workspaces set up for the case study

- Comparing wind resource maps from the Observational Wind Atlas (OWA) and Numerical Wind Atlas (NWA) as well as for verification and comparing predicted wind climate at the M05 location
- Wind farm calculations from OWA
- Wind farm calculation from NWA



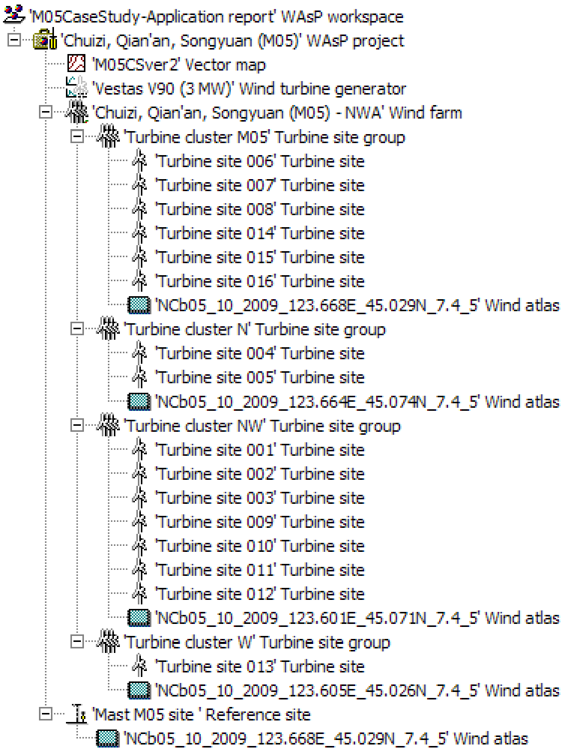
- 'M05CaseStudy-Application report' WAsP workspace
  - 'Chuizi, Qian'an, Songyuan (M05)' WAsP project
    - 'M05CSver2' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Chuizi, Qian'an, Songyuan (M05)' Wind atlas
      - 'M05+detail+roughness+bdr(UTM51WGS84)' Vector map
      - 'Chuizi, Qian'an, Songyuan (M05)' Met. station
        - 'Chuizi, Qian'an, Songyuan (M05) at 70.0 m' Observed wind climate
    - 'Coarse resolution total' Resource grid
    - 'M05' Resource grid
      - 'NCb05_10_2009_123.668E_45.029N_7.4_5' Wind atlas
    - 'N' Resource grid
      - 'NCb05_10_2009_123.664E_45.074N_7.4_5' Wind atlas
    - 'NE' Resource grid
      - 'NCb05_10_2009_123.727E_45.077N_7.4_5' Wind atlas
    - 'E' Resource grid
      - 'NCb05_10_2009_123.732E_45.032N_7.4_5' Wind atlas
    - 'SE' Resource grid
      - 'NCb05_10_2009_123.736E_44.987N_7.4_5' Wind atlas
    - 'S' Resource grid
      - 'NCb05_10_2009_123.673E_44.984N_7.4_5' Wind atlas
    - 'SW' Resource grid
      - 'NCb05_10_2009_123.609E_44.981N_7.4_5' Wind atlas
    - 'W' Resource grid
      - 'NCb05_10_2009_123.605E_45.026N_7.4_5' Wind atlas
    - 'NW' Resource grid
      - 'NCb05_10_2009_123.601E_45.071N_7.4_5' Wind atlas
    - 'Mast M05 site ' Reference site
      - 'NCb05_10_2009_123.668E_45.029N_7.4_5' Wind atlas

Figure 32. M05 resource grids from OWA + NWA



- 'M05CaseStudy-Application report' WAsP workspace
  - 'Chuizi, Qian'an, Songyuan (M05)' WAsP project
    - 'M05CSver2' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Chuizi, Qian'an, Songyuan (M05)' Wind atlas
      - 'M05+detail+roughness+bdr(UTM51WGS84)' Vector map
      - 'Chuizi, Qian'an, Songyuan (M05)' Met. station
        - 'Chuizi, Qian'an, Songyuan (M05) at 70.0 m' Observed wind climate
    - 'Chuizi, Qian'an, Songyuan (M05)' Wind farm
      - 'Turbine site 001' Turbine site
      - 'Turbine site 002' Turbine site
      - 'Turbine site 003' Turbine site
      - 'Turbine site 004' Turbine site
      - 'Turbine site 005' Turbine site
      - 'Turbine site 006' Turbine site
      - 'Turbine site 007' Turbine site
      - 'Turbine site 008' Turbine site
      - 'Turbine site 009' Turbine site
      - 'Turbine site 010' Turbine site
      - 'Turbine site 011' Turbine site
      - 'Turbine site 012' Turbine site
      - 'Turbine site 013' Turbine site
      - 'Turbine site 014' Turbine site
      - 'Turbine site 015' Turbine site
      - 'Turbine site 016' Turbine site

Figure 33. M05 wind farm + OWA



- 'M05CaseStudy-Application report' WAsP workspace
  - 'Chuizi, Qian'an, Songyuan (M05)' WAsP project
    - 'M05CSver2' Vector map
    - 'Vestas V90 (3 MW)' Wind turbine generator
    - 'Chuizi, Qian'an, Songyuan (M05) - NWA' Wind farm
      - 'Turbine cluster M05' Turbine site group
        - 'Turbine site 006' Turbine site
        - 'Turbine site 007' Turbine site
        - 'Turbine site 008' Turbine site
        - 'Turbine site 014' Turbine site
        - 'Turbine site 015' Turbine site
        - 'Turbine site 016' Turbine site
        - 'NCb05_10_2009_123.668E_45.029N_7.4_5' Wind atlas
      - 'Turbine cluster N' Turbine site group
        - 'Turbine site 004' Turbine site
        - 'Turbine site 005' Turbine site
        - 'NCb05_10_2009_123.664E_45.074N_7.4_5' Wind atlas
      - 'Turbine cluster NW' Turbine site group
        - 'Turbine site 001' Turbine site
        - 'Turbine site 002' Turbine site
        - 'Turbine site 003' Turbine site
        - 'Turbine site 009' Turbine site
        - 'Turbine site 010' Turbine site
        - 'Turbine site 011' Turbine site
        - 'Turbine site 012' Turbine site
        - 'NCb05_10_2009_123.601E_45.071N_7.4_5' Wind atlas
      - 'Turbine cluster W' Turbine site group
        - 'Turbine site 013' Turbine site
        - 'NCb05_10_2009_123.605E_45.026N_7.4_5' Wind atlas
    - 'Mast M05 site ' Reference site
      - 'NCb05_10_2009_123.668E_45.029N_7.4_5' Wind atlas

Figure 34. M05 wind farm + NWA

7.3.2 Topographic data

Figure 35 and Figure 36 show the topography used for generation of Observational Wind Atlases from measurements at M05 and topography used for generation of Numerical Wind Atlas, wind resource assessment, calculation of Predicted Wind Climate and for wind farm case studies at M05, respectively. The map files represent adequately terrain up to 10 km away from any point of interest for the various elements of the study.

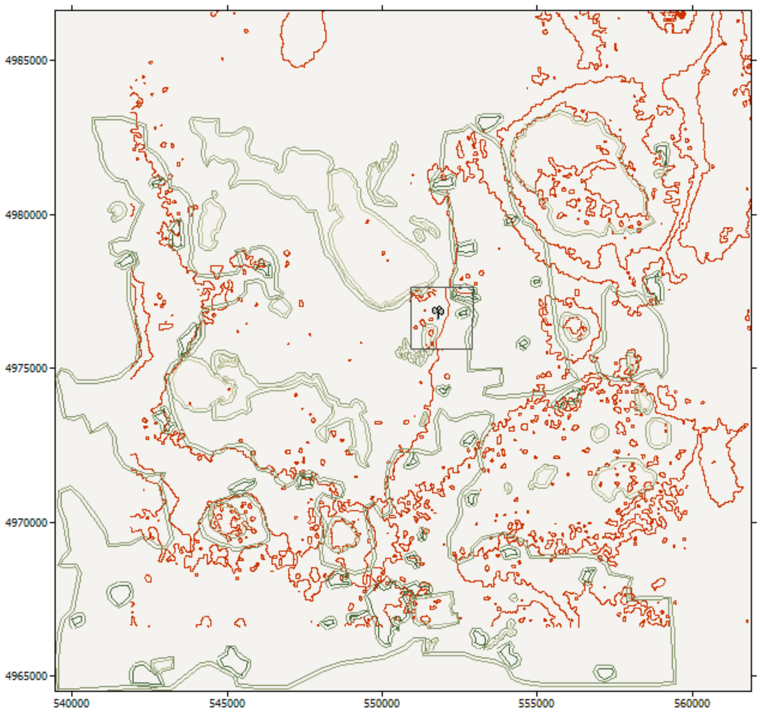


Figure 35. Hand digitised topography from paper maps used for generation of Observational Wind Atlas from measurements at M05

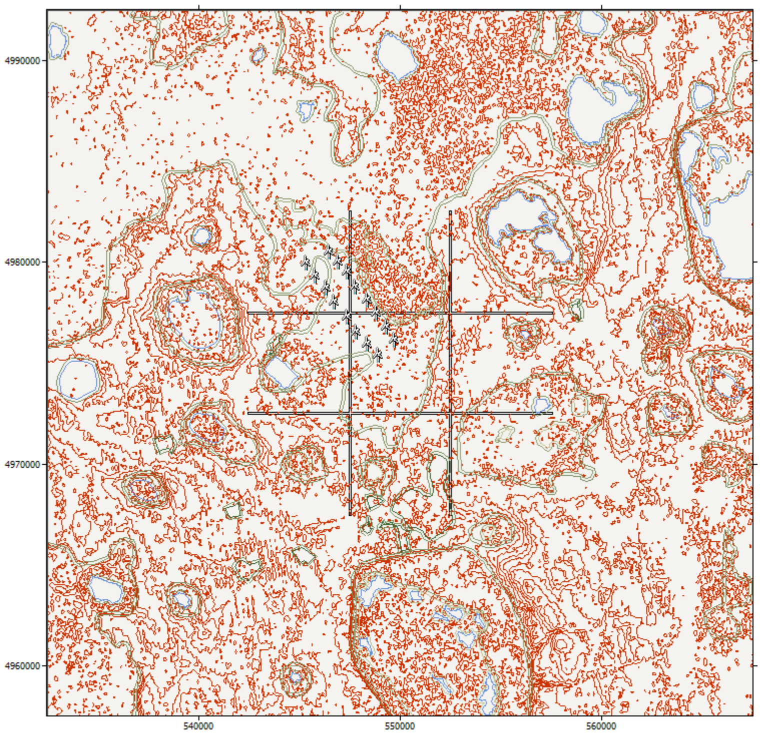


Figure 36. Topography used for generation of Numerical Wind Atlas, wind resource assessment and wind farm studies at M05

7.3.3 Wind resource prediction from measurements

Mapping of wind resources near the M05 mast is possible – as shown in Figure 37.

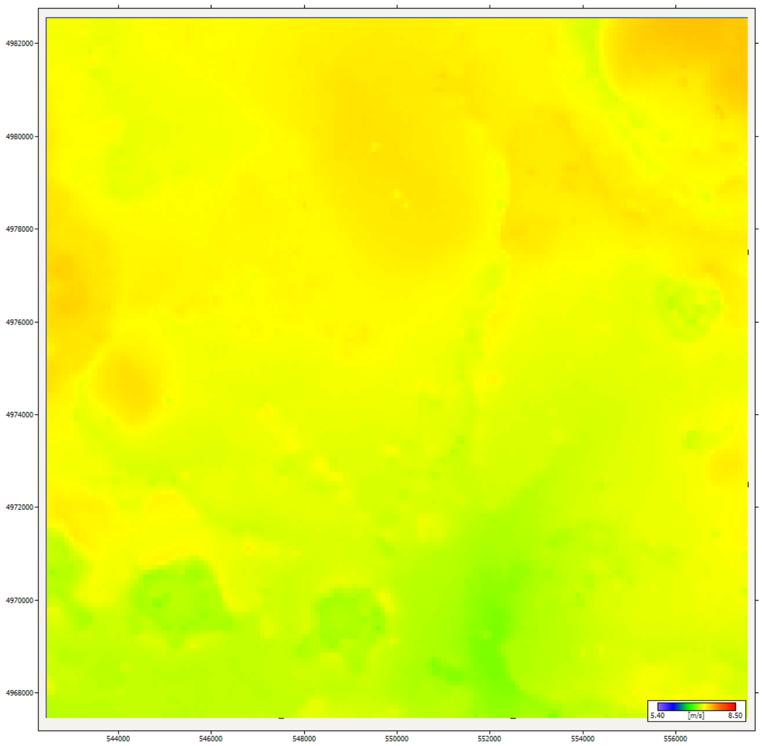


Figure 37. Predicted Wind Climate from Observational Wind Atlas shown as mean wind speed at 80 m a.g.l. in a 15 km×15 km area around M02.

7.3.4 Wind farm calculations from measurements

Wind farm calculations for studying siting, layout and estimation of Annual Energy Production (AEP) may be performed based on the Observational Wind Atlas at M05 as shown in Table 7, Figure 38 and Figure 39.

Table 7.Resulting AEP for the case study wind farm layout illustrated in Figure 38 and Figure 39.

Parameter	Total	Average	Minimum	Maximum
Net AEP [GWh]	125.679	7.855	7.743	7.927
Gross AEP [GWh]	129.120	8.070	7.993	8.113
Wake loss [%]	2.67	-	-	-

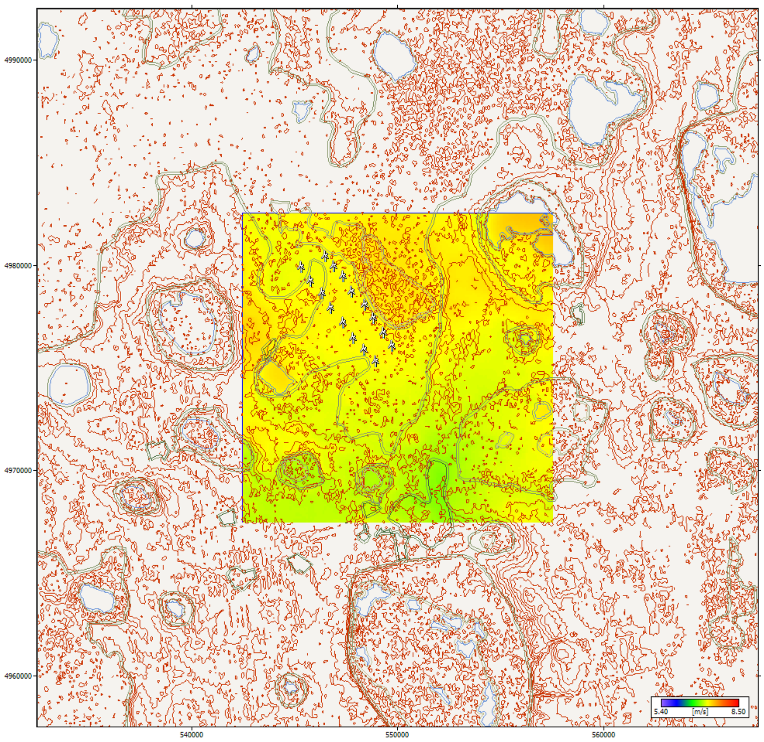


Figure 38. Case study wind farm layout illustrated on wind resource map at M05.

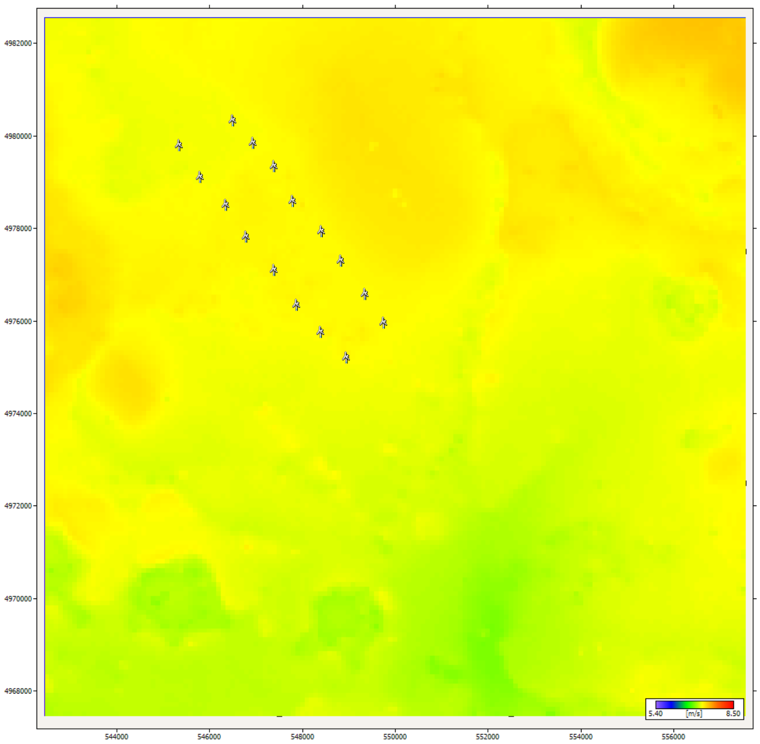


Figure 39. Case study wind farm layout illustrated on wind resource map at M05 – zoomed to the 15 km×15 km modelled area

7.3.5 Comparing measurements to Numerical Wind Atlas for nearest cell

The self-prediction of the M05 measurements and the Predicted Wind Climate at M05 made by WAsP using the Numerical Wind Atlas are shown in and for comparison.

The M05 site coordinates are (551871, 4976609) at an elevation of 136 m above sea level. The height above ground level for which the comparison is made is 70 m.

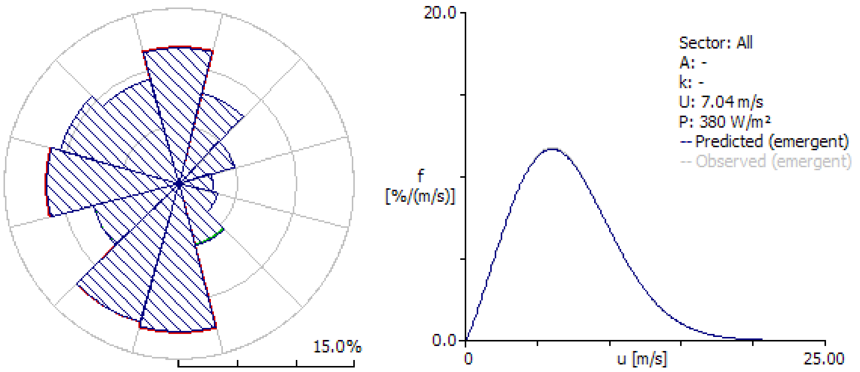


Figure 40 Measurements and self-prediction by WAsP using measured data

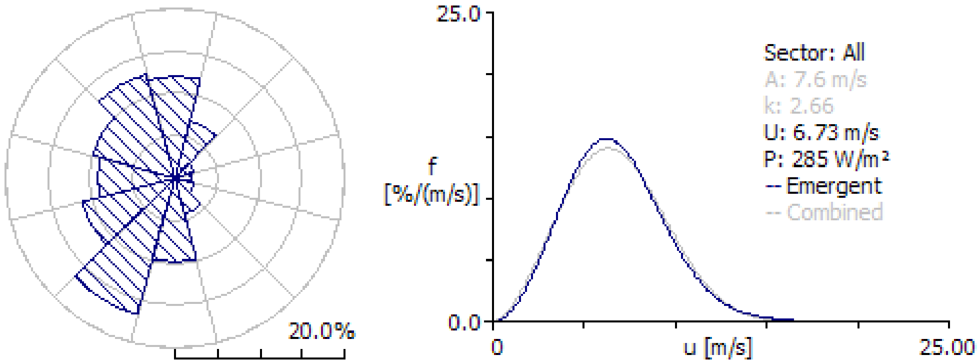


Figure 41 Predicted Wind Climate at M02 made by WAsP using the Numerical Wind Atlas

The Numerical Wind Atlas prediction of the annual average wind speed and the measurements differ by 0.31 m/s or 4.4%, which is in accordance with what was found in the verification, and which makes the results in the surroundings of M05 seem applicable for wind resource assessment studies and planning purposes.

7.3.6 Wind resource prediction from the Numerical Wind Atlas

Mapping of wind resources near the M05 mast is possible using the Numerical Wind Atlas for the relevant grid cells as shown in Figure 42. Hardly any discontinuities are seen at the overlapping boundaries between mesoscale grid cells in this area with small mesoscale effect gradients.

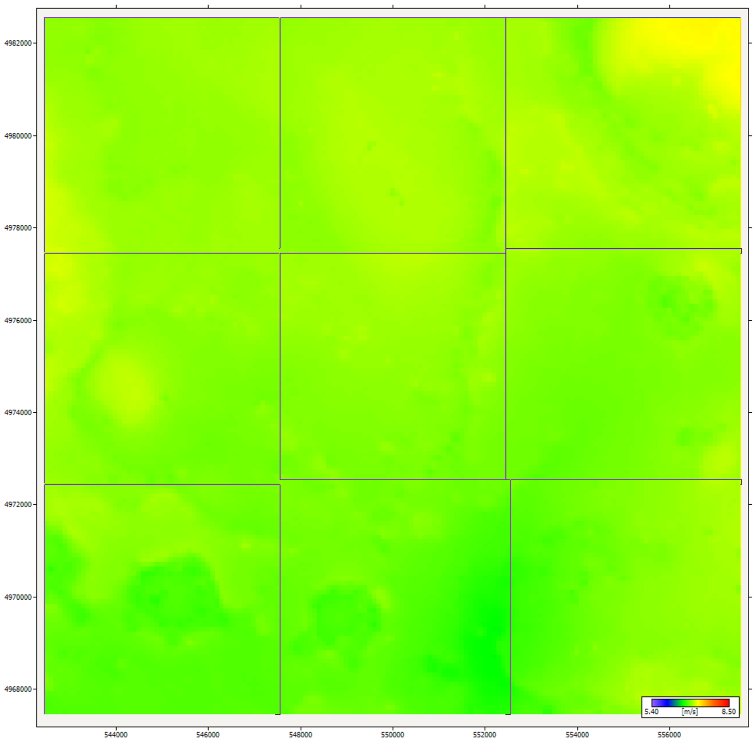


Figure 42. Predicted Wind Climate from Numerical Wind Atlas shown as mean wind speed at 80 m a.g.l. in a 15 km×15 km area around M05 made from 9 mesoscale grid cells.

7.3.7 Wind farm calculations from the Numerical Wind Atlas

Wind farm calculations for studying siting, layout and estimation of Annual Energy Production (AEP) may be performed based on the Numerical Wind Atlas at M05 as shown in Table 8, Figure 43, Figure 44 and Figure 45.

Table 8.Resulting AEP for the case study wind farm layout illustrated in Figure 43, Figure 44 and Figure 45.

Parameter	Total	Average	Minimum	Maximum
Net AEP [GWh]	108.508	6.782	6.654	6.959
Gross AEP [GWh]	112.264	7.017	6.964	7.055
Wake loss [%]	3.35	-	-	-

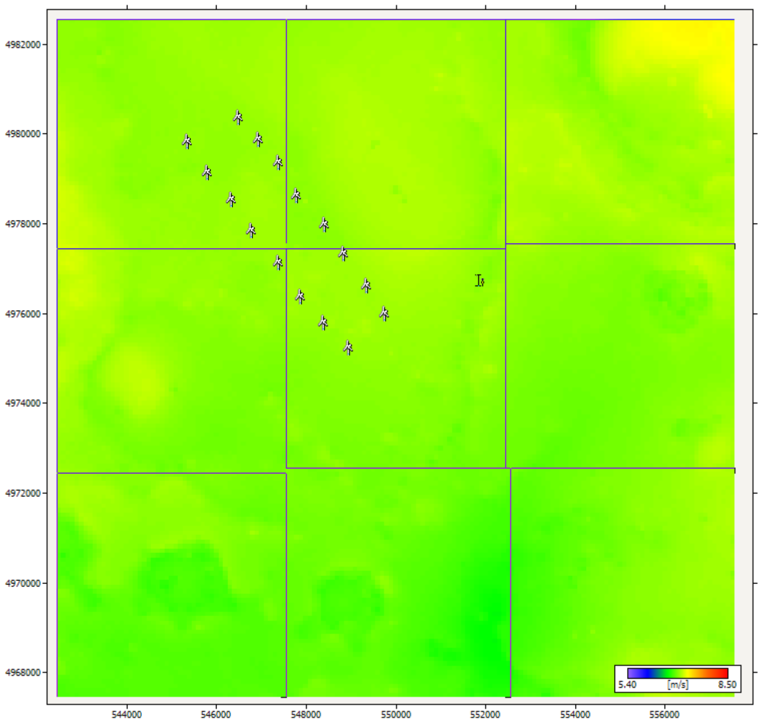


Figure 43. Case study wind farm layout illustrated on wind resource map at M05.

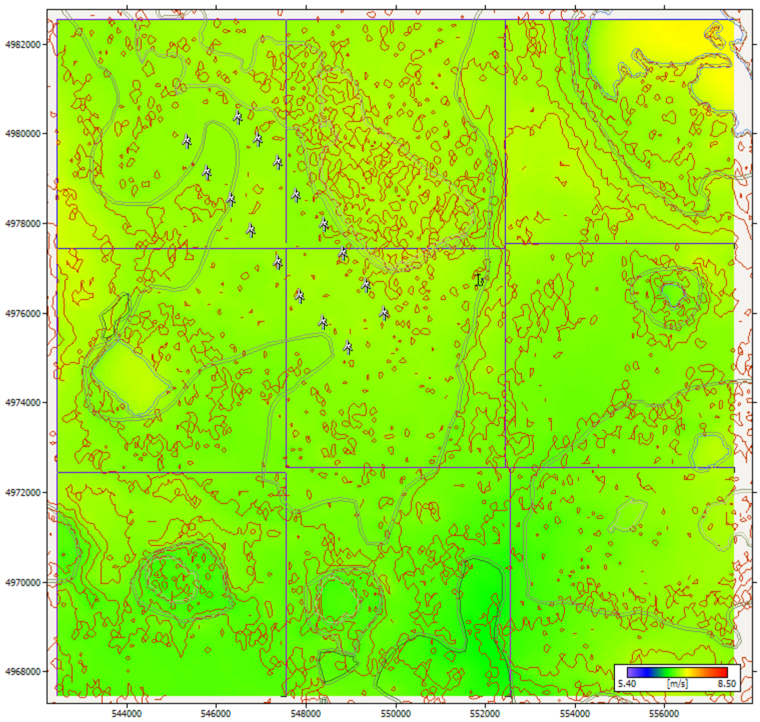


Figure 44. Case study wind farm layout illustrated on wind resource map at M05 - with height and roughness contour lines

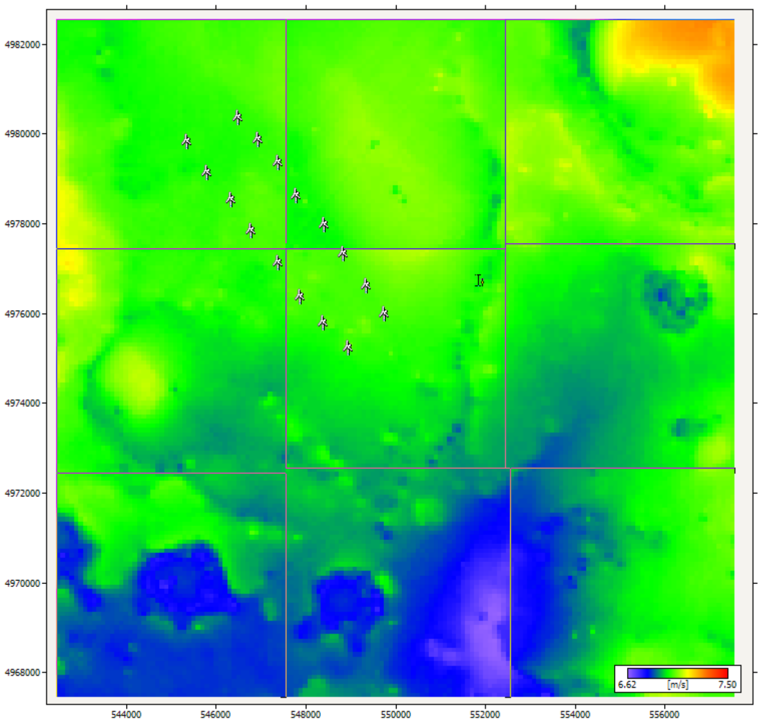


Figure 45. Case study wind farm layout illustrated on wind resource map at M05 - plotted in a different colour scale for highlighting of wind resource variations

Differences of approximately 15% in AEP is found between applying the Observational and the Numerical Wind Atlases, which is a fair level of uncertainty for considering the Numerical Wind Atlas as a basis for project development studies and wind energy planning in this area.

7.4 Heilongjiang (MH5)

7.4.1 Setting up the WAsP workspace

7.4.2 Topographic data

7.4.3 Wind resource prediction from measurements

7.4.4 Wind farm calculations from measurements

7.4.5 Comparing measurements to Numerical Wind Atlas for nearest cell

7.4.6 Wind resource prediction from the Numerical Wind Atlas (*.LIB)

7.4.7 Wind farm calculations from the Numerical Wind Atlas (*.LIB)

8 Concluding remarks and recommendations

Wind atlas databases are now being made available in the public domain from a web-site at CMA, although any use of these databases will be fully at the users own risk. Neither CMA nor Risø DTU will have any liability in connection with the use of the databases or the reports made by the project.

A general method has been developed and tested that enables comparison and verification of various mesoscale models (KAMM and WRF) against each other and against measurements. A mean absolute error of 8% of the Numerical Wind Atlas verified against the 9 measurement stations M01 – M09 has been found, which is within what was expected.

Multiple sensitivity tests have been carried out for the whole of the numerical wind atlas methodology (from the determination of the geostrophic wind and the appropriate temporal sampling needed for wind/weather classification, to consideration of how mesoscale modelling is fed to microscale models, i.e. wind generalization). The results of which assist in the assessment of sources of error, and it is expected soon to provide input for mapping uncertainty estimates. Results indicate larger uncertainty and error in the mountain/hill terrain and/or coastal regions. This is reinforced in the results of the verification and an indexing of the mesoscale terrain complexity in relation to numerical wind atlas error. In areas where sensitivity and uncertainty is high a joint campaign of more specific modelling (using higher resolution and specific surface temperature configuration) and wind measurement is recommended.

Wind atlases are generally applied for determination of wind conditions and energy production estimation for many uses and users, however, basically for either for planning or wind farm project development or design purposes.

The various uses require coverage and modelling of different size geographical domains and different levels of accuracy. The wind atlas method employing both the numerical wind atlas method and the observational wind atlas method verified against measurements offer opportunities to serve all purposes. Implementation may then be planned with a refinement of resolution, accuracy and detail for the areas of interest – both with respect to the measurement programme and the modelling.

Three case studies for illustration of the wind atlas method and the use of the Observational Wind Atlases as well as the Numerical Wind Atlas developed for N.E. China have been performed in close cooperation between CMA and Risø DTU.

The main findings and conclusions as a result of the case studies may be summarised as follows

- Wind atlas databases are available for planning and project studies in areas of N.E. China with low or limited degree of complex terrain.
- Bankability of wind farm projects requires on-site measurements, and recommendations for measurements have been made based on the analyses comparing the different types of sensors used. However, if the project's measurement masts remain operational as references, project development time can be reduced through MCP.
- Differences of up to 40% in AEP between applying the Observational and the Numerical Wind Atlases have been found at the M02 site, which is a prohibitive for considering the Numerical Wind Atlas as a basis for project development in this area. This finding is not yet fully understood although a relation between terrain complexity and the performance of the mesoscale modelling has been seen. Further refinement of modelling resolution and detailing of differences between domains may lead to improved performance. For the time being the Numerical Wind Atlas in complex terrain types like at M02, M03, M08, and M09 should be used with extreme care.

Recommendations for application of the wind atlas databases

- Use sensitivity analyses for uncertainty assessment

- Use model parameters recommended for local conditions
- Be aware of additional uncertainties not described by the present project, such as inter-annual variations and large-scale wind farm effects
- Risk assessment of wind farm projects should look for gradients in the NWA
- Masts should remain operational as reference, which will reduces project development time and which will be useful in the further improvement of the wind atlases
- Update the Numerical Wind Atlas every year with improved verification
- Courses in application of the Wind Atlas should be offered by CMA and experience from the use of it in N.E. China should be collected by CMA

Recommendations for measurements

- Follow international standards for high quality measurements
- Use top-anemometer
- Minimize flow distortion effects from booms, masts, etc
- Use highest sensor quality and calibrations in traceable wind tunnels
- Use data acquisition system with redundancy to get >95% data recovery

Recommendations for microscale modelling

- Apply WAsP correctly in order to obtain correct performance as was found by the sensitivity studies at the 9 masts in N.E. China
- Use recommended parameters for WAsP in N.E. China
- Ensure high accuracy of wind and topographic data to achieve low uncertainties
- Use of *.LIB files from NWA recommended
- A check list of requirements, best practices and recommendations for microscale modelling is annexed in A. The list is not exhaustive, but is meant to provide a brief summary of some important considerations regarding Microscale modelling of general importance when applying the Numerical Wind Atlas or making Observational Wind Atlas from the measurements of this project or from any other measurements in N.E. China.

Further studies are required to relate more generally the sensitivity analysis of the numerical wind atlas methodology to the uncertainties in the resulting wind resource data. Uncertainty estimation for all locations within the mapped area is now a step closer to realization after the development of indexing of the mesoscale terrain complexity presented in Badger et al (2010). It would be of great value as it helps the user of the modelled data to assess to what extent further measurement campaigns are required in a given area.

It should be remembered that only one year of measurement data is used for the model verification. When the verification period is shortened one normally expect an increase in the uncertainty, therefore further measurements at current sites and additional sites would be of great value for verification. Multi-year measurements would allow for an assessment of uncertainty for single year mean wind statistics. More measurement sites would not only allow verification of modelled wind resources but also importantly would provide much needed data for verification of uncertainty estimation.

All in all it may be concluded that the mesoscale numerical wind atlas in combination with observational wind atlases offer new opportunities for doing planning on a large scale even with a limited availability of wind data from meteorological measurement stations. At wind farm sites and in project preparation it provides a consistent basis for verification of model results against each other and against measurements when employing the wind atlas method and together it may be applied with a view to reducing uncertainties. Evidently techniques may be improved through a continued research effort making use of the ever increasing computing power of new computers and new measurement technologies, mapping techniques and satellite imagery.

9 References

[1] Troen, I. and E.L. Petersen (1989). *European Wind Atlas*. ISBN 87-550-1482-8. Risø National Laboratory, Roskilde. 656 pp.

[2] Mortensen, N.G., D.N. Heathfield, L. Myllerup, L. Landberg and O. Rathmann (2007). Wind Atlas Analysis and Application Program: WAsP 9 Help Facility. Risø National Laboratory, Technical University of Denmark, Roskilde, Denmark. 353 topics. ISBN 978-87-550-3607-9.

[3] Frank, H. P., L. Landberg, 1997. Modelling the wind climate of Ireland. *Boundary-Layer Meteorology*, 85:359-378

[4] Frey-Buness, F., D. Heimann, R. Sausen, 1995. A statistical-dynamical downscaling procedure for global climate simulations. *Theor. Appl. Climatol.*, 50:117-131

[5] Kalnay E, Kanamitsou M, Kistler R, Collins W, Deaven D, Gandin L, Irebell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Huggins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D, 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437-471

[6] Adrian, G., F. Fiedler, 1991: Simulation of unstationary wind and temperature fields over complex terrain and comparison with observations. *Beitr. Phys. Atmosph.*, 64:27-48

[7] Mortensen, N.G., J.C. Hansen, J. Badger, B.H. Jørgensen, C.B. Hasager, L. Georgy Youssef, U. Said Said, A. Abd El-Salam Moussa, M. Akmal Mahmoud, A. El Sayed Yousef, A. Mahmoud Awad, M. Abd-El Raheem Ahmed, M. A.M. Sayed, M. Hussein Korany, M. Abd-El Baky Tarad, 2005. Wind Atlas for Egypt, Measurements and Modelling 1991-2005. New and Renewable Energy Authority, Egyptian Meteorological Authority and Risø National Laboratory. ISBN 87-550-3493-4. 258 pp.

[8] Clausen, N.-E., P. Lundsager, R. Barthelmie, H. Holttinen, T. Laakso, S.C. Pryor: Chap 7 Wind Power in Impact of Climate Change on Renewable Energy Sources edited by J. Fenger, Nordic Council of Ministers Copenhagen 2007. ISBN 978-92-893-1465-7.

[9] Badger, J., X.G. Larsén, A. Hahmann, R. Zhu, C. Yuan (2010). Mesoscale modelling in China: Risø DTU numerical wind atlas calculation for NE China (Dongbei). Risø-I-3070(EN). 68 pp.

[10] Zhou Rong, et al (2010). Mesoscale modelling in China: CMA numerical wind atlas calculation for NE China (Dongbei). ? pp.

[11] Lindelöw-Marsden, P and Enevoldsen, K (2010). Meso- and Micro-scale Modelling in China: Wind Measurements at 12 meteorological stations in NE China (Dongbei), June 2010. Risø-I-3071(EN). 65 pp.

[12] Mortensen, N.G., J.C. Hansen, Z. Yang, H. Yu, J. Xie and G. Yuan (2010). Meso- and Micro-scale Modelling in China: Site inspection trip to Dongbei, June 2009. Risø-I-2900(EN). 61 pp.

[13] Mortensen, N.G., Z. Yang, J.C. Hansen, O. Rathmann and M. Kelly (2010). Meso- and Micro-scale Modelling in China: Wind atlas analysis for 12 meteorological stations in NE China (Dongbei). Risø-I-3072(EN). 71 pp.

[14] IEC 61400-12-1. Wind turbines-Part 12-1: Power performance measurements of electricity producing wind turbines, 2005

[15] IEC (1999) International standard IEC61400-1, Safety requirements, 2nd edition

[16] IEC (2005) International standard IEC61400-1, Safety requirements, 3rd edition, FDIS

[17] IEC (2009) International standard IEC61400-1/A1, Safety requirements, amendment of 3rd edition, FDIS

[18] Frandsen, S. (2007) Turbulence and turbulence-generated fatigue loading in wind turbine clusters. Risø-R-1188(EN), pp. 130.

[19] Nielsen, M.; Jørgensen, H. E.; Frandsen, S. T. (2009), Wind and wake models for IEC 61400-1 site assessment, 2009 European Wind Energy Conference and Exhibition. Marseille (FR), 16-19 Mar, 6 p.

Web pages and ftp sites

A. List of requirements, best practices and recommendations

The following list of requirements, best practices and recommendations is not exhaustive, but is meant to provide a brief summary of some important considerations regarding WAsP modelling. More information is available in the WAsP help system and at www.wasp.dk.

Measurement programme

- Design measurement programme based on preliminary WAsP analysis
    - Use SRTM elevation data and land-use from Google Earth
- Follow similarity principle as much as possible when siting the mast(s)
- Height of reference anemometer(s) similar to hub height (preferably > 2/3 h_{hub})
- Optimum boom direction is @ 90° (lattice) or @ 45° (tubular) to prevailing wind
- Deploy 2 or more masts for horizontal extrapolation analyses
- Deploy 2 or more masts if RIX and ΔRIX analyses are required
- Deploy 2 or more levels on masts for vertical wind profile analyses
- Deploy 2 or more levels on masts for redundancy in instrumentation
- Measure temperature and pressure for air density calculations

Wind data analysis

Collect required information, e.g. by filling out the WAsP Data Description Form

- All fields in Climate Analyst protocol editor should correspond to data spec's
- Plot and inspect time traces of all meteorological measurements
- Visual inspection of time-series – in particular reference wind speed and direction
- Visual inspection of polar scatter plot – any patterns or gaps?

Observed wind climate

- Use an integer number of whole years when calculating the OWC
- Check Weibull fit: is power density discrepancy < 1%?
- Check Weibull fit: is mean wind speed discrepancy < a few per cent?
- Check within context of long-term wind climate (MCP)

Elevation map(s)

- Size of map: should extend at least max(100×h, 10 km) from any site – meteorological mast, reference site, turbine site or resource grid point.
- Coordinates and elevations must be in meters
- Set projection and datum for map in the Map Editor
- Add spot heights within wind farm site
- Check range of elevations in map

Roughness/Land-use map(s)

- Size: map should extend at least max(100×*h*, 10 km) from any site – meteorological mast, reference site, turbine site or resource grid point.
- Coordinates and elevations must be in meters
- Set projection and datum for map in the Map Editor
- Set roughness length of water surfaces to 0.0 m!
- Check range of roughness values in map
- Map date should correspond to modelling scenario (met. mast or wind farm)
- Check for dead ends and cross points – and edit map as needed
- Check consistency of roughness values – there must be no LFR-errors!

Sheltering obstacles

- Is site closer to obstacle than 50 obstacle heights, and is height lower than about 3 obstacle heights?
- If yes to both, treat as sheltering obstacle; if no, then treat as *roughness element*

WAsP modelling – site visit

- Go on a site visit! Use e.g. the WAsP Site/Station Inspection Checklist
- Print and bring the WAsP forms for recording the necessary information
- Bring GPS and note projection and datum settings – change if required
- Determine coordinates of all masts, landmarks and other characteristic points on site
- Take photos of station and surroundings (12 × 30°-sector panorama)
- Download GPS data and photographs to PC as soon as possible (daily)

WAsP modelling – parameters

- Wind atlas structure: standard roughness classes should span site conditions
- Wind atlas structure: standard heights should represent project
- Adjust off- & on-shore mean- and RMS-heat flux values to site conditions (*caution*)
- Ambient climate: Set air density to site-specific value (WAsP 10 only)

WAsP modelling – analysis and application

- Get site-specific wind turbine generator data from manufacturer
- Within forest: effective height = nominal height minus displacement length
- Complex or steep terrain is when RIX > 0 for one or more sites (terrain angles > 17°)
- Make RIX and ∆RIX analyses if RIX > 0 for any site

WAsP modelling – offshore

- Roughness length of sea (and other water) surfaces: set = 0.0 m in WAsP!
- Add combined elevation/roughness change line around wind farm site
- Change wake decay constant to offshore conditions

WAsP modelling and sensitivity analyses

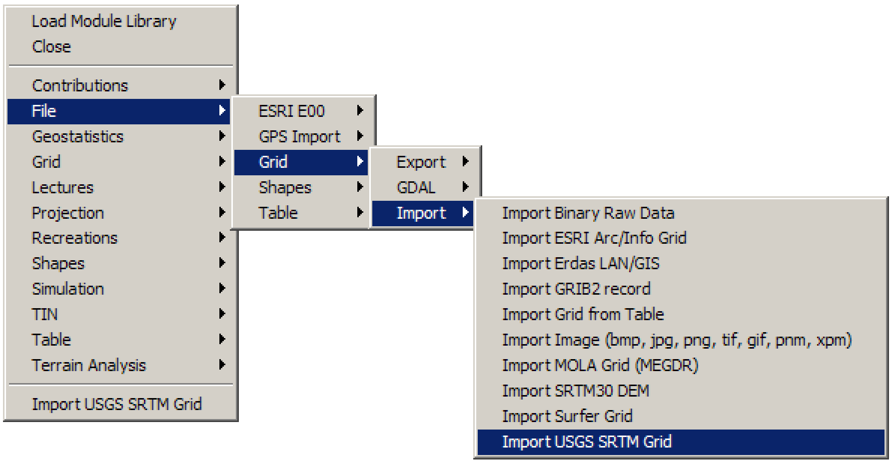
- Identify and try to estimate uncertainties
- Sensitivity of results to background roughness value and other important parameters

B. On the use of SAGA GIS

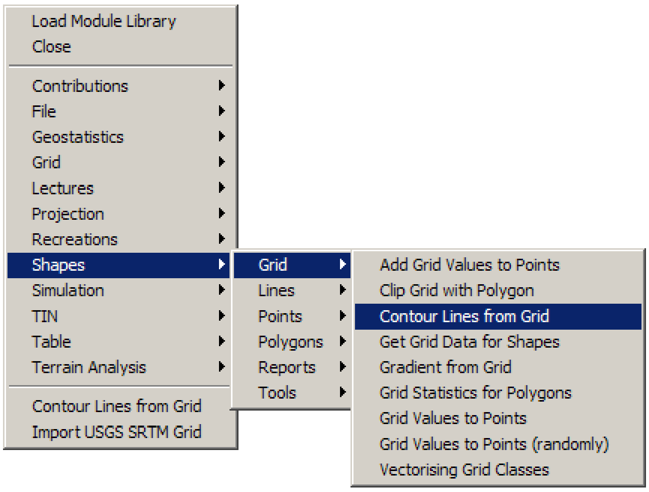
SAGA – **S**ystem for **A**utomated **G**eoscientific **A**nalyses – is a free-ware GIS system developed by University of Göttingen; the home page is http://www.saga-gis.org/en/index.html. SAGA GIS can be used to make WAsP height contour (vector) maps from different kinds of gridded (raster) data.

Processing an SRTM grid for WAsP use

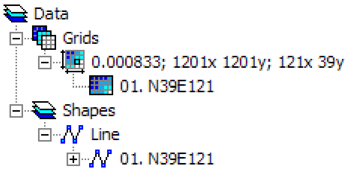
Once you have downloaded and unzipped a 1°×1° tile, import the grid from the **Modules** menu:



Make the height contours from the **Modules** menu, selecting the range and contour interval:

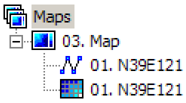


The **Data** workspace should now look something like this:

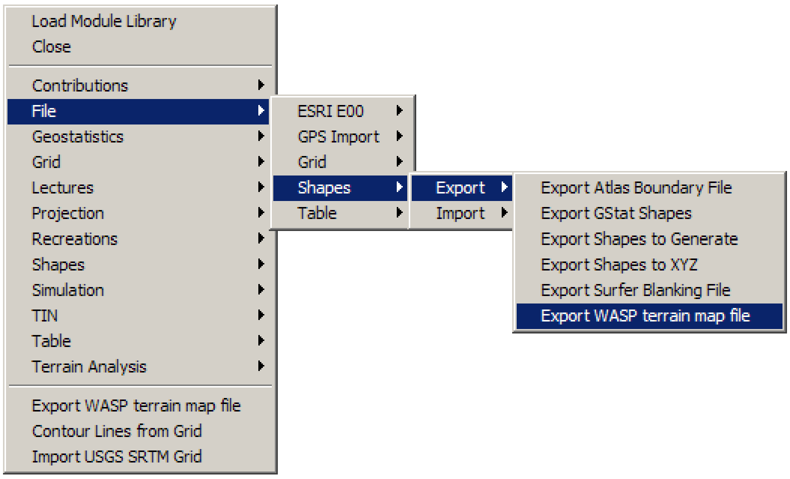


where the **Grids** section contains the SRTM grid and the **Shapes** section the contour lines.

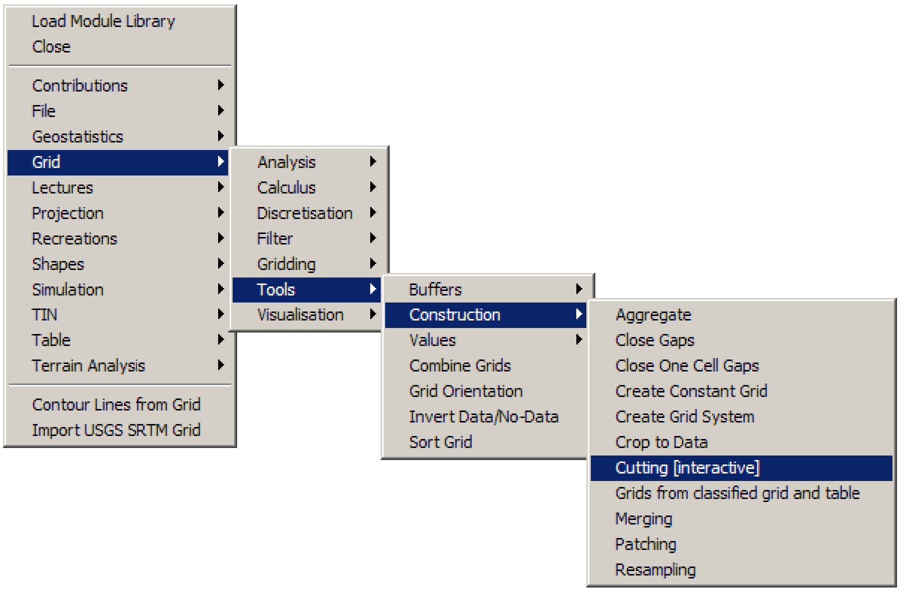
Double-click the grid, e.g. “01. N39E121”, to display it – same goes for the Shape “01. N39E121”. The **Maps** workspace could look something like this:



Finally, export the height contours to a WAsP terrain map file from the **Modules** menu:

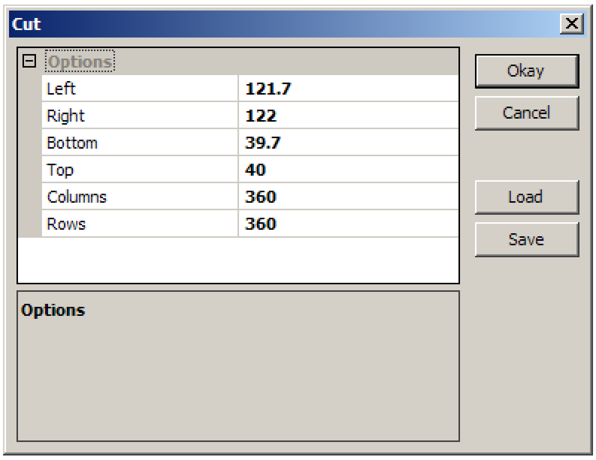


Each SRTM3 grid file covers a 1°×1° tile and contains 1201×1201 cells; an SRTM1 (US only) grid file also covers a 1°×1° tile but contains 3601×3601 cells. This is sometimes too much information too process or too large an area. The imported SRTM grid can then be cut from the **Modules** menu:



First, show the grid in a **Map** window. Next, start the **Cutting** tool, select the grid system and grid and click **Okay**. Next, select the **Action** pointer (the black arrow) in the toolbar:

In the **Map** window, drag out (left click and drag) the approximate area for the sub-grid that you would like to extract. A **Cut** window now pops up:

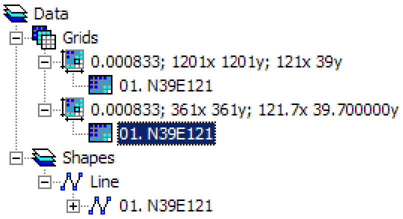


Options	
Left	121.7
Right	122
Bottom	39.7
Top	40
Columns	360
Rows	360

Options

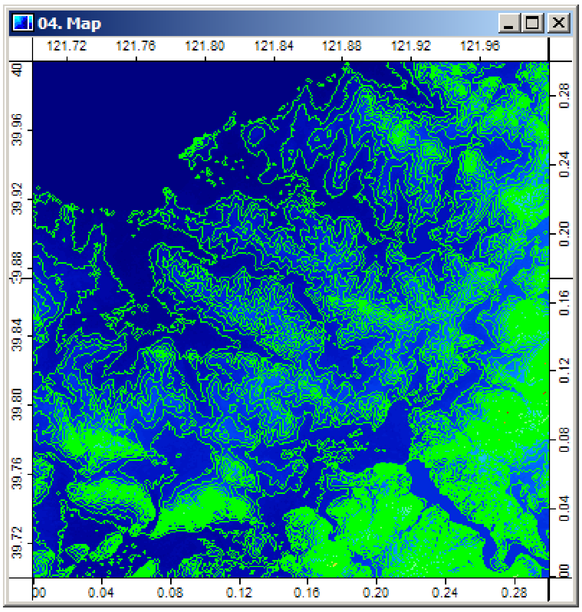
The sub-grid configuration may be changed here. Press **Okay** to continue. Finally, you must stop the interactive cutting module again by deselecting it in the **Modules** menu. You will not be able to use other modules before this interactive one has been shut down!

The **Data** workspace should now look something like this:



Data
- Grids
  - 0.000833; 1201x 1201y; 121x 39y
    - 01. N39E121
  - 0.000833; 361x 361y; 121.7x 39.700000y
    - 01. N39E121
- Shapes
  - Line
    - 01. N39E121

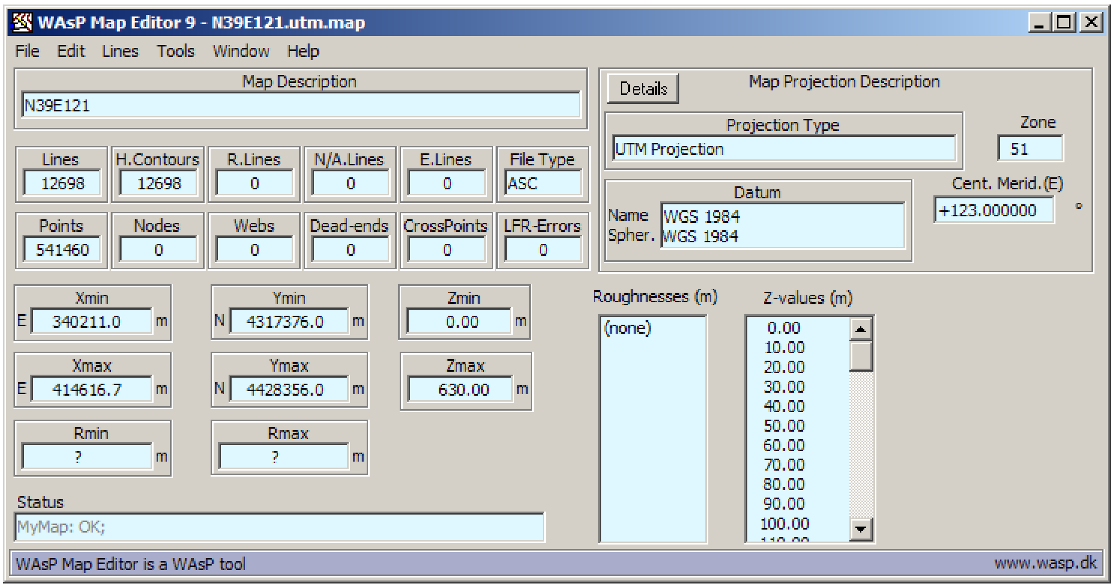
The new (sub)grid can be contoured and exported as a WAsP map file as described above.



The coordinates of the exported WAsP map file are geographical latitude and longitude; these must be transformed to a metric coordinate system in the WAsP Map Editor:

1. **Open** the map in the Map Editor.
2. Click **Yes** to switch to geographic Lat-Lon coordinate system, and then **Ok** twice.
3. Next, select **Tools** | **Transform** | **Projection**.
4. Select **Global Projections** | **UTM projection** for the Projection Type.
5. Leave Datum as WGS 1984 (or change to other) global/local datum.
6. Press Ok to transform map coordinates.

The map editor window could now look something like this:



Map Description: N39E121

Lines	H.Contours	R.Lines	N/A.Lines	E.Lines	File Type
12698	12698	0	0	0	ASC
Points	Nodes	Webs	Dead-ends	CrossPoints	LFR-Errors
541460	0	0	0	0	0

Xmin: E 340211.0 m
Ymin: N 4317376.0 m
Zmin: 0.00 m
Xmax: E 414616.7 m
Ymax: N 4428356.0 m
Zmax: 630.00 m
Rmin: ? m
Rmax: ? m

Status: MyMap: OK;

Map Projection Description
Projection Type: UTM Projection
Zone: 51
Datum
Name: WGS 1984
Spher.: WGS 1984
Cent. Merid.(E): +123.000000 °

Roughnesses (m): (none)

Z-values (m): 0.00, 10.00, 20.00, 30.00, 40.00, 50.00, 60.00, 70.00, 80.00, 90.00, 100.00

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on development of energy technologies and systems with minimal effect on climate, and contributes to innovation, education and policy. Risø has large experimental facilities and interdisciplinary research environments, and includes the national centre for nuclear technologies.

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