Alpine Windharvest

ALPINE WINDHARVEST

Development of information base regarding potentials and the necessary technical, legal and socio-economic conditions for expanding wind energy in the Alpine Space*

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Alpine Space Wind Map

Modeling Approach

METEOTEST
Fabrikstrasse 14
3012 Bern
Switzerland
office@meteotest.ch

Edited by: Beat Schaffner, Jan Remund

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ALPINE WINDHARVEST

…is an interdisciplinary research project funded by the EU Interreg IIIB "Alpine Space Programme" (Project No. A/I-2/3.1/5) and by national and regional co-financing bodies of the project partners. The project started in May 2002 and will end at the end of April 2005.

Background of the project:

Wind power became a leading renewable energy technology in flat terrain, especially near shore. While the alpine space also promises some excellent wind locations, much of the knowledge and experience accumulated about wind power so far cannot simply be transferred to the alpine setting.
The lack of experience concerns all levels of government confronted with problems of siting, spatial planning, nature protection/environmental impact analyses, road and electric grid requirements, appropriate tariff regulation etc. The project aims at remedying these deficiencies.
This lack of experience also regards entrepreneurs, investors and even producers of equipment given the special climatic and geological conditions. This increases economic risks, inhibits site exploration and planning activities even for attractive locations. The small number of existing projects in the alpine space impedes standard procedures.
Lack of experience also affects the acceptance of wind power by nature protection organisations and local residents. There is much need for additional knowledge and information; standard models for the resolution/mediation of conflicts will be useful.
For this reason, it is essential to pool the limited experience with wind power in the alpine space for synergy effects, cross-fertilisation and greater efficiency in developing data sets, methods, approaches and solutions for public and private actors, particularly since many of the underlying phenomena are trans-national while most research so far was primarily national (e.g. meteorology).
A common approach will facilitate a harmonised European approach to the problems under consideration, particularly with regard to government policy.

Main activities:

Develop knowledge basis for deploying wind energy:
a) Methods and instruments for identifying wind energy potential in complex terrain more efficiently (meteorologists, geographers, digital relief analyses and actual wind measurements; includes pilot measurements on specific locations).
b) Deal with problems peculiar to wind turbines in alpine conditions (blade icing; access - need for special mounting equipment); standardise technologies, estimates of access requirements (roads and grid). Common approaches for entire alpine space will create bigger market for improvements and induce responses from equipment manufacturers.
c) Analyse ecological impact of turbines in different alpine settings on fauna and flora according to altitude, soil/rock and meteorological conditions; establish check list of factors for whole alpine space. Develop strategies to minimise impact. Improve information for local/ regional authorities.
d) Analyse and compare legal, social, political and economic framework conditions for deployment of wind power in alpine space and their impact on its competitiveness. Formulate regulatory proposals.
e) Prepare methods of resolving conflicts between wind power and other interests (environmental organisations, local residents, hunting). Improve visualisations (more difficult in alpine terrain), standardise participation in administrative procedures and mediation. Facilitate work of local and regional authorities.
f) Measure potential contribution of this energy source to regional development, particularly when joined with hydro storage and electricity generation from biomass.

Alpine Windharvest Report Series:

The Alpine Windharvest Report Series is published by the Alpine Windharvest partnership network in order to disseminate the results of the project to the interested public and to experts in the field. Reports are edited by the responsible project partner(s) who commissioned and approved the report according to our internal division of labour. Reports can be downloaded from our homepage. Printed versions can be directly ordered from the project coordinator by e-mail: dieter.pesendorfer@sbg.ac.at.

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Alpine Windharvest Partnership Network:

Lead Partner

University of Salzburg Department of Political Science http://www.sbg.ac.at/pol	Project Coordinator: Dr. Dieter Pesendorfer Department of Political Science Rudolfskai 42 5020 Salzburg Tel: +43-662-8044-6608 Email: dieter.pesendorfer@sbg.ac.at

Project Partners

Amt für Luft und Lärm Bozen (ALL) – Agenzia Provinciale per la protezione dell'ambiente e la tutela del lavoro http://www.provinz.bz.it/umweltagentur	Mr. Norbert Lantschner ALL Amba-Alagistr. 35 39100 Trention-Alto Adige IT 31 Bozen Italy Coordinator: Mr. Alexander Dorfmann Email: a.dorfmann@arcon-bozen.it
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Edited by:
METEOTEST
Fabrikstrasse 14
3012 Bern
Switzerland
office@meteotest.ch

Abstract

In work package 7 of the Interreg IIIB project "Alpine Windharvest", one goal was to produce a wind map covering the whole Alpine Space. While such maps exist for certain areas within the Alps (for Switzerland, Italy, and the Austrian states Steiermark and Vorarlberg), a detailed wind map covering the whole region was not yet published. The aim of this map is to provide basic information on wind resources on a scale that allows identifying promising sites for wind energy use.

There are two general approaches to wind modeling and mapping on this scale: the numerical and the statistical approach. The numerical flow modeling approach is usually performed with mesoscale meteorological flow models. Meteorology is calculated based on large scale reanalysis data for a certain period in the past. Wind climatologies are aggregated from the results. The results may be refined by subsequent microscale modeling. The second approach is based on statistical wind modeling. Wind statistics measured by meteorological stations are interpolated using statistical models that take into account topography. The two approaches may be combined when results from flow models are weighed using observed wind statistics.

For the Alpine Space wind map, a statistical model approach based on wind measurements was adopted. Elevation data from the Space Shuttle Topography Mission (SRTM) data set was interpolated to a 250 m grid and errors were patched using local elevation data sources or interpolation algorithms. Roughness was determined from the CORINE data set and the Swiss national data set. Wind data was collected from approximately 600 stations and standardized. Wind speed was interpolated spatially and in function of elevation. The data was corrected for roughness and specific terrain forms. The resulting wind maps show mean wind speeds at different heights with an accuracy of ±1.5 m/s.

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1. Introduction

METEOTEST was mandated within the Interreg IIIB Alpine Space Programme Project "Alpine Windharvest" with the implementation of work package 7 "digital relief analysis". In this work package, one goal was to provide an overview on wind resources in the Alpine Space.

Although some regional maps have been produced, no wind map covering the whole Alpine region existed prior to the Alpine Windharvest project. It was therefore decided to compile such a map.

Prior to the description of the mapping methodology and the results, this reports gives an overview on large-scale wind mapping approaches and introduces existing wind maps in the Alpine region and elsewhere.

We would like to thank all the providers of wind data, many of which supplied the wind data for this study free of charge. Without their help, it would not have been possible to produce the Alpine wind map.

2. Wind Mapping Approaches

Generally speaking, two approaches to wind mapping for bigger regions can be distinguished:

- **Numerical flow modeling** is based on large and mesoscale weather modeling for a significant period or a selection of significant situations in the past (in other words, a weather hindcast). The result of these calculations is aggregated to compile a wind map. Microscale modeling or interpolation algorithms may refine the results.

- **Statistical modeling** is based on measurements within the area of interest. The wind measurements are transferred to climatological statistics which are spatially interpolated by statistical modeling.

2.1. Numerical Flow Modeling Approach

Numerical flow modeling approaches are usually based on global reanalysis data by NCEP/NCAR[1] or ECMWF[2].

The NCEP/NCAR model is a global model that includes parameterizations of all major physical processes, i.e., convection, large scale precipitation, shallow convection, gravity wave drag, radiation with diurnal cycle and interaction with clouds, boundary layer physics, an interactive surface hydrology, and vertical and horizontal diffusion processes.

The ECMWF model is similar to the NCAR/NCEP model. ECMWF has reanalyzed meteorological data using a special version of their operational data assimilation system and model. Table 1 summarizes the information contained in these data sets.

Tab. 1: Reanalysis data sets.

Parameter	NCEP/NCAR	ECMWF
period	1948–ongoing	1957–2001 (ERA-40[3])
horizontal resolution	approx. 2°	approx. 125 km
vertical resolution	28 model levels	60 model levels
time step	6 hours	6 hours

1 http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml

2 http://www.ecmwf.int/research/era/

3 http://www.ecmwf.int/publications/library/ecpublications/_pdf/era40/ERA40_PRS17.pdf

The resolution of the reanalysis data is not high enough for wind mapping purposes. Therefore, it is usually used as input data to a mesoscale meteorological model such as ETA[4] or MM5[5]. MM5, for example, is a limited-area, non-hydrostatic, terrain-following model designed to simulate or predict mesoscale atmospheric circulation. Such models are standardly used in weather forecasting.

For wind mapping purposes, a weather modeling (or hindcast) based on the reanalysis data is performed. Wind parameters are extracted from the model results and aggregated to wind climatologies at every grid node. The typical horizontal resolution of such models lies in the range of 20–50 km. Nesting techniques – i.e. modeling of smaller areas with higher resolution using the bigger area's results as input data – allow refining this resolution up to typically 2 km.

The resolution may be further enhanced by subsequent use of a microscale model.

The hindcast is either performed for a climatologically relevant period (e.g. 20 years) or for a significant selection of weather situations that are weighed according to their frequency. The second option requires less resources at the cost of accuracy.

Observed data (e.g. from meteorological stations or from radio sondes) is sometimes tied into the mesoscale model. In MM5, for example, a data assimilation system is available for including measured surface data in the model.

2.2. Statistical Modeling Approach

The statistical modeling approach is based on climatological data collected by permanent meteorological stations in the area of interest. This data is supplemented by temporary measurements e.g. from wind energy projects. Temporary measurements are often crucial because – in the case of wind assessments – these are performed at locations interesting for wind energy, while the permanent meteorological stations' locations are often unsuitably situated. This is especially the case in mountainous regions, where meteorological stations are often situated in valleys. It is not possible to transfer this data to hilltops and crests.

Measurement data is transformed to climatologies through a process of validation and aggregation. This includes a validation process, consideration of local effects (roughness, obstacles), normalization for a certain climatologically significant period as well as extrapolation to a certain height above ground.

Several modeling techniques may be applied to interpolate the measurement stations' climatological values spatially. Which modeling technique is the most suitable

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[4] http://www.srh.noaa.gov/ssd/nwpmodel/html/eta.htm

[5] http://www.mmm.ucar.edu/mm5/mm5-home.html

depends on several factors, such as density of measurements and complexity of topography, as well as desired resolution and accuracy of the wind map.

Typical modeling techniques include:

- statistical interpolation models: wind data from measurements is interpolated spatially and usually also in function of the altitude. Corrections may be applied for specific terrain characteristics as well as roughness.

- linear models such as WAsP: Measured wind data is corrected for terrain influence by using a combination of statistical and physical models. The corrected wind statistics can be re-introduced into the terrain at any location by reversing the corrections and inserting the new location's details.

2.3. Combined Approach

Wind flow over terrain is calculated for several standard situations (wind direction and vertical profiles at the model boundary) with a numerical flow model, e.g. a Computational Fluid Dynamics (CFD) model. Measured wind statistics in the model domain are used for weighting the results.

3. Existing Wind Maps in the Alpine Space

3.1. Steiermark, Austria

In the scope of a study on the framework for wind energy use in Steiermark[6], a wind map (fig. 1) was produced. Modeling was performed with the mesoscale model MM5. Data assimilation was performed with numerous measurement stations. Triple nesting was performed resulting in a horizontal resolution of 4 km. Finally, data was interpolated to a 1 km grid. NCEP data was used as boundary conditions for the first model domain. The years 2000 and 2001 were reanalyzed. Wind conditions were calculated at 50 m above ground level.

The results were compared to an empirical analysis and corresponded relatively well. The smoothened model topography – resulting from the relatively rough resolution of 1 km – was found to be the main cause of discrepancy.

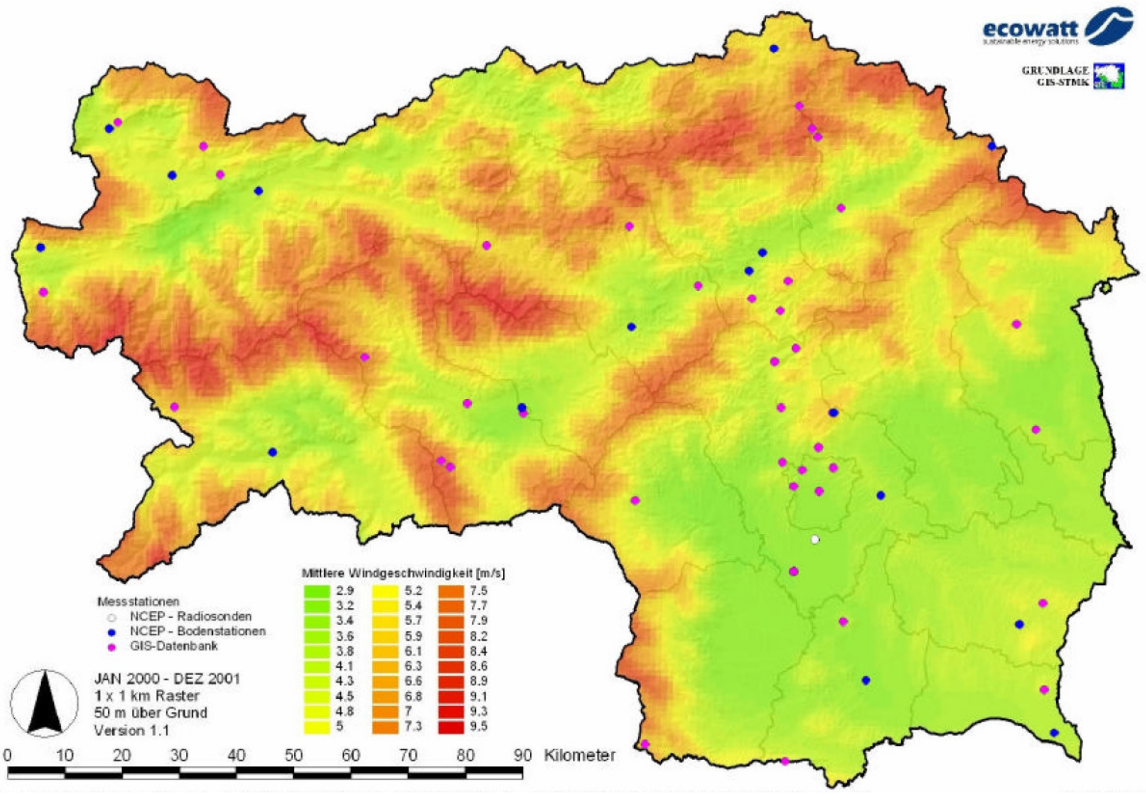

Fig. 1: Wind map of Steiermark showing mean wind speed at 50 m above ground level.

[6] LandesEnergieVerein Steiermark: Rahmenbedingungen für eine Nutzung der Windkraft in der Steiermark.

3.2. Vorarlberg, Austria

In the scope of a study on the wind energy potential in Vorarlberg[7], a wind map (fig. 2) was compiled on the basis of data from 12 measurement stations. Wind modeling was performed with the WAsP model for 50 m above ground level and a horizontal resolution of 500 m. There is no information on accuracy.

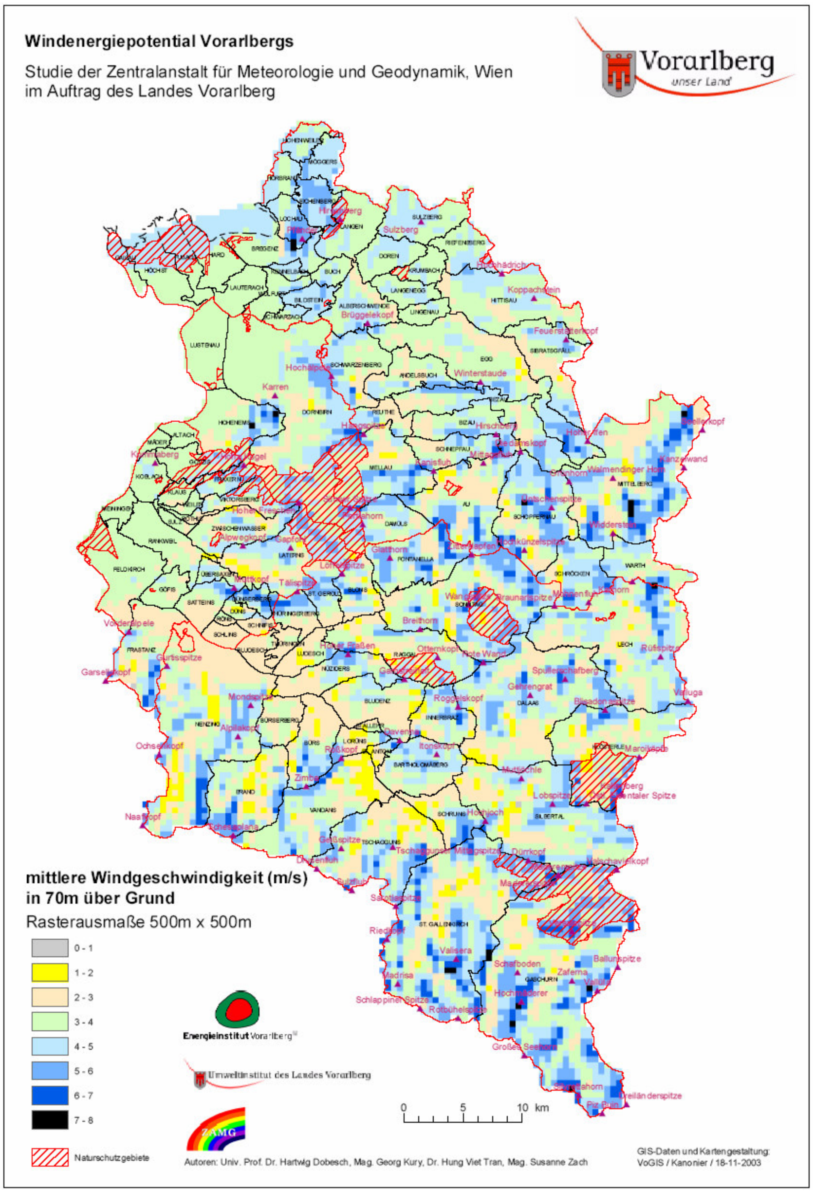

Fig. 2: Wind map of Vorarlberg showing mean wind speed at 50 m above ground level.

[7] Dobesch et al.: Das Windenergiepotenzial Vorarlbergs.

3.3. Switzerland

In the scope of a conceptual study on wind energy in Switzerland, a wind map at 30, 50, 70 and 100 m above ground level at a resolution of 100 m was compiled[8] (fig. 3). Data from 103 measurement stations was interpolated spatially and as a function of altitude in a statistical model. Corrections were included for roughness, inclination, crests and valleys. In an uncertainty analysis, a typical error of +/- 1 m/s was found.

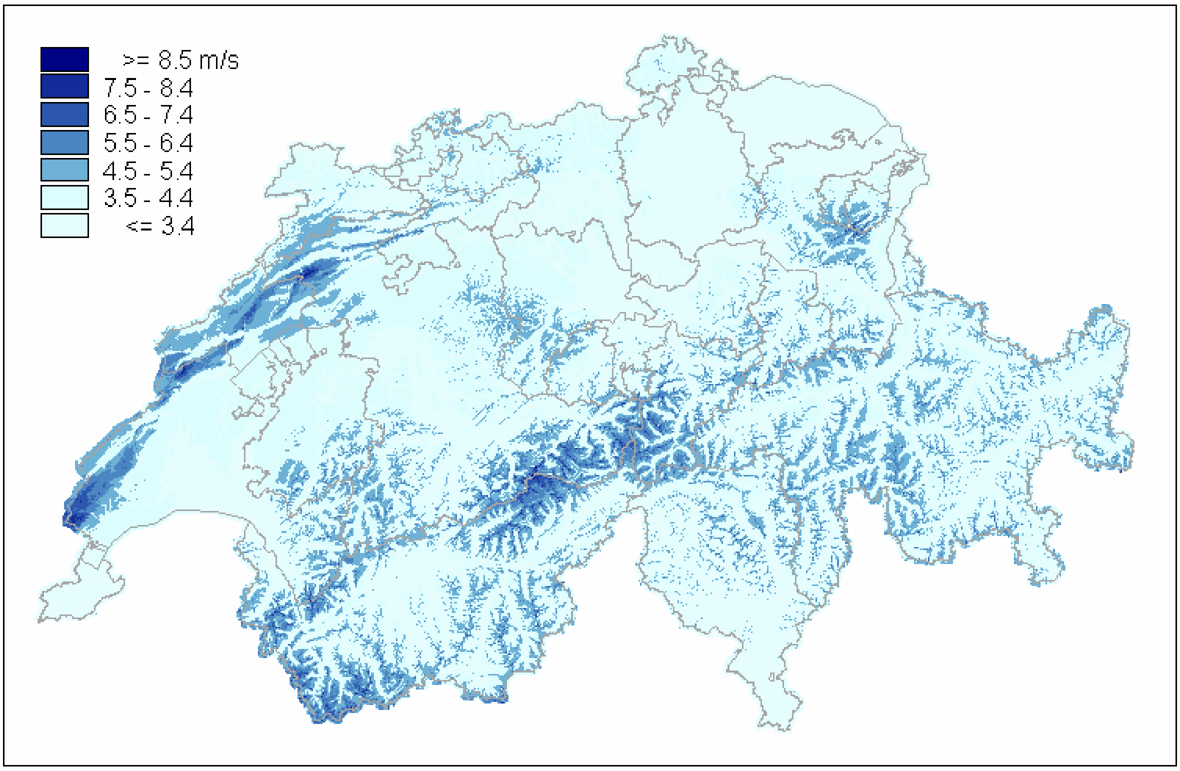

Fig. 3: Wind map of Switzerland showing mean wind speed at 70 m above ground level.

[8] BFE, BUWAL, ARE: Konzept Windenergie Schweiz

3.4. Italy

The Italian Wind Atlas[9] was compiled on the basis of ECMWF reanalysis data. This data was used as input for regional mesoscale model runs with WINDS[10] on a horizontal resolution of 1 km. The results were compared with ground measurement data from 240 stations. Correctional factors were calculated, interpolated across the country and applied to the map. An mean uncertainty of 0.9 m/s was found.

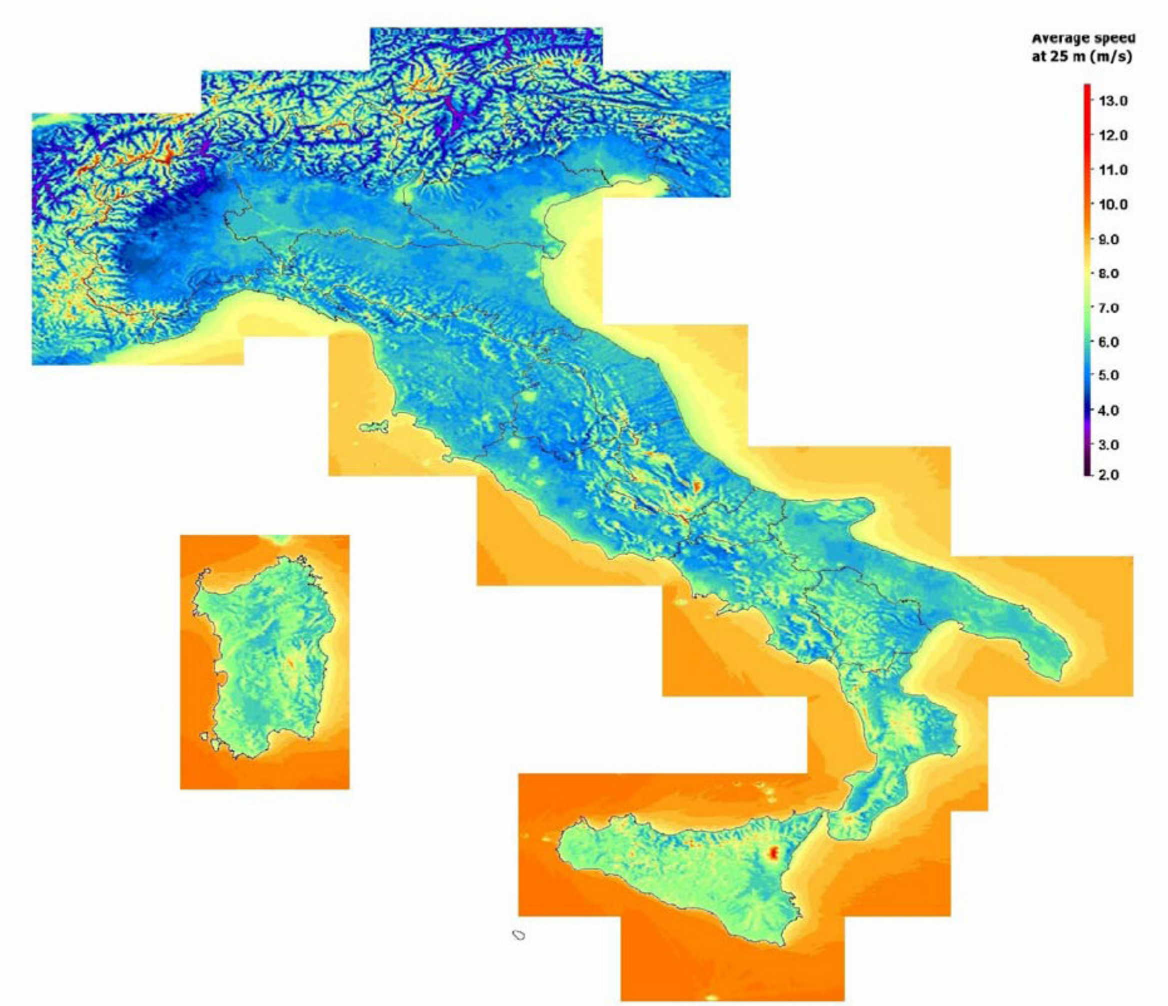

Fig. 4: Wind map of Italy showing mean wind speed at 25 m above ground level.

9 http://www.ricercadisistema.it/html/ita/doc/3/37/index.htm

10 http://www.fisica.unige.it/~atmosfe/winds_intro.htm

4. Other Wind Mapping Examples

4.1. KAMM/WAsP wind maps

The KAMM/WAsP method[11] was developed by Risø National Laboratory of Denmark. It combines the Karlsruhe Atmospheric Mesoscale Model (KAMM) with the Wind Atlas and Analysis Application Program (WAsP). The KAMM model is run using NCAR/NCEP-Reanalysis data. The resulting mesoscale wind statistics are used as input to the WAsP model in order to calculate wind resources on a fine grid with a horizontal resolution of 200 m. The KAMM/WAsP method has been employed by Risø to produce wind maps of Denmark, Ireland, Northern Portugal and Galicia as well as Faroe Islands. Figure 5 shows the Danish wind map.

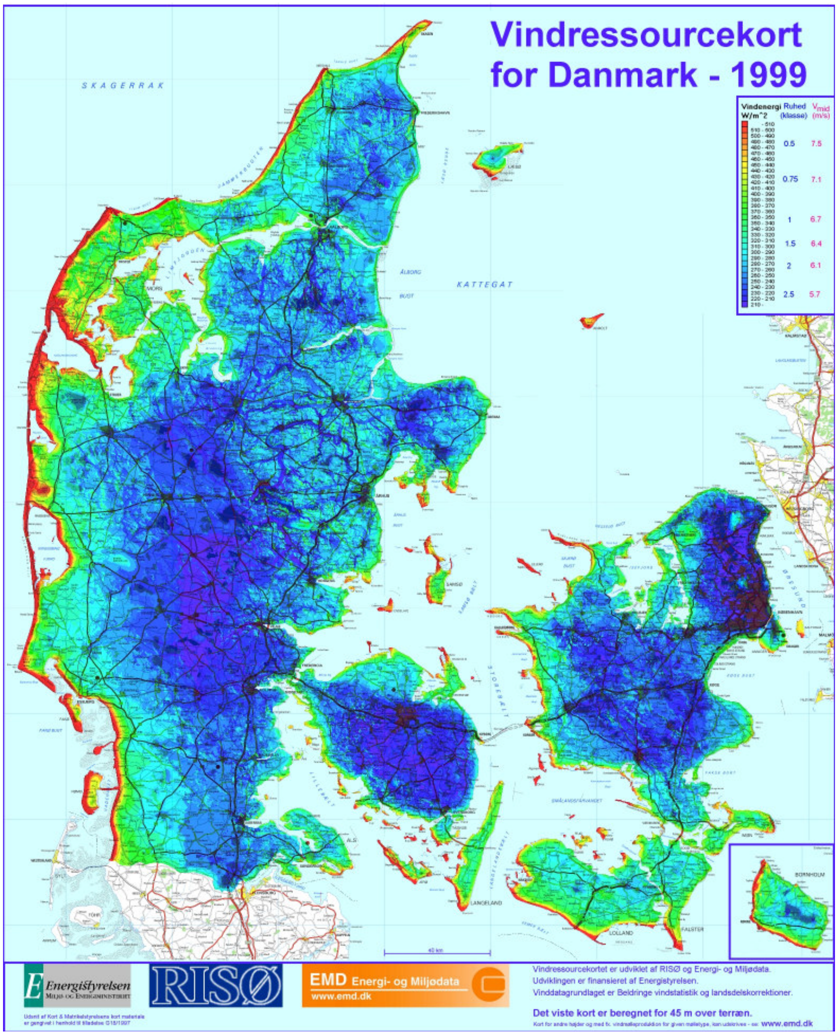

Fig. 5: The wind map of Denmark showing wind energy at 45 m above ground.

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[11] http://www.risoe.dk/rispubl/VEA/ris-r-1252.htm

4.2. MesoMap wind maps

MesoMap[12] was developed by Truewind, USA. With this modeling technique, wind resources are assessed over large regions at a high resolution (typically 200 m) using a combination of mesoscale and microscale models and weather data (NCAR/NCEP reanalysis data). It has been proven effective, even in complex terrain and wind regimes, in over 30 countries throughout the world. Wind maps and atlases have been produced for Southeast Asia, Brazil, China, Canada, India, the United States, Great Britain, Ireland, Poland. Validation with data measurement stations established a typical uncertainty range of 5–7% in mean speed at hub height. Figure 6 shows an extract of the Brazilian wind map.

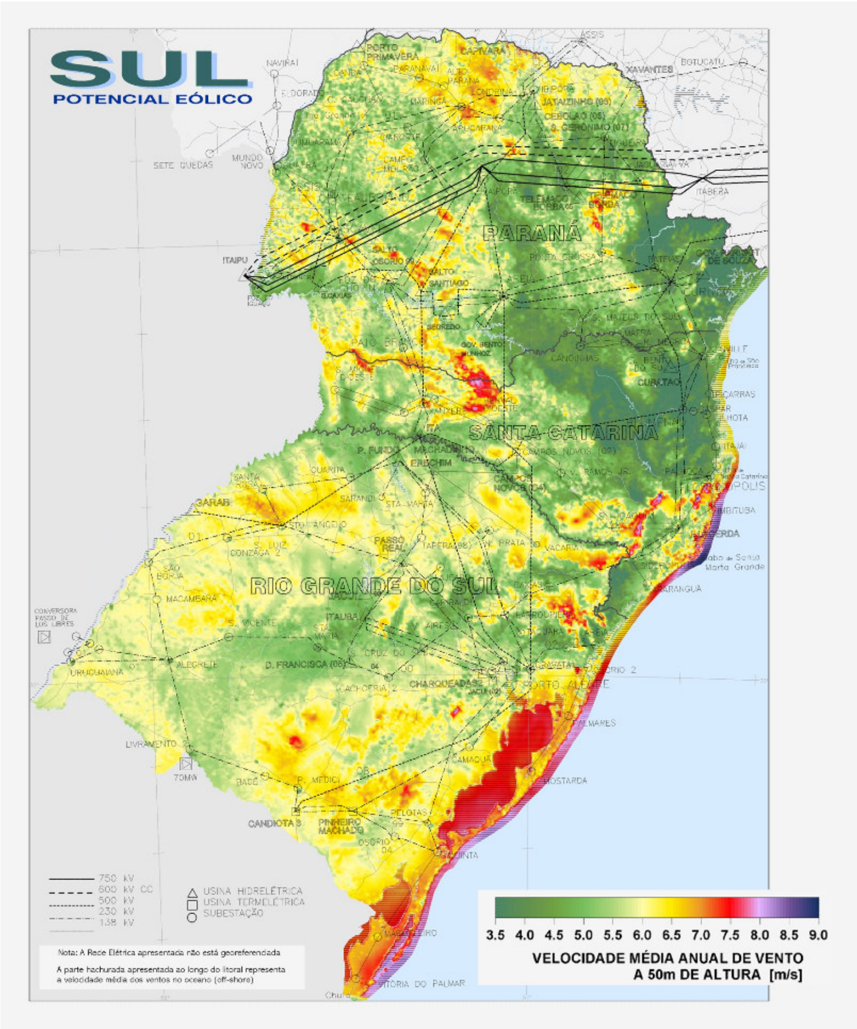

Fig. 6: Extract of the wind map for Brazil showing mean wind speed at 50 m above ground for the southern part of the country.

12 http://www.awstruewind.com/inner/services/windmapping/mesomap/mesomap.htm

4.3. SWERA NREL wind maps

The Solar and Wind Energy Resource Assessment (SWERA[13]) project develops databases and analytical tools on wind and solar energy for developing countries. In the SWERA project, wind maps for Central America, Cuba, Ghana and Sri Lanka were produced by NREL with their Wind Resource Assessment and Mapping System (WRAMS). Reanalysis data (NCAR/NCEP) as well as observed data are used as input to a numerical weather model (MASS) coupled to a wind flow model (WindMap). MASS delivers results on a 2.5 x 2.5 km resolution and WindMap refines the results to a 1 x 1 km grid. Uncertainty is expected to be approximately 10% in wind speed and 20% in wind power at more than 80% of locations.

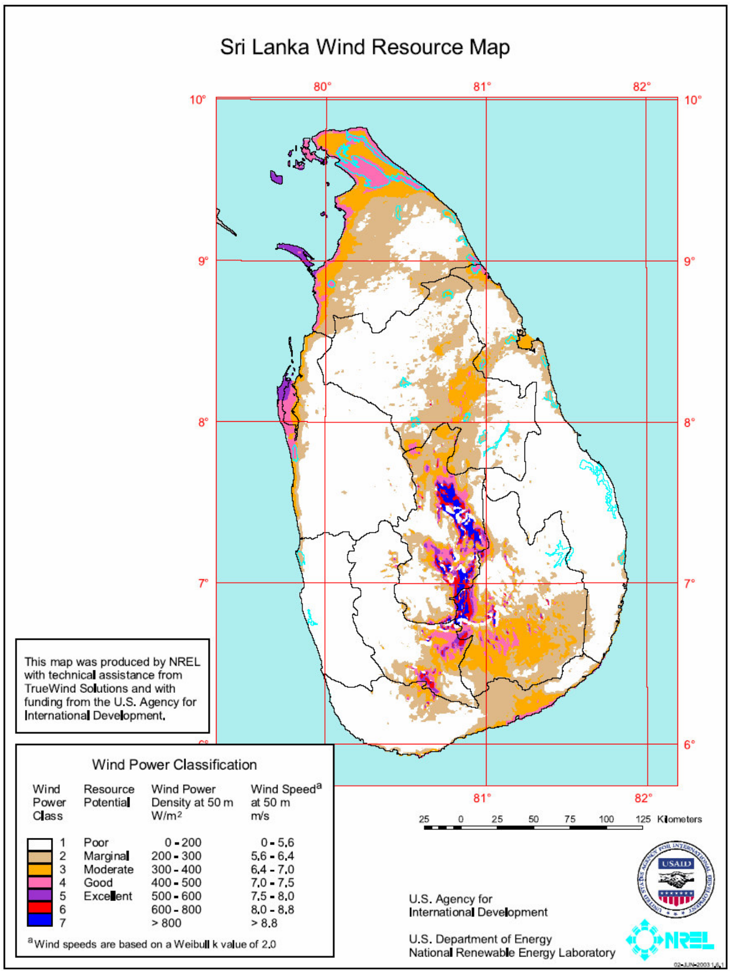

Fig. 7: Wind map for Sri Lanka showing mean wind speed and power density at 50 m above ground.

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[13] http://swera.unep.net/swera/index.php

4.4. WindSim wind maps

WindSim is a modeling package developed by Vector, Norway[14]. For the Norwegian Wind Atlas, more than 120 mesoscale models were established covering the Norwegian coast. The wind fields in these models were calculated with WindSim, a Computational Fluid Dynamics (CFD) modeling package. Long-term wind data from 30 meteorological stations were used for weighting the resulting wind fields. Microscale WindSim models were used around the meteorological stations to filter out microscale effects from the long-term wind data. Figure 8 shows an extract of the wind map of the Norwegian coast.

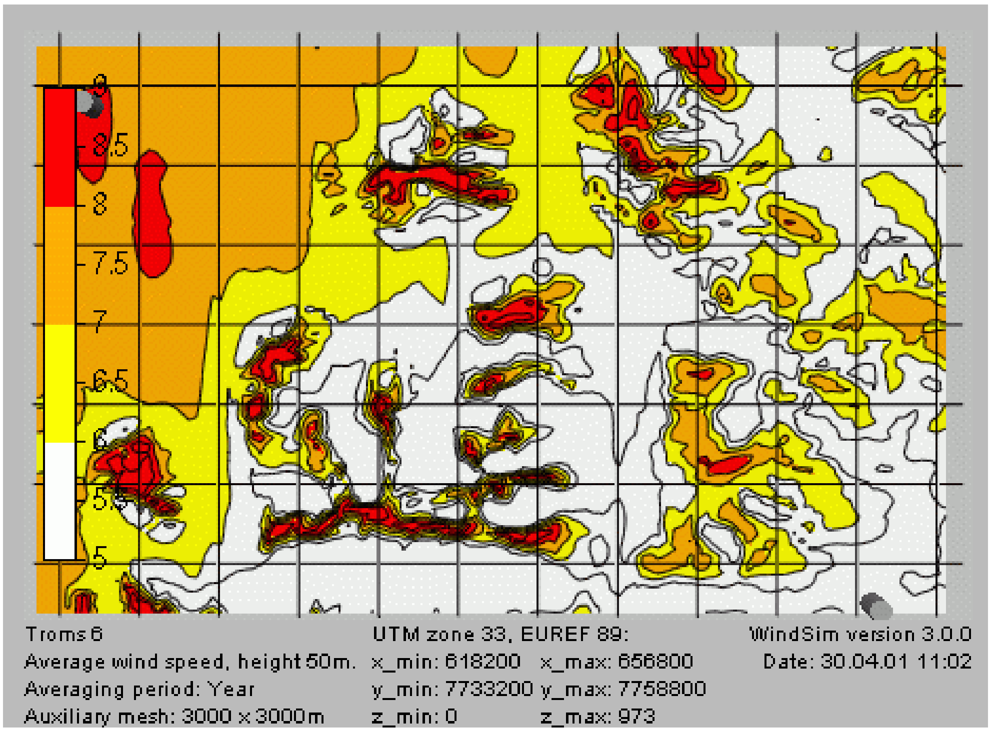

Fig. 8: Wind speed at 50 m above ground level in the Troms region.

[14] http://www.windsim.com/

4.5. Sander Partner wind maps

Sander Partner[15] employs MM5 modeling with NCAR/NCEP Reanalysis data as input to produce wind maps with horizontal resolutions of a few km. Wind maps for Poland and Sardinia have been produced. Figure 9 shows the wind map of Sardinia.

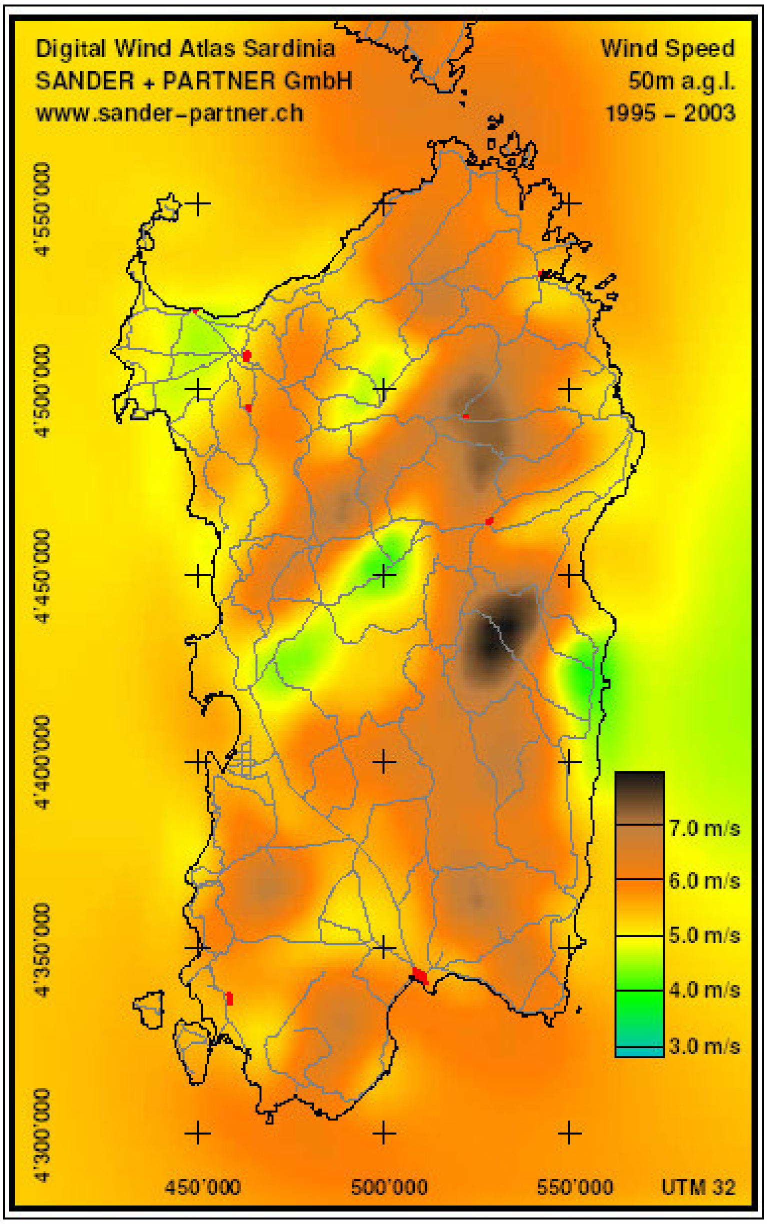

Fig. 9: Wind map of Sardinia showing mean wind speed at 50 m above ground.

15 http://www.sander-partner.ch/

4.6. German wind map

Deutscher Wetterdienst (DWD)[16] produced a wind map of Germany using its SWM (Statistisches Windfeldmodell). Multiple regression analysis was performed for 218 wind measurement stations, taking into account altitude, location, terrain form and land use. The resulting wind map shows wind resources at a resolution of 1 km and 200 m. Figure 10 shows the German wind map for the state of Hessen.

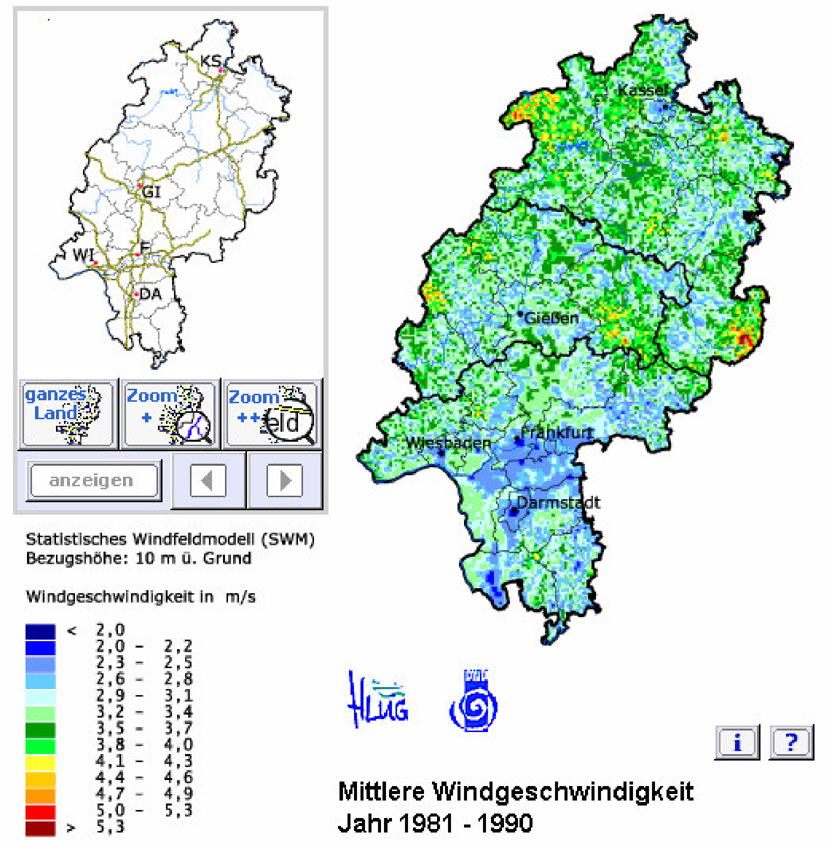

Fig. 10: Wind map for Hessen, Germany showing mean wind speed at 10 m above ground.

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[16] http://www.dwd.de/

5. The Alpine Space Wind Map

Table 2 compares benefits and drawbacks of the approaches described in chapter 2.

Tab. 2: Benefits and drawbacks of different wind mapping approaches.

Factor	Numerical Flow Modeling Approach	Statistical Modeling Approach
resolution	low (using mesoscale modeling only) high (including microscale modeling)	high
accuracy	medium	low–high (depending on quality and quantity of input data, modeling technique)
CPU time	very high (months)	low–high (depending on modeling technique)

The financial resources for the Alpine Space Wind Map were very limited. It was therefore important to use a modeling approach that required little development as well as little CPU time but still provides an acceptable accuracy that allows identifying promising wind power sites.

It was decided to adapt a statistical modeling methodology formerly used to compile a wind map for Switzerland[17]. It was possible to adopt many of the empirically determined parameters from the former model.

5.1. Data

5.1.1. Digital Elevation Model

The SRTM (Space Shuttle Radar Topography Mission[18]) 3 arc-second digital elevation model (DEM) was used as a basis. The original grid resolution of approx. 70x90 m was regridded to 250 m. The currently available SRTM data for Europe is a raw data set that contains some holes and artifacts. These were corrected by either using local DEMs for interpolation or by using interpolation algorithms.

A slope angle data set (250 m grid) was calculated from the DEM.

[17] http://stratus.meteotest.ch/mme/winfo/

[18] http://www.dlr.de/srtm

5.1.2. Land Use Data

Land use data is needed to estimate surface roughness. The CORINE[19] data set is used, except for Switzerland, where a local data set was used. Land use data was transformed to roughness using the values in table 3.

Tab. 3: Roughness lengths used in the Alpine Space Wind Map.

Description	Roughness length [m]
Artificial, urban fabric	1.0
Artificial, industrial	0.2
Agricultural, arable land	0.1
Forest	1.0
Agricultural, heterogenous	0.2
Wetlands	0.02

5.1.3. Wind speed data

Data of 592 permanent or temporary wind measurement stations was included (Fig. 11). For each station the WMO number, coordinates, altitude, mean annual (long term) wind speed and height above ground of measurement were obtained.

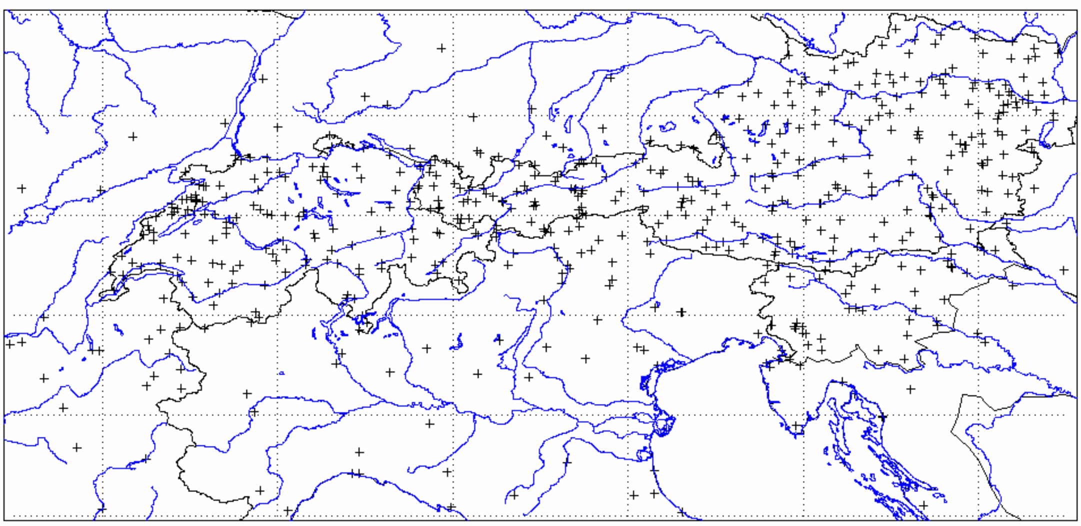

Fig. 11: Wind measurement stations included in the Alpine Space Wind Map.

[19] http://dataservice.eea.eu.int/dataservice/metadetails.asp?id=571

Wind speed data was obtained from the sources listed in table 4.

Tab. 4: Wind data sources.

Source	Country
METEONORM, www.meteonorm.com	all
Alpine Windharvest Work Package 6 "wind potential and wind measurements"	all
H. Dobesch et al., 1997: WIND ATLAS for the Central European Countries: Austria, Croatia, Czech Republic, Hungary, Slovak Republic and Slovenia.	A, Slo
C. Draxl, 2004: Wind Energy Potential at Wind Measurement Sites in the Tyrolean Alps.	A
Verein Energiewerkstatt, www.energiewerkstatt.org	A
Blue Sky Wetteranalysen, www.blueskywetter.com	A
METEOmeetsENERGY, stratus.meteotest.ch/mme	CH
Environmental Agency of the Republic of Slovenia	Slo
Wep 1, 2003: Study of wind potential in five European regions.	Slo
MeteoFrance	F
Landesamt für Energieeinsparung, Bozen, Südtirol	I
A.R.P.A.V. - Centro Valanghe Arabba	I
Wetterdienst, Hydrographisches Amt, Autonome Provinz Bozen, Südtirol	I

Mainly long term measurements were used. At 26 stations, mean values covering less than 5 years were available and at 2 stations only 1 year was available. Long term corrections were not performed because adequate reference data was lacking and effects on the result were expected to be minimal due to the high density and usually long measurement periods of the data.

5.2. Model Domain

Modeling was performed in the UTM zone 33 coordinate system for the domain described in table 5:

Tab. 5: Modeling Domain.

Parameter	Size/Extent
X coordinates UTM zone 33 [m]	-397’000 to 663’250
Y coordinates UTM zone 33 [m]	4'760'750 to 5'486'250
Grid spacing	250 m
Number of points	4'241 x 2'902 (= 12'307'382)

5.3. Method

The spatial interpolation is performed with the help of altitude gradient corrections and a Kriging interpolation method. The following three steps are performed:

1. Preparation
2. Kriging interpolation
3. Corrections

These steps are described in detail in the following chapters. Figure 12 contains a diagramm that describes the procedure.

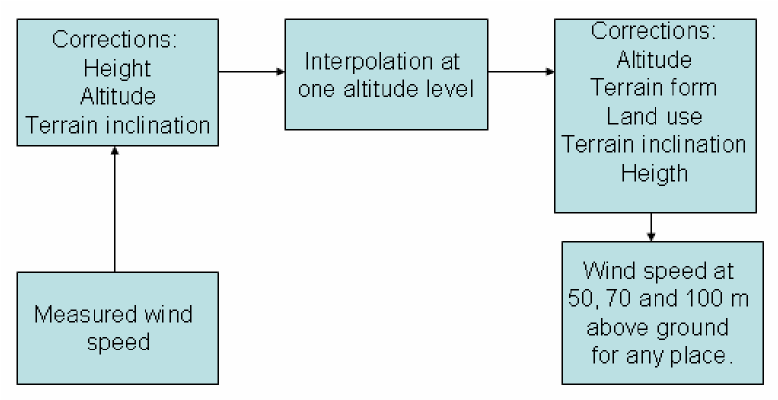

Fig. 12: Diagram showing the most important steps from measured wind speed to wind speed maps at 50, 70 and 100 m above ground.

All modeling procedures were programmed with Interactive Data Language (IDL) software[20].

5.3.1. Preparation

Extrapolation to 50 m above ground

The wind speeds at the stations were extrapolated to 50 m above ground with an assumed shear factor (α) of 0.14. For alpine sites above 2'000 and 3'000 m, a shear factor of 0.10 and 0.05 was assumed, respectively. For the Swiss stations of Jungfraujoch and Gütsch a shear factor of 0.0 was assumed, based on SODAR measurements at Gütsch.

$$v_{50} = v_x \left(\frac{50}{x} \right)^{\alpha}$$

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[20] www.rsinc.com/idl/

A threshold of 2 m/s was defined for v_{50}. Values lower than this were set to this threshold.

Correction of the altitude gradient and calculation to a certain altitude level

Linear regressions between the difference of the altitude and a smoothed altitude (with a smoothing distance of 40 km) and the wind speed were calculated. These regressions were performed for the regions with positive and negative smooth differences.

$$v_{50} = a + b \cdot [z - smooth(z,40)], \quad [z - smooth(z,40)] > -100$$
$$v_{50} = c + d \cdot [z - smooth(z,40)], \quad [z - smooth(z,40)] < +100$$

The following values were obtained:

a = 3.69 m/s (offset at 0 m altitude for function above the smoothed level)
b = 0.0020 m/s km (gradient above the smoothed level)
c = 3.23 m/s (offset at 0 m altitude)
d = 0.0010 m/s km (gradient below the smoothed level)

The gradient of wind speed above the smoothed level is twice as high as the gradient below it. The altitude of the level, where the gradient makes a sharp bend and the linear function changes, is 463 meters lower than the smoothed level.

The wind speed values are calculated with the found gradients to the smoothed altitude surface. On this surface the horizontal Kriging interpolation will be made.

This altitude correction model delivers better results than regionalized or simple linear regressions.

Correction of the slopes

In slopes, there is generally a lower wind speed. This is taken into account by the following formula, empirically found for Switzerland.

$v_{100} = v_{100}$ + 0.011*slope angle [°]

5.3.2. Kriging interpolation

Kriging is a family of linear least squares estimation algorithms. The aim of Kriging is to obtain a best estimate for all unsampled locations.

Kriging interpolation was performed on a grid of 400 x 200 cells. An exponential form of the semivariogram was assumed. To obtain a smoother interpolation, two different Kriging interpolations are performed. One with a search distance (range) of 100 km and an error at measurement points (nugget) of 0.8 m/s and another one with a range of 110 km and a nugget of 0.7 m/s. No stretching or rotation was performed. The 400 x 200 grid of the Kriging interpolation was retransformed to the original 250 m grid using a cubic spline.

5.3.3. Corrections

The operations performed in the preparation step before Kriging interpolation are reversed in the corrections step. Now the operations are performed for the whole grid instead of only the measurement locations. A slope correction factor of -0.011 is again applied. The altitude correction is reversed.

Corrections based on the DEM

Five correction terms, based on the digital elevation model are added to the interpolated wind speed.

$$v_c = v + c_{rc} + c_{bv} + c_{sv} + c_{flat} + c_{sea}$$

v = wind speed after Kriging interpolation, with slope and altitude correction

v_c = corrected wind speed

The values of the corrections have been found making the Swiss map (chap. 3.3).

Five corrections are performed based on analysis of the digital elevation model:

1. Corrections for ridges and canyons (less wind speed in canyons, more on ridges):
   - Smoothing of the DEM with 5 grid points (approx. 1 km)
   - Calculation of the differences DEM – smoothed DEM (dZ_5)
   - In a previous analysis the following relationships were found:
     - for dZ_5 > 20 m: c_{rc} = (dZ_5-20)*(0.01)
     - for dZ_5 < -20 m: c_{rc} = (dZ_5+20)*(0.01)
     - -1.5 < c_{rc} < 1.5
   - Addition of c_{rc} to the interpolated field

2. Corrections for big valleys (enhanced wind speed at valley grounds):
   - Smoothing of the DEM with 41 and 161 grid points (approx. 10 and 40 km)
   - Calculation of the differences smoothed DEM 41 – smoothed DEM 161 ($dZ41\_161$)
   - In a previous analysis the following relationship was found:
     - c_{bv} = (0.7+ $dZ41\_161$ * 0.0025)
     - 0 < c_{bv} < 1.2
   - Addition of c_{bv} to the interpolated field

3. Corrections for valleys (less wind speed in narrow valleys):
   - Smoothing of the DEM with 5 and 41 grid points (approx. 1 and 10 km)

- Calculation of the differences DEM 5 – smoothed DEM 41 (*dZ5_41*)
- In a previous analysis the following relationship was found:
  - Eqn.: *dZ5_41*< -20 m: c_{sv} = (*dZ5_41*+20)*(0.01)
  - -1.2 < c_{sv} < 0.0
- Addition of c_{sv} to the interpolated field

4. Corrections for flat areas (more wind speed in flat areas):
   - The whole grid is smoothed with 1.25 km and is checked for areas with no changes in altitude (c_{flat}). In these areas a wind speed of 0.3 m/s is added.

5. Corrections for offshore areas (more wind speed at sea):
   - At sea level an extra wind speed of 0.3 m/s is added (c_{sea}, correction for offshore areas).

Corrections based on vertical profile

Wind speed is corrected for the 50 m level and extrapolated to different heights based on the roughness length (Tab. 3). A roughness length z_0 of 0.1 is taken as mean roughness, which is assumed for the result after Kriging interpolation.

The basic idea behind the correction procedure is that for the uncorrected map (after Kriging interpolation) a mean roughness is used (to calculate from general measurement height of 10 m to 50 m) instead of the real one. The factors of the two steps (down and up) are therefore multiplied to obtain the correction factors at 50 m (Fig. 13).

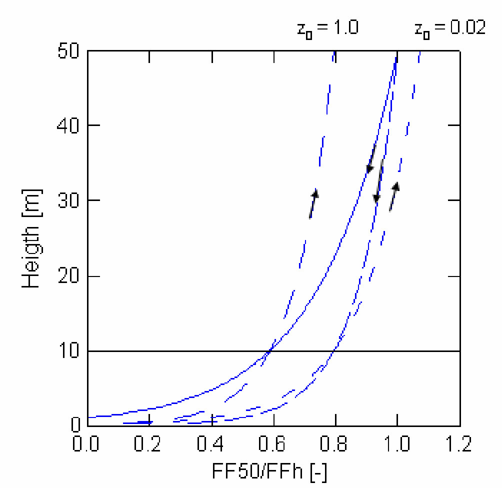

Fig. 13: Correction of wind speed at 50 m depending on the roughness length shown for two examples (z_0=1.0 and z_0=0.02).

The following equation is used for the correction (based on a logarithmic wind profile):

$$v_y = v_x \cdot \left[\ln\left(\frac{y}{z_0} \right) \right] \Big/ \left[\ln\left(\frac{x}{z_0} \right) \right]$$

with x, y = heights above ground [m]

The result is a lowering of the wind speed at 50 m for higher roughness values than 0.1 and an enhancement of the wind speed for lower roughness values. For wind speeds at 70 and at 100 m above ground the same equation was used based on the corrected 50 m values. Table 6 gives an overview of the factors.

The following exceptions were applied:

- At ridges (c_{rc} values bigger than 0.35) the wind speed is not enhanced.
- Above 2'000 m and 3'000 m the enhancement is lowered by one third and two thirds, respectively.
- The wind speed at 50 m was set to a minimum of 1.0 m/s, at 70 m to 1.2 m/s and at 100 m to 1.4 m/s.

Tab. 6: Correction factors based on vertical profile. The value at 10 m is a theoretical value not used for mapping.

roughness length / altitude class	**10 m**	**50 m**	**70 m**	**100 m**
0.02	0.794	1.072	1.117	1.166
0.1	0.741	1.000	1.054	1.112
0.2	0.708	0.956	1.014	1.076
1.0	0.588	0.794	0.863	0.935
2000 < h < 3000	-	1.000	1.036	1.072
3000 < h	-	1.000	1.018	1.035
Ridges	1.000	1.000	1.000	1.000

5.4. Results

The results of the interpolation are wind maps (figs. 15 and 16) at 50 and 100 m above ground as well as ArcInfo Gridascii formatted output files with wind speed at 50, 70 and 100 m in dm/s. Interactive maps of the results are available online at http://stratus.meteotest.ch/windharvest.

5.5. Accuracy

At 50 m above ground the wind speed varies between 1.0 and 10.1 m/s; at 100 m between 1.2 and 10.1 m/s. The standard deviation at the measurement points is 1.1 m/s. For 14 randomly chosen stations the interpolation was tested, not taking the station's own data into account. The standard deviation of this test is ±1.5 m/s.

Figure 14 shows that the interpolated values slightly underestimate the wind speed. Big overestimations do not occur, but some bigger underestimations can be observed.

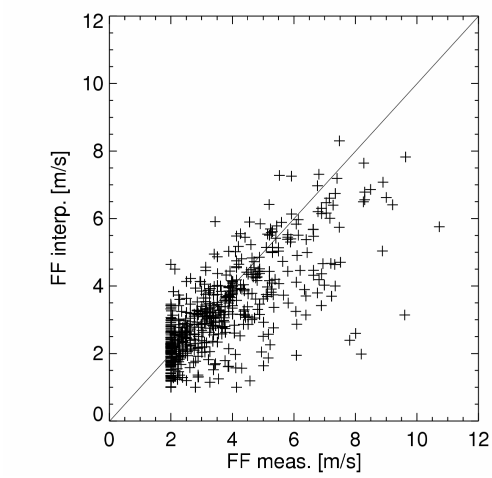

Fig. 14: Measured wind speed vs. interpolated wind speed for all measurement stations included.

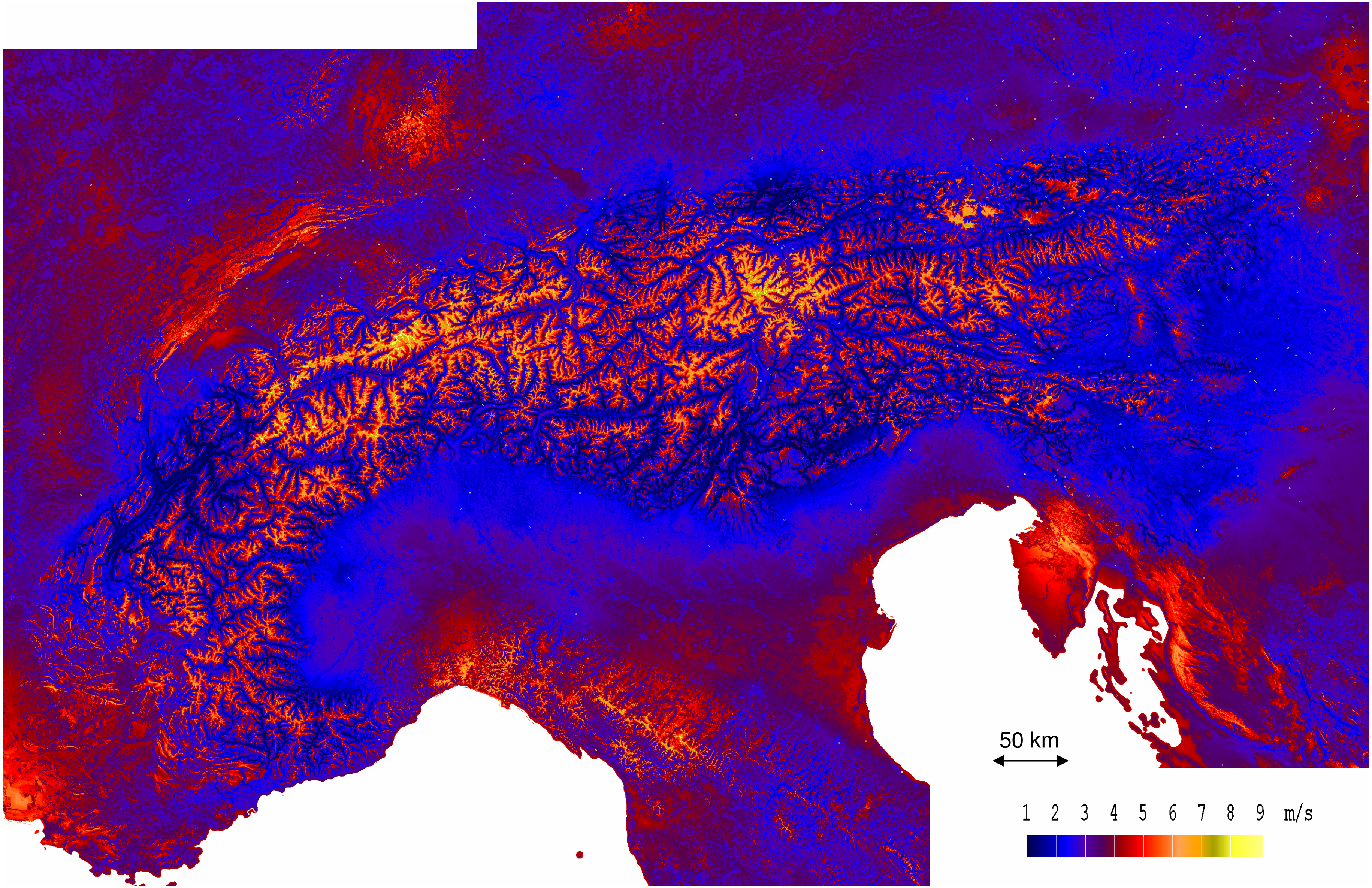

Fig. 15: Wind map at 50 m above ground.

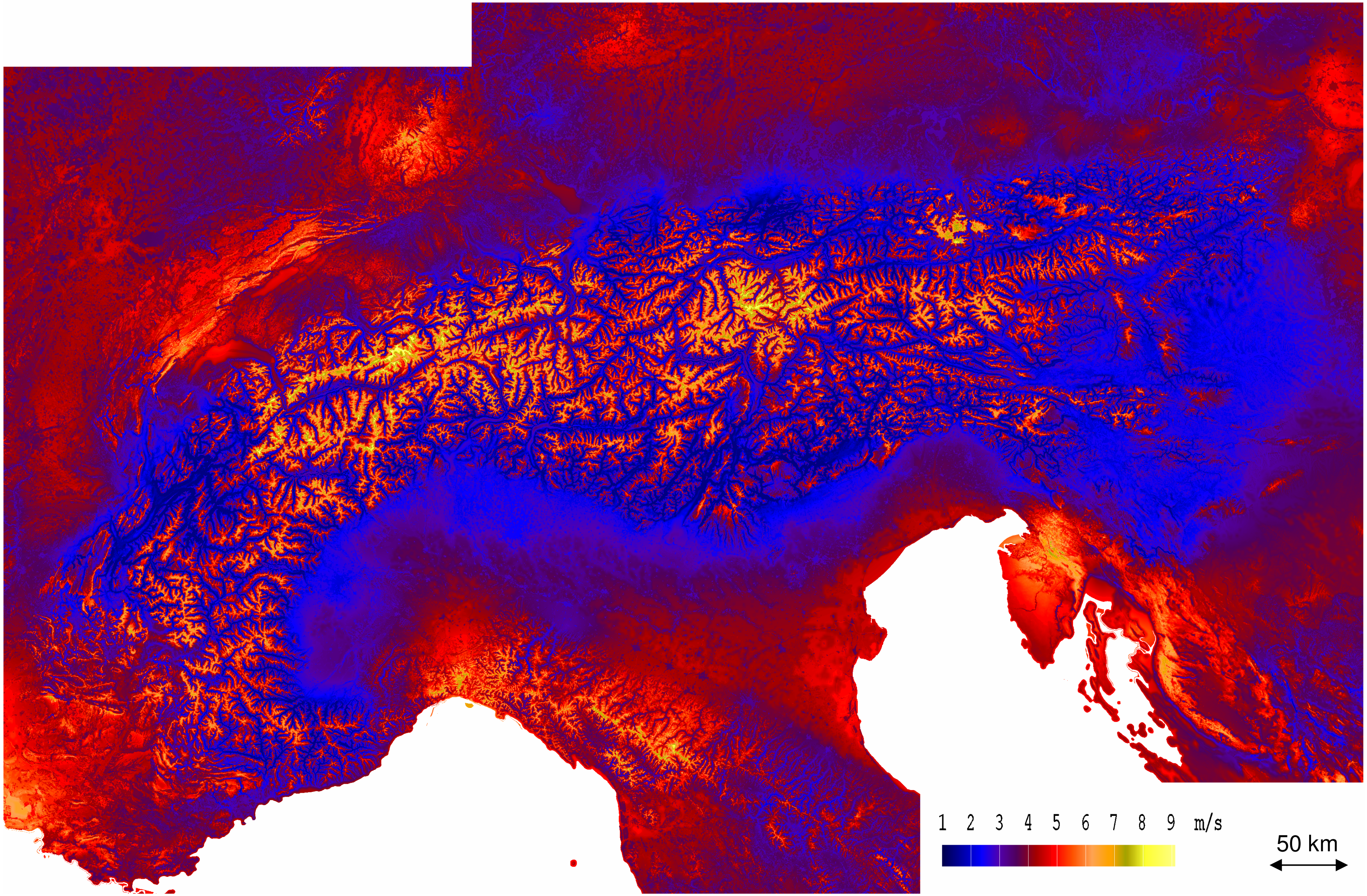

Fig. 16: Wind map at 100 m above ground.