

Master Thesis

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„Spatial dynamic modelling“ Wind energy flow and turbulence visualization for windfarm optimization

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For feedback and discussion of the topic the reader is welcome to contact me at R.Schauenburg@web.de .

Declaration

I assure that the present master thesis was carried out without external help and without using further than the stated sources. I also confirm that this thesis in an equal or comparable form was not submitted to another examination board. All statements within this thesis that have been quoted literally or by intended meaning are marked adequately.

Hamburg, the 31st of August 2006

A handwritten signature in blue ink, consisting of a large, stylized initial 'R' followed by several horizontal strokes and a long horizontal line extending to the right.

Ronald Schauenburg

Abstract

A tool for the modelling, visualization and analysis of 3D-windfields is developed with the intention of identifying and evaluating most suited sites for wind turbines in complex terrain.

The topic is introduced by an overview to wind energy and the role of GIS towards a management decision support system in the full lifecycle of a windfarm project. With spatial and atmospheric information interrelated closely, atmospheric science information systems, their models and GIS should be integrated, though by structure and history differences are great.

Apart of standardization in data models, the OGC "Sensor Web Enablement Initiative" may be a thriving factor towards integration. Crucial is GIS-development towards handling 3-dimensional multitemporal data and corresponding analysis functionality.

Meteorological models generally known by their application for climate and weather prediction, are lately more frequent applied to wind energy with a round robin in progress to evaluate experiences gained.

The mesoscale model METRAS PC is used to model 3D windfields for a fictitious wind farm at the fjord-type site of Squamish, north of Vancouver, British Columbia, Canada, by respect of thermic wind effects. A landuse classification of Landsat 7 satellite images and a digital surface model are exposed to considerable downscaling towards the resolution of the model. Analysis of the large scale "NCEP-DOE Reanalysis 2" data from 2000-2005 provides the geostrophic wind model-drive to a set-up of multiple simulation experiments. Analysis of ground weather stations data provides for reference to and validation of the modelled windfields.

The modelled windfield of a typical west-wind situation is 2- and 3-dimensionally visualized in GIS. Also the annual prospect for wind distribution potential is aggregated for from the individual simulation experiment's results.

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List of Symbols and Acronyms

API	Application Program Interface
ASIS	Atmospheric Sciences Information System
C	Celsius
CFD	Computational Fluid Dynamics
CDED	Canadian Digital Elevation Data
CO ₂	Carbon dioxide
DSM	Digital Surface Model
GHz	Gigahertz
GIS	Geographic Information System
GML	Geography Markup Language
IDW	Inverse Distance Weighted
ISO	International Organization for Standardization
k	Kelvin
MB	Megabyte
OGC	Open Geospatial Consortium
RAM	Random-access memory, referred to as working memory
SW	Software
u	eastward wind
v	northward wind
WCS	Web Coverage Service
WD	Winddirection
WFS	Web Feature Service
WMS	Web Map Service
WV	Windvelocity

1 Introduction

The application of fluid simulation has lately become an issue to the field of wind energy, as it is the target to maximize the portion of energy from the wind converted to electrical power, for example by aerodynamically optimized blade-profile.

However the purpose of this thesis is not the focus on a single technical apparatus, but rather the selection of suitable micro-sites for wind turbines adapted to local topographical conditions in a setup of wind farm configuration.

The character of individual prospected sites (form of terrain, texture of surface, obstacles and restrictions) but also energy losses due to inter-shadowing of wind turbines are the site specific factors by which the amount of energy output can be maximized.

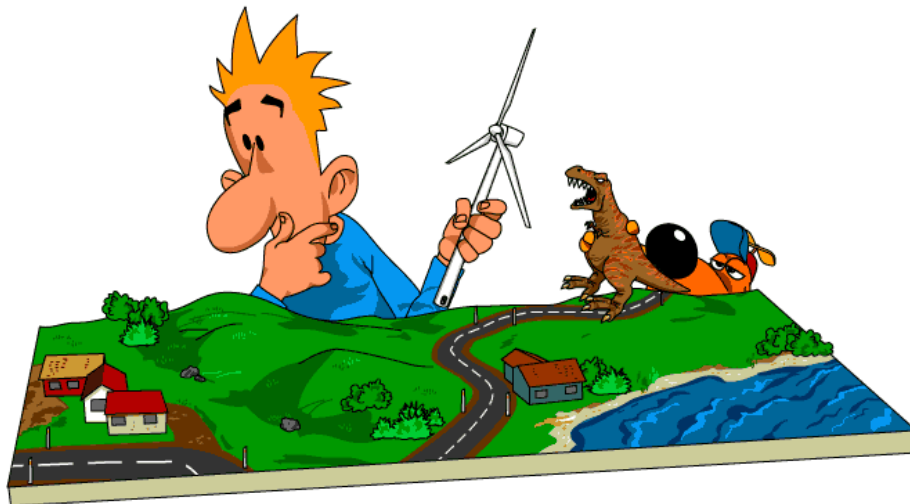


Figure 1: Factors in micro-siting of wind turbines

While the prospering industrial sector of renewable energies in general and wind-energy in special faces increasing pressure on cost-structures in order to be economically competitive to finite fossil combustible driven power production plants, also less gainfully sites for wind farms have to be made use of since many ideal places have already been equipped.

A professional approach to yield optimized wind farm layouts contains considerable potential towards meeting the mentioned challenges.

Software available for the computer aided support in the planning process of wind energy projects is well suited to calculate for and display of i.e. wind conditions by various approaches, as well as resultingly prospected wind farm yields. However the application of fluid simulation in the sense of physically based models, versus the

simpler statistically based models, to wind energy is fairly new – with relatively few experience having been made.

A round robin (see DEWI, 2002) initiated by DEWI Deutsches Windenergie-Institut, with participating assessors all over the globe, has been initialized in 28.03.2002 with prospected results on how valuable physically based models will be for wind energy by the end of 2006.

While physically based models used in the atmospheric sciences amongst other appliances to forecast the weather by today with great reliability, they initially have been developed, tested and certified at least a decade before the “actual technological and industrial development for the use of windenergy started at the beginning of the 80s, first in Denmark and in California” (ALT, CLAUS, SCHEER 1998)

This technique enables for the simulation of the impact of local terrain to the windflow, whereas the new approach is to visualize these impacts if possible in a 3-dimensional room: i.e. “clouds of high energy-density” or “clouds of high turbulence intensity”. This will result in a more precise and touchable approach to justify good from poor micro-sites for wind turbines than this ever could be the case analyzing energy yield by tables consisting of numbers or by 2-dimensional windpotential maps.

Precise modelling for local conditions of the windfield aimed at optimized yields thus could be realized in the planning process. With precise wind fields, available algorithms for computer aided optimization, comparable to the look and feel of playing against a chess computer, can additionally be applied.

2 Wind energy – an overview

A brief overview on the development of renewable energies from an economic perspective, the technical state of the art of wind turbines, the main steps in the lifecycle of a windfarm (including planning steps and critical factors) is given emphasizing on the potential role of GIS to the topic.

2.1 Renewables – from ecological idealism to high-tech

Arguments for renewable energies in general and wind energy in special are illustrated by the campaign “no fuel” by the European Wind Energy Association (EWEA, 2006):



Figure 2: Key facts of campaign “no fuel” by EWEA

An excerpt from the open letter ahead of the G8 Summit in St Petersburg on 15-17 July 2006 calling G8 leaders by Global Wind Energy Council (GWEC, 2006) summarizes the evolutionary state of wind energy:

"... representatives of the American, Canadian, European and Japanese Wind Energy Associations ..., the letter warns that the days of cheap and abundantly available fuel are over and that heavy investments in clean, safe, renewable energy technologies are needed to ensure supply security, combat climate change and satisfy increasing energy demand in the long term.

Wind technology is not a dream for the future – it is real, it is mature and it can be deployed on a large scale. Thanks to twenty years of technological progress, wind turbines have come a long way and a wind farm today acts much more like a conventional power station. A single modern turbine annually produces 180 times more electricity and at less than half the cost than its equivalent twenty years ago. Moreover, wind power generation is increasingly competitive with conventional fossil fuel sources and already today is on a par with new coal or gas fired power stations."

The Global Vision of the Global Wind Energy Council (GWEC, 2006) is that by the year of 2020 a 12 per cent share of the world 's electricity needs will be supplied by wind power against a projected two thirds increase in electricity demand.

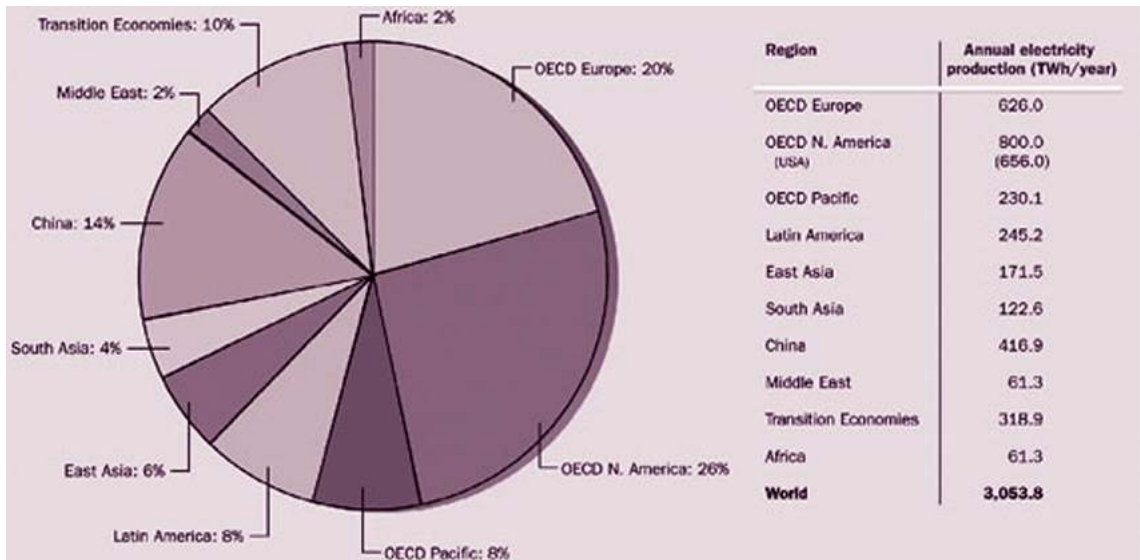


Figure 3: Distribution of the 12% electricity production from wind power in 2020

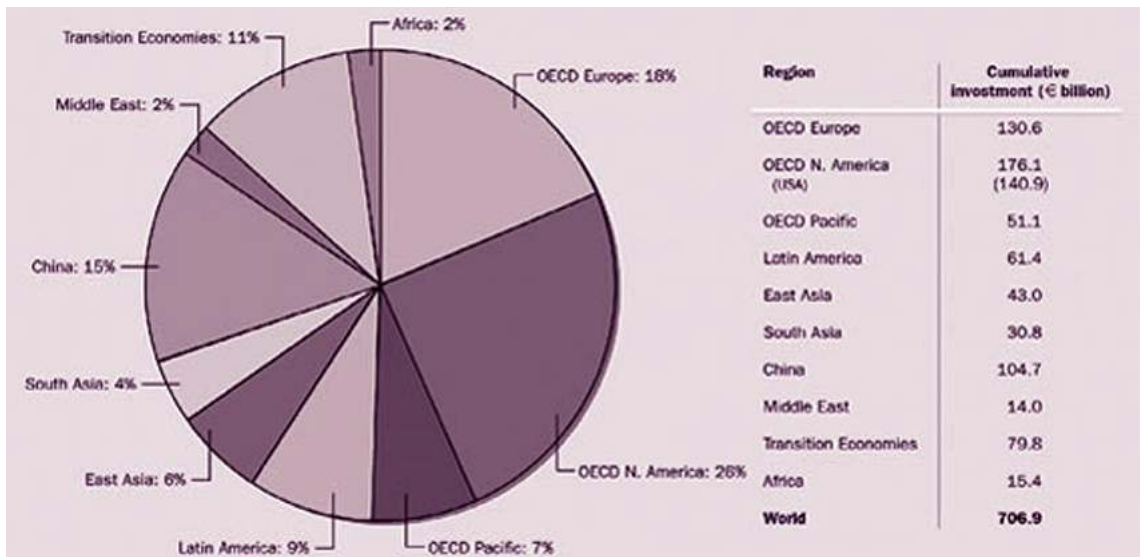


Figure 4: Cumulative investment per region up to 2020

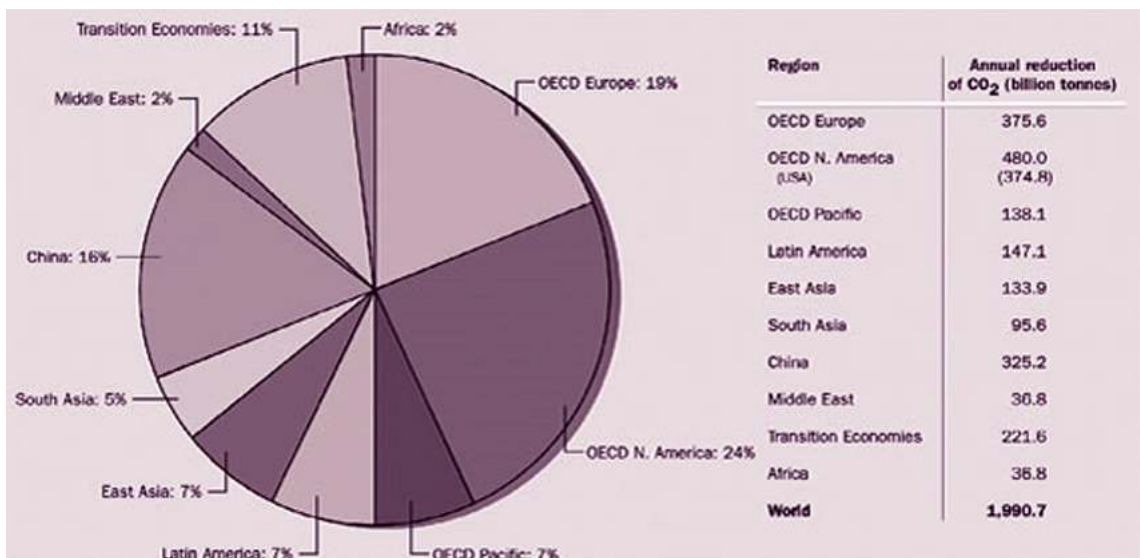


Figure 5: Annual reduction of CO2 in 2020

Not entering the subject further, it can be concluded that the present state of wind energy is remarkable and that there are optimistic expectations for the future.

2.2 Wind turbines –technical state of the art

Turbine power, size and technology involved are often underestimated. For an idea on sizes for example the superjumbo Airbus A380 (WIKIPEDIA, 2006) has a length of 73m and a span of 79.8m. The dimensions of the currently largest wind turbine REpower 5M are a total height of 183m and a rotor diameter of 126m (REPOWER SYSTEMS AG, 2006).

Another record regarding height will be set in 2006 with a lattice tower of 160m, adding up to the total's turbine height of 205m engineered by SeeBA (SEEBA, 2006) at the site of Laasow (Brandenburg, Germany).



Figure 6: Photocomposition of 160m-lattice tower by SeeBA

With the REpower 5M's rated power output of 5 megawatt a single turbine satisfies the energy needs of a typical 4,500 three-households, if located at a wind attractive

site (17.000 kWh/a at the prototype site of Brunsbüttel nearby the Elbe-river inflow to the North-Sea, Germany).

Generally with higher towers greater and steadier winds can be harvested. Rotor diameters and power capacity increase as know-how in the technology of turbine manufacturing advances. The outcome is a continuous process of making the turbines technically and economically more efficient and competitive to other forms of power generation.

As a result traditionally less favorable sites away from the sea to the inland, from flat surfaces to structured or even forest covered lands are getting more attractive as development proceeds. An example of a challenging site is the "Tauernwindpark" (TAUERNWIND, 2006), at an height above sea-level of 1900m actually the highest windfarm of Europe, located in the mountain range of the "Niedere Tauern" in the western part of the Steiermark county, Austria. While it is not only difficult to predict the wind conditions in such called "complex terrain", it is also strong vertical and turbulent winds as well as inhospitable weather (temperatures, ice and snow) that considerably stress and wear on the turbines.



Figure 7: "Tauernwindpark" (first turbine installed)

Offshore wind farms are to be believed the power production plants of the future with first experiences already being made. Facing enormous challenges to technology and logistics, an ongoing field of research is how adequate attention can be spent to the nature of the sea and its inhabitants

2.3 The lifecycle of a wind energy project

The planning of wind farms is only one aspect in the lifecycle of a wind energy project. With the realization of the project the management and monitoring of the windfarm has to ensure for at least a decade's operation that economic expectancies are met. The complexity of wind energy projects is illustrated by an general overview:

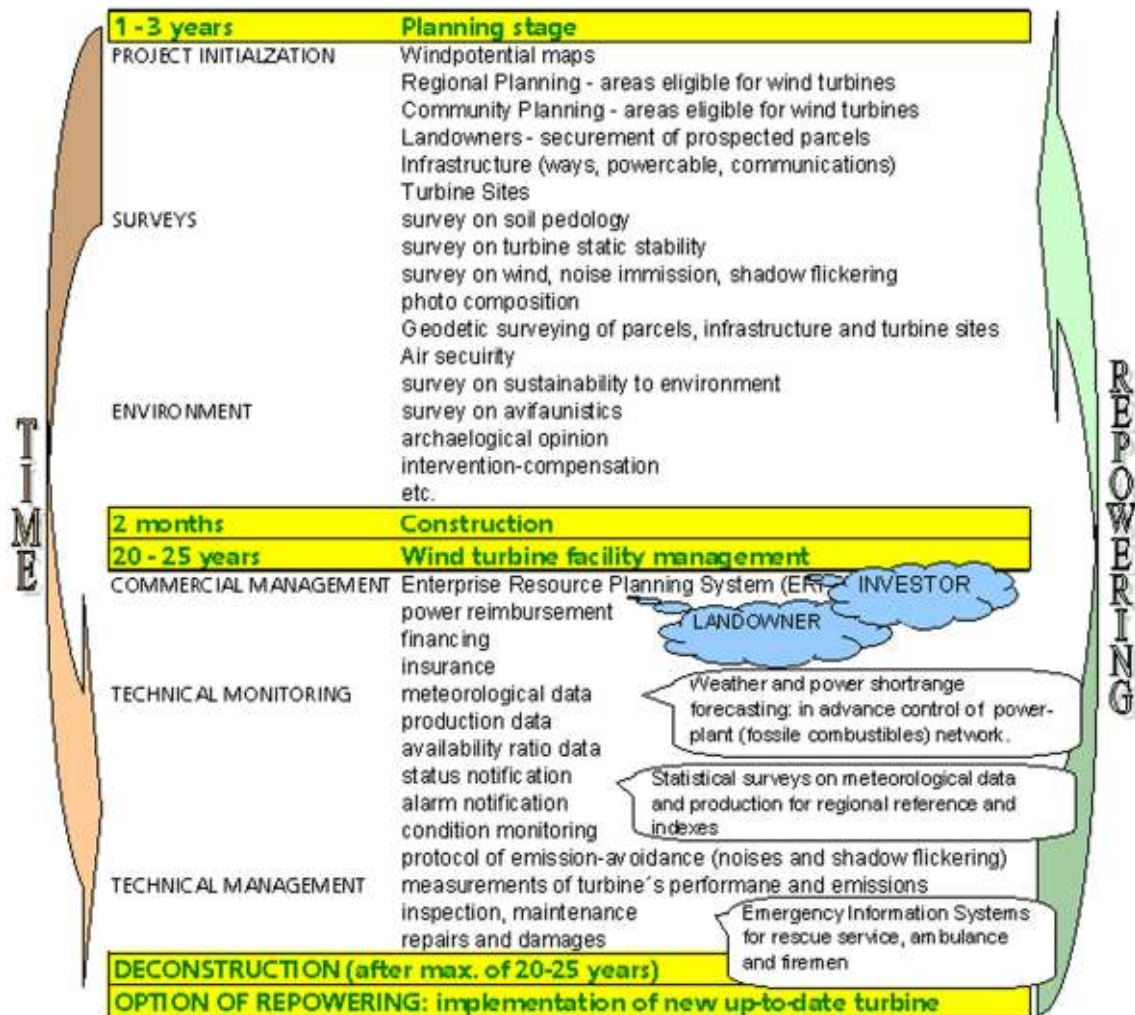


Figure 8: Lifecycle of a wind energy project

Usually the management and operation of wind farms is done by companies that in most case have portfolios of many wind farms. The different types of turbines from various manufacturers are generally equipped with distinct software often lacking interfaces to standard database formats. Also requirements towards documentation are continuously increasing.

What in the management and operation of wind farms is required to meet expectancies is not only richness of winds but also an **effective management decision support system**, which will be focussed in the issue of coupling GIS to modelling software in a network approach with other relevant software.

2.4 Software applied in wind energy projects

Specialized software packages exist for all the above areas, out of which – concerning the planning stage - WindPRO (EMD) and WindFarmer (Garrad Hassan) combine tools for planning in one package.

WindPRO as well as Wind farmer offer a cartographic display, by which the wind farm can be outlined (placement of turbines and other objects of relevance on various maps) and a project administration window, which is used for calculating and reporting on energy yields and environmental impacts (noise, shadow flickering, visualization, etc.).

Despite the availability of specialized software there are good reasons for GIS in addition to these packages:

- Flexibility and handling of various (map) data formats
- Reference systems available and precision in projection capabilities
- Construction tools (CAD functionality) integrated
- Data manipulation and analysis
- Interconnection/interfaces with and in between related software (specialized wind energy package, project management, standard office appliances, etc.)
- Database connection, option of Web GIS

...the most important argument though is, that the greatest portion of information dealt with in wind energy projects has spatial reference. Without the possibility for cartographic display and analysis of information the overview can hardly be kept.

This argument is especially true if documentation and data is built up beginning from the very first start of a project through the full lifecycle displayed above – with the prospect of information advantages towards a efficient decision-making.

3 Squamish – “mother of the wind”



Figure 9: The area of Squamish looking southwards the Howe Sound¹

In order to demonstrate the application of the concepts and proceedings elaborated in this thesis, a fictitious wind farm at the site of Squamish, British Columbia, Canada will be examined for potential energy yield. The prospected sites for wind turbines have not been analysed for any potential conflicts such as environment, wildlife or landuse-plan.

¹ www.britishcolumbia.com_photogallery (04.02.2006)

3.1 Site description



Figure 10: Map of south-western British Columbia

At Canada's most south-western spot in the province of British Columbia, Vancouver Island, shelters the Strait of Georgia from the Pacific Ocean. Within the Strait of

Georgia, Vancouver is located east as the largest city on the mainland. Northwest of Vancouver Howe Sound, a triangular shaped fjord, is spreading northwards into the Coast Mountains, which is a forerunning mountain range to the eastward Rocky Mountains.

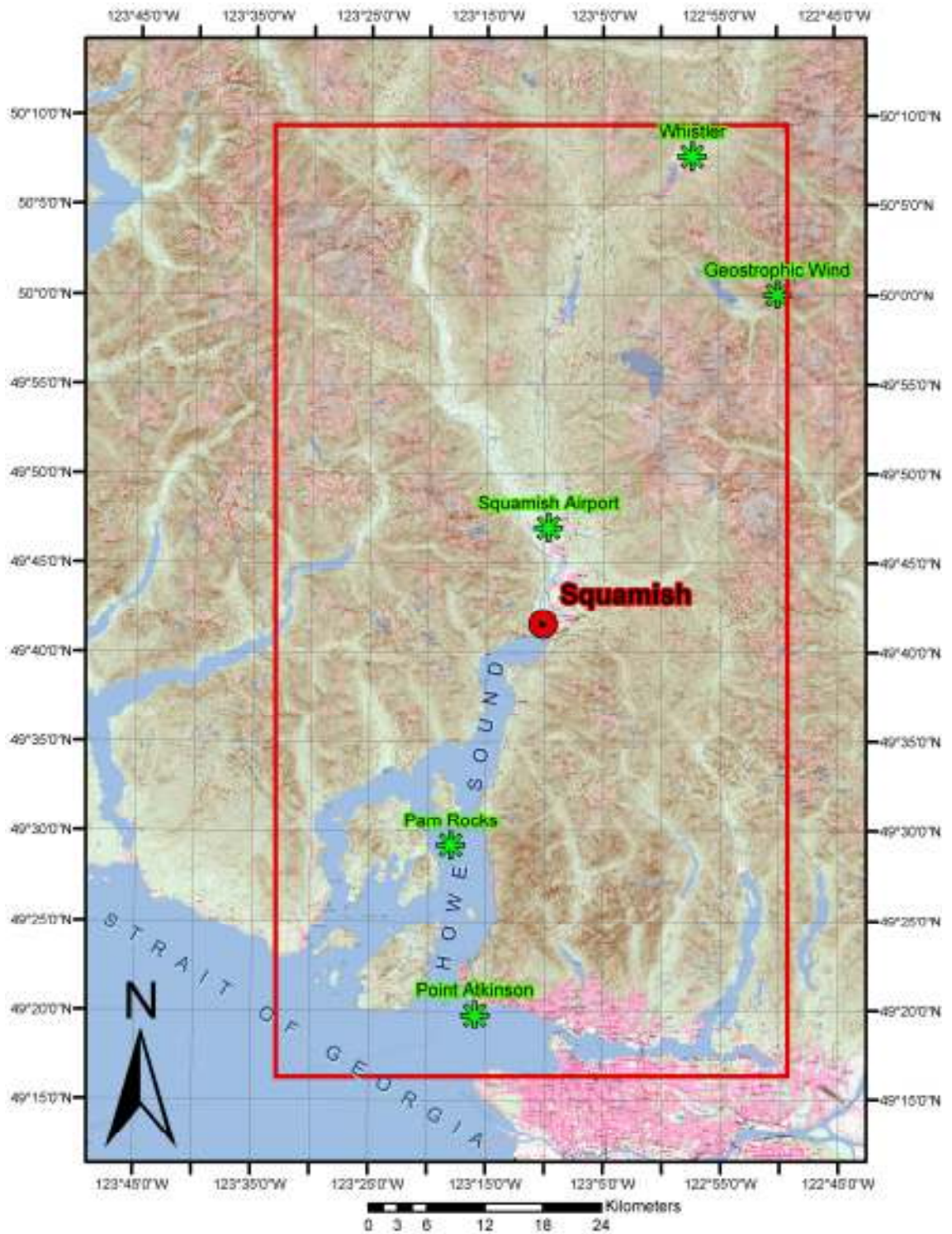


Figure 11: Howe Sound area map - relevant weather stations and final model area

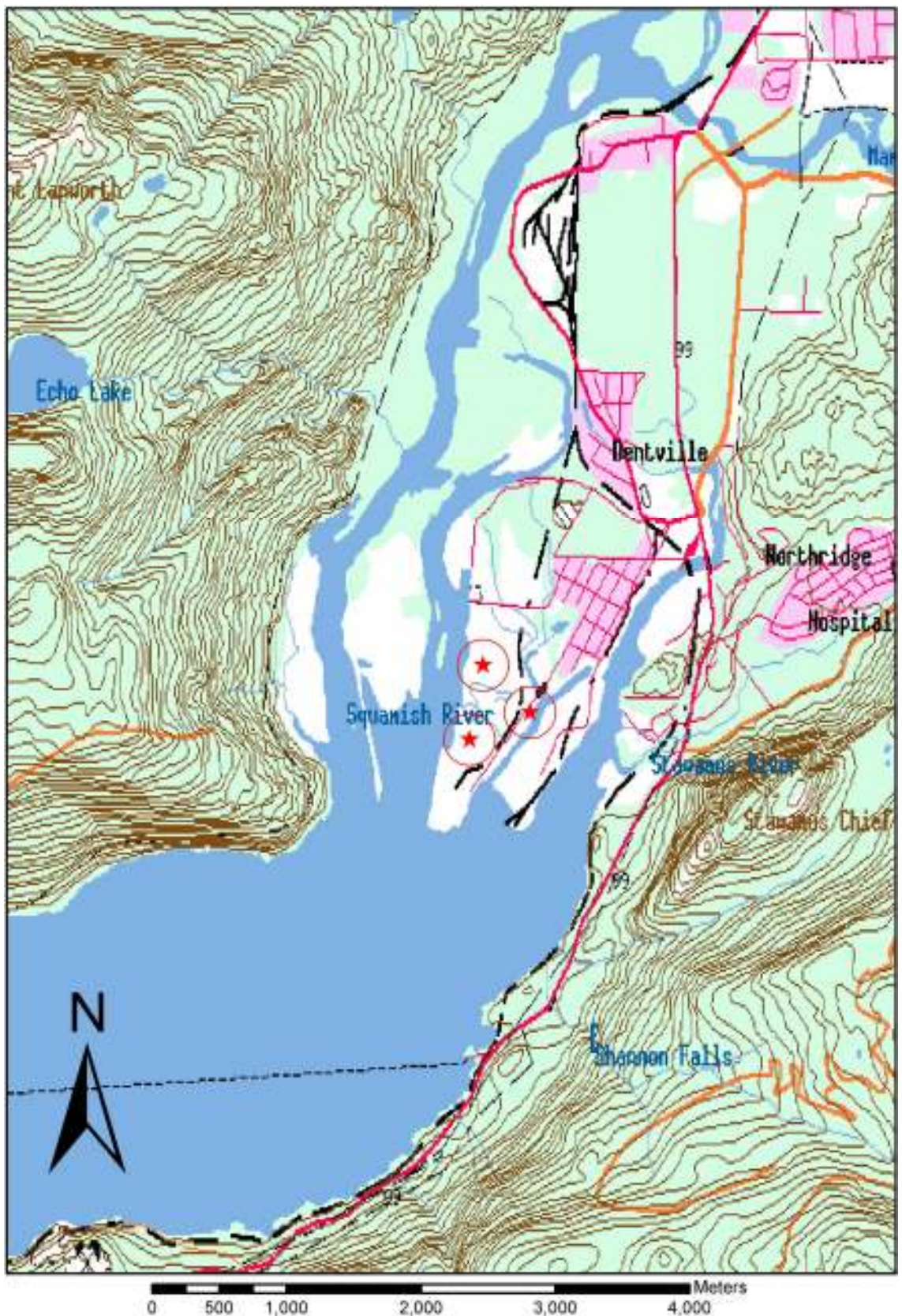


Figure 12: Squamish topographic map - prospected wind turbine sites

The mountains to the West and East of the Howe Sound are steeply rising to heights above 2800m. Howe Sound contains a plentitude of islands, three out of which are steep and mountainous.

At the northern head of the Howe Sound is the community of Squamish with the Squamish river (WIKIPEDIA) heading further northwards at a length of 80km originating by its main source closely to the community of Whistler, a resort for the alpine sports, approx. 110km north of Vancouver accessible by the "Sea-to-Sky Highway", BC Highway 99. Whistler marks the highest base elevation point (approx. 650m) within the valley that further north decreases in height towards the community of Pemberton.

Described in (WIKIPEDIA) "Squamish is also the name of the First Nations people who have inhabited this part of southwest BC (including North and West Vancouver) since before the time of contact with Europeans. The meaning is "mother of wind", pertaining to the intense winds that blow through the valley"

3.2 Topography and climate situation



Figure 13: Howe Sound northwards: rainforest and mountains

North of Squamish at the head of Howe Sound (WIKIPEDIA) the biggest mountain is Mount Garibaldi, a triangular-shaped volcano. Nearby Squamish, the Stawamus Chief, a vertical rising cliff-faced granite wall of 500m height, is a great attraction to rock climbers.

With such steep mountains prevailing the topography, the prospected site of Squamish and its surroundings are to be classified as complex terrain.

Though located north of Vancouver relatively few civilization is seen in the area, so that most of the landscape is left to nature. The land surface is mainly covered by ancient temperate rainforest (WILDERNESSCOMMITTEE) indicating high relative

humidity during summer and winter. Going up to the greater mountain heights grass and heather prevail, when in the alpine year-round snowfields and glaciers are found due to the height of the mountains.

3.2.1 Winter time “squamishes”

The strong arctic outflow winds in the winter time are characterized by (WIKIPEDIA): “that at the extremely steep and conical island Anvil Island’s north facing bay is exposed to strong overnight and winter outflow northerly winds. Also at Christie Islet and Pam Rocks just south of Anvil Island, winter northerly gales can reach close to hurricane force. Pam Rocks is a reporting weather station.

As described in (WIKIPEDIA) “A squamish (also known as an arctic outflow wind in winter months) is a strong and often violent wind occurring in many of the fjords, inlets and valleys of British Columbia. Squamishes occur in those fjords oriented in a northeast-southwest or east-west direction where cold polar air can be funnelled westward, the opposite of how the wind generally flows on the coast. These winds in winter can create high wind chills by coastal standards of -20C to -30C ... Squamishes lose their strength when free of the confining fjords and are not noticeable more than 25 km offshore.

In the Lower Mainland of British Columbia, the name for them is outflow winds, and they are noticeable especially in the winter, when a cold arctic air mass holding in the high plateau country of the Interior flows down to the sea through the canyons and lower passes piercing the Coast Mountains towards the sea.”

3.2.2 Summer time thermic winds

The thermic wind system of the summer months causes reliable and strong winds around Squamish according to (SQUAMISHCHIEF), “when most days in the warm months the daily inflow winds kick in once the heating action of the morning sun warms the land. When the land temperature surpasses the water temperature, mother nature pushes strong air currents from the water onto the land.”

3.2.3 Windatlas of Canada

In the WindAtlas of Canada (ENVIRONMENT CANADA) wind potential maps as well as wind data are available for all over Canada. The wind maps have a spatial resolution of 5km, which appears low to the geographer but high to the

meteorologist. The WindAtlas has been created applying a mesoscale meteorological model. It is advised to use the information provided for a detailed investigation at a higher resolution.

In (DOYLE, 2005) concerning the WindAtlas of Canada it is stated that "an examination of the 10 m (above sea-level) average wind field indicated a number of salient points... data from Pam Rocks..., shows good correspondence with the wind map. Its calculated average windspeed is approximately 5.0 m/s and the wind model indicates 4 - 5 m/s in the area."

With this information in the background the idea is to examine the prospected area at a greater resolution to find out how well the site of Squamish is suited to the harvest of wind energy.

4 Modelling and GIS

4.1 Definition of what is modelling

Since humankind has been starting to shape their spaces of living, models supposedly have been the thriving means to put ideas into realization. Models nowadays exist for all sort of things from model railway to display models, colour models i.e. CMYK, various models of economy, marketing models, communication models, procedure models, structural models, nuclear models, physical data models and so on.

Concerning the realization of wind energy projects various models are imaginable: small scale replicas of windmills or potential wind farms, lease of land sharing models, intervention-compensation-models, imission-prediction-models for noise propagation or shadow flickering as well as models to predict wind capacity to derive power yield (affecting financial models) and wind loads to calculate for a turbines statical stability.

Definition "Model":

"Model, models, or modelling may refer to: An abstract representation of an object or system from a particular viewpoint." (WIKIPEDIA)

Definition "Simulation":

"Simulation is an approach mainly for the analysis of dynamical processes. By simulation experiments are exercised on a model in order to gain knowledge about the real system. In the context of simulation one speaks of the system-to-be-simulated and of a simulator as an implementation or a realization of a simulation

model. The latter is an abstraction of the system-to-be-simulated (structure, function, behaviour). The running of the simulator with concretized values (parameterisation) is described as a simulation experiment. The results of an simulation experiment can be interpreted and transferred to the system-to-be-simulated.” (WIKIPEDIA)

Distinction between model and simulation:

A model is the representation of an object or system that may consist of individual simulations. Thus in the following with model the general approach to describe a real world’s phenomenon is described, while with simulation the analysis of individual (meteorological) situations is addressed.

4.2 Types of modelling techniques

After a review on the “market” of models modelling techniques that are suitable to the modelling of wind fields are:

- Continuous surface
- Statistical models
- Physically based models

By taking a closer look at these modelling techniques, only common software products are displayed. A representative but incomplete overview is given by (METEOTEST, 2001). Also software designed for wind energy is presented by (QUASCHNING, 2003).

Continuous Surface

Most GIS today are equipped with modelling techniques that enable for the estimation of continuous surfaces for areas where few measuring points are known. This technique interpolates all missing values as implemented i.e. in the method of “inverse distance weighted” (IDW).

Generally this technique is applied to digital elevation models, as demonstrated in (BRIMICOMBE, 2003) where IDW is used to create an continuous surface from measured point data set to a gridded DEM or height contours. Used with i.e. the attribute of wind potential a map displaying average annual wind potential can be derived. The condition that data of a tighter red of weather stations is known in the relevant area of interest most often though is not encountered.

While this method works well for simple terrain, the main disadvantage apart from the requirement of many weather stations is that the wind potential could only be calculated for the same height as where the stations data was measured.

As it is up to the user to choose the parameters for IDW, such as power and search radius, it is important to test for the accuracy of results. Some GIS offer geostatistical functions to test for validity of the results.

Statistical Models

Various statistical models exist for the modelling of wind conditions. Compared to the first method of "continuous surface estimation" these models not only respect one factor (attribute) for the estimation of a continuous surface. Statistical models with the focus on wind modelling commonly interpolate values by considering the following factors:

- Measurements of ground weather stations (projected to prospected height of wind flow over ground)
- Topography in the sense of height contours (hills, troughs, valleys)
- Orography as the roughness of the surface depending on landuse (a rough surface creates turbulences and slows down the wind)
- Annual fluctuations i.e. between summer and winter
- Increasing winds at higher levels above sea
- Lower air density and less energy of the winds at higher levels above sea

The most prominent statistical model in the field of wind energy has become WAsP (Wind Atlas Analysis and Application Program), developed by the Wind Energy Department at Risø National Laboratory, Denmark. WAsP has been applied within the creation of the European Wind Atlas (TROEN, PETERSEN, 1989)

WAsP is not solely suited for the creation of wind potential maps over large areas, but also at high resolution in the scope of meters. WAsP enables for the rapid calculation of energy yields of wind turbines in cluster configurations respecting their energetic shadowing (windfarm park efficiency).

WAsP-Advantages:

- Fast calculations
- One calculation for all wind direction sectors and all occurring windspeeds
- Easy to use, the user is likely to choose applicable parameters
- Recalculation with adjustment of parameters possible due to rapidity: input parameters are generally adjusted as to what fits best to production data of nearby turbines.
- Model integrated in WindPRO
- Park shadowing model(s) integrated in model
- Calculation of wind maps at high spatial resolution due to rapidity or for large areas (e.g. European Wind Atlas)
- Wind statistics from weather stations are integrated and can be chosen from.

WAsP-Disadvantages:

- Developed for hub heights up to 50m (TROEN, PETERSEN, 1989), up to date applicability questionable (FREY, GROSS, TRUTE, 2002)
- Not applicable to complex terrain.
- Black box phenomenon: results are always produced, prone to “garbage in, garbage out” principle
- No distinction between night / day, summer / winter effects
- No modelling of thermic effects

Another example is the statistical model used to create the wind potential maps for the “WINFO – Geo-Informationssystem for WindEnergy” maintained by Suisse Eole. Detailed information about the model is stated by (METEOTEST), (SWISS FEDERAL OFFICE FOR ENERGY).

Statistical models rely on the simplification of physical processes. The more complex the topography of a terrain gets, the greater is the probability that these simplifications cannot be applied. As a measure for the complexity of topography the ruggedness index (RIX) is helpful to decide, if the appliance of a statistical model, such as i.e. WAsP will deliver trustworthy results. According to the model description of WINFO – Geo-Informationssystem by (METEOTEST) “areas with an RIX greater than 30% do not permit the physical simplifications of the calculation models (such as e.g. WAsP)”.

The program rix.exe to calculate the RIX-index is included with the “WAsP Utility Programs 3.1”.

Physically based models

Suited to general situations as well, but especially where the terrain is complex physically based models are applied for wind predictions. These types of models are apart from installing met mast(s) the only applicable ways to get realistic ideas about potential sites, whenever the above mentioned RIX is very high, the terrain is predominated by mountains, steep passages or deep valleys. Vertical winds and turbulence are a risk at placing turbines not only for yield but also stability of the construction.

As described in (BOEKELMANN, DIJK, RIENTJES, 1999) "physically based models are based on the understanding of the physics of the processes involved and describe the system by incorporating equations grounded on the laws of conservation of mass and energy. An assumed advantage of physically based models is that they do not require long meteorological and hydrological records for calibration, since their parameters have physical meaning. Unfortunately, also physically based models are mere representations of the true physical processes, and calibration is just essential. This limitation of representation is caused by the equations underlying the models. These equations are good descriptors of spatially homogenous processes, but in real world problems heterogeneity is introduced which leads to uncertainties. This implies that even physically based models should be verified, by comparing predicted and measured values, to evaluate the modelling error."

Physically based models differentiate in their scale of representation: "the scale at which process variations occur in the real world is infinite; for modelling purposes, however, we must average this infinite (spatial and temporal) variability to some degree into finite elements. Such a finite element (often a square grid) is then assumed to be homogeneous and to have uniform parameters (altitude, slope, crop, soils, etc.)."

Computational fluid dynamics (CFD) belong to the physically based models, mainly used in engineering for aerodynamic or hydrodynamic optimisation in streamline of products. An appliance of CFD for optimized rotor blade efficiency, less loads and minimized sound-emissions is demonstrated by (ENERCON, 2004).

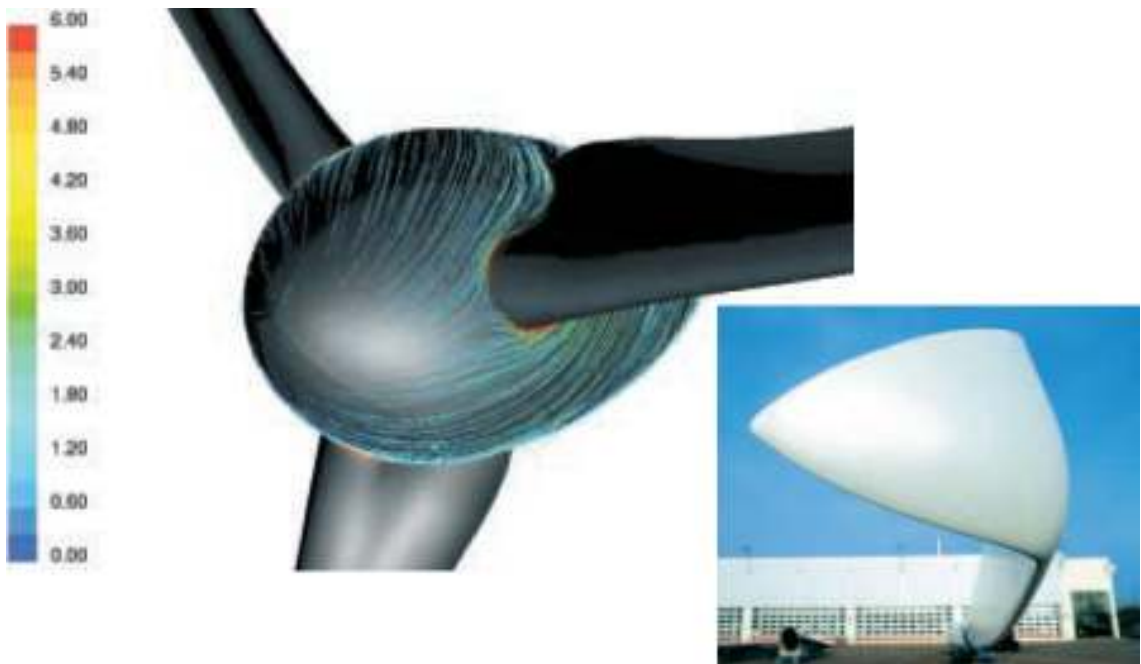


Figure 14: rotor blade optimized by use of CFD

The TÜV Nord e.V. has used CFD as a modelling tool to predict the wake of a wind turbine on the basis of its geometry and operating data (HAHM, KRÖNING, 2001)

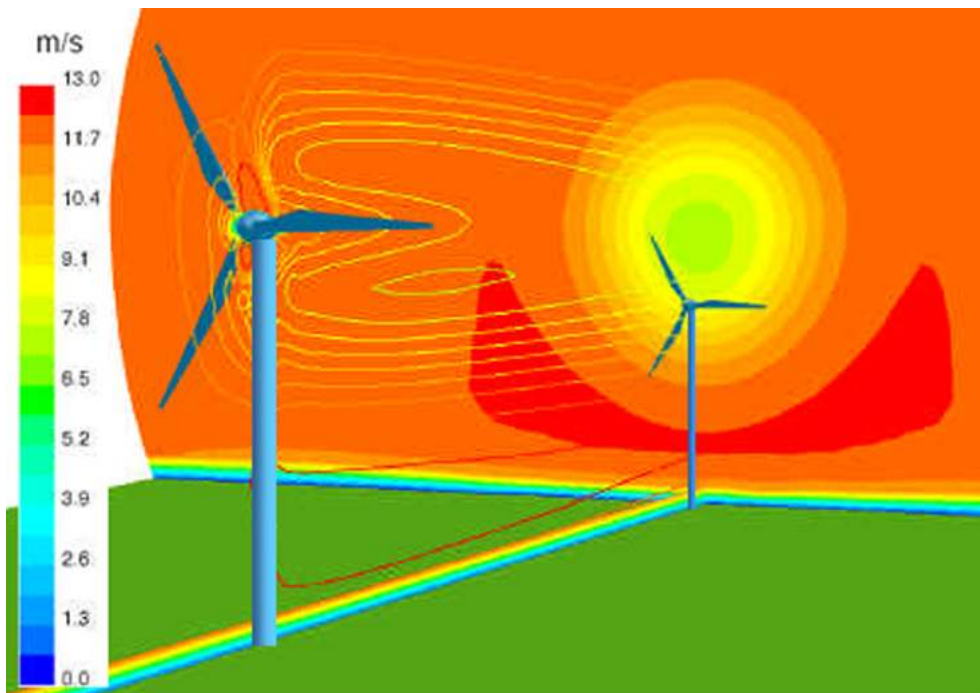


Figure 15: 3D wake of a wind turbine simulated by CFD

Weather prediction models fit in the concept of CFD but contain all relevant meteorological components: apart from wind flow these are parameterisations for turbulence, temperature, humidity, albedo of landuse, etc.

Weather prediction models are derived from the theory of hydrodynamics, the individual behavioral equations consist of Navier-Stokes-Equations or derivatives of these. (WIKIPEDIA).

The theories of the physical basis and the applied behavioral equations are described in a variety of literature. The mechanics of environmental fluids from a geo-scientific point of view are treated i.e. in (KOLDITZ, 2002).

While being engaged with the subject, the realization of the author is that the application requires a profound knowledge of the concepts behind, which is to be further deepened. Warnings at the use of physical-based models as "black-box" have to be taken seriously as the principle "garbage in, garbage out" fully applies. Again, a validation of the results by comparison to measured data is essential.

For the Squamish area the use of a physically based meteorological model is required due to the complexity of the area's terrain firstly and secondly due to the known effect of thermic winds, which this type of model can only resemble. Such complexity is met in many other prospected and realized windfarm projects, as indicated by the project of "ALPINE WINDHARVEST " for the expansion of wind energy in the Alpine space (ALPINE WINDHARVEST).

4.3 Limitations in modelling

As stated in (WIKIPEDIA.DE) "to all types of simulations limitations apply which always have to be kept in mind: the first limitation results from the scarcity of resources such as the finitude of energy (i.e. computer-capacity), time and money. Thus a simulation also has to make sense from an economic point of view. From these restrictions a model has to be as simple as possible. This however means that the results of a simulation represent only a rough representation of reality. The second limitation consequently is that a model only in a certain context produces results that resemble reality. In other areas of parameterization the results could simply be wrong. Thus the verification of models for each individual area of application is an important issue of simulation technology. Further possible limitations are inaccuracies of base or raw data (i.e. measurement errors) as well as subjective obstacles (i.e. scarcity of information)"

Scope:

As in (KIRKBY, 2000) the scientific simplification of models is not only a result of resources, as stated above, but first is the key for substantial advances in understanding which then enables for the development of more complex model structures. Thus the priorities for computationally intensive research are thought to lie primarily in the areas of “reconciling models at different scales, and improved calibration and validation”.

Models cover spatial scales from the soil crumb to continental or global scales, a range of 10^{10} times. Time scales are covered from fractions of a second up to the age of the earth, an even greater relative range. Most models have time or space scopes of at most 10^3 times, so that fundamentally different structures have to be used to cover the full range of relevant scales. Understanding the structural changes between models at different scales is the greatest challenge.

Target

As stated in (BRIMICOMBE, 2003) “no model will provide perfect predictions, because models are necessarily simplifications of reality. What is desired is an acceptable fit with the observed reality that is being modelled... In general this involves a comparison between some observed data and the simulated outputs, often somewhat restricted to the statistical distribution of residual errors (observed values – the expected values) to see if an acceptable goodness-of-fit has been achieved (Beck et al., 1993)”

“There is now a great deal of evidence about the climate of the past” (SCORER, 1998). However stable the climate may be or not, modelling for wind energy yields implies that the past climate can be used to predict for the future with an scope of the limited wind turbines lifetime of a prospected 20 to 25 years. Still though no guarantee can be given to that predictions will eventuate at all.

4.4 Ways of coupling models to GIS

According to (BRIMICOMBE, 2003) GIS “and environmental simulation models started to be used together round about the end of the 1980s”.

The difference in between technologies is that “GIS focus on representations of location, the spatial distribution of local phenomena and their relationships to one another in space”, which are usually static representations. Environmental simulation

models are “concerned with system states, mass balance and conservation of energy, focusing on quantities ... in time.”

Both technologies can be used independently from another, while eventual synergetic effects are not realized.

Advantages of coupling both technologies are (BRIMICOMBE, 2003):

- o Making models in- and output data spatial representations explicit
- o Using GIS manipulation tools and capacities for spatial data handling
- o Allow modellers to concentrate on modelling
- o Needs of both technologies are complementary, bringing them together, jointly they become more useful and robust in their solutions.

Four levels of integration for environmental simulation modelling are suggested (BRIMICOMBE, 2003).

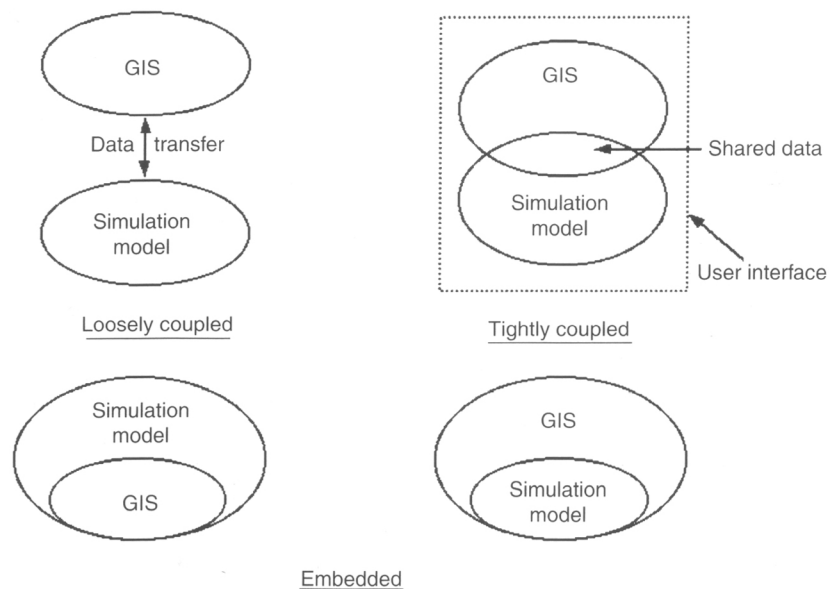


Figure 16: Levels of integration between GIS and environmental models

Independent

No integration, but GIS and environmental modelling are used independently on projects to achieve a common goal. An example would be data manipulated by GIS in the desired format to serve as an input to the model. The output of the model is not necessarily needed to be reimported to the GIS but could be analysed and visualized by any other independent viewer.

Loosely coupled

GIS and environmental model can share data files. This includes not only input data to the model but also output data, especially when data from various scenarios is to

be visualized and analysed in GIS. Eventually the files to be shared need to be transferred to an export file.

If data interfaces are provided by both software-packages fittingly, the main advantages are that first no further development costs are required and second that there is almost (apart for the interface) no interdependence between the two software-packages to their individual further development (upgrades, etc.). The disadvantage is that simulation and GIS tasks have to be done sequentially and cannot be performed simultaneously (i.e. live plotting diagrams from the output files of a running simulation).

Tightly coupled

A common interface runs and provides access both to the GIS and environmental model. Data files are of the same type, otherwise a file management system provides seamless data sharing. Advantages are that both software-packages can still be used in the loosely coupled option but no manual manipulation is required for data interchange. With lots of data sets interchanged automatically the chance of human errors is reduced and timesavings as well as flexibility can be realized. As well (WITTMANN, 2002) stresses, that this approach is less prone to data redundancies and consequently consistency problems.

The disadvantage is the probable immense development costs for the interface and successive maintenance with regard to the GIS's and environmental model's development (likely delayed in keeping pace with newer versions of the GIS or environmental model, change to another GIS or environmental model).

Embedded

Either GIS is embedded in the environmental model or the environmental model is embedded in GIS. In contrary to the tightly coupled level of integration one package likely dominates the other. Often the embedded package only contains parts of their full functionality or is less performing. If such limitations are the case, full integration is yet not given: full integration implies a complete GIS and environmental model being developed as an integrated product.

Main difficulties in coupling (BRIMICOMBE, 2002):

- Different data models: GIS data organization is rather for static representation while environmental model data for dynamics.
- Types of models that can be built within GIS are limited to what is possible within the software's internal analytical engine accessed through the user interface. In-built macro languages are too slow and less powerful for dynamic systems.

- GIS is limited in representing fuzziness or imprecision in most spatial data → limited use in studying trends and gradients.
- GIS limited functionality in handling uncertainty inherent in the analysis of and simulation using spatial data. (lack of uncertainty / sensitivity analysis).

But growing interoperability of software, increasing use of networked databases, growing number of geocomputational tools besides or in addition to GIS lead to mature conceptualisations of how GIS and environmental models can work more closely together. In the future “it should be the database ... or databases that form the core from which GIS, other geocomputational tools and simulation models draw input data and submit processed output data. These databases will be increasingly networked and the network will thus become the key to the integrated use of diverse tools and data sets.”

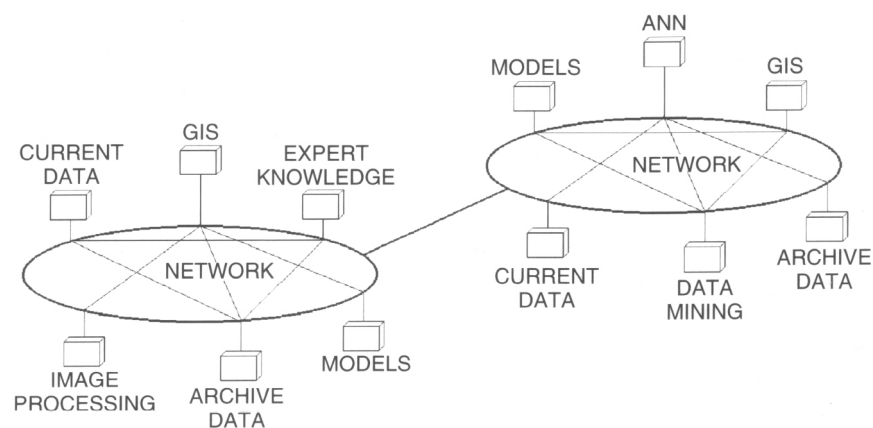


Figure 17: The network as the core technology (BRIMICOMBE, 2003)

When GIS in the early stages has evolved from inventory activities to the analysis of spatial phenomena, the movement to management is in the final stage. As the importance of modelling and simulation in a decision support system environment is implicit, the coupling of GIS with environmental simulation models becomes integral to that evolution.

4.5 Limitations to modelling in GIS

Limitations to modelling in GIS are stated in (BRIMICOMBE, 2002):

- o “GIS are not very good in handling time since layers are predominantly snapshots.” However flows and interactions are temporally dependent.
- o “Modelling in conventional GIS is limited to how we express real world objects as data (data modelling) and ways in which we might transform and analyse that data. Fairly simple simulations can be achieved, but not of complex environmental processes.”

- Concerning analysis “statistical functionality is limited” and that many analysis tools are missing – while much functionality is available for 2 dimensions, for temporal multidimensional data this still has to evolve.

For what is demanded of a GIS to collaborate with environmental modelling efficiently, a threefold classification is suggested for types of stored knowledge in the spatial domain:

- geometrical
- structural
- procedural

Geometrical knowledge refers to location, dimension and spatial relationships (topology) of geographical features - the graphical element of a GIS-database

Structural knowledge refers to the additional thematic (attribute) information that provides for a further understanding of the form and characteristics of the geographical features.

Procedural knowledge refers to the understanding we have, of how physical (and social) processes operate over time and space as expressed in simulation models.

In order to be able to make better use of GIS in environmental modelling, GIS databases should be able to store these three aspects of knowledge. However most GIS packages of today are limited to the geometrical and structural aspects, while environmental models focus procedural aspects.

In general the role of GIS to environmental modelling has been:

- Pre-processing of spatial-data for input to model
- Assisting in modelling tasks such as calibration and scenario building
- Post-processing the outputs for visualization and analysis.

4.5.1 Status in multidimensional GIS

Stated in 2001 (BREUNIG, 2001), “today’s geoinformation's systems are still mainly 2D information systems ... the first approaches to 3D or 4D-GIS can be subdivided into two categories:

- 2D GIS with 3D or 2.5D extensions
- 3D / 4D GIS modelling and visualization tools, e.g. for geology.”

2D GIS with 3D or 2.5D extensions “support the visualization of TINs or grids for digital elevation models (2,5D). Some GIS also allow the visualization of 3D scenes. ... advanced geometric 3D operations are not yet provided.”

3D / 4D GIS modelling and visualization tools support many algorithms to analyse 3D geometries (i.e. interpolation algorithms), support time models for the simulation of 3D geometries and topologies in time and thus should be able to visualize movements of 3D objects. Few examples of the latter category exist yet.

Theoretical aspects on what data modelling techniques are required towards multi-dimensional GIS is given in (BREUNIG, 2001) and (COORS, 2005).

Facing these limitations of GIS for now the priority should be the ability of a GIS to handle 3D/4D data at all and to provide for interoperability and data interfaces with environmental models. To investigate into what GIS might be suited for best interaction with environmental models, in (COORS, ZIPF, 2005) a market overview to 3D/4D GIS is given, also an updated online market overview is featured (FH MAINZ)

4.6 *Boundaries between ASIS and GIS*

It is important to understand the developments and viewpoints of the atmospheric sciences, in addition to the perspective of geoinformation sciences. An insight is given by (NATIVI, S. et al) though with the focus on the differences in data models:

In the atmospheric sciences both observational instrumentation and numerical forecasting technology have been improving so rapidly that techniques to manage and make use of the resulting data are struggling to keep pace.

As well the increase in resolution leads to the increasing demand to cross the borders between the GIS and ASIS (Atmospheric Science Information Systems) communities. However differences in the way the two communities think about their data results in different ideas how integrated analysis and display of datasets should perform. The issue of distinct viewpoints on dimensions in space and time between the two communities has traditionally led to - in some cases dramatically - differing data systems.

Distinguishing the notion “Geographic information” by phenomena and locations, AS (atmospheric science) datasets are used to capture and represent information to complex observed phenomena. Location aspects of these datasets are traditionally kept simple, as resolution and geo-collocation have been inaccurate for many satellite

datasets. Observed phenomena are rather imprecisely positioned towards structured regular grids over the Earth, seldom containing metadata on reference system or geodetic-datum. Time being essential to understand phenomena is commonly treated either by running clock (experiment time) or epoch based (calendar time).

In GIS the location has the same importance as its phenomena itself: the most popular structures for representing observed phenomena (e.g. geometric entities such as point, line, polygon, etc.) are explicitly positioned over the earth to enable for complex and precise spatial topology-based analysis. As discussed above GIS are traditionally not very performing in managing time. If time is supported at all, they support only the epoch based (calendar time) approach.

An untypical component of GIS datasets is what in the AS is known as aggregation structures. AS datasets generally contain complex information describing complex phenomena. Aggregation structures enable to analyse data at the desired level of detail. In GIS-diction the idea of "various views made up of various thematic layers" hints at how aggregation structures of the AS work in such complex datasets.

4.6.1 ASIS data models such as netCDF and VisAD

According to (NATIVI, S. et al) comparable to the general feature abstract data models used by OpenGIS (statement by the author: now the Opengeospatial Consortium (OGC)) and ISO TC 211 by the GIS community, some of the most common data models for the AS community are i.e. netCDF and VisAD.

The VisAD data model assumes that data objects are approximations to mathematical functions. Data objects can be cartographically interpreted by an image as a functional relation from (latitude, longitude) i.e. pairs to radiances. Additionally a time sequences could be realized comparing the above data objects over time.

The netCDF data model contains dimension, variable and attributes relating to these dimension(s) and variable(s). The attributes are attribute objects characterized by a name and identified by an ID value. These attribute objects are combined together in an array-oriented dataset to analyse the data.

Comparing these models to the GIS “general feature model” the following differences occur:

- o The geometries of objects in VisAD and netCDF are implicit as these are made up of regular and irregular multidimensional grids or sampled fields.
- o Different root concepts: data objects in AS models, feature objects for GIS models

International initiatives such as ISO and OGC have released geo-information standard models, which conceived to support general interoperability. Such it should be possible to overcome the differences in the data models described.

Concerning data models the GIS-concept of coverages by definition already contain what is needed in the AS. Coverages are vector-based models in which features contain multi attributes within their spatiotemporal domain. However the complex data structures of AS data require for a simplification to be fully interoperable in the GIS data environment.

With NcML-G_{ML} an encoding of netCDF datasets using GML (Geography Markup Language) has been realized by (BIGAGLI et al):

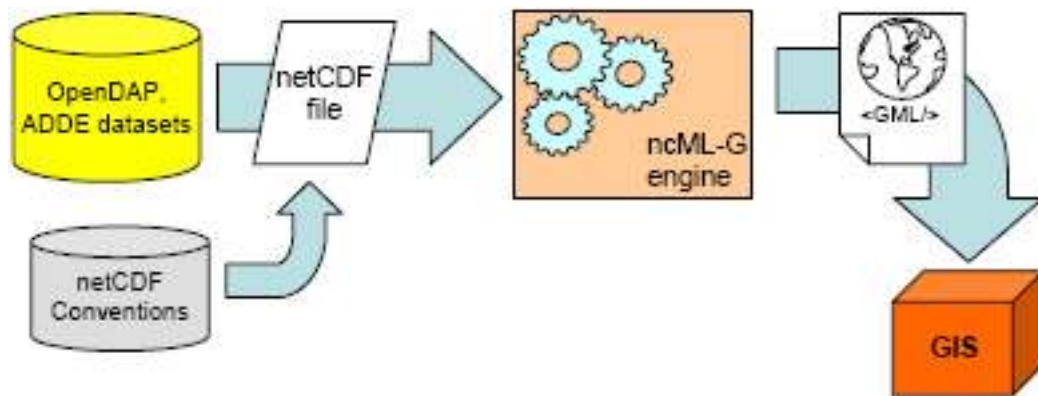


Figure 18: NcML-G_{ML} - encoding of netCDF datasets using GML

Also a prototype Web Coverage Service (WCS) has been set up by (CARON, NATIVI) that can read datasets through the netCDF API and translates them into GeoTIFF files, which can be imported to GIS. The specification to Web Coverage Services (WCS) stems from the efforts of the OpenGIS Consortium (OGC): a Web Coverage Services is a client-server-protocol with enough generality to handle gridded and image type scientific datasets.

Within the project of AtmoGIS/VirGIS (BERNARD) an extension to ArcGIS 3.2 has been realized for the import of net CDF offering comfortable visualization and statistical analysis of the data by choice of theme, height levels and time:

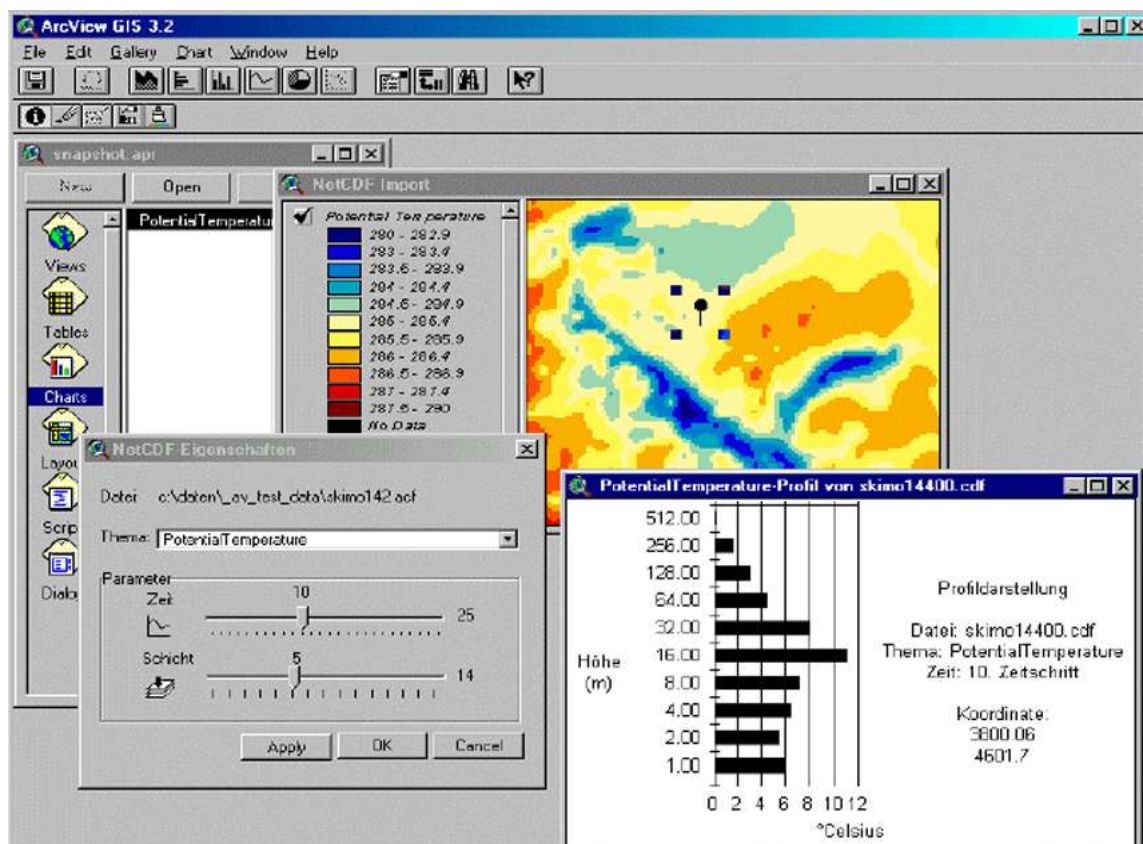


Figure 19: multilevel and multitemporal display and analysis of netCDF in GIS

Actually available display and analysis tools that read netCDF files are suggested in (NOAA-CIRES Climate Diagnostics Center). It would be very desirable to find GIS, as demonstrated in the above approach, listed as well.

However more favorable than the approach of translating netCDF into individual GeoTIFFs (raster dataset) for multiple vertical levels and time, would be the conversion to true multidimensional coverages (vector datasets).

4.7 Future synthesis of GIS and ASIS by OGC sensor web?

The idea to the concept of sensor web stems from the science and techniques of extraterrestrial exploration. It is very expensive and heavy in air cargo, to send sensor-equipped-vehicles to other planets. Their radius of exploration is limited.

With the advanced techniques of manufacturing sensors economies of scale are pushed, that ideally it would be cheaper to launch multiple tiny sensors spreading all

over a planet. Then all sensors would form a network in which sensed data is interchanged and also the individual sensors could be controlled.

An initiative at the OGC has been taken to promote this idea and to start the necessary process of standardization for the realization of a sensor web not in space but yet on the Earth.

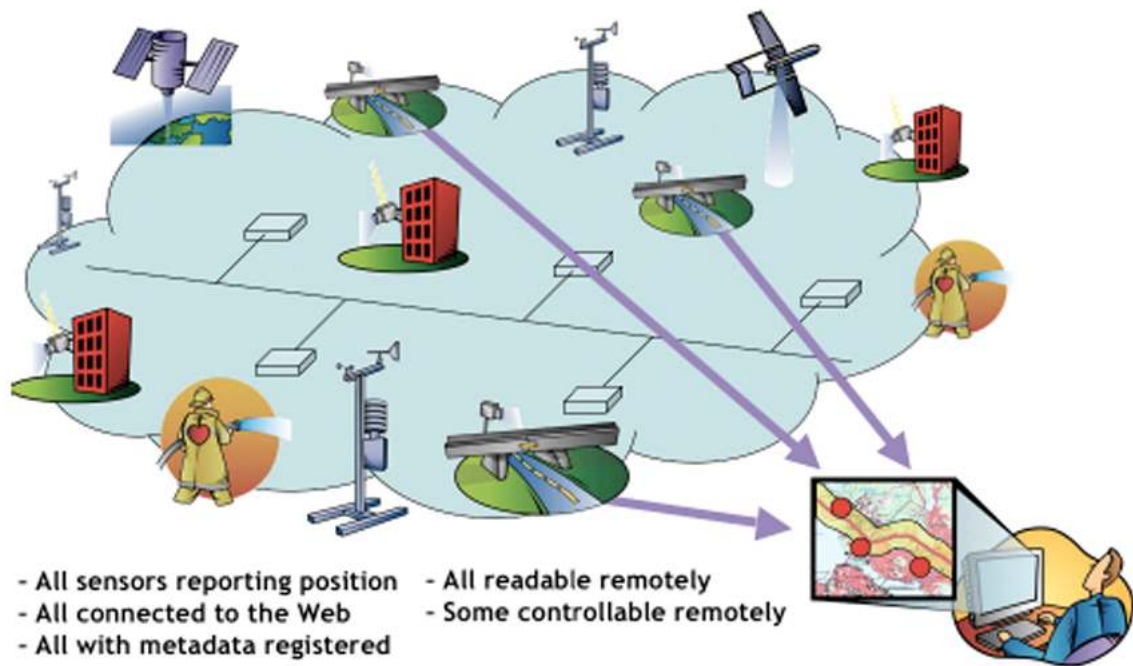


Figure 20: Sensor Web Concept

The "OGC Sensor Web Enablement: Overview and High Level Architecture" has been released in the July of 2006 (OGC, 2006) which is summarized by the press release:

"A sensor network is a computer accessible network of many spatially distributed devices using sensors to monitor conditions at different locations, such as temperature, sound, vibration, pressure, motion or pollutants. A Sensor Web refers to Web accessible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application programs interfaces (APIs).

In the OGC Sensor Web Enablement (SWE) activity, members of the OGC are defining, testing, and documenting a consistent framework of open standards for exploiting web-connected sensors and sensor systems of any type. Sensor Web Enablement presents many opportunities for adding a real-time sensor dimension to the Internet and the Web. This has extraordinary significance for science, environmental monitoring, transportation management, public safety, facility security, disaster management, utilities' SCADA operations, industrial controls, facilities management and many other domains of activity. The OGC voluntary

consensus standards setting process coupled with strong international industry and government support in domains that depend on sensors is expected to result in SWE specifications that will become established in all application areas where such standards are of use.”

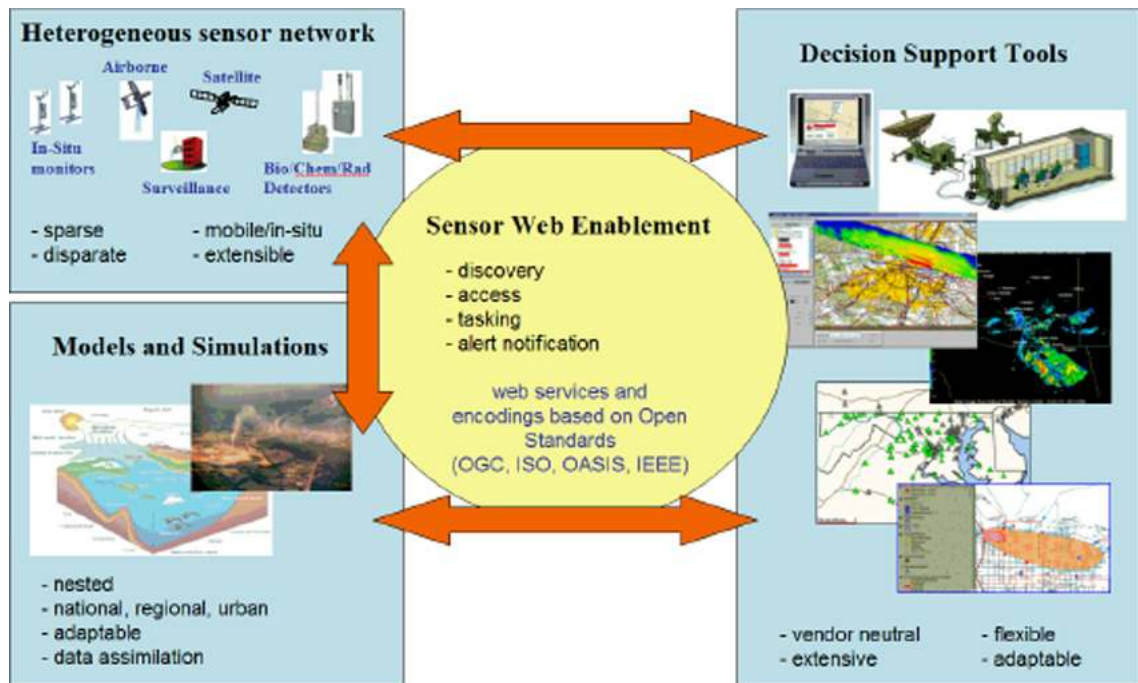


Figure 21: Models and Simulations within the Sensor Web Concept

As the limitations of GIS in environmental modelling and the difference in data models between the GIS and ASIS communities have been discussed, the OGC Sensor Web Enablement is of great potential to bridge the gaps between GIS and Environmental Modelling in the future:

- o Sensors are exactly 3dimensionally positioned in space, at a given XY position numerous sensors may exist for various heights Z (i.e. wind measuring mast has anemometers at 10m, 30m and 60m)
- o Sensors produce multitemporal data. This data is stored so that via web-access historic to present data shall be made available.
- o Not only sensor’s measured data but also model and simulation output data will be contained in the Sensor Web (i.e. by use of NcML-G_{ML}).
- o Environmental data is interlinked and interoperable through a network as discussed above

This chance for bringing atmospheric sciences and geo-sciences together will hopefully be utilized not only by the geographic communities but the atmospheric (as well as many other) communities as well. The support of the ASIS community is essential, as their atmospheric data has to be transferred and offered in the data models supported by the Sensor Web High Level Architecture.

This implies the hope that the development of GIS will follow this technological advancement towards true 3D/4D interoperability, visualization and more over multidimensional analysis capabilities. Readily accessible atmospheric data to GIS directly from the Web as today cartographic data is available by the techniques of web-map-services (WMS) and web feature services (WFS) would be not only of invaluable benefit to scientists but to all people concerned with questions about their environment.

Last but not least it has to be mentioned that wind turbines are globally spread sensors as well, not only with respect to generation of data but also to analysis such as i.e. large scale area short-term production forecasting or ad hoc verification of production performance.

5 Choice of a physically based meteorological model

With the decision on the application of a physically based atmospheric model the main differentiation between these is their scale, which is described by (MARBURG-GRUBER, 1998):

Scale:	Macro Scale	Meso Scale	Micro Scale
Area extent (length)	500km to hemisphere	2 km to 500km	10m to 2 km
Resolution	100km to a couple of 100 km	10m to a couple of km	1m to 10m
Systems	Weather determined by high and low pressure areas	Effects of macro scale high and low pressure areas reduced to constant flow in meso scale. Model area to great to respect individual surface structures. Relief influences wind flow and surface structure is represented by roughness.	Respect of individual surface structures such as i.e. buildings, trees, dams, rivers, cliffs
Applications	Numerical weather prediction, research on global climate change	Avoidance of air pollution, wind energy site evaluation, decisions in city and regional planning	Dispersion of traffic emissions in street canyons.

Table 1: Scales of physically based atmospheric models

While atmospherical models can be differentiated by various other factors, by this distinction a focus is set to mesoscale models for windfield modelling in wind energy, since usually an area extent by length of 40-80 km is respected.

The development of mesoscale models in Germany is stated by (GROSS, 2002):

“Within the DFG research program ... the development of numerical mesoscale models has been supported which are suitable to simulate boundary layer phenomena with an appropriate resolution in space and time. Due to the small scale features only nonhydrostatic models are applicable in this scale.

Such a model development initiative was necessary, since the numerical weather prediction models used routinely are, still today, not suitable to resolve the complete spectrum of the mesoscale in the daily forecast. Beginning with the DFG research Program 1978-1985, different groups started to develop the requested nonhydrostatic mesoscale models. At this time Germany had the highest density of nonhydrostatic models worldwide. Nowadays the level of development of this type of models is extremely high and together with the experience gathered over the last decades, nonhydrostatic models are extremely valuable tools for studying and solving of a wide variety of environmental problems in the atmospheric boundary layer. ...It is worth pointing out that every other nonhydrostatic mesoscale model with a comparable stage of development should produce similar results. Especially in Germany there is a long history in such a model development resulting in a wide variety of models ...”

5.1 Overview on available models

Various modelling packages are available: models in all scales are listed and described in (STADTKLIMA). In searching for a suited model, the author limits his choice to those of knowledge having been applied to wind energy:

Title	Programmsystem WIEN (Windenergy), based on WiTraK	FITNAH	KAMM	METRAS (PC)	GESIMA
Sub title	menu-controlled program system for wind turbine site evaluation in structured terrain	Flow over irregular terrain with natural and anthropogenic heat sources	Karlsruher atmosphärisches mesoskaliges Modell	Mesoskaliges Transport und Strömungsmodell (mesoscale transport and fluid model)	Gesichtlicher Simulationsmodell für die Atmosphäre
Availability	WIEN: Will be made available when further development is completed. WiTraK: Available for scientific purposes	Not available to public	No detailed information available	METRAS PC is a simplified Public Domain version of METRAS set of models	Source code available for scientific purposes, licence to be requested from GKSS Research Centre
Description	Based on WiTraK, toolkit specialized for Wind Energy: includes statistical evaluation of the 3D-windfileds for output of wind frequency distribution.	---	Non-hydrostatic 3D modell	---	Non-hydrostatic mesoscale model suited for the simulation of atmospheric flows over structured terrain
Platform	MS-DOS based: Windows	---	Supercomputer	Windows	---
Scale / Resolution	Micro to meso scale: typically 100 - 500m for windenergy	---	1 - 5 km	couple of 10m - 10 km	100m - 5 km
Timerange	---	---	---	Stationary and instationary (max. 2 days)	Days to weeks
Development	T. Sperling, R. Hänsch, M. Kerschgers	G. Gross (1992)	Adrian (1994)	Schlünzen (1996)	Kapitza and Eppel (1992)
Institution	Universität zu Köln, Institut für Geophysik und Meteorologie	Institut für Meteorologie und Klimatologie Universität Hannover	Institut für Meteorologie und Klimaforschung, Universität Karlsruhe	Meteorologisches Institut Universität Hamburg	GKSS - Institute for Coastal Research Abteilung Statistik und Modellbewertung (KSS)
WWW	www.meteo.uni-koeln.de/meteo.php?show=De_Fo_Nu (30.08.2006)	www.muk.uni-hannover.de/forschung/gross/ (30.08.2006)	www.imk.uni-karlsruhe.de/ (30.08.2006)	www.ru.uni-hamburg.de (30.08.2006)	www.gkss.de/pages.php?page=k_models_gesima.html&language=d&version=g (30.08.2006)

Table 2: Overview of models applied to wind energy

5.2 Choice of model METRAS PC

According to (BOEKELMANN, DIJK, RIENTJES, 1999) "before choosing a model, the following few questions should be answered:

- What is the purpose of the model
- What is the degree of accuracy required for the model results?
- Which are the temporal and spatial scales of the model?
- How many data are available?
- Which are the computing hardware requirements"

The main factors, leading to the choice of METRAS PC as model for this project are:

- PC / Windows favoured as to fit to already existing environment
- ASCII import and export files as a base to exchange data with GIS
- Competence and eventual support in local reach to the author, as being able to speak to people how develop and apply the model
- Mesoscale models are comparably similar in results (GROSS, 2002)
- Documentation available
- Tested with various climates and regions of the world

5.3 METRAS PC – description of model

"Based on the mesoscale model METRAS, a user-friendly version of the mesoscale transport and fluid model METRAS has been developed for PCs. METRAS PC² is a 3-dimensional nonhydrostatic mesoscale model. METRAS PC calculates meteorological quantities such as horizontal and vertical winds, pressure, temperature and humidity with fixed boundary values or by calculating and including the diurnal changes of surface temperature and humidity. The model can be applied over complex terrain using nonuniform grid spacing in all three dimensions. The model results can be used to drive pollution transport models (e.g. Lagrangian particle models, kinetic simulation particle models, Eulerian dispersion models). Thus, the model may be used as a meteorological pre-processor for pollution transport models. ... METRAS PC has been evaluated." (METEOROLOGICAL INSTITUTE UNIVERSITY OF HAMBURG)

While in the METRAS version cloud and ice building processes are respected this is not implemented in METRAS PC Version 1.0. (SCHLÜNZEN, BIGALKE, 1998). An

² METRAS PC (Version 1.0, for windows PCs) is a public domain program, developed in 1998 by K.H. Schlünzen, S. Dierer, H. Pankus (Meteorological Institute, University of Hamburg) and K. Bigalke (METCON Umweltmeteorologische Beratung, Pinneberg) in a project funded by the Umweltbundesamt (Berlin) under grant number FE 104 04 354.

alarm in regarding such events is given to the user to be cautious in the analysis of results.

Though the title of this thesis states the phrase of turbulences, turbulence intensities are neither analysed nor visualized, since turbulence data is not an output option in METRAS PC Version 1.0. This is included in the METRAS model though. It needs pointing out, that turbulence behaviour and its effects are respected adequately by the model by turbulence schemes (SCHLÜNZEN, BIGALKE, 1998):

- Subscale turbulent flows are parameterised by a first order closure. These respect subscale vegetation features by parameter survey.
- Above the prandtl layer turbulent flows are calculated for at neutral and stable stratification by a "mixing length approach" and for labile stratification by a "counter gradient scheme".

Therefore the turbulence information can be interpreted as of being included within the modelled wind intensity and direction (horizontally and vertically) information". In the broad controversy topic of turbulences this interpretation is supported by the statement (SCORER 1998): "... we arrive at the idea that there is in existence a mean motion with some fluctuations added. The mean motion is fully described, but of the fluctuations we only have statistical information."

6 Squamish wind field simulation and GIS visualization

Within this chapter the procedure towards the simulation of 3D wind fields, their validation and the calculation of wind farm yields as well as the visualization of the windfields are described.

To retain the focus on the main project's procedures, detailed work steps are embedded to the text but by separate excursions.

6.1 Principle of wind field modelling

The illustration by (SPERLING, HÄNSCH, KERSCHGENS, 1999) is suited to explain the main processes briefly:

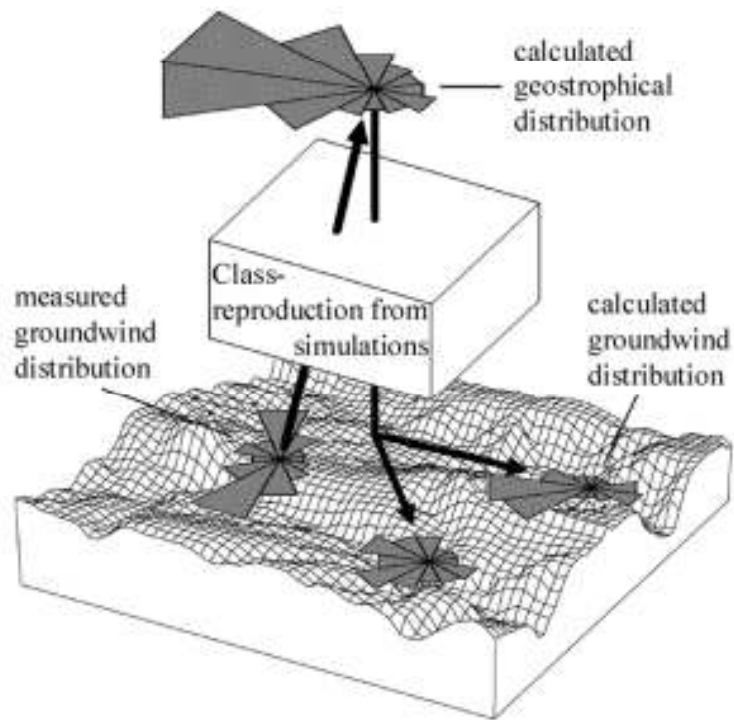


Figure 22: Diagram of exhaustive wind climatology calculation

While in (SPERLING, HÄNSCH, KERSCHGENS, 1999) measured groundwind data is used to calculate for geostrophical wind distributions, in the case of Squamish information on geostrophical wind data is used available from the "NCEP/NCAR Reanalysis 2 Project". So in this case with the geostrophical wind data as the drive to the mesoscale model the output is the calculation of groundwind distributions.

6.2 Implementing project – software applied

The software used for the project pre- and post processing of spatial data is ArcGIS 8.3 with the extensions Spatial Analyst and 3D Analyst.

The landuse classification from satellite imagery is performed with the software ERDAS Imagine 8.6

The pre- and post processing of meteorological data is exercised with the spreadsheet calculation software Microsoft Excel. The conversion of upper air climatic data from netCDF files to ASCII-text-files is achieved by software LeoNetCDF 1.11

The analysis of wind distribution (windrose diagrams) and calculation of wind farm yield is performed with the wind energy package WindPRO 2.5.

3D windfields are simulated by the mesoscale model METRAS PC Version 1.0.

6.3 Geodata

Canada's policy in distribution of geodata is very generous: all maps required for the project have been available at no cost at all and immediately downloadable from the worldwide web. Only the Landsat 7 satellite imagery scenes required a processing time for being made available for download (at no cost) with the request for all image channels included.

The orthofotos used within the project were acquired by a demo-account of DigitalGlobe's Globeexplorer for instant web-access.

A word on coordinate systems prevailing to the area: Most geo-data is available either in geographic or projected UTM systems with the datum of WGS 84 and NAD 1983. Conversion of projections with the reprojection tool in ArcGIS has been done using the transformation *"Convert from GCS_WGS_1984 to GCS_North_American_1983 using "NAD 1983_To_WGS_1984_1"* and vice versa.

It is worth knowing that (SCHWARZ, 1989) both the North American Datum of 1983 and the World Geodetic System of 1984 (WGS 84) of the U.S. Defense Mapping Agency (DMA) "were defined (in words) to be geocentric, and oriented as the BIH Terrestrial System. In principle, the three-dimensional coordinates of a single physical point should therefore be the same in both systems; in practice, small differences are sometimes found. ..."Small" differences must be properly understood here. The actual difference between coordinates may quite possibly be a meter or more."

6.3.1 Topographic maps of scale 1:250,000 and 1:50,000

An overview of Canadian Topographic Maps including metadata is available from the Centre for Topographic Information of Natural Resources Canada³.

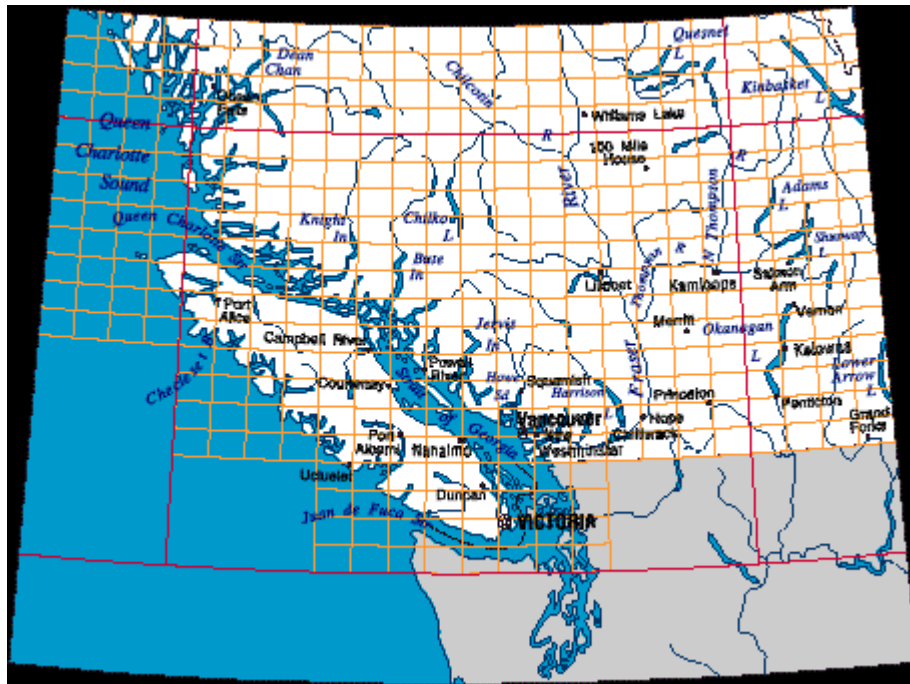


Figure 23: overview on topographic maps by “Canadian NTS System Index Maps”

The so-called “toporama” maps are available for download in a reduced quality compared to the printed map editions at the scale of 1:250,000⁴ and at the scale of 1:50,000⁵ for the relevant area by the longitudinal identifier number “9”

The instructions⁶ followed for bulk download and batch assignment of geospatial reference a large area of topographic maps can be covered within reasonable effort.

Excursion: Preparation of Toporama 250 and Toporama 50 topographic maps

- A) Bulk downloading referred to as “mirroring websites” of all 1:50,000 maps between 128° and 120° longitude with software WinHTTrack Website Copier 3.23⁷.
- B) Delete all map tiles which are not of area “92” (northern areas such as 93, 94, etc). Area “92” consists of 198 map tiles at the scale of 1:50,000 and of 14 map tiles at the scale of 1:250,000 in the .gif format
- C) Batch conversion of all gif-files to tif-files (LZW) by the software Convert Image⁸.

³ Canadian NTS System Index Maps <http://maps.nrcan.gc.ca> (30.08.2006)

⁴ Toporama 1:250,000: <http://toporama.cits.nrcan.gc.ca/images/b250k/09/> (30.08.2006)

⁵ Toporama 1:50,000: <http://toporama.cits.nrcan.gc.ca/images/b50k/09/> (30.08.2006)

⁶ <http://members.shaw.ca/pdops/toporama.html> (30.08.2006)

⁷ WinHTTrack Website Copier 3.23: <http://www.httrack.com/index.php> (30.08.2006)

- D) Georeferencing world-files for the toporama maps are - fortunately enough - downloadable at⁹, however, exploring the data with ArcCatalog it turns out that the world-files contain the definition of extent, yet not the projection.
- E) Batch assign projection in ArcCatalog GCS_North_American_1983.prj with the tool by "AssignProjection_vika_9.0"¹⁰
- F) Result is all 198 map tiles (1:50,000) and 14 map tiles (1:250,000) in ArcMap.

6.3.2 Canadian Digital Elevation Data scale 1:250,000 and 1:50,000

Canadian Digital Elevation Data is provided by Geobase, an initiative overseen by the Canadian Council on Geomatics (CCOG)¹¹. The elevation data in the scales of 1:250,000 and 1:50,000 is organized in map-tiles according to the topographic maps, with reference to the "Canadian NTS System Index Maps":

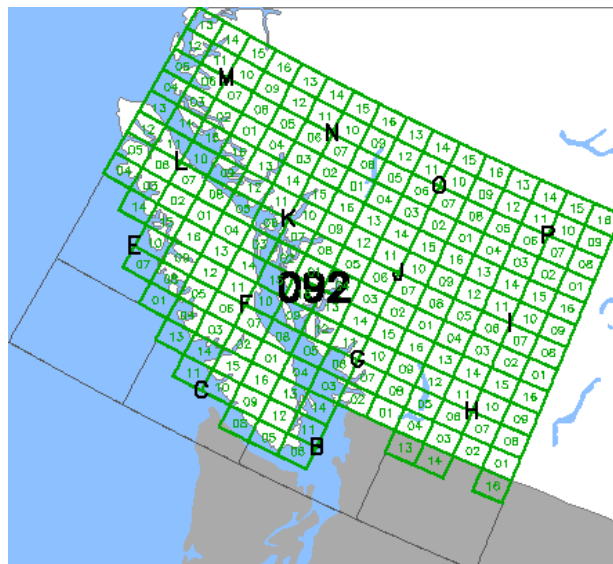


Figure 24: CDED 50 map-tile overview of relevant area "92"

Excursion: Preparation of CDED 250 and CDED50 digital elevation data model

- A) Load terrain data into public domain software "3DEM Terrain Visualization"¹², save as single Tiff-file

⁸ Convert Image: <http://softinterface.com/Convert-Image/Foreign/German/JPG-umwandeln.htm> (30.08.2006)

⁹ <http://gis-lab.info/qa/tfws-toporama.html> (30.08.2006)

¹⁰ "AssignProjection_vika_9.0": Viktoria Magnis, <http://arcscrips.esri.com/details.asp?dbid=13555> (30.08.2006)

¹¹ Geobase: <http://geobase.ca/> (30.08.2006)

¹² 3DEM Terrain Visualization: www.visualizationsoftware.com/3dem (30.08.2006)

- B) In ArcMap, add data "CDED50_AI.tif", conversion of floating point GRID to integer by raster calculator formula $\text{int}([\text{CDED50_AI.tif}] + 0.5) / 0.5$ is added as $\text{int}([\text{CDED50_AI.tif}])$ only truncates, but doesn't round.
- C) By Spatial Analyst: convert raster to point-features, output name CDED50AI.shp
- D) Reprojection from geographic (GCS_WGS84) to UTM (NAD 1983) Zone 10 by ArcToolbox's Projection Wizard. Check with other maps for correct position.
- E) Result is point-shapefile "CDED_utm.shp"

6.3.3 Orthofotos for derivation of significant buildings & DSM

Orthofotos for Canada are available from the National Air Photo Library¹³ and can be searched for and ordered via the map tool "NAPL-Online". Searching by the NTS Map-index "092G11" an orthofoto is available at a scale of 1/60,000 from a flight in 1993.

As not free of charge, limited in area to the picture ordered and facing delivery time, preference is given to a test of DigitalGlobe's GlobeXplorer's ImageConnect extension for ArcGIS¹⁴ by which orthofotos, fittingly to display extent, can be directly downloaded while working within an ArcGIS project.

6.3.4 Landsat 7 satellite imagery for classification of landuse & DSM

Maintained by the Natural Resources of Canada and provided at Geogratias¹⁵ Landsat7 satellite imagery is available to the public free of charge, covering the entire landmass of Canada.

All available Landsat 7 scenes are nearly cloud-free, precision orthorectified and of high actuality. Landsat 7 scenes in the visible range RGB-channels can be accessed directly via the internet, while all channels of the Landsat 7 scanners are provided by request via web-access after a custom set-up of one day.

As Squamish is located in the corner section of the potential scenes, four overlapping scenes are acquired:

¹³ National Air Photo Library: http://airphotos.nrcan.gc.ca/photos_e.php (30.08.2006)

¹⁴ GlobeXplorer: <http://www.globexplorer.com/products/imageconnect.shtml> (30.08.2006)

¹⁵ Geogratias: www.geogratias.ca (30.08.2006)



Figure 25: Landsat 7 displayed as R: 5 (infrared), G: 4 (near infrared), B: 3 (blue)

By these scenes an area of approx. 280 km in East West and approx. 320 km in North East direction is covered, allowing for an investigation radius around Squamish of approx. 130 km. Landsat 7 scenes are high-resolution satellite imagery: a resolution of 30m is featured for all but the panchromatic channel with a more advanced resolution of 15m.

Yet not as high in resolution as orthofotos or as by today (commercially) available very high resolution satellite imagery, it is not only to view what the project area and its far surroundings (bearing in mind the great extent of the Landsat 7 scenes) looks like for a good impression, but furthermore with visible, infrared and thermic bands available, the actual landuse of the project area can be classified.

From the landuse classification the topography's surface structure is an essential influence factor to the winds behaviour. Wind over the sea flows very freely opposed to rocky alpine surfaces creating turbulences and slowing down the wind

tremendously. Thus what will be derived from the landuse map is a so-called roughness map, in which roughness classes are assigned to landuse classes as input required by Metras PC.

The mesoscale model respects the effects from daily / nocturnal temperature changes due to the albedo of the individual landuse, which is required for the simulation of thermic effects, also

6.3.5 Landuse-map: classification of Landsat 7 satellite imagery

The choice, that each of the four scenes is classified at their full extent of roughly 180 x 180 km, results from not to limit data availability should a limited model area not lead to desired results.

The classification is optimized towards the application for "wind energy" concerning surfaces roughness and thermic relevant albedo of landuse. Compared to landuse classifications from satellite imagery for other purposes, relatively few classes are needed while manual editing is required to distinguish i.e. in between the class of "rock and concrete sealed" for very flat and "windy" airport runways opposed to rocky mountain cliffs causing strong turbulent flows.

The classification for landuse is performed with the software ERDAS Imagine 8.6 following the processing steps described (ERDAS Inc., 1997). The main topics within the classification process are covered within the following excursion:

Excursion: topics within unsupervised classification of four Landsat 7 scenes

- A) Though better results concerning accuracy are possible by the method of supervised classification for classification of a full Landsat 7 scene this method is not suitable due to computation time involved with each selection and definition of individual classes (Celeron 2,6 GHz, 512 MB RAM: processing time > ½ hour)
- B) For the area size required, the method of unsupervised classification is suitable mainly due to adequate processing time. Experiments with i.e.30 classes "unsupervised" computed do not resolve classes adequately. 120 classes are finally chosen, as the effort towards definition on individual's class meaning is acceptable towards generally good results concerning class resolvment.
- C) Major-classes defined are: water (for Sea, lakes and rivers), woods (including various tree types, mostly forests), grass (for grasslands including alpine meadows), rock (for rock covered surface in the alpine as well as concrete covered surfaces and developments by

civilization), snow. Major classes are few as minimized towards the need of “wind-energy roughness map”.

D) Classification of sub-classes by training areas. Problems seen will be left to postprocessing by GIS:

“non-unique class 1”: water where very shallow areas are put in same sub-classes with forest.

“non-unique class 2”: water where very shallow areas as well as high portions of minerals in water, are put in same sub-classes with rock

“non-unique class 3”: snow below snow level, i.e. for “B.C. Place” stadium, but also partially within Squamish river

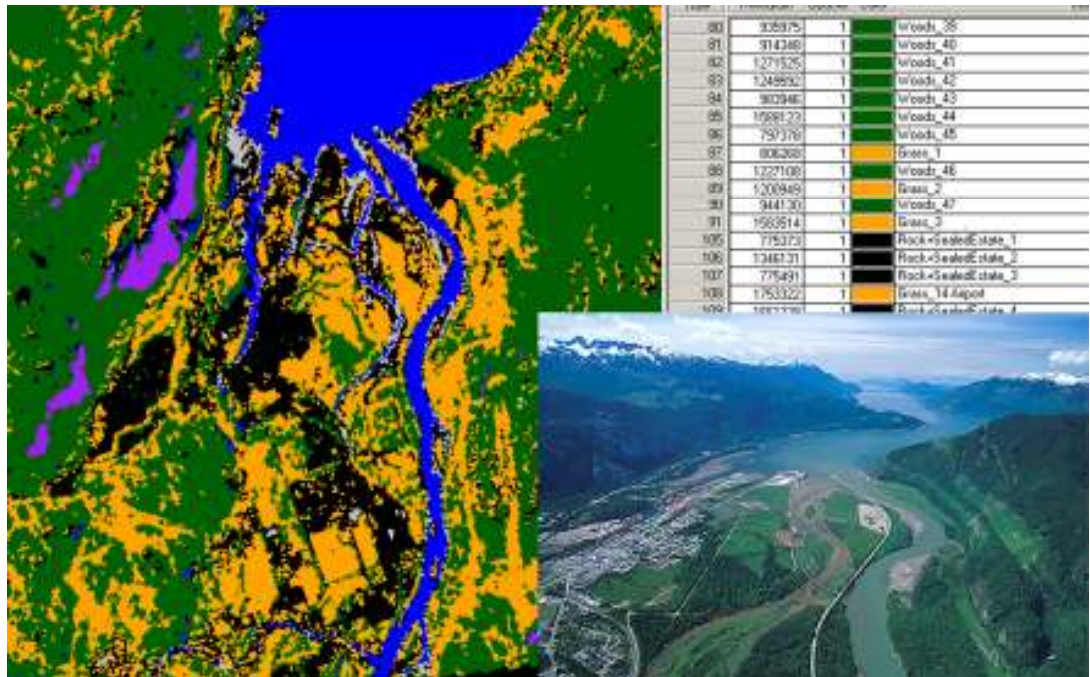


Figure 26: Training Area Squamish, problem “snow” in Squamish river

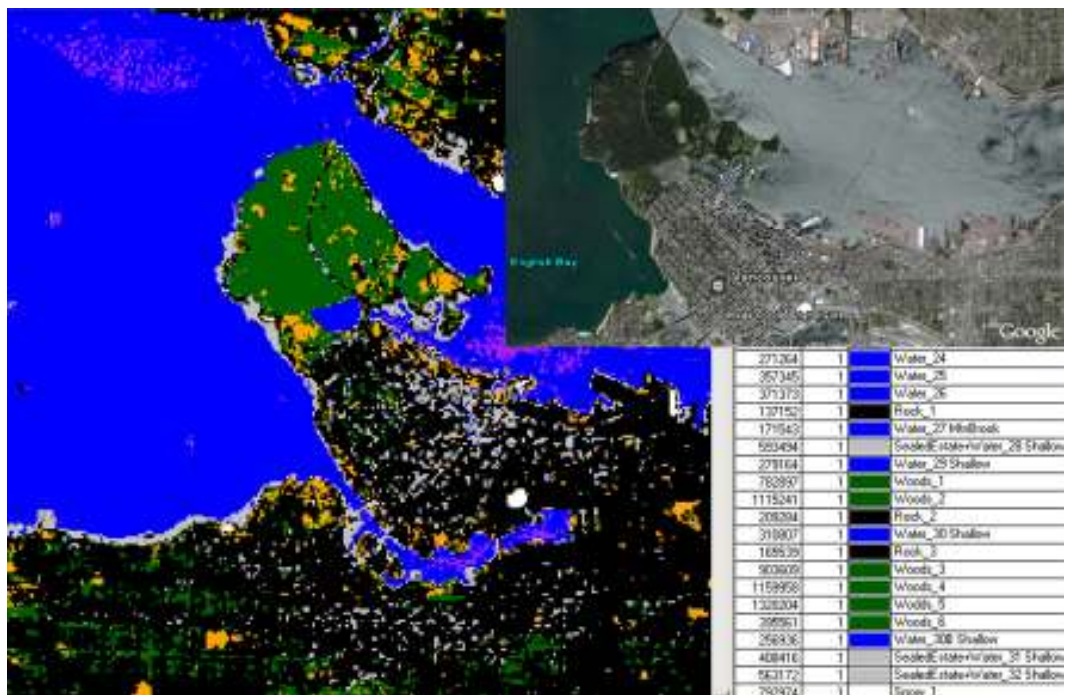


Figure 27: Trainig Area Vancouver Downtown and Stanley Park

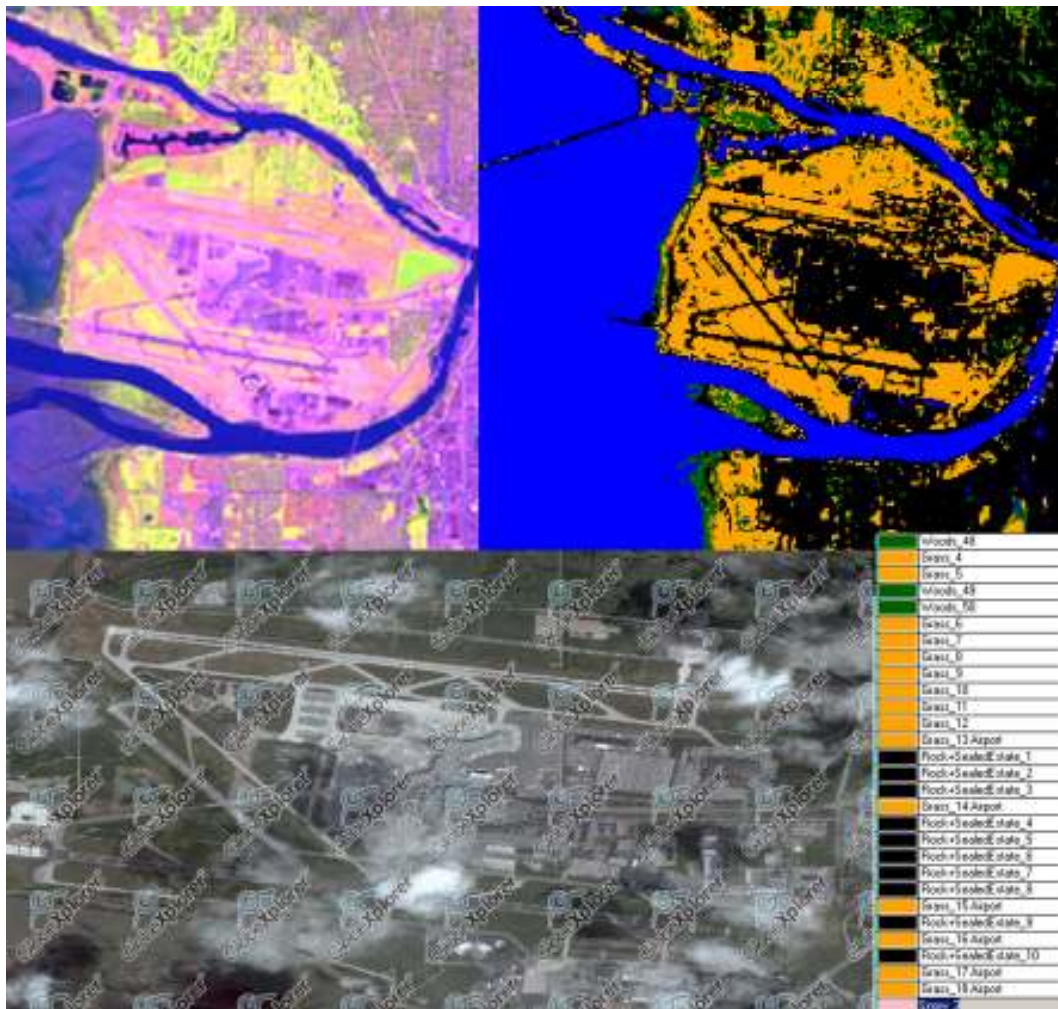


Figure 28: Training Area Vancouver Airport

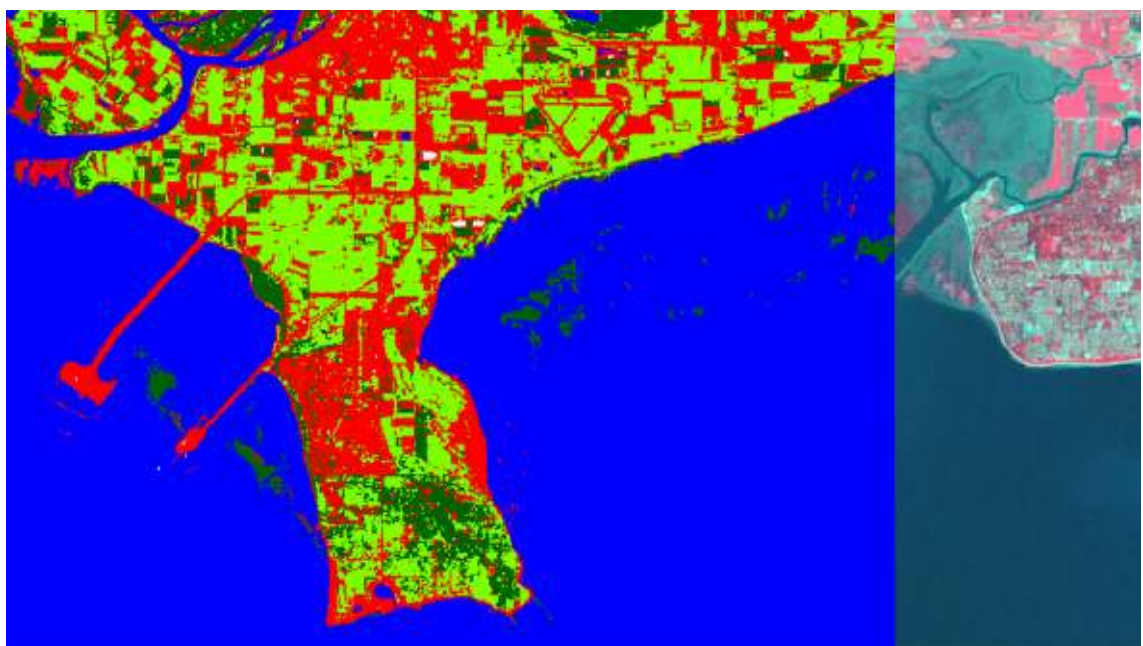


Figure 29: Training Area South Delta, close to US-border.

E) Reclassifying of all sub-classes to final classes (“recode”) results in full scene, i.e Vancouver region:

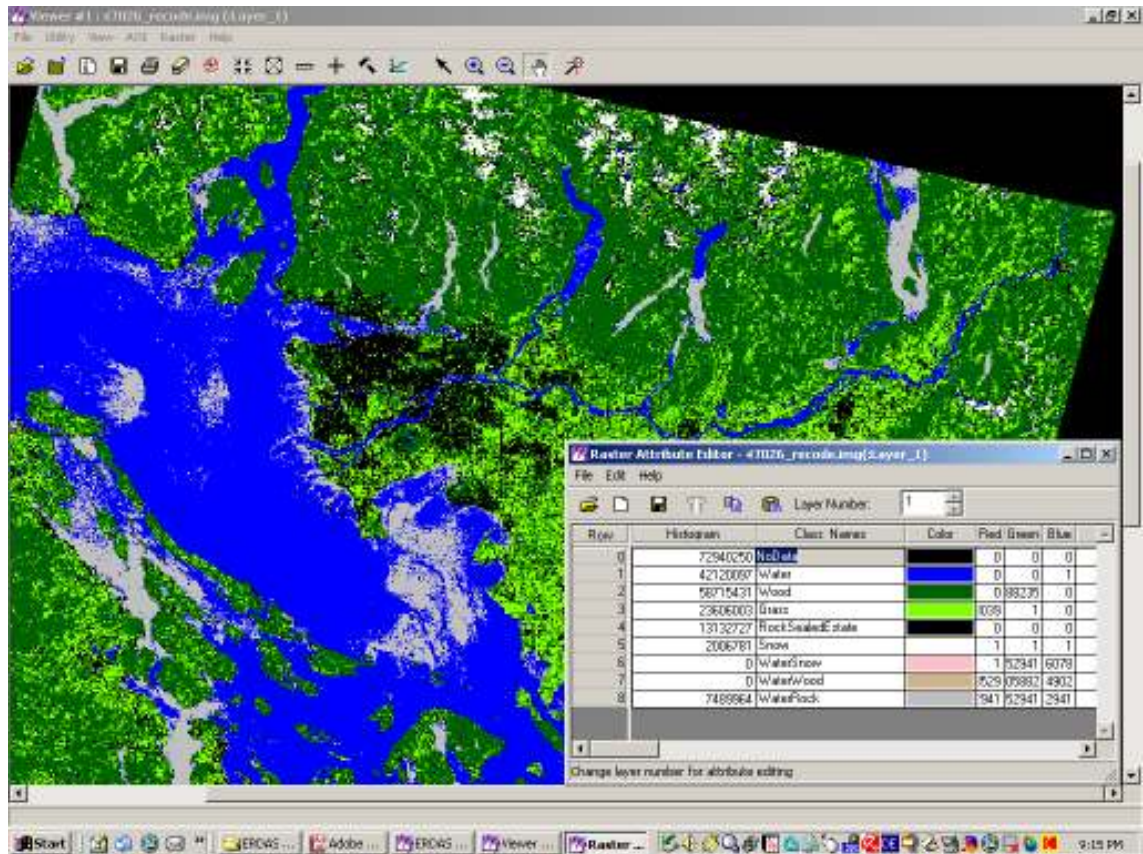


Figure 30: Full scene „47026“ recoded

- F) Repeat procedure for other three scenes. Finally combination of all four scenes to one by mosaic tool.
- G) Result is a landuse map in a resolution of 15 m from the actuality of 2000 to 2001 surrounding Squamish within a radius of 130 km.

Due to the issue of non-unique classes, which stem from the unsupervised classification further processing is required before the final map of landuse can be derived. Non-unique classes have been coded for by distinct class-ids to be subdivided by GIS.

Excursion: post-processing of non-unique class “water” by water surfaces from toporama 50 maps

- A) Reduction of extent to map area available from prepared Toporama 50 map tiles. Creation of a polygon-shapefile "squamish_AOI.shp" by which to clip Landsat-7 scene to area of interest using "Multi-Bands Raster Clipper v1.0"¹⁶.

¹⁶ "Multi-Bands Raster Clipper v1.0": Min-Lang Huang, <http://arcscripts.esri.com/> (30.08.2006)

B) Non-unique classes relating to water (landuse classification converted to polygons):

- "water vs. snow" (number of features = 2543),
- "water vs. wood". (number of features = 19.017),
- "water vs. rock"(number of features = 109.844)

Instead of manually by use of Editor correcting these “non-unique” classes the shortcut to this issue is deriving water-surfaces by the Toporama 50.000 maps and then using the Raster Calculator (map algebra) to extract the water surfaces from these classes. The polygons left not to be water surfaces automatically are then reclassified to the appropriate gridvalue (i.e. snow).

C) Derivation of water area from toporama 50 by mosaicking of map tiles using "RasterMerge for ArcGIS 8.x"¹⁷, conversion to polygon features. . Identifying gridcode-attribute for water-surfaces is "127". Export of features selected by this attribute to shapefile of water surfaces "top50water.shp"

D) Use of editor-tools to merge Polygons where applicable and to eliminate place names, signs, etc. which stem from toporama-map's symbolism. Reconversion to raster.



Figure 31: Water surfaces from toporama 50,000

E) Before summarizing the “water-surfaces map” to the “landuse-map” using the raster calculator a reclass of water-surfaces from grid-value “127” to “100” makes the non-unique classes easily distinguishable.

¹⁷ "RasterMerge for ArcGIS 8.x": Thomas Emge, <http://arcscrips.esri.com> (30.08.2006)



Figure 32: Sum of "water-surfaces map" and "landuse-map" before reclass

F) Renewed reclassifying as indicated in the above figure, results in the desired cleaned-up landuse-map.

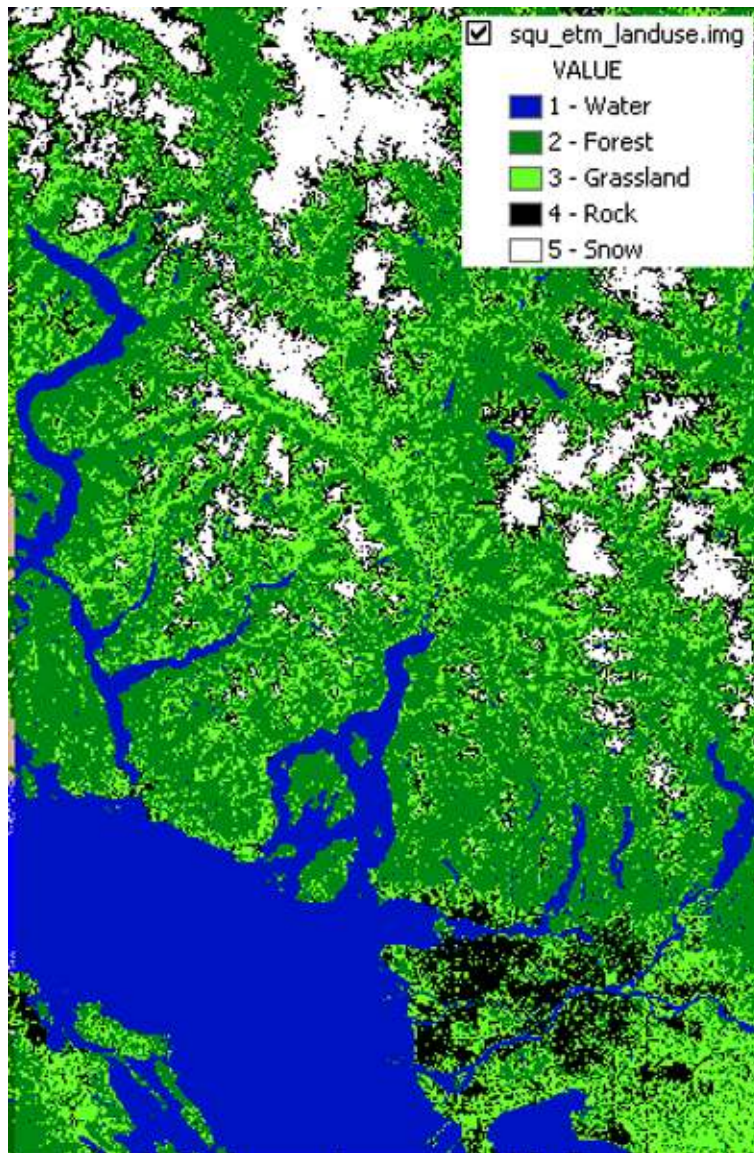


Figure 33: post-processed landuse-map

As the wind effects at the site of Squamish are of higher interest than for the greater surrounding areas a refinement to the landuse classification is of importance. As an example the Squamish harbour area's surface is covered by concrete, classified correctly as rock. However the surfaces as seen from orthoimages are very flat and thus need to be classified into a separate class named "flat". The same is valid for airport-runways where weather stations, likely relevant to validation of modelled windfields, are situated.

Excursion: refinement of classification to the immediate surroundings of prospected turbine site at Squamish

- A) Conversion of raster-based landuse map to polygon-shapefile
- B) Use of Editor to local manipulation of landuse-class values attributes and eventually cutting polygon's shapes to separate for landuse.
- C) The following manipulations are done referring to the photograph of Squamish and the orthoimages:
 - i. The very flat riverbed of the Squamish river close to the turbine site consists mostly of the class rock, being very high in roughness value. These riverbeds are converted to water surfaces as well as best approximation concerning impact on wind.
 - ii. The Squamish dock area with flat concrete surfaces comparable to airport-runway is converted to the new class "flat" with a gridvalue-attribute of "10". The storey hall buildings also have flat roofs; their height is treated in the same way as with forests, as explained in iii.
 - iii. In the area of the Squamish river delta where only few trees exist, the class of "wood" has been changed to "grass", since forests not only represent high roughness, but in the later derivation of digital surface model by adding the height of trees to the grounds elevation, forests become true obstacles to the wind.
 - iv. The airport-runways of the Squamish, Vancouver and Pemberton Airports are digitised to a new shapefile and assigned the class "flat" (grid value of 10). Conversion to raster at size and extent of landuse map, then sum of both maps via map algebra



Figure 34: Pemberton Airport digitised for classification as “flat”

- D) Reclassification to the final land use map by the same procedure as in the previous excursion. In addition to the existing five classes, now also the class “flat” is contained.

6.4 Meteodata

6.4.1 Ground based weather stations

The net of Ground Weather stations is very tight in Canada. Data is available for most of the stations, for which either daily or hourly data can be downloaded from the National Climate Data and Information Archive maintained by Environment Canada. Depending on initialisation of the individual weather stations, actual and historic data – in some cases - back to decades is available.

Excursus: process steps “Canadian weather stations map”

- A) Climate online data available from National Climate Data and Information Archive¹⁸, operated and maintained by Environment Canada.
- B) For a map display of all Canadian Climate Stations: download file “metstat1e.txt”.
- C) Import “metstat1e.txt” to Excel "fixed width", so that Latitude-Longitude coordinates are separated to individual columns.
- D) Copy geographic-coordinate “objects” to WindPRO, transform to UTM_Zone10_WGS84. Export to Excel txt file.

¹⁸ National Climate Data and Information Archive: www.climate.weatheroffice.ec.gc.ca (30.08.2006)

- E) Extract UTM_Zone10_WGS84 X/Y-values. Add XY-data into ArcGIS.
- F) Export to point-shapefile, then join attribute table. Finally export to “Weather Stations Environment Canada.shp”

For the area of Howe Sound and north to Whistler there are more stations available then finally in focus. Out of all the stations offering hourly data, for example *Entrance Island CS* (a lighthouse in the Strait of Georgia) has not been taken into consideration because it was too far away from the area to be modelled, *Vancouver International Airport* was too far as well, *Vancouver Harbour CS* was considered not adequate because of very sheltered topography considerably unrepresentative to wind distribution. Others such as *West Vancouver AUT* or *Squamish Government Building* could not be exactly located so the representativity towards wind could not be evaluated. Further north at Whistler there has also been station data available from two mountain peaks, however the data stems from only very recent, so that not much information on the past was available. Further to the north the station *Pemberton Airport* is also reporting, but not contained within the modelling area.

By online search it is possible to find pictures of some of the weather stations and more general information as to get an idea on height’s of anemometers reporting on wind and the general setting of the station. By the use of orthofotos by GlobeXplorer it has for some stations been possible to find out the exact location, for others however this was not possible due to the vague coordinates given by meteorological institutional catalogues or websites.

6.4.1.1 Point Atkinson

STATION CATALOGUE	1106200 POINT ATKINSON	
CLIMATE STATION NAME		
Reporting period	1996 onwards (hourly)	
Height of anemometer:	18.3m above ground level	
Height above sea level	14.6m (CDED 50)	
Position by Meteorological Service of Canada	123 15 51''W	49 19 47''N
	http://ftp.cmc.ec.gc.ca/metadata/SIS/SIS_1106200.xml	
Position by orthofoto	123°15'52.63''W	49°19'49.26''N



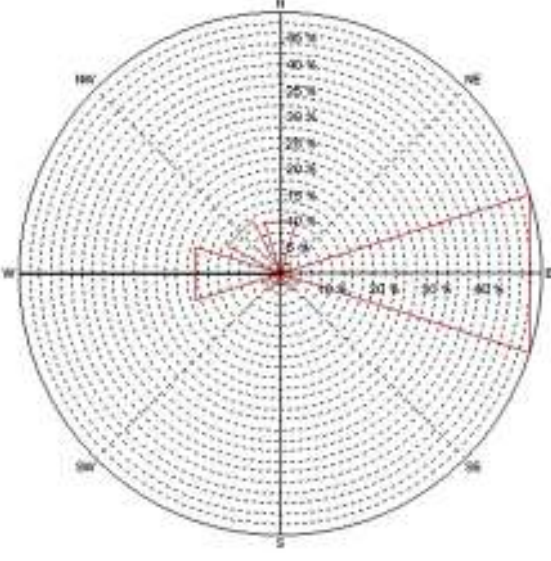
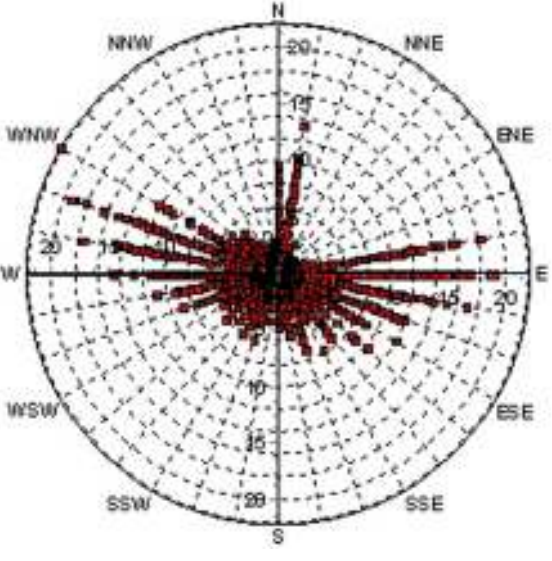
Picture of Climate Station	Orthofoto of Climate Station
	
	
Frequency (0% - 50%)	Windspeed (0m/s - 22m/s)

Table 3: Point Atkinson

Description of Climate Station:

The Point Atkinson Lighthouse in West Vancouver is the first of three lighthouses serving the Port of Vancouver. The original lighthouse at Point Atkinson was built in 1874. It was replaced by the current hexagonal concrete structure in 1910¹⁹. As inscribed in the sign²⁰ the tower has a height of 18,3m, focal plane above high water 32,9 meters

¹⁹ www.sewellsmarina.com/photos.html?gallery=Howe%20Sound (30.08.2006)

²⁰ <http://www.seethenorthshore.com/light/light.htm> (30.08.2006)

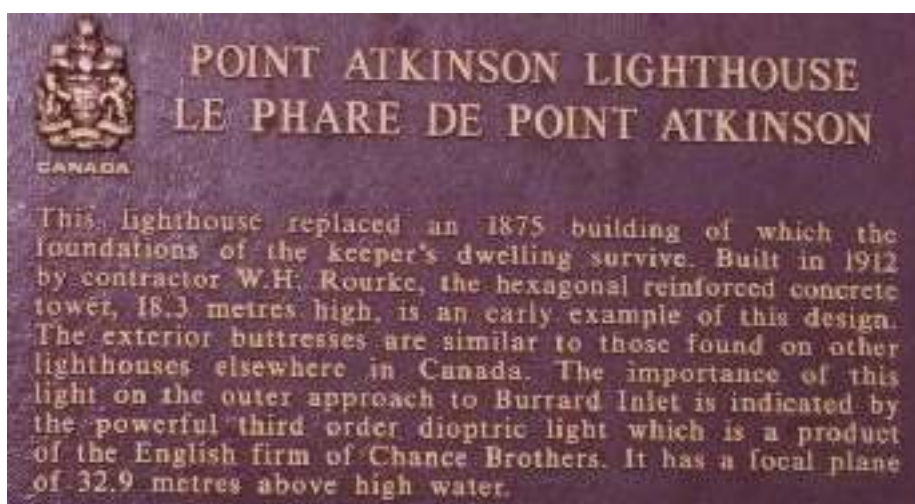


Figure 35: Explanatory sign of Point Atkinson Lighthouse

It is assumed by the author that the weather and wind data are either located at the top of the tower or the mast seen next to the outhouse. This means that winds passing the station from all but north and north-eastern wind directions are relatively free in flow.

6.4.1.2 Howe Sound – Pam Rocks

STATION CATALOGUE	0459NN+HOWE SOUND - PAM ROCKS	
CLIMATE STATION NAME		
Reporting period:	1988 onwards (hourly)	
Height of anemometer:	Estimated 3m above ground level	
Height above sea level	7m (CDED 50)	
Position by Meteorological Service of Canada	123°17'53"W	49°29'17"N
	http://ftp.cmc.ec.gc.ca/metadata/SIS/SIS_10459NN.xml	
Position by Orthofoto	123°17'58.36"W	49°29'16.52"N



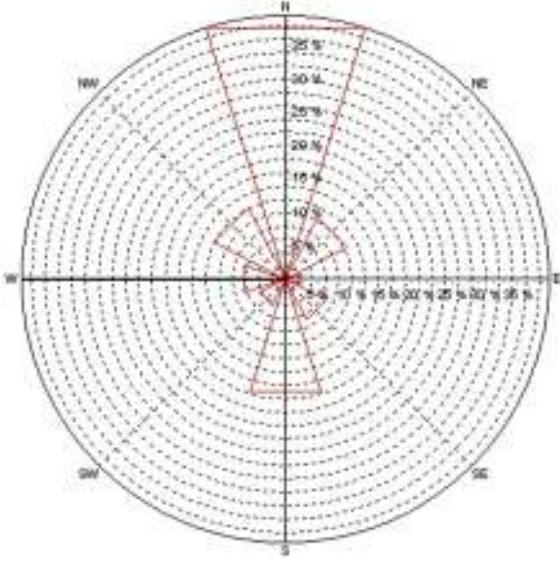
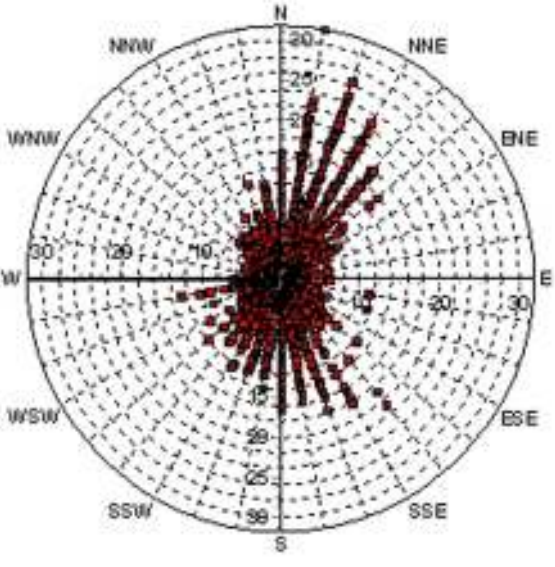
Picture of Climate Station	Orthofoto of Climate Station
	
	
Frequency (0% - 40%)	Windspeed (0m/s – 32 m/s)

Table 4: Pam Rocks

Description of Climate Station:

Pam Rocks is a reporting weather station for the marine weather system. Winter northerly gales can reach close to hurricane force here (WIKIPEDIA).

Information concerning the height of the anemometer is not available. Judging by the image though it is estimated to be 10meters in height above sea-level.

6.4.1.3 Squamish

STATION CATALOGUE	047FF0 SQUAMISH AIRPORT	
CLIMATE STATION NAME		
Reporting period	1982 onwards (hourly), 1959-1996 (daily)	
Height of anemometer:	Typically 10m, no more detailed information available	
Height above sea level	47m (CDED 50)	
Position by Meteorological Service of Canada	-123°10'00''W	49°47'00''N
	http://ftp.cmc.ec.gc.ca/metadata/SIS/SIS_1047FF0.xml	
Position by Orthofoto	123°17'58.36''W	49°29'16.52''N


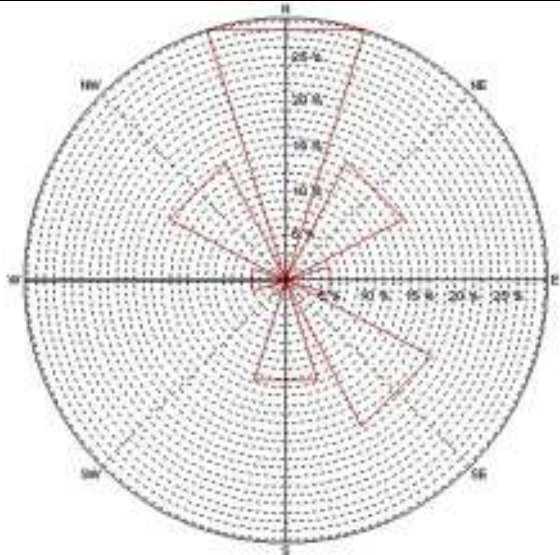
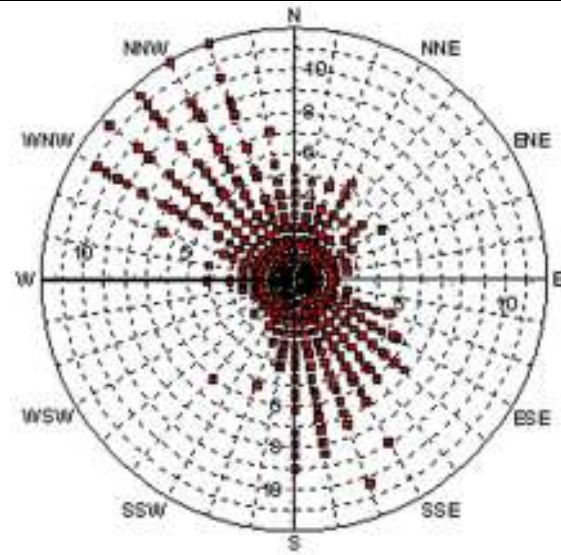
Picture of Climate Station	Orthofoto of Climate Station
<p><u>NO PICTURE AVAILABLE</u></p>	
	
Frequency (0% - 30%)	Windspeed (0m/s - 12m/s)

Table 5: Squamish

Description of Climate Station:

The difference in location by coordinates is tremendous, however it could be ensured that the location identifiable by orthofotos is correct (airport). The station of

Squamish is of importance as being closest to the wind farm site. With forests surrounding the station though, wind-data should be treated carefully as free flow is unlikely.

6.4.1.4 Whistler

STATION CATALOGUE	048898+WHISTLER	
CLIMATE STATION NAME		
Reporting period:	1983 onwards (hourly)	
Height of anemometer:	Typically 10m, no more detailed information available	
Height above sea level	658m (CDED 50)	
Position by Meteorological Service of Canada	122°57'17"W	50°07'45"N
	http://ftp.cmc.ec.gc.ca/metadata/SIS/SIS_1048898.xml	
Position by Orthofoto	Not possible, as no description on exact location found.	


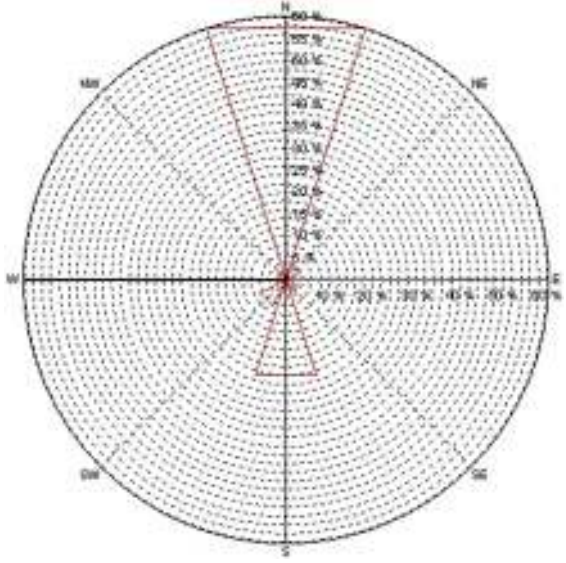
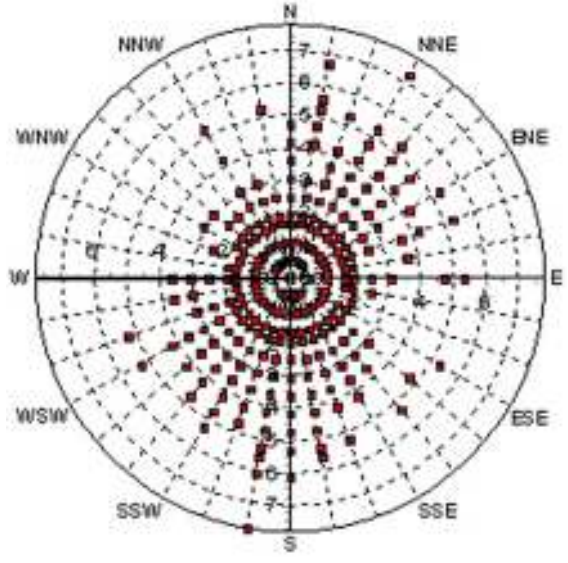
Picture of Climate Station	Orthofoto of Climate Station
NO PICTURE AVAILABLE	
	
Frequency (0% - 60%)	Windspeed (0m/s - 8m/s)

Table 6: Whistler

Description of Climate Station:

An exact positioning for the station of Whistler was not achievable, so that a better impression on the station set-up is missing. The station of Whistler is of importance as Whistler marks the most upper point of the valley before further northwards in the direction of Pemberton height decreases again. Such Whistler is believed to mark a weather shed. Same as in Squamish, with forests surrounding the station though, wind-data should be treated carefully as free flow is unlikely. Another issue concerning data is that data-availability is restricted from morning to late afternoon (7 a.m. to 5p.m.), so care is essential in analysing the data.

Excursus: process steps “ground station climate data”

- A) Climate online data available from *National Climate Data and Information Archive*, operated and maintained by *Environment Canada*.
- B) Choose station and download of “hourly” data by individual months restricted to 6 years from 01/01/2000 to 12/31/2005 due to max. number of rows (65,536) in excel. For six years 52,560 individual hourly values are respected.
- C) Build timeseries from separate csv-files in batch mode by using tool “merge csv”²¹
- D) Resulting are the ground station timeseries “ts_pamrocks.xls”, “ts_pointatkinson.xls”, “ts_squamish.xls”, “ts_whistler.xls”.
- E) Completion of missing time values where “meteorological values” M = Missing, especially for whistler (no values from 18 pm to 7 am). Also recheck for data holes (USE formula “timestep – last_timestep MUST BE 1:00” then apply filter in search for values > 1:00), also filter “1997” (ts_copy in blank.xls).
- F) Completion of missing time values by taking separate time series into one table, comparing side by side that time steps are the same (especially 24hour differences by the first time check have not been found. Help of Colours by marking all 5,10,15,20,25 day before in separate datasets.
- G) Various formatting, especially attention to values equalling “0” – i.e. “0 m/s” or “NO VALUE” for wind-speed, same regarding wind direction:
 - Test 1.: wind direction = blank -> “M” for windspeed, wind direction & temperature
 - Test 2: wind direction = 0 → allow 0 only if there has data been available in other fields (meaning that 0 came from format conversion calculations, otherwise insert “M”)
 - Test 3: Temperature C = blank -> “M”

²¹ “merge csv”: Ron de Bruin, <http://www.rondebruin.nl/csv.htm> (30.08.2006)

H) Resulting, timeseries are identical organized by continuous time-steps so that the 4 individual timeseries can be placed next to each other in one worksheet. The weather events of the 4 stations can now be compared hour by hour.

Preparation of single timeseries for windstatistics-analysis in WindPRO:

- I) Manipulation of individual timeseries from step 1, delete all lines where there are missing values (M), and reduce rows to fields date / time/ wind direction / windspeed (m/s).
- J) Save individual time series as .csv (comma separated values) and import to WindPRO for windstatistics-analysis

Out of the ground climate stations Pam Rocks appears to be the most reliable and representative station because it is situated openly within the Howe Sound. Its position is also exactly known and the images available allow for a very good impression on the station's wind and climate data.

Point Atkinson Lighthouse is exhibited to the sea as well, but under the influence not only of Howe Sound but also the Strait of Georgia. Northeastern winds are not likely to be represented at the site of Point Atkinson, as these windsectors are subject to coverage of forests and the rising inland elevation.

Whistler and Squamish Airport are surrounded by high forests and lie within structured topography, so that temperatures and relative humidity are trustworthy, while data on wind is likely to be unrepresentative (at low anemometer heights of assumable 10m). Whistler moreover could not be exactly positioned and data is only available during the daytime.

Interesting though is to see that all stations indicate northern, northeastern or eastern winds. They are relatively strong at the sea-level (Point Atkinson and Pam Rocks and but low over land (Squamish Airport and Whistler)

For these reasons the validation of the simulated wind fields will be exercised by comparing the windstatistics of the climate station of Pam Rocks with the modelled windstatistics.

6.4.2 Upper air climate data

As an atmospherical input to many modelling projects the largescale data of the "NCEP-DOE Reanalysis 2 project" are used. The *NCEP Reanalysis 2 data, provided by*

the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>, offer a global atmospheric data coverage:

- o spatial coverage: global grid of 2.5-degree latitude x 2.5-degree longitude grid
- o temporal coverage: data from 1979 up to the previous year available with a resolution to 4-times daily events (0h – 6h – 12h – 18h local standard time).
- o vertical levels: 17 pressure levels from 1000 hPa to 10 hPa.

For these pressure levels atmospheric the following data is accessible²²:

- o air temperature (Kelvin),
- o relative humidity (%),
- o u-wind (eastward wind - m/s),
- o v-wind (northward wind - m/s),
- o omega (vertical velocity - Pascal/s),
- o Geopotential height (m).

The data is available in netCDF format, a conversion to ASCII / XML has been performed to enable for data analysis by spreadsheet calculation SW. See chapter “netCDF GML” and data format issues of the ASIS.

For the geostrophic wind input data the 850 hPa Level has been chosen as recommended by (METEOROLOGICAL INSTITUTE UNIVERSITY HAMBURG).

From the explanation given, 850 hPa is an appropriate level for being above those levels subject to friction (from averaging at 1000m +/- 1000m above ground level), which is simulated for by the model. Would a lower level be applied, the natural friction would already be respected by the model driving input data and within the model be calculated a second time, resulting in double the friction involved in the solution. Thus the 850 hPa in most cases are suggestive. In METRAS PC the driving input data is assigned a height at which the model is initialized. Suggestive is the selection of the lowest point in the model area, concerning the site of Squamish thus sea level.

For the focussed years of 2000 to 2005 the following wind-distribution has been analysed for the nearest NCAR/NECP grid point at Lon 122°5 W, Lat 50° N:

²² NCEP-DOE Reanalysis 2 project: <http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis2.html> (30.08.2006)

NCEP REANALYSIS 2: geostrophic wind (850 hPa) 01.01.2000-31.12.2005

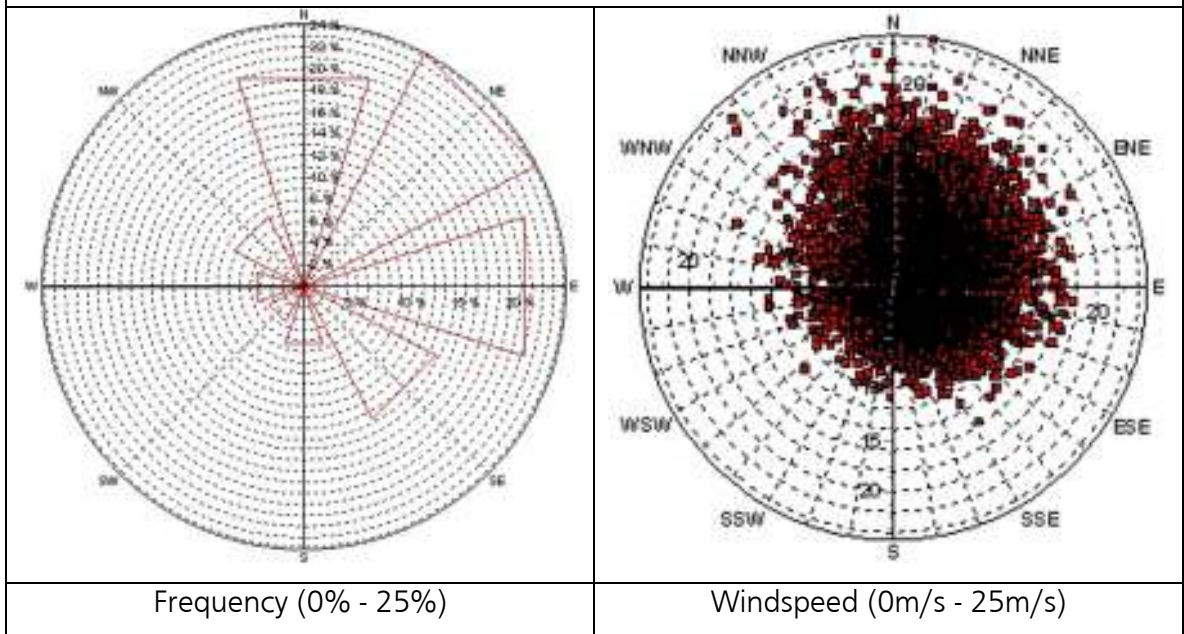


Table 7: NCEP REANALYSIS 2: geostrophic wind (850 hPa)

Excursus: process steps “upper air climate data”

- A) Download of 4x daily data into separate datasets of “u-wind”, “v-wind”, “air temperature”, “relative humidity”, “geopotential height”, for the grid point of Lon 122°5 W, Lat 50° N in the focused time range of 01/01/2000 to 12/31/2005.
- B) Import individual netCDF-files to XML and save to ASCII-text by use of the software “LeoNetCDF 1.11”²³.
- C) Values, i.e. u-wind, are listed in a single row of data without corresponding date/time-as attributes. So checking which values belong to which date/time (beginning? end?) can be done by downloading the same time series only for i.e. the year of 2005 and hereafter comparison of both timeseries.
- D) Combination of the individual value datasets (individual ASCII files) within one excel-file „ts_all_NCEPdata.xls”.
- E) Build date/time index manually for calendar dates and daily times of “00:00”, “06:00”, “12:00”, “18:00”. Date/time index must fit with the number of values, therefore and as an identifier key to values creation of a field “value_no”.
- F) As no other information has been found by the author, it is assumed that date/time refers to local time zones. Plausibility check has been done by examination of values (winter/summer seasonality, diurnal/nocturnal change).

²³ “LeoNetCDF 1.11”: Dr. Leonid Sakharov, <http://www.leokrut.com/leonetcdf.html> (30.08.2006)

„ts_all_NCEPdata.xls” contains all values by column-fields “year”, “month”, “day”, “time”, “value_no”, “u-wind”, “v-wind”, “air temperature”, “relative humidity”, “geopotential height”

G) Mark “missing values=32767” and “fill values”=-32767” as “M”, so that statistical analysis is possible.

H) Format conversion: Conversion of relative netCDF-values to interpretable absolute values
 Values contained in the netCDF files are stated in a relative format made up of the values portion within the attributes minimum and maximum values. Absolute values are computed by the formula:

$$\text{Absolute_value} = (\text{data_value} * \text{scale_factor}) + \text{offset}$$

I) Format conversion: Celsius from Kelvin

As stated in (WIKIPEDIA) a temperature difference of 1 degree in the Celsius scale is the same as a 1 K (kelvin) temperature difference. The scale is the same as the Kelvin scale, but has its offset by the temperature at which water freezes (273.15 K). The equation used to convert from degrees kelvins to Celsius is:

$$^{\circ}\text{C} = \text{K} - 273.15$$

J) Format conversion: windspeed and wind direction from u-wind and v-wind vector

The formulas to derive windspeed and winddirection from u-wind and v-wind vector is given in a technical description of an anemometer data-logger (MEIER-NT):

WV = windvelocity

WD = wind direction

u_1 [north wind] = (-1) * **v-wind** (northward wind)

u_2 [east wind] = (-1) * **u-wind** (eastward wind)

Windspeed is defined as:

$$\overline{WV} = \sqrt{\overline{u_1}^2 + \overline{u_2}^2}$$

Wind direction is defined as:

$$\overline{WD}' = \arctan \left| \frac{\overline{u_2}}{\overline{u_1}} \right|, \text{ with } 0^{\circ} \leq \overline{WD}' \leq 90^{\circ}$$

As $\overline{u_1}$ and $\overline{u_2}$ can be relative and the arctan is only defined for 0° to 90°, the true angle

\overline{WD} of direction is defined by the following table:

$\overline{u_1}$	+	-	-	+
$\overline{u_2}$	+	+	-	-
$\overline{WD'}$	$\overline{WD'}$	$180^\circ - \overline{WD'}$	$180^\circ + \overline{WD'}$	$360^\circ - \overline{WD'}$

Also $\overline{u_1} = 0$ is defined as $\overline{WD} = 0^\circ$. This latter definition is mathematically correct, but adaptable only if “windstill”: if straight Eastern or Western winds, Northern or Southern winds are encountered, these have to be treated as separate cases in addition to the definitions of the above table.

- K) Combine ground stations data and geostrophic NCEP data. The timeseries of both data files must match correctly. Now for every point in time it can be compared what the weather situation has been like at the ground and geostrophic level.

With having a combined timeseries of upper air climate data and ground level climate data from the 4 stations of Point Atkinson, Pam Rocks, Squamish and Whistler, the initial idea by the author has been that this information ideally could be used as a direct input to drive the model (caused by the thought that the more information available as an input the better the results).

However the next step in pre-processing meteorological data is the analysis and classification of individually representative weather situations. These weather situations are then individually modelled by simulation experiments.

For wind energy yield prospecting it is required to have the information on historic weather and wind behaviour concerning all wind directions (usually 8 or 12 sectors) and windspeeds (usually at a resolution by 1 m/s steps). Also weather behaviour depends on seasonality (i.e. winter, spring, summer, fall) and stratification. As defined in (WIKIPEDIA) “ atmospheric stratification is the division of the atmosphere into distinct layers, each with specific properties such as temperature or humidity.”

Detailed information about wind’s behaviour in solely its main wind direction at a relevant windspeed’s range generally is not enough for a conclusion on annually expected yields. As a result a multitude of individual simulation experiments are required, each of them time consuming not only concerning processor time (approx. 5-7 hours each (Celeron 2,6 GHz, 2 GB RAM) but also hands-on post-processing of the output data:

Example "high resolution":

12 speed classes (2 m/s, 4 m/s, ..., 24 m/s)
x 12 sectors (30°)
x 4 seasons = (winter, spring, summer, fall)
+ 4 seasonal speed classes 0 m/s.....
576 simulation experiments

Example "Squamish":

4 speed classes (0 m/s, 5 m/s, 10 m/s, 15 m/s)
x 8 sectors (45°)
x 2 seasons (winter & summer)
+ 2 seasonal speed classes 0 m/s.....
64 simulation experiments

By statistical analysis of the weather occurrences chances are, that certain combinations do rarely occur, so these situations can be included to more prevailing ones and do not require separate simulation experiments. Also the speed class of 0 m/s will not be simulated for each direction, but only for seasonality.

However, to minimize postprocessing effort, each simulation is performed twice: first to generate timeseries output files for the prospected site of Squamish (height of 100m = turbine tower height) and second for the ground weather station of Pam Rocks (height of 20m = somewhat above the measure mast)).

6.4.3 Windspeed and -direction classes for simulation experiments

In order to decide on which windspeed classes are most suited to the prospected site of Squamish a look at the range of prevailing windspeeds was taken. For the geostrophic windspeeds from 0 m/s to 22 m/s occurred with only very few records above this. As the classes are meant to be meaningful to what they represent, the description of wind intensities (WIKIPEDIA) is another factor in the classification procedure:

Potential windspeed classes				Wind intensity				
Wind m/s	Class 3m/s	Class 5m/s	Class 7m/s	Beaufort number	Windspeed km/h	Windspeed m/s	Wind Description	Land conditions
-1								
0	0	0	0	0	0	0-0.2	Calm	Calm. Smoke rises vertically.
1				1	1-6	0.3-1.5	Light air	Wind motion visible in smoke.
2								
3	3			2	7-11	1.6-3.3	Light breeze	Wind felt on exposed skin. Leaves rustle.
4								
5		5		3	12-19	3.4-5.4	Gentle breeze	Leaves and smaller twigs in constant motion.
6	6		7	4	20-29	5.5-7.9	Moderate breeze	Small branches begin to move.
7								
8								
9	9							
10		10		5	30-39	8.0-10.7	Fresh breeze	Smaller trees sway.
11								
12	12							
13				6	40-50	10.8-13.8	Strong breeze	Large branches in motion. Whistling heard in overhead wires.
14	15	15	14	7	51-62	13.9-17.1	Near gale	Whole trees in motion. Effort to walk against the wind.
15								
16								
17	18							
18				8	63-75	17.2-20.7	Gale	Twigs broken from trees. Cars veer on road.
19								
20	21	20	21					
21								
22								
23	24			9	76-87	20.8-24.4	Strong gale	Light structure damage.
24								
25		25						
26				10	88-102	24.5-28.4	Storm	Trees uprooted. Considerable structural damage.
27								

Table 8: Windspeed Classification - description of wind intensity

For the simulation experiments it has been decided to use the windspeed-classes of 0 m/s, 5 m/s, 10 m/s, 15 m/s and 20 m/s. These classes are displayed as following:

5 m/s	Direction	Degree	u-wind (eastward wind)	v-wind (northward wind)	calculated windspeed	calculated winddirection
1	N	0	0	-5	5.000	0.0
2	NO	45	-3.54	-3.54	5.006	45.0
3	O	90	-5	0	5.000	90.0
4	SO	135	-3.54	3.54	5.006	135.0
5	S	180	0	5	5.000	180.0
6	SW	225	3.54	3.54	5.006	225.0
7	W	270	5	0	5.000	270.0
8	NW	315	3.54	-3.54	5.006	315.0

10 m/s	Direction	Degree	u-wind (eastward wind)	v-wind (northward wind)	calculated windspeed	calculated winddirection
1	N	0	0	-10	10.000	0.0
2	NO	45	-7.08	-7.08	10.013	45.0
3	O	90	-10	0	10.000	90.0
4	SO	135	-7.08	7.08	10.013	135.0
5	S	180	0	10	10.000	180.0
6	SW	225	7.08	7.08	10.013	225.0
7	W	270	10	0	10.000	270.0
8	NW	315	7.08	-7.08	10.013	315.0

15 m/s	Direction	Degree	u-wind (eastward wind)	v-wind (northward wind)	calculated windspeed	calculated winddirection
1	N	0	0	-15	15.000	0.0
2	NO	45	-10.61	-10.61	15.005	45.0
3	O	90	-15	0	15.000	90.0
4	SO	135	-10.61	10.61	15.005	135.0
5	S	180	0	15	15.000	180.0
6	SW	225	10.61	10.61	15.005	225.0
7	W	270	15	0	15.000	270.0
8	NW	315	10.61	-10.61	15.005	315.0

Table 9: Classes of windspeed and direction for simulation experiments

Missing in this figure is the class of 20 m/s, which is due to occurrences of less than 1% in the overall wind situation. This shows that for a reduction in individual simulation experiments, but also necessary for prediction of annual wind-distributions, the next step is the statistical analysis of frequencies to the wind-classes being decided for.

Excursus: process steps “analysis of all climate data”

- A) Basis for analysis is xls-file containing all climate data (ground stations & upper level climate data)
- B) From reduction of hourly to 4x daily data at the station of Whistler data availability is for the greatest part reduced to data at 6:00 am and 12:00am. Generally and in total for night climate values are missing or “0”: this station for analysis of climate has to be treated carefully.

- C) Addition of temperatures in kelvin to ground stations
- D) Manual classification by insertion of new field rows “spd_class_5” and “winddirection_class_8”. By “sort by” function attributes values are then pasted according to classes:

Min / Max							
-15.8	-13.1						
17.4	24.5						
Mean							
-15.8	-15.8	-15.8					
Units							
m/s	m/s	m/s	deg				
eastward vs northward wind							
DateTime	u wind	v wind	windspe	winddir_850	spd_class	winddir_class	winddir_name
01/08/2000 00:00	5.6	2.9	6.3	62.6	5.0	45.0	NE
01/08/2000 06:00	11.1	-1.8	11.2	99.2	10.0	90.0	E
01/08/2000 12:00	6.6	-1.8	6.8	105.3	5.0	90.0	E
01/08/2000 18:00	6.1	-5.0	7.9	129.3	5.0	135.0	SE
02/08/2000 00:00	2.7	-1.4	3.0	117.4	5.0	135.0	SE
02/08/2000 06:00	2.7	-3.7	4.6	143.9	5.0	135.0	SE
02/08/2000 12:00	2.2	-1.1	2.5	116.6	0.0	135.0	SE
02/08/2000 18:00	0.6	-1.5	1.6	158.2	0.0	180.0	S
03/08/2000 00:00	0.1	-0.5	0.5	168.7	0.0	180.0	S
03/08/2000 06:00	-1.3	-4.3	4.5	196.8	5.0	180.0	S
03/08/2000 12:00	-2.5	-2.8	3.8	221.0	5.0	225.0	SW
03/08/2000 18:00	-3.6	-0.5	3.6	262.1	5.0	270.0	W
04/08/2000 00:00	-1.6	1.2	2.0	306.9	0.0	315.0	NW
04/08/2000 06:00	-2.7	-0.2	2.7	265.8	0.0	270.0	W
04/08/2000 12:00	1.1	1.1	1.6	45.0	0.0	45.0	NE
04/08/2000 18:00	2.1	1.4	2.5	56.3	0.0	45.0	NE
05/08/2000 00:00	3.3	0.5	3.3	81.4	5.0	90.0	E

Figure 36: Classification of climate data in Excel

- E) Situation analysis of low upper level winds but strong ground level winds, by filtering for speed classes 0, 5, 10, and 15 m/s at ground station “Pam Rocks”, second Filter for 8 direction classes N, NE, E, etc. at ground station “Pam Rocks”:

Higher winds of class 15m/s and 20 m/s at Pam Rocks occur especially during November to March in wind directions of 10° to 40° (NNE) where temperatures north in the mountains at Whistler (base station) are around – 10°C and at the sea level Pam Rocks are around –2° C.

Higher winds of class 10m/s at Pam Rocks occur during the whole year however only in wind directions North (N) and Northeast (NE) from 337.5° to 22.5°.

Winds of class 5m/s at Pam Rocks occur during the whole year to equal parts for all wind directions excluded Eastern and Western winds.

This results in that simulation runs with 0 m/s in the winter time could / should lead to strong winds from N and NE (approx. 15 - 20 m/s) and in the summer time winds from North OR South at a medium level of 5 m/s to 10 m/s could be expected.

- F) Daily and monthly averages of temperature and humidity, by first filter „time“ 0:00, 12:00, 18:00 and 24:00, second filter „month“, third filter „day“, to enable for averaging for all stations. Missing values „M“ are correctly respected as “no data” by average formula.
- G) Computing for frequency of individual wind-classes by separation between summer (March to October) and winter situations (November to February). Some windclasses are only represented in the summer or only in the winter. In these cases minor portions are added to the other season. Also the frequency classes of windspeeds “20m/s” were so low (< 1%) that their portions were included in the “15 m/s” classes.
- H) Resulting the windclasses with frequencies close or above 1% will be simulated in individual runs. Later these frequencies are used to build a prospected annual timeseries by multiplying the individual’s situation occurrence.

Sector	0° N		45° NE		90° E		135° SE		180° S		225° SW		270° W		315° NW	
All Values	485	5.5%	322	3.7%	390	4.4%	628	7.2%	1757	20.0%	2121	24.2%	1867	21.3%	1198	13.7%
0 m/s	172		146		140		172		254		279		275		254	
	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S
	60	112	60	86	51	89	61	111	89	165	96	183	76	199	60	194
	0.7%	1.3%	0.7%	1.0%	0.6%	1.0%	0.7%	1.3%	1.0%	1.9%	1.1%	2.1%	0.9%	2.3%	0.7%	2.2%
19.3%	553 events "0 m/s" winter, share of: 6.3%								1139 events "0 m/s" summer, share of: 13.0%							
5 m/s	289		164		212		299		674		1000		1087		761	
	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S
	136	177	79	97	148	102	198	101	362	312	515	485	360	727	272	489
	1.6%	2.0%	0.9%	1.1%	1.7%	1.2%	2.3%	1.2%	4.1%	3.0%	5.9%	5.5%	4.1%	8.3%	3.1%	5.0%
52.0%																
10 m/s	24		12		36		121		614		676		433		172	
	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S
	0	0	0	0	0	0	157	0	457	157	441	235	276	157	112	71
	0	0	0	0	0	0	1.8%	0	5.2%	1.8%	5.0%	2.7%	3.1%	1.8%	1.3%	0.8%
23.5%																
15 m/s	0		0		2		29		194		153		72		11	
	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S
	0	0	0	0	0	0	0	0	215	0	166	0	72	0	0	0
	0	0	0	0	0	0	0	0	2.5%	0	1.9%	0	0.8%	0	0	0
5.2%																
20 m/s	0		0		0		7		21		13		0		0	

W = Winter, S = Summer

Table 10: Frequencies of wind-classes for simulation experiments

6.4.4 Analysis and classification for temperatures and relative humidities

Having analysed the frequencies of the wind classes, it is seen that – untypical to areas not influenced by thermic effects - most windy situations occur in the summer

and in the wintertime. As the site is characterized by wintery polar outflow winds and summerly thermic land-sea circulation winds, no separate classes for the spring and fall are decided for.

In attempt to respect these phenomena, the average temperatures and relative humidities for the “extreme” winter and summer months are respected: January and February representing the winter-season, July and August representing the summer-season.

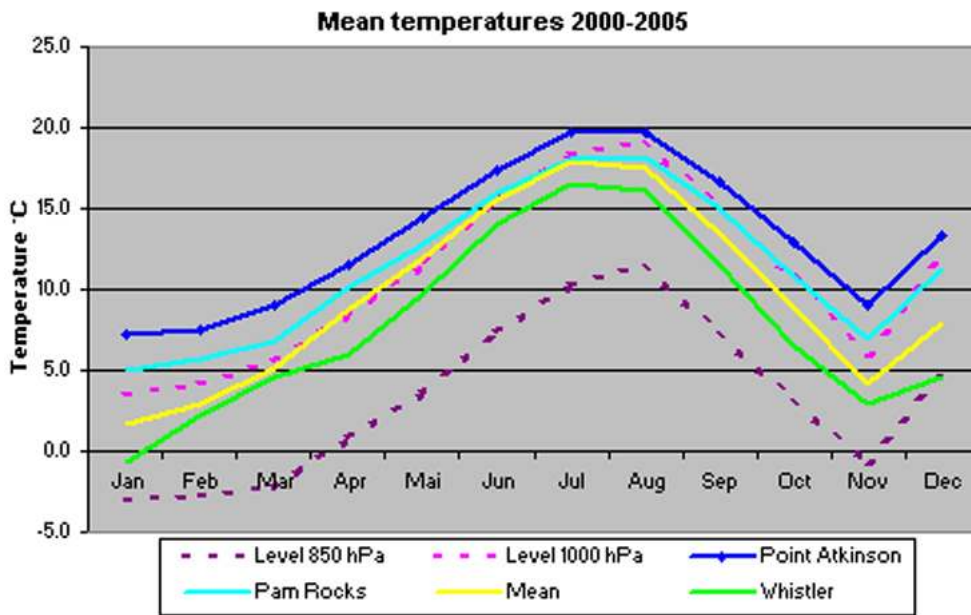


Figure 37: temperatures (°C) ground stations, 1000 hPa and 850 hPa level

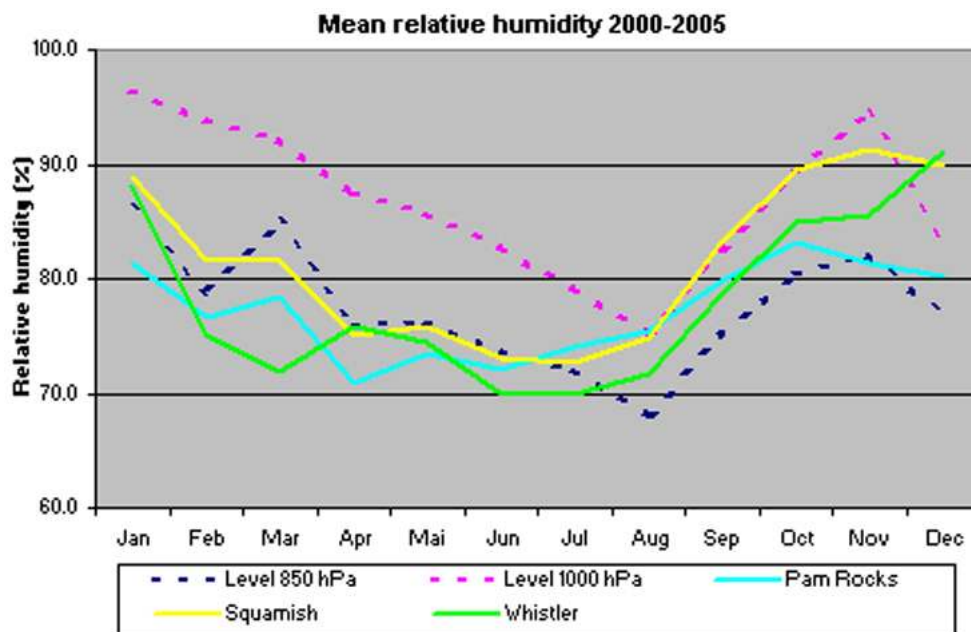


Figure 38: relative humidity (%) ground stations, 1000 hPa and 850 hPa level

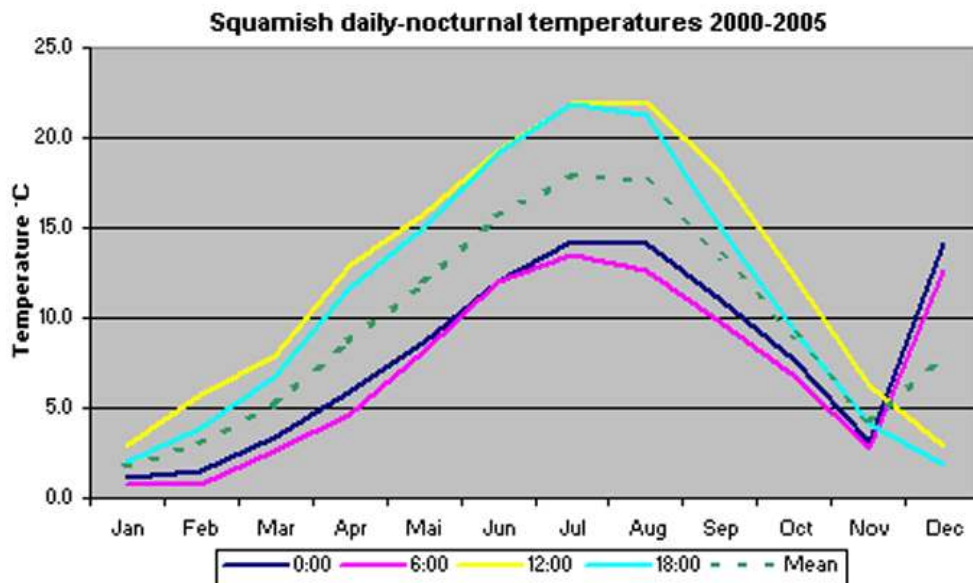


Figure 39: Squamish daily-nocturnal temperatures 0:00, 6:00, 12:00 and 18:00

Point Atkinson	Temperature					Relative Humidity		
Height: 0m	Mean	Jan-Feb	Jul-Aug	Jan-Feb	Jul-Aug	Mean	Jan-Feb	Jul-Aug
0:00	13.5 °C	7.2 °C	19.6 °C	280.3 °k	292.7 °k	M	M	M
6:00	12.5 °C	6.5 °C	18.2 °C	279.7 °k	291.3 °k	M	M	M
12:00	12.9 °C	7.8 °C	19.5 °C	281.0 °k	292.7 °k	M	M	M
18:00	13.9 °C	8.1 °C	21.6 °C	281.2 °k	294.7 °k	M	M	M
Mean	13.2 °C	7.4 °C	19.7 °C	280.5 °k	292.9 °k	M	M	M

Pam Rocks	Temperature					Relative Humidity		
Height: 0m	Mean	Jan-Feb	Jul-Aug	Jan-Feb	Jul-Aug	Mean	Jan-Feb	Jul-Aug
0:00	11.5 °C	5.1 °C	17.5 °C	278.3 °k	290.6 °k	79.3%	80.1%	78.2%
6:00	10.6 °C	4.7 °C	16.1 °C	277.9 °k	289.3 °k	80.6%	80.3%	80.6%
12:00	11.4 °C	5.6 °C	18.7 °C	278.7 °k	291.9 °k	74.8%	76.0%	72.7%
18:00	12.1 °C	5.9 °C	20.3 °C	279.0 °k	293.5 °k	74.3%	79.9%	67.4%
Mean	11.4 °C	5.3 °C	18.2 °C	278.5 °k	291.3 °k	77.3%	79.1%	74.7%

Squamish	Temperature					Relative Humidity		
Height: 60m	Mean	Jan-Feb	Jul-Aug	Jan-Feb	Jul-Aug	Mean	Jan-Feb	Jul-Aug
0:00	8.1 °C	1.3 °C	14.2 °C	274.5 °k	287.3 °k	90.4%	89.2%	88.7%
6:00	7.3 °C	0.8 °C	13.1 °C	273.9 °k	286.3 °k	91.5%	89.3%	91.1%
12:00	12.3 °C	4.3 °C	21.9 °C	277.5 °k	295.1 °k	68.5%	77.4%	57.2%
18:00	11.0 °C	2.9 °C	21.5 °C	276.1 °k	294.7 °k	75.4%	85.3%	58.2%
Mean	9.6 °C	2.3 °C	17.7 °C	275.5 °k	290.8 °k	81.5%	85.3%	73.8%

Whistler	Temperature					Relative Humidity		
Height: 660m	Mean	Jan-Feb	Jul-Aug	Jan-Feb	Jul-Aug	Mean	Jan-Feb	Jul-Aug
0:00	M	M	M	M	M	M	92.2%	89.0%
6:00	7.3 °C	-3.2 °C	10.6 °C	270.0 °k	283.8 °k	92.4%	92.3%	91.4%
12:00	10.1 °C	0.7 °C	22.0 °C	273.9 °k	295.1 °k	67.8%	81.6%	50.2%
18:00	M	0.2 °C	21.5 °C	273.4 °k	294.7 °k	M	85.1%	52.2%
Mean	7.8 °C	0.7 °C	16.3 °C	273.9 °k	289.5 °k	78.1%	81.6%	70.8%

Table 11: Temperatures and relative humidities ground level and 850 hPa level

6.4.5 Temperatures and relative humidity for the upper model border

The upper-model border has been set to a height of roughly 11km. As temperatures and relative humidity have to be specified for both the winter simulations and the summer simulations, data available from the NCEP reanalysis 2 project is suited for use.

However this does not require downloading and analysing netCDF-data, since relevant values are displayable by graphs online. The relevant pressure level for the height of 11km is searched for by analysis of geopotential heights data:

For the years 2000-2005 (all year round) the geopotential heights of pressure levels are:

- o 400 hPa: 7157m – 7247m
- o 250 hPa: 10310m – 10427m
- o 200 hPa: 11742m – 11856m

The analysis of geopotential height (m) at pressure level (hPa) for the two seasons of “January / February” and “July / August” results in that the average of both 200 hPa and 250 hPa level best represents geopotential height of approx. 11 km.

Ideally midnight (start of simulation) situations at 00:00 should be taken. However analysis of the graphs (instead of netCDF data) allows for no such filter of values. Thus the assumption is made that the influence of day and night for these parameters can be ignored.

Temperature averaged over 250hPa to 200hPa

Jan-Feb	2000	2001	2002	2003	2004	2005	Mean	Temp °C
Max	219.3 °k	218.4 °k	218.3 °k	216.6 °k	217.1 °k	216.9 °k	217.8 °k	-55.4 °C
Min	217.6 °k	217.8 °k	217.5 °k	215.8 °k	216.4 °k	215.9 °k	216.8 °k	-56.3 °C
Mean							217.3 °k	-55.9 °C

Relative humidity, averaged over 250hPa to 200hPa

Jan-Feb	2000	2001	2002	2003	2004	2005	Mean
Max	38.4%	44.2%	49.3%	57.0%	50.2%	48.9%	48.0%
Min	29.2%	34.1%	35.3%	43.1%	38.1%	43.8%	37.3%
Mean							42.6%

Table 12: Winter (January - February) temperatures and relative humidity

Temperature, averaged over 250hPa to 200hPa

Jul-Aug	2000	2001	2002	2003	2004	2005	Mean	Temp °C
Max	222.7 °k	223.2 °k	222.5 °k	223.6 °k	221.8 °k	222.3 °k	222.7 °k	-50.5 °C
Min	222.4 °k	222.4 °k	222.1 °k	223.1 °k	221.4 °k	222.2 °k	222.3 °k	-50.9 °C
Mean							222.5 °k	-50.7 °C

Relative humidity, averaged over 250hPa to 200hPa

Jul-Aug	2000	2001	2002	2003	2004	2005	Mean
Max	46.1%	53.9%	53.3%	50.9%	59.7%	52.3%	52.7%
Min	42.2%	45.2%	48.8%	41.5%	57.6%	47.6%	47.2%
Mean							49.9%

Table 13: Summer (July-August) temperatures and relative humidity

The bold marked average values are the temperatures and relative humidities chosen for the upper model border. Depending on stratification distribution, temperatures are specified as vertical gradients i.e. from ground level to the upper model border set at 11km. Also height levels in between can be defined allowing for representation of more complex stratifications. Detailed information about stratification distribution could be gained from analyzing more pressure levels. As well the ground stations are located up to heights of 660m.

For the simulation experiments a constant stratification situation is chosen, where temperatures from sea level by constant gradient decrease to the upper model border.

This assumption is made for simplification and the reason of climate data at Whistler improbably representantive for i.e. the more southern mountains near Point Atkinson (horizontal diffusion).

Moreover with the simulation option set up to model for nocturnal to daily change, the thermic processes, which Squamish is known for, are respected. With modelling thermic effects, the likely situation of a constant stratification by the author is believed to be an adequate starting base.

6.5 Pre-processing of input files to model METRAS PC

Two input files are required for the model: first the meteorological initialisation profiles and second the topography of the model area. The meteorological initialisation file is derived from the climate data analysed in the previous chapter. Example initialisation files each for the winter and summer season are displayed in the appendix. The two initialisation file types of winter and summer are then adapted to the various derived windclasses. A further explanation of the meteorological

initialisation files is left to the detailed description given in the METRAS PC manual (SCHLÜNZEN, BIGALKE 1998).

The topography file of the model area consists of upper surface height data, (base elevations plus heights of forests and buildings) and of the landuse classes for thermic and surface roughness attributes. In effect a considerable downscaling of high-resolution geodata to lower resolution meteorological model is seen.

6.5.1 Definition of relevant modelling area and grid size

The definition of the modelling area and grid size is carefully undertaken weighing cost and benefit factors. Besides further aspects, enlarging the modelling area, increasing the amount of height layers or altering the grid resolution, leads to exponential rise in memory requirements and computation time. Though Metras PC allows for application of rotated model areas as well as inequidistant grids (high resolution in centre, lower to the outer boundaries) these possibilities are not considered for keeping things simple.

The main factor for defining the modelling area is that the area is large enough to respect all meteorological effects, but small enough to allow for detailed analysis. By this measure with the aim of achieving a high resolution of a desired 300m grid the modelling area is defined as limited from the North with the boundary of an assumed weather shed located at Whistler (due to highest point within the valley) southwards to the Howe Sound entering into the sea at the Strait of Georgia. To the definition in width the assumption is made that two rows of mountain ranges to the East and West side are thought to be sufficient to resemble wind flows within the Howe Sound fjord.

However later the aspired grid resolution of 300m turns out being to demanding in computation time, superseding memory availability and eventually causing initialisation problems to the model. Therefore the resolution is changed to a 2,4 km.

Excursion: Creation of the model-grid (polygons and cell midpoints)

A) First a grid is manually drawn for the area located directly at the prospected site by use of Editor. This is to ensure that the grid best fits to the topography of the site, i.e. all potential turbine sites are within one “representative” grid cell of homogenous elevation and topography. Such potential model-grid-cell midpoints are derived.

- B) With MS Excel from the midpoint XY coordinates (i.e. X=486150; Y=5504150) the prospected coordinates for the borders of the modelling-area can be calculated for.
- C) By GIS creation of a raster grid with prospected extent of modelling area. Then conversion to point shapefile by the model resolution (first 300m, second 2400m). Reconversion to raster followed to a conversion to polygons by the grid-cell-ID with the spatial analyst's extent enlarged by two times half the grid-cell distance for outer borders.

6.5.2 Generation of a digital surface model

Generally with coarse resolutions obstacles are not resolved for precisely by the impact on wind-flows, but are respected by the assigning of surface roughness classes to individual grids. With the high resolution of 300m grids aspired and the option to run micro-scale simulations at even higher resolutions for micro-siting, from the Canadian Digital Elevation Data (CDED50) by adding tree and building heights a digital surface model shall be derived and used as a input for the model.

6.5.2.1 Height of western red cedar forests

In the Canadian rainforest, limited by climate to the narrow rainbelt bordering the Pacific Ocean a record height of 95 m is set by the giant tree *Sitka spruce* (WILDERNESSCOMMITTEE). The forest covered land is prevailed by the Western red cedar. Described by (CANADIANFORESTRY) "the Western red cedar (*Thuja plicata*) is characteristic to the Coast and Columbia Forest Regions of British Columbia. Its foliage is a dark, lustrous green; the bark is dark reddish-brown, fibrous, shreddy and vertically ridged. In moist bottomland soils trees of this species can stretch to heights of 45 to 60 m with a diameter of 1 to 2.5 m. Cathedral-like western red cedar groves are havens for outdoor enthusiasts mesmerized by these towering trees."

The decision on general height for forests is assumed to be 45 m, not to overestimate forests heights where trees of other kinds, especially lower trees and composed in smaller groups are located. The height is also kept modest, as close to the prospected wind turbine sites smaller groups of tree arrangements are found.

6.5.2.2 Height of selected relevant buildings

Guessing on how high buildings or other constructions are, answers are likely to be difficult, as the eye is not trained upon such questions. High Buildings with the effect

of obstacles to the wind should be respected where in direct circumference of the potential wind turbine sites.

In building bylaws or also development plans such as the "Squamish Downtown Waterfront Initiative (DRAFT) Concept Plan"²⁴ often building heights are regulated, so that an official measure can be applied within a project. For example this plan states that for planned areas of "3.2.2 Residential - High Density Residential" only "four story 45 foot to roof eve maximum building height" houses are permitted.

Four story houses in the neighborhood of the author equipped with scaffolds allowed to do some measurements (each scaffold two meters in height, addition of approx. 30cm base-distance) with the result that each story has an approximate height of 2,65m, a four story house having an approximate height of 12m to the roof beginning and 16m to a saddleback's top. A two-story house would approx. be 6m to the roof's beginning and 10m to a saddleback's rooftop

With a better impression on typical building heights, now for the buildings encountered at the Squamish harbor close to the prospected turbine sites these assumptions are made:

- o Office-buildings with 2 stories, medium saddleback roof: 8m
- o Large storage hall equivalent to a 4-story home flat roof: 12m
- o Large round silo towers: 20m



Figure 40: DSM from landuse woods (green) and digitized building heights (pink)

²⁴ "Squamish Downtown Waterfront Initiative (DRAFT) Concept Plan":
<http://www.sgog.bc.ca/uplo/sdw3.pdf> (30.08.2006)

Excursion: process steps in generation of digital surface model

- A) Export of all landuse features selected by attribute of “wood” from landuse map polygon-shapefile. Reconversion to raster by extent and resolution of landuse-raster map.
 - B) Reclassification of wood’s gridvalues representing height in meters to “45” and value “noData” to “0”, save as “Z_woods.img”.
 - C) Digitizing building-outlines from orthofotos to polygon shapefile "Z_buildings.shp".
 - D) Assign attribute values to "height" field according to building heights decided for.
 - E) Convert Features to raster by the output cell size of 15m (cell size and extent same as “Z_woods.img”). Eventually due to lower resolution of landuse map 15m compared to 2m by orthofoto it is necessary to expand the building shapes to get buildings heights respected (done for the inner 2 of 4 the silo buildings).
 - F) Reclass height values same as before, but “noData” to "0", final “Z_buildings.img”
 - G) Convert "CDED_utm.shp" to raster adapting the extent and spatial resolution to the "Z_woods.img"
 - H) Raster Calculator for calculation of $DSM = [CDED_utm.img] + [Z_woods] + [Z_buildings]$
-

6.5.2.3 Downscaling DSM data to model grid resolution

To fit the high-resolution digital surface model (DSM) to the lower resolution model grid it is important to average all height data within one model-grid-cell. Eventually to speed up processing time, at first a downscaling in the resolution of the DSM is required, before individual height measurements can be averaged to the model-grid cell heights.

Excursion: Generation of model elevation data from DSM

- A) Conversion of raster based DSM to Point Shape at a resolution suited to represent height values within individual model-grid cells. (i.e. 60m).
 - B) Calculation for average height values by the points within polygons by spatial join.
-

6.5.3 Roughness map: assigning roughness class to landuse

As stated (SCHLÜNZEN, BIGALKE, 1998) “in METRAS PC ten landuse-classes are used, which are differentiated to albedo A_0 , thermic diffusiveness k_s , thermic conductivity v_s , penetration of temperature waves h_0 , availability of groundwater α_q ,

groundwater saturation W_k and roughness length z_0 . The properties of close-to-surface are calculated by the percentile proportions of these 10 landuse-classes for each grid-cell. The following table gives an overview about the ten landuse-classes respected by METRAS PC and their properties:“

Class	Type	A_0	k_s [m ² s ⁻¹]	v_s [J(Ksm) ⁻¹]	h_0 [m]	α_q	W_k [m]	Z_0 [m]
0	Water	F(Z(t))	0.15*10 ⁻⁶	100.0	0.11	0.98	100.0	F(u*)
1	Wadden	0.10	0.74*10 ⁻⁶	2.20	0.25	0.98	0.322	0.0002
2	Sand	0.20	0.57*10 ⁻⁶	1.05	0.22	0.10	0.026	0.0003
3	Mixed use	0.20	0.52*10 ⁻⁶	1.33	0.21	0.20	0.138	0.01
4	Grassland	0.20	0.52*10 ⁻⁶	1.33	0.21	0.40	0.015	0.01
5	Heather	0.15	0.24*10 ⁻⁶	0.30	0.14	0.10	0.423	0.05
6	Bushes	0.20	0.52*10 ⁻⁶	1.33	0.21	0.30	0.081	0.10
7	Mixed forest	0.15	0.80*10 ⁻⁶	2.16	0.26	0.30	0.121	1.00
8	Conifer forest	0.10	0.80*10 ⁻⁶	2.16	0.26	0.30	0.161	1.20
9	Development	0.15	2.30*10 ⁻⁶	4.60	0.45	0.05	0.968	0.70

Table 14: METRAS PC landuse classes

With the landuse classification containing 6 classes, these could relatively well be matched. Assumable the class of rock, representing on the one hand mountainous rock and cliff zones as well as developments has been assigned the METRAS-class “development”. For the class of “flat concrete surface” (i.e. airports) the METRAS-class of “sand is chosen for best representing albedo and roughness. The class of snow (mountain peaks) is assigned the METRAS-class of water (“sand” thermally would likely lead to modelling vulcanoe-effects).

Excursion: Assigning landuse classes to model grid

- A) From the raster based landuse classification convert to point shapefile, decreasing resolution to i.e. 60m due to computation performance. Selecting by attributes then individual landuse classes are exported to individual landuse point-shapes (0_water.shp, 2_flat.shp, 4_grass.shp, 8_forests.shp, 9_rock.shp). To each of the landuse shapefile insertion of a “count” field, assigning the value of “1” for each point
- B) Counting the numbers of landuse points within each polygon model-grid-cell by spatial join (sum of field “count”) processing from the first “0_water.shp” through to the last shapefile “8_forests.shp”. Resulting within one shapefile all points are counted separated by their METRAS-landuse classes.
- C) Calculate for percentages using field calculator. For control sum of these must equal 100%.

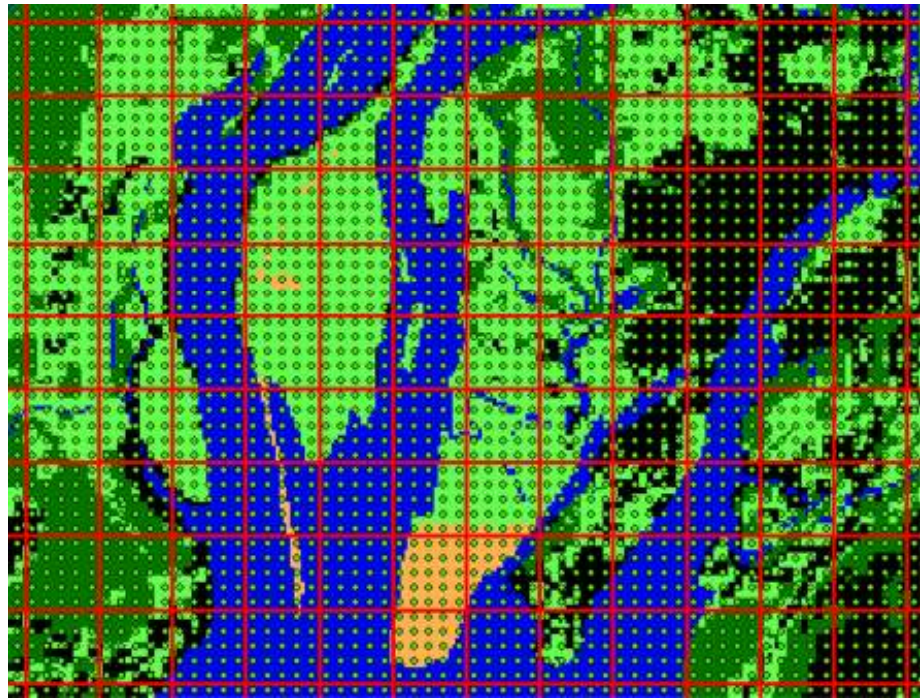


Figure 41: 60m resolution landuse-points in initial300m model-grid-polygons

6.5.4 Formatting model-grid to requirements of METRAS PC

6.5.4.1 Attribute "geographic DMS coordinates"

The topography file requires the attribute of geographic coordinates stated in the format of degree, minutes, seconds: "-DDD.MMSS". The "-" is required representing western longitudes. This issue is solved by the freely provided calculator expressions "Easy Calculate 5.0"²⁵ for the ArcGIS field calculator.

While the coordinates are stated in the usual form of i.e. longitude X_DMS = 123d33'26.6"W and latitude Y_DMS = 49d16'03.24"N, these later need further formatting to the format of "-DDD.MMSS".

6.5.4.2 Attribute "Index"

An index to identify the model-grid-cells has to be created. While the features of the model-grid-shapefile are by ID top-down sorted from cartographic top left (NW) line by line to down right (SE), the MetrasTOPO file in contrary requires a listing from down left to top right. For resorting and required as attributes a row-index "X_IJ_INDEX" and line-index "Y_IJ_INDEX" is calculated by the differences in relative model-grid-cell positions:

²⁵ "Easy Calculate 5.0": Ianko Tchoukanski, <http://www.ian-ko.com> (30.08.2006)

The down left coordinate is $X_{II_0}=459450$ and $Y_{IJ_0}=5457350$, grid distance is i.e. 300m, thus it can be calculated for each model-grid-cell:

$$X_{II_INDEX} = ([X_UTM]-459450)/300$$

$$Y_{IJ_INDEX} = ([Y_UTM]-5457350)/300$$

6.5.5 Attribute "horizontal and vertical distances"

The attribute of the horizontal and vertical dimensions of the grid cells is the same for each cell, since the model grid is equidistant at 300m and 2400m. However with inequidistant grids, which METRAS PC does handle, as to before distances could be calculated by the differences in relative model-grid-cell positions.

6.5.6 Equalize border values to outer three cell rows and lines

In order not to cause waves by the instreaming winds at the model area's borders, the topography of the outer three lines and rows have to be equalized concerning height and landuse profile.

By sorting for the X_{II_INDEX} and Y_{IJ_INDEX} within MS Excel this issue is handled. Various formatting requirements are performed next, especially coordinate formats need changing from i.e. longitude "123d33'26.6"W" to "-123.33266".

Saving the table as CSV-text (comma separated values), in Word all delimiting "comma" need to be replaced by " "(space). Careful attention has to be taken that all data-contents are in the appropriate places of the METRAS topography file, so that accepted and interpreted right by the model. In the appendix an excerpt of the topography file is displayed.

6.6 Initialising model: running simulation experiments

With both topography and meteorological initialisation files elaborated, the simulation experiments are exercised.²⁶

All simulation experiments are exercised twice: one with an timeseries output file for the control station of Pam Rocks and one for the potential turbine site of Squamish.

²⁶ The simulation experiments have been exercised with METRAS PC (Version 1.0, for windows PCs). METRAS PC is a public domain program, developed in 1998 by K.H. Schlünzen, S. Dierer, H. Pankus (Meteorological Institute, University of Hamburg) and K. Bigalke (METCON Umweltmeteorologische Beratung, Pinneberg) in a project based on the model METRAS and funded by the Umweltbundesamt (Berlin) under grant number FE 104 04 354.

The individual simulation experiments are named as displayed in the following figure. To their codex the prefix "squ" is added for Squamish and "pam" for Pam Rocks:

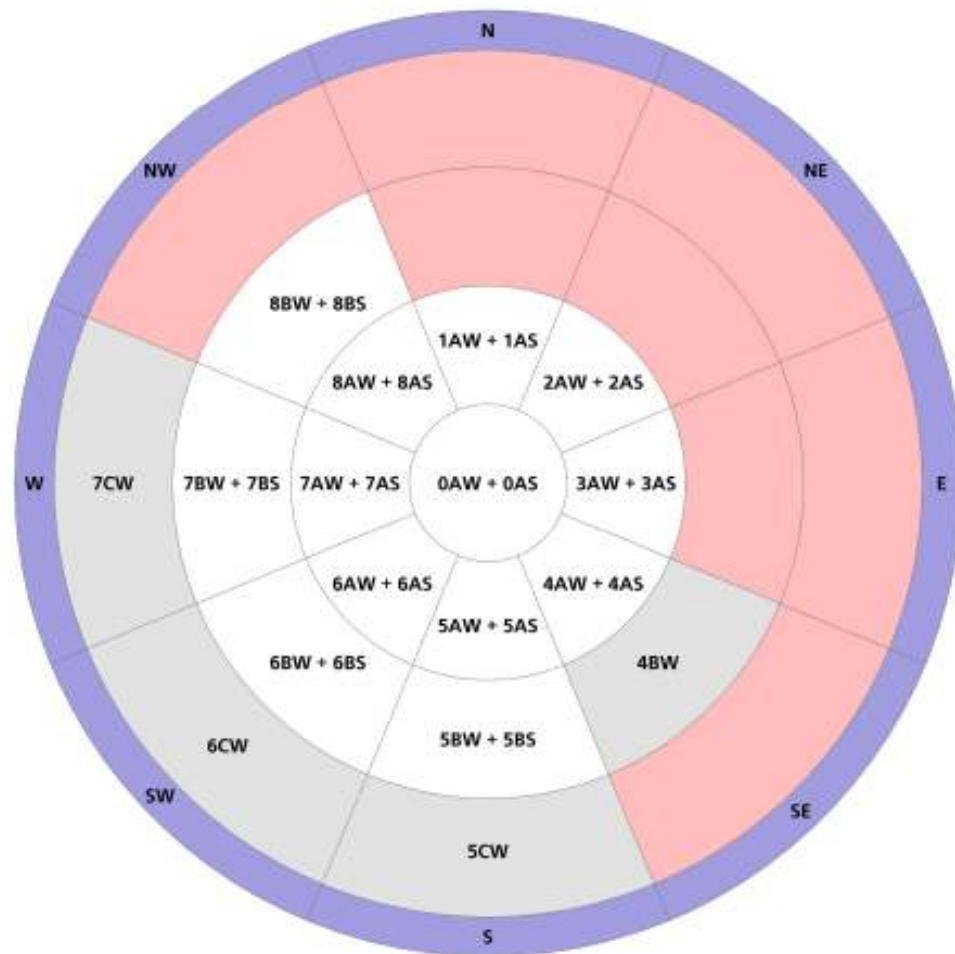


Figure 42: Windrose-diagram with sectors describing simulation codex

For the model with the simulation option set up "instationary" to model for nocturnal to daily change, the simulation experiments do model a full day by time. Starting at midnight constant winds are instreaming the apriori plain-leveled model area. The "blow up" of elevation is set to 25 minutes, so that the model produces analysable data from half past twelve on, resembling "reality" with thermic effects from the warming of the sea and landmasses during the morning to noon and cooling down from evening during night again. The simulation experiments end at 24:00.

Formatted 3D climate-data output is set for every 3 hours. Unfortunately by applying the elaborated meteorological parameters most simulation experiments do not complete the full simulation time of a full day. Experimenting with the meteorological parameters enables to complete a greater part of simulation experiments than before, but especially for the more prevalent geostrophic south southwest and western wind directions the changing of parameters can only endure

simulation time. With the option of modelling “stationary”, that is nocturnal to daily change is disregarded and a steady situation in windflow is aspired, for these sectors some experiments could be finished as well, but by no means this option would have been a solution to finish all simulation runs adequately.

With simulation experiments not finishing due to numeric instabilities as seen in this project, the problem arises that no formatted 3D climate-data output files are generated. As an attempt to still produce an as good as possible annual wind distribution for Squamish it is decided to:

- a) adjust meteorological parameters to increased simulation stability,
- b) to interpolate “missing” model time from as much time available (i.e. if model error occurs at 16:00, data from night , morning and noon is taken to resemble late afternoon, evening and following night hours)
- c) output control data is produced for every model’s calculation time step (1sec to 30 sec) regardless of model finishing upon completion or due to error. Use of control data output for the control station of Pam Rocks (height 20m) and one for the potential wind turbine-site of Squamish (height 100m).

By this method of resolution, multiplying simulated day situations by their frequency of occurrence the annual wind distribution for Squamish could be derived enabling for wind energy yield prospecting and also an corresponding validation of modelled annual wind distribution to measured annual wind distribution at the weather station of Pam Rocks, by information gathered appearing quite representative to the Howe Sound’s wind conditions.

Concerning a) increased simulation stability is attained by setting the stratification from stable (constant temperature decline with height) to neutral, meaning that the sea-level temperature stay the same up to a height of 1000m or even 2500m (unrealistic). With the high humidity the “project” site could be considered quite wet (“British Columbian rainforests”), reducing humidity from 60% at sea level to 20% at 11km height as well as from 40% to 10% led to better results. However neither of these alternative parameters represents a general solution.

An overview of all simulation experiments and results with varying parameters is given in the annex. It has to be noted that concerning most simulation experiments it has been alarmed that cloud and ice building processes were prone to occur. In METRAS PC Version 1.0 these are not implemented.

6.7 Possible explanations to encountered difficulties

Thanks to MEMI Team of the Meteorological Institute of the University of Hamburg, a general discussion and check of meteorological parameters has been done. Due to lack of time it was not possible to test the beta version of Metras PCL, based on Linux. Presumably the main difficulties result from the project's "extremely" complex terrain with high and steep mountains (vertical 500m wall "Stawamus Chief") with strong vertical up- and downwinds as well as strong horizontal diffusion processes of humidity. Some of the questions and problems discussed were published on the 08/09/2006 by (METEOROLOGICAL INSTITUTE UNIVERSITY HAMBURG), in the section of "Frequently Asked Questions"

"stack overflow

reason: central memory is not sufficient.

* *solution:* use less grid points or computer with larger memory.

instability occurs

reason 1: unstable stratification up to the model top.

→ *solution:* use stable layer for at least upper 8 grid points above unstable lower layers.

reason 2: orography imposes 2 delta-x wave.

→ *solution:* filter orography.

reason 3: orography changes normal to boundaries.

→ *solution:* ensure the orography is constant at three grid-points in normal direction to the boundaries.

reason 4: use of METRAS PC with stable stratification and high orography, which results in unnaturally heated areas in the higher altitudes.

→ *solution:* use METRAS PCL, where the initialisation is within temperature profile changes or use METRAS PC with neutral stratification in the lowest about 1000 m.

Last update 08/09/2006"

The most probable explanation seems to be the instabilities resulting from the stated "reason 4". A test of the beta version of Metras PCL beyond this thesis's scope is aspired by the author.

With an initial prospected resolution of 300m simulation experiments did not pass the model's initialisation test procedures. Though RAM-capacity with 2GB by requirements should have been sufficient the hint at "stack overflow" resulted in the 2400m grid spacing. As well horizontal diffusion processes of humidity, as stated in (SCHLÜNZEN, BIGALKE, 1998) are "not respected for horizontal grids of less than 1000m", which as well might be a cause for error.

By the enlarged grid spacing to 2400m it became possible to run simulations on a computer equipped with 128MB RAM (650 GHz Celeron). Also this resulted in acceptable processing times of 5-7 hours for each simulation experiment for a 2.6 GHz Celeron Processor.

Respecting that Metras PC 1.0 was published first in 1998 , the advancements of the METRAS model group suitably offer resolution.

Another aspect is that *transferability studies* are carried out, investigating if the application of regional model to other areas may cause problems, as most models are parameterised by dynamics and physics to certain regions (TAKLE et al, 2005) and (ROCKEL et al, 2005)

6.8 Exporting 3D wind field to GIS for display

Due to the vast amount of data created by all simulation runs and an awkward output format, desirable is a database scripting routine writing the data of all individual weather situations into a preferably spatially enabled database. For visualization and analysis a GIS would then ideally be used to query the data from such a database directly. Such a solution has been realized by (MOLDENHAUER, 2006).

As this task is of too much complexity concerning the scope of this thesis, the windfields have been visualized for one specific weather situation "7BS" (west-wind, 10 m/s, summer), with hands-on post-processing on separate simulation runs for each output factor. This is the basis for understanding the structure of the output files for the above-mentioned task. Also moving within the 3D windfields in ArcScene an impression is realized by which investigation on benefits from such visualization towards the cost of such an investment can be weighted.

A reference to post-processing ASCII based METRAS-data files in GIS is given by (SCHLÜNZEN, KIRSCHNER, 2006) The actual METRAS output files are stating the attributes of each point, defined by XYZ coordinates, directly while in METRAS PC Version 1.0 all individual attribute data are stated in bulk within single blocks (u_1, u_2, \dots, u_n). Also while in METRAS all formats are formatted to windspeed, wind direction, absolute temperatures in Celsius and absolute relative humidity, METRAS PC output files require hands-on post processing

Excursion: post-processing 3D format output data for visualization

- A) For each variable as output one individual simulation is run.
- B) Analysis of output file "formatted model results", no value output for the southern and western one borderline analysed:
 - All height values are output in ONE row by 34 values (dimension z=35-1)
 - All vertical wind values are output in ONE row by 34 values (dimension z=35-1)
 - All U-wind values are output in ONE row by 35 values
 - All V-wind values are output in ONE row by 35 values
 - All temperature values are output in ONE row by 35 values
 - All relative humidity values for all levels equal "0", considerably implausible though.
- C) Convert CSV-file line structured data values to row orientation: in Word by Find ",",. Replace "^p" .for carriage return this is performed. Save File as plain Text.
- D) Build index for above data value rows from 1-34 or 1-35 from beginning to end, as then data can be sorted referring to height level (index indicates height level of values).
- E) Build one .xls file for each of the height levels step by step adding all attribute data to the model-grid-cells. Calculate for windspeed and –direction. Calculate from temperature change to absolute temperatures in Celsius. Add XY coordinates and index to each shapefile.
- F) Import data-files into ArcMap, symbolize wind by scaled and rotated arrows, export as raster map and in ArcScene for 3D drape over calculated TINs from each levels model-grid-cell's elevation.

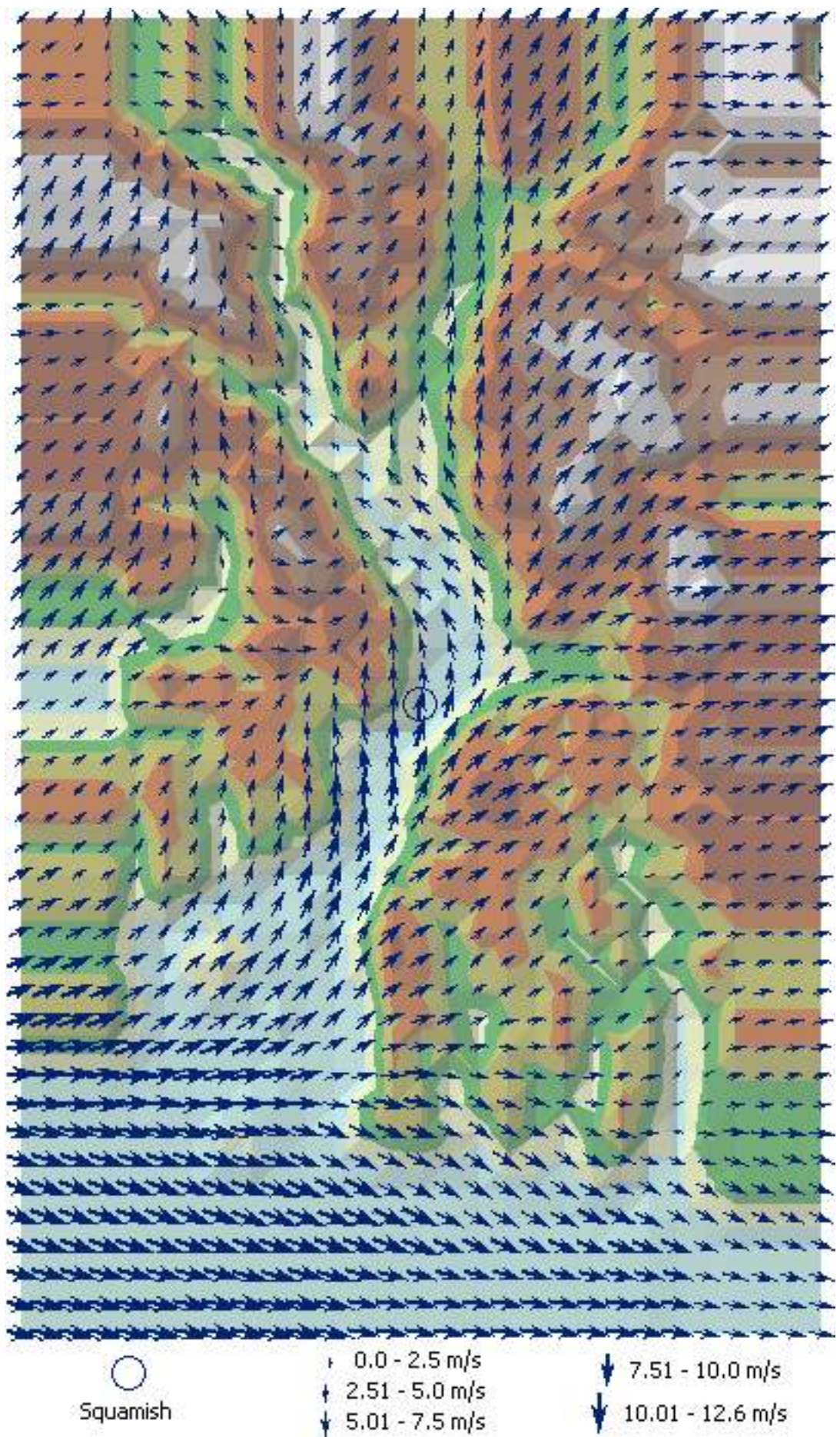


Figure 43: 2-dimensional windfield, level 100m

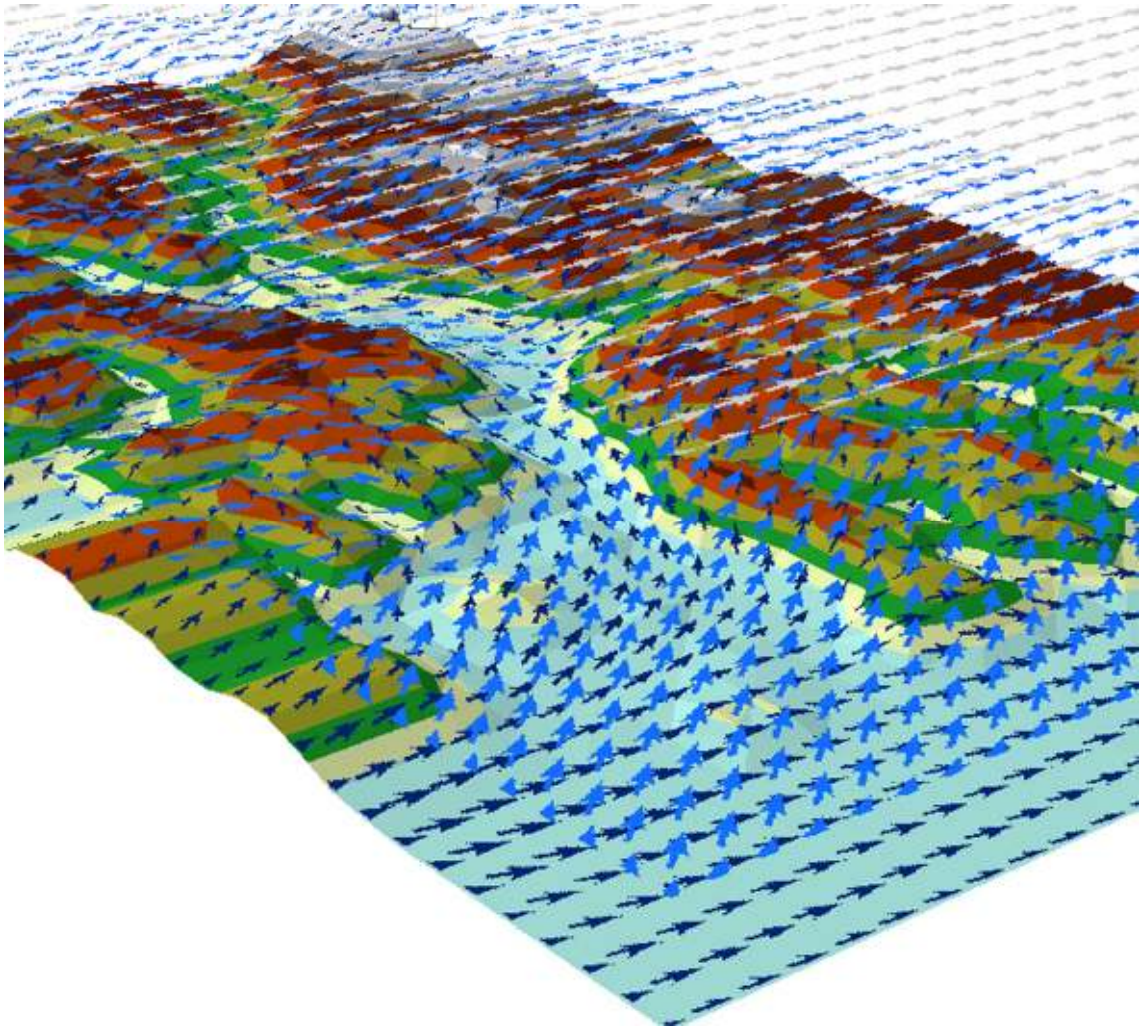


Figure 44: 3-dimensional windfield, levels 100m, 2853m, 11481m

Three dimensional wind turbines have been created for the site of Squamish most kindly by Dirk Tiede, who is the author of the script "Create 3D wind turbines"²⁷ for ArcGIS 3. In (TIEDE, BLASCHKE, 2005) 3D-visualization capabilities of ArcGIS 3, ArcGIS 8 and ArcGIS 9 are described as well as wind turbines are displayed in detailed 3D symbolization making use of the enhanced 3D visualizing functionality of ArcGIS 9.

With ArcGIS 9 detailed 3D symbols eventually the wind arrows could be created more nicely not by use of raster but vector data, desirably enabled for individual wind arrow's attribute query in the scene. However the raster approach in ArcGIS 8 has the advantage of the wind arrows following the layer's individual elevation profile. This enables for a good visual assignment to the corresponding layers and creates nice flow profiles. Considerably though the vertical wind data attributes are by this method not respected.

²⁷ "Create 3D wind turbines": author: Dirk Tiede, <http://arcscripts.esri.com/details.asp?dbid=12468> (30.08.2006)

So visually analyzing and interpreting the wind field by moving in the 3D scene it has to be kept in mind that the wind-field in display is not truly 3-dimensionally but 2,5 dimensionally composed of layer structures topping one another.

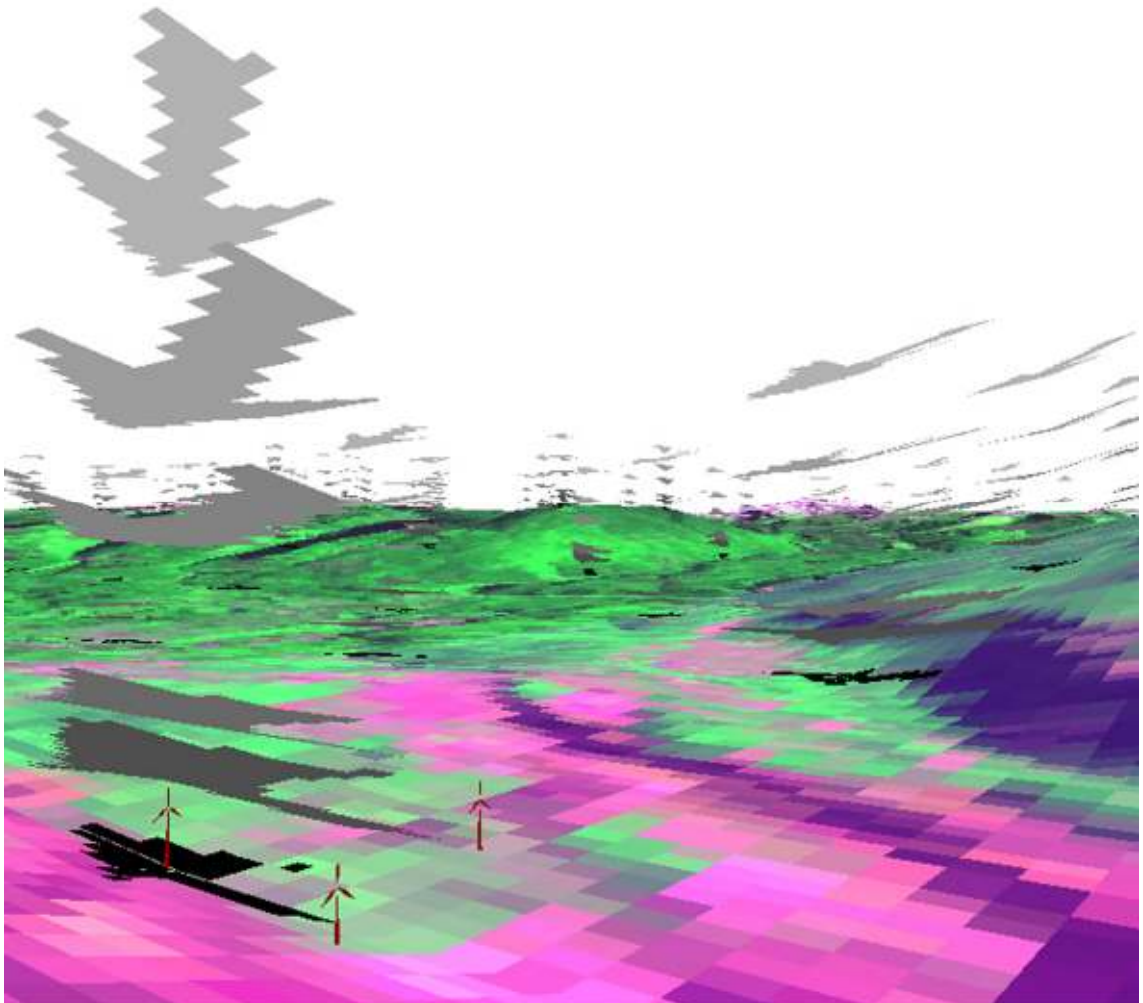


Figure 45: 3-dimensional windfield at site of Squamish

However the visualization concerning micro-siting of turbines would require a resolution as first intended to be 300m, or better even higher.

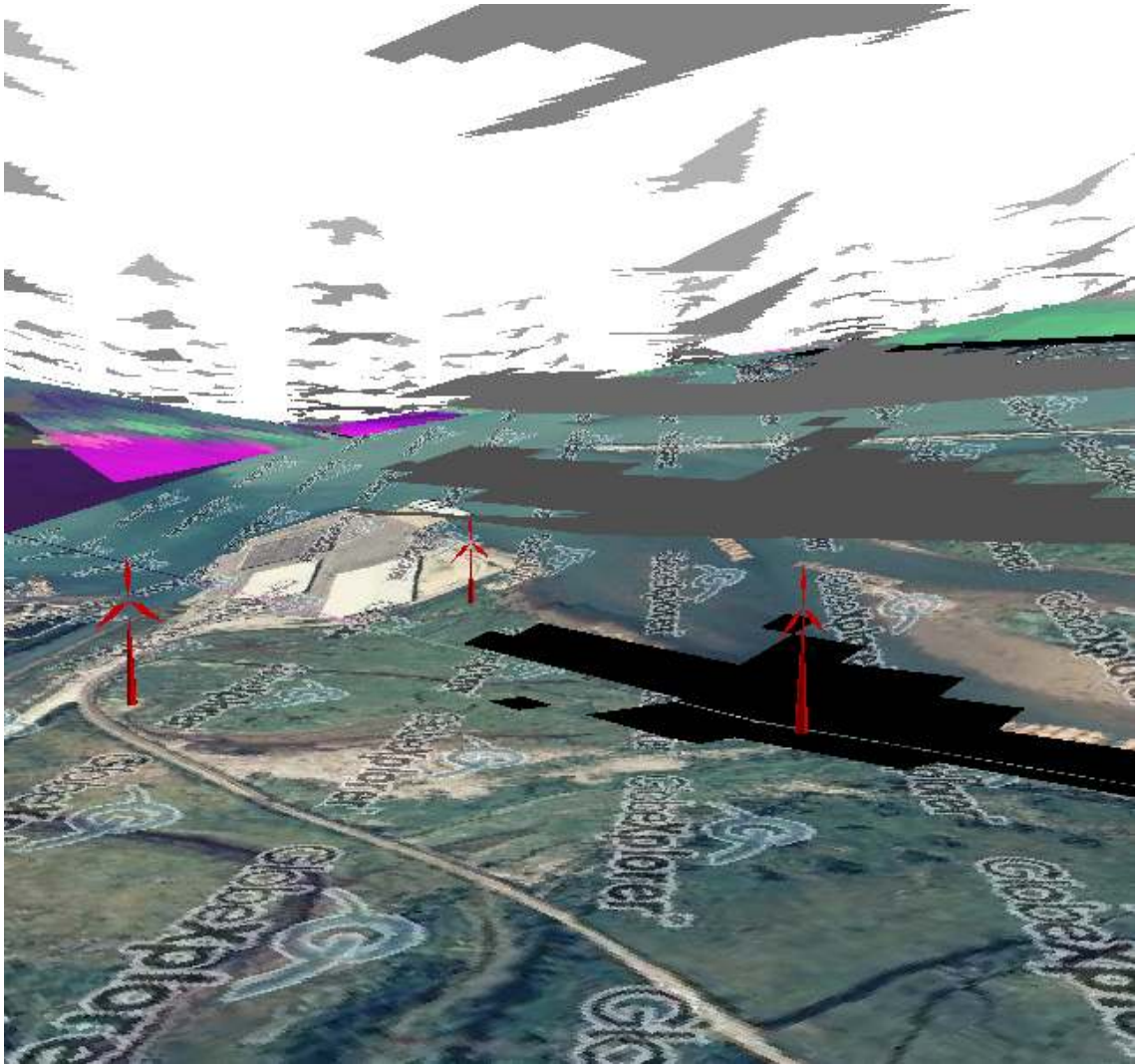


Figure 46: 3-dimensional windfield at site with orthofoto – issue resolution

The 2.4 km grid resolution is too coarse to define which spots are the best suited to placement of turbines judging by view within a 3D scene. With increased resolution and also analysis tools available this would be the tool for optimizing micro-sitings as intended by this thesis.

6.9 Aggregation of wind distribution potential

As decided for in chapter 6.6 the wind distribution potential of Squamish is to be composed of the climate data output of all simulation runs multiplied by their individual's frequency of occurrence.

A second wind distribution potential is proposed for the control point of Pam Rocks, to validate model data against the measured ground station data.

As output control data is produced for every model's calculation time step (approx. 1sec to 30sec) what is known as temporal aggregation or more generally data

aggregation has to be performed. As a tool for automatic aggregation has not been found by the author this is a very time consuming process prone to human error. Though theoretically allowing for a very desirable resolution of i.e. values each 10minutes (typical resolution from wind measuring masts) due to the effort involved a resolution of 1 hour is chosen.

Excursion: post-processing timeseries analysis from control points

- A) Manual time aggregation of all values available at time range from 1.5 second to 30 seconds to hourly data. Each simulation experiment equaling one day consists of 24 data values, one for each hour.
- B) Interpolate “missing” from “available” model time data as described above
- C) Multiplication by frequency (see table 10) realized by multi-times copying of individual timeseries-csv-files and final use tool “merge csv”²⁸.

total winter situations	total summer situations
51,5%	48,5%
516 files	486 files

Table 15: Total winter / summer situations for wind-dataseries

- D) In excel insertion of field season and attributes "winter"/"summer", sort by season, then simulation-name (squ0AW, squ1AW, etc), so sector by sector is "stepped through", first in the winter, then in the summer time.
 - E) Calculation for windspeed and wind direction
 - F) Import to WindPRO for creation of wind rose diagram and energy yield calculation for wind turbines
-

While post-processing the control output file’s data the rude awakening happens, that the timeseries data had not been given out at the defined control points but for the same point in the centre of the model at a height of 730m. Even a third simulation experiment set-up with the control point set to the lower left corner grid cell does not the control point as defined. This at once destructs all plans on validation and yield prospection for the wind turbines from the modelled wind data.

²⁸ “merge csv”: Ron de Bruin, <http://www.rondebruin.nl/csv.htm> (30.08.2006)

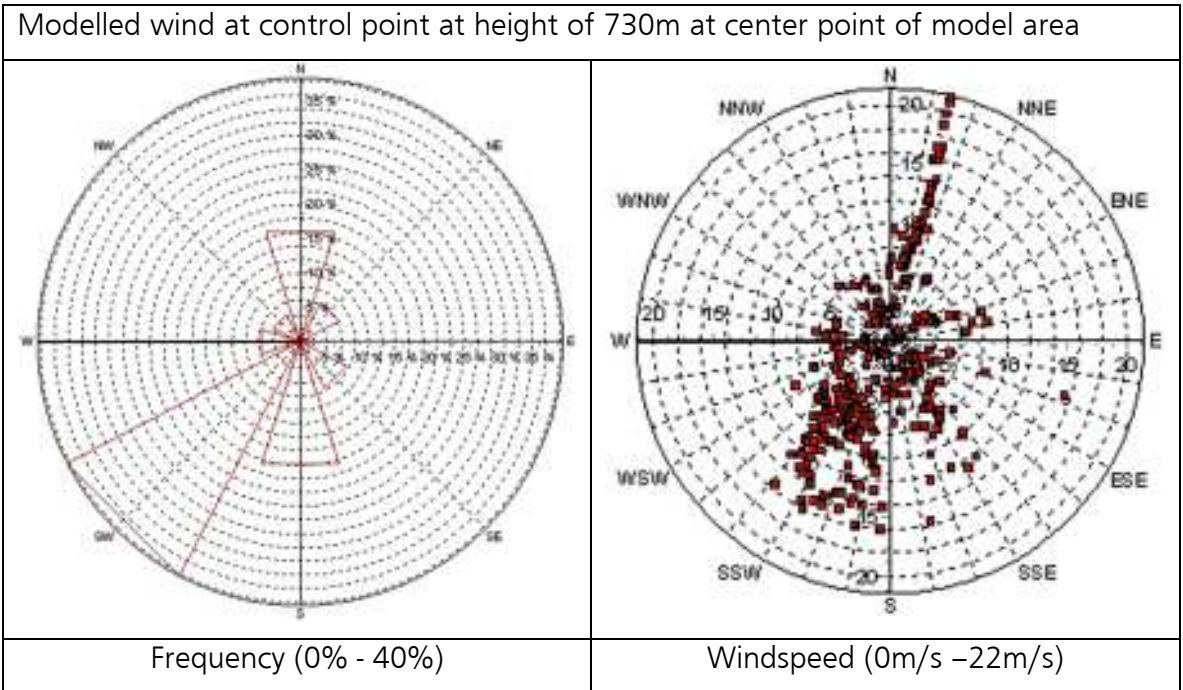


Table 16: Simulation results with time-aggregation to 60 minutes at control point

With the data from this height it is hard to judge if the modelled wind fields do represent realistic wind-distributions at ground level.

Described in (FAUCHER, BURROWS, PANDOLFO, 1999) by measures at marine ocean buoys prevailing south-western wind directions are known. This resembles the model input geostrophic NCEP wind data:

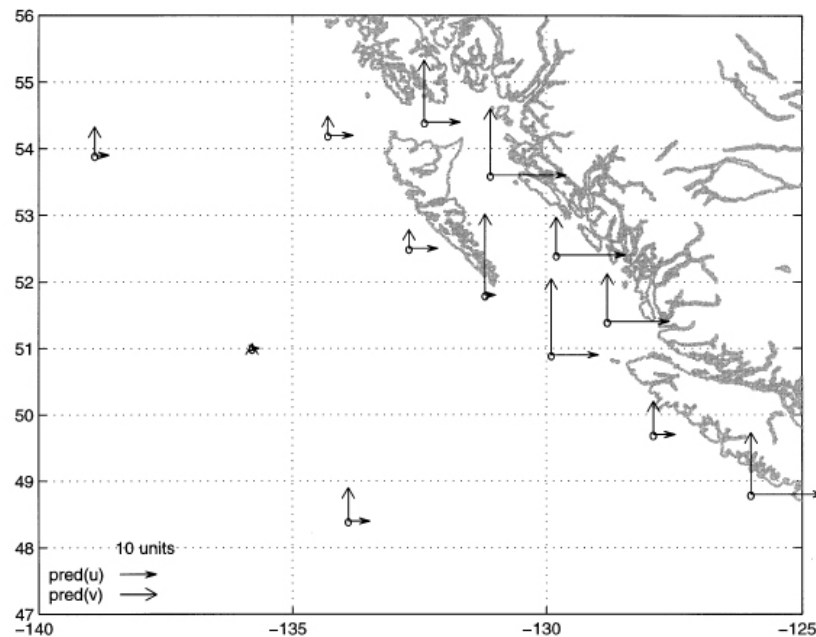


Fig. 4. Number of relevant predictors for each predictand (u and v) at each buoy site. Vector length along u and v axes is proportional to the number of predictors required to model the given wind component as determined by CART

Figure 47: Main wind direction to Pacific Ocean at Vancouver Island is Southwest

The Canadian WindAtlas described in Chapter 3.2.3 shows that the prevailing wind directions at ground level in the Howe Sound in contrary to the large scale conditions are North East. This fits well with the ground stations data analysed.

Wind Rose and Wind Speed Histogram at 80m

Frequency distribution of wind by sector and by speed class
Latitude=49.685, longitude=-123.176

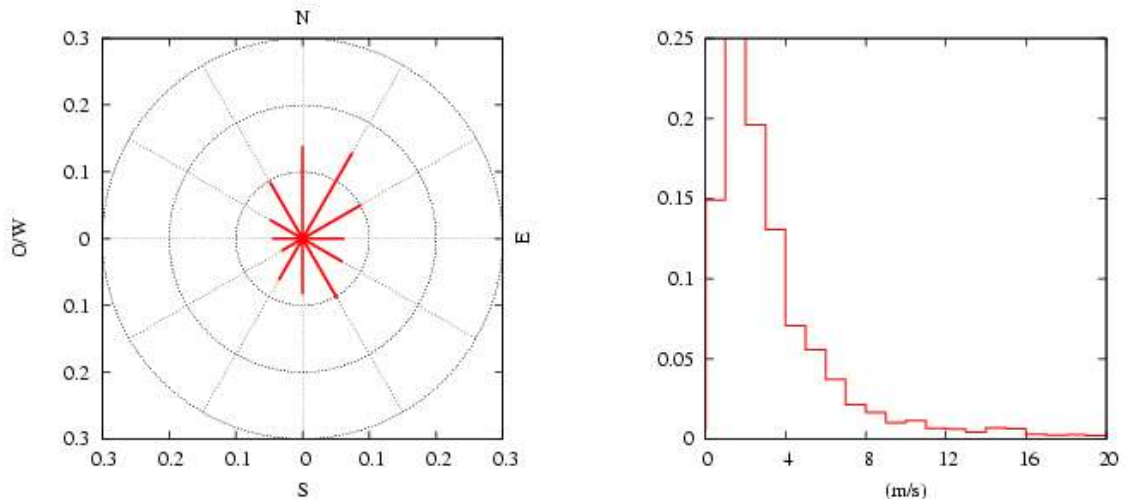


Figure 48: Canadian WindAtlas windrose-diagram at height of 80m for Squamish

As such the expected wind distributions are well known the overall question is, if the wind fields modelled by the set-up chosen do resemble especially the geostrophic main wind direction to be South-West and the ground level's main wind direction to be North-East.

If such a fit is achieved would mainly depend on:

- o the model area chosen great enough to contain all relevant atmospherical effects
- o large scale climate data being applicable to i.e. lower-scale model-area
- o accuracy of large scale data

Judging by the experience gained of the area it is likely that the wind distribution at Pam Rocks is likely the most representative weather station for Howe Sound. Assuming a vertical height gradient from ground level to the turbines hub height of i.e. 100m a calculation for wind energy yield could give a hint on what likewise could be harvested at the site of Squamish. As this method being a quick task with WAsP due to the complexity in terrain should not be considered accurate so that no prediction on potential yields is made in this thesis

With the meteorological data analysed from the years 2000-2005 for one aspect most recent data and for the other aspect data from a 6 years time range can be considered quite representative opposed to shorter time ranges. For example most

wind measurements undertaken for the purpose of micro-siting are collecting data for one year. Such with 6 years as a fair basis for a good average index, it is possible to compare this to timeseries of greater range, i.e. the last 10 or the last 30 years.

The ability to make useful forecasts is clearly limited due to (KIRKBY 2000a):

- o inherent unpredictability of non-linear systems
- o great breadth of uncertainty bands
- o difficulties in moving between time and space scales

In general the principle of historic information used to predict future climate behaviour is prone to uncertainty and such subject to the theory of probability.

7 Summarizing the shared vision

The developments towards integrating the technologies of environmental models and GIS range from the level of simple interfaces over coupling towards network approaches interchanging data based on uniform standardized data formats. Modelling for multidimensional data in space and time for the siting of wind turbines the immense effort required on pre- and post-processing of the data does let the vision appear far from today's standpoint. With developments seen by the time of this thesis being written, the vision of environmental models and GIS multidimensional growing together has become more substantiated:

Development 1:

Most up to date the development of the METRAS PCL version 1.0 has been announced by (METEOROLOGICAL INSTITUTE UNIVERSITY HAMBURG):

"Last updated 08/09/2006: Extensions and improvements on METRAS PC will not be made. Care has to be taken when using this model over topography with a specified stable stratification.

METRAS PCL (linux, beta version) is a public domain program, developed in 2005 by K.H. Schluenzen, V. Reinhardt (Meteorological Institute, University of Hamburg). METRAS PCL is based on METRAS (version 6) and uses the features available in METRAS PC concerning input and output. The initialisation is changed by no longer balancing the temperature field in the 1D part of METRAS PCL for intialising the 3D part. This reduces instabilities in the 3D runs over topography found in METRAS PC when using a stable stratification at for initialisation. Based on user feedback a METRAS PCL version 1.0 is in development. "

Development 2:

The answer towards "Can Computational Fluid Dynamics be a Solution to Uncertainty of Energy Yield Prognoses?", expected to be brought up by the round robin at DEWI

by the end of 2006, assumably will be influential on applied techniques concerning the state of the art in wind assessment practices.

Development 3:

The release of the "OGC Sensor Web Enablement" in July of 2006 is of great potential to bridge the gaps between GIS and Environmental Modelling in the future. Hopefully the development of GIS will follow this technological advancement towards true 3D/4D interoperability, visualization and more over multidimensional analysis capabilities

8 Outlook

It is believed by the author that atmospherical models will gain in importance to wind energy – gaining further experience is aspired.

As well it is believed, that integration of the various techniques and software involved is crucial to the achievement of the target of having a powerful yet efficient set of tools to answer questions by GIS and ASIS.

Hopefully research and commercial institutions find ways to develop this set of tools to their maximum benefit conjointly.

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APPENDIX I:

Individual simulation experiments - parameters, model run time, eventual error statements

Season / Winddirection / Season / Windspeed A=3m/s B=10 m/s C=15 m/s	Stratification 0m - 11km stable relative humidity: default	Stratification 0m - 11km stable relative humidity: 60% - 20%	Stratification 0m - 11km stable relative humidity: 40% - 10%	Stratification 0 - 2.5km neutral 2.5 - 11km stable relative humidity: 60% - 20%	Stratification 0 - 2.5km neutral 2.5 - 11km stable relative humidity: 40% - 10%	Simulation experiments with other parameters	Stationary, no respect of daily to nocturnal change (endtime 09:00)
0 0 Winter Summer	AW AS 0S const 80-43 2.4h 0S const 78-50 2.4h						
1 N Winter Summer	AW AS 1AW const 80-43 2.4h 1AS const 78-50 2.4h						
2 NE Winter Summer	AW AS 2AW const 80-43 11h5.3 HUMIDITY 2AS const 78-50 2.4h						
3 E Winter Summer	AW AS 3AW const 2500m 13h1.6 OZEIT 3AS const 78-50 12h2.5 OZEIT						
4 SE Winter Summer	AW BW AS BS 4AW const 80-43 8h5.5 OZEIT 4BW const 80-43 5h5.0 OZEIT 4AS const 78-50 8h0.6 OZEIT 5AW const 80-43 8h5.5 OZEIT						
5 S Winter Summer	AW BW CW AS BS 5AW const 78-50 13h5.0 OZEIT 5BW const 80-20 1h5.8 HUMIDITY 5CW const 80-43 8h0.0 OZEIT 5AS const 78-50 8h1.6 OZEIT 5BS const 78-50 8h0.6 OZEIT						
6 SW Winter Summer	AW BW CW AS BS 6AW const 78-50 13h5.0 OZEIT 6BW const 80-43 2.4h 6CW const 80-43 2.4h 6AS const 80-43 2.4h 6BS const 80-43 2.4h						
7 W Winter Summer	AW BW CW AS BS 7AW const 80-43 2.4h 7BW const 80-43 2.4h 7CW const 80-43 2.4h 7AS const 80-43 2.4h 7BS const 80-43 2.4h						
8 NW Winter Summer	AW BW AS BS 8AW const 80-43 18h0.8 U-WIND 8BW const 78-50 18h1.8 U-WIND 8AS const 78-50 18h1.8 U-WIND 8BS const 78-50 18h1.8 U-WIND						

APPENDIX II:

Meteorological initialisation file "winter, northern wind 5m/s"

```
#
#   metras_TAPE5 (Steuerdatei für die METRAS PC-Version)
#   =====
#
# Die Steuerdaten werden von METRAS formatfrei aus dieser Steuerdatei
# eingelesen. Folgende Regeln sind zu beachten:
#
# 1. Leerzeilen sind erlaubt.
# 2. Kommentare werden durch "#" eingeleitet. Sie koennen am Zeilenanfang
#    oder im Anschluss an Steuerdaten in der gleichen Zeile stehen.
# 3. Steuerdaten sind durch
#    "schluesselwort = wert [wert [wert [wert ...] ]]"
#    definiert.
#    Leerzeichen davor und dazwischen werden ignoriert. Allerdings muessen
#    mehrere Werte fuer ein Schluesselwort durch mindestens ein Leerzeichen
#    getrennt werden.
# 4. Innerhalb einer Zeile darf nur einem Schluesselwort (ein) Wert(e)
#    zugewiesen werden.
# 4. Characterwerte muessen in "' ' (Apostroph) eingeschlossen werden.
#    (z.B. run_case = 'Test1')
# 5. Die Reihenfolge der Schluesselwoerter innerhalb der Steuerdatei
#    ist beliebig.
#
#=====
#
run_case   = 'squ1AW'
start_date = '06.01.16'
start_time = 0.00
blow_up    = -0025
run_time   = -2400
first_output = -0300
delta_output = -0300
#
restart_ctrl = 0
diurnal_temp = 1
timestp_ctrl = 1.
cpu_minutes = 1440.
#
time_geol = -123.1009
time_geob = 49.4138
time_geoh = 100.
#
outrecord_no = 11 12 13 1000 2000 2100 2200 5000 7000
#
topo_file   = 'd:\metras\squ1AW\indat\squ.top'
form_file   = 'd:\metras\squ1AW\outdat\AF-'
binar_file  = 'd:\metras\squ1AW\outdat\AB-'
time_file   = 'd:\metras\squ1AW\outdat\ATC-'
integr_file = 'd:\metras\squ1AW\outdat\ATI-'
#
profile_geol = -123.1009
profile_geob = 49.4138
sur_pressure = 101325.
height_ug = 0.
lscale_ug = 0.
height_vg = 0.
lscale_vg = -5.
height_t0 = 0.
lscale_t0 = 278.
height_tg = 0.
lscale_tg = 0.0055
height_rh = 0. 11000.
lscale_rh = 80. 43.
```


APPENDIX III:

Meteorological initialisation file "summer, northern wind 5m/s"

```
#
#   metras_TAPE5 (Steuerdatei für die METRAS PC-Version)
#   =====
#
# Die Steuerdaten werden von METRAS formatfrei aus dieser Steuerdatei
# eingelesen. Folgende Regeln sind zu beachten:
#
# 1. Leerzeilen sind erlaubt.
# 2. Kommentare werden durch "#" eingeleitet. Sie koennen am Zeilenanfang
#    oder im Anschluss an Steuerdaten in der gleichen Zeile stehen.
# 3. Steuerdaten sind durch
#    "schluesselwort = wert [wert [wert [wert ...] ] ]"
#    definiert.
#    Leerzeichen davor und dazwischen werden ignoriert. Allerdings muessen
#    mehrere Werte fuer ein Schluesselwort durch mindestens ein Leerzeichen
#    getrennt werden.
# 4. Innerhalb einer Zeile darf nur einem Schluesselwort (ein) Wert(e)
#    zugewiesen werden.
# 4. Characterwerte muessen in " '" (Apostroph) eingeschlossen werden.
#    (z.B. run_case = 'Test1')
# 5. Die Reihenfolge der Schluesselwoerter innerhalb der Steuerdatei
#    ist beliebig.
#
#=====
#
run_case   = 'squ1AW'
start_date = '06.01.16'
start_time = 0.00
blow_up    = -0025
run_time   = -2400
first_output = -0300
delta_output = -0300
#
restart_ctrl = 0
diurnal_temp = 1
timestp_ctrl = 1.
cpu_minutes = 1440.
#
time_geol = -123.1009
time_geob = 49.4138
time_geoh = 100.
#
outrecord_no = 11 12 13 1000 2000 2100 2200 5000 7000
#
topo_file   = 'd:\metras\squ1AW\indat\squ.top'
form_file   = 'd:\metras\squ1AW\outdat\AF-'
binar_file  = 'd:\metras\squ1AW\outdat\AB-'
time_file   = 'd:\metras\squ1AW\outdat\ATC-'
integr_file = 'd:\metras\squ1AW\outdat\ATI-'
#
profile_geol = -123.1009
profile_geob = 49.4138
sur_pressure = 101325.
height_ug = 0.
lscale_ug = 0.
height_vg = 0.
lscale_vg = -5.
height_t0 = 0.
lscale_t0 = 278.
height_tg = 0.
lscale_tg = 0.0055
height_rh = 0. 11000.
lscale_rh = 80. 43.
```

APPENDIX IV:

Topography initialisation file (excerpt)

'ANZAHL DER GITTERPUNKTE: NX3 =' 33 ', NX2 =' 45 ', NX1 =' 27
'BEZUGSPUNKT [dd.mm.ss]: BREITE =' 49.4255 ', LAENGE =' -123.1009
'DREHWINKEL DES GITTERS =' 0.0000

'VEKTORIELLE Z-PUNKTE:' -20. 0. 20. 40. 60. 80.
100. 120. 145. 184. 230.
284. 347. 421. 508. 610.
730. 871. 1037. 1232. 1461.
1730. 2046. 2417. 2853. 3365.
3967. 4674. 5505. 6481. 7481.
8481. 9481. 10481. 11481. 12481.

YXMIN= -32400. YYMIN= -54000.

II	IJ	YDX	YDY	ZSURF	YZ0	0	1	2	3	4	5	6	7	8	9	LON.	LAT.		
0	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.374410	49.130219	
1	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.354546	49.130282	
2	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.334683	49.130341	
3	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.314819	49.130398	
4	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.294955	49.130450	
5	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.275091	49.130500	
6	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.255227	49.130546	
7	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.235363	49.130588	
8	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.215499	49.130627	
9	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.195634	49.130663	
10	0	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.175770	49.130696	
11	0	2400.	2400.	0.00	0.100E-01	0.02	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.02	0.89	-123.155905	49.130725
12	0	2400.	2400.	11.00	0.100E-01	0.02	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.09	0.77	-123.140041	49.130750	
13	0	2400.	2400.	1.00	0.100E-01	0.03	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.07	0.82	-123.120176	49.130773	
14	0	2400.	2400.	0.00	0.100E-01	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.08	0.83	-123.100312	49.130792	
15	0	2400.	2400.	17.00	0.100E-01	0.03	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.10	0.81	-123.080447	49.130807	
16	0	2400.	2400.	9.00	0.100E-01	0.03	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.03	0.90	-123.060583	49.130819	
17	0	2400.	2400.	11.00	0.100E-01	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.94	-123.040718	49.130828	
18	0	2400.	2400.	32.00	0.100E-01	0.02	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.02	0.91	-123.020853	49.130833	
19	0	2400.	2400.	65.00	0.100E-01	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.06	0.85	-123.000989	49.130835	
20	0	2400.	2400.	75.00	0.100E-01	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.13	0.78	-122.581124	49.130834	
21	0	2400.	2400.	125.00	0.100E-01	0.02	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.30	0.51	-122.561259	49.130829	
22	0	2400.	2400.	143.00	0.100E-01	0.02	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.38	0.39	-122.541395	49.130821	
23	0	2400.	2400.	64.00	0.100E-01	0.02	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.37	0.51	-122.521530	49.130809	
24	0	2400.	2400.	48.00	0.100E-01	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.36	0.55	-122.501666	49.130794	
25	0	2400.	2400.	81.00	0.100E-01	0.01	0.00	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.23	0.65	-122.481801	49.130776	
26	0	2400.	2400.	81.00	0.100E-01	0.01	0.00	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.23	0.65	-122.461936	49.130754	
27	0	2400.	2400.	81.00	0.100E-01	0.01	0.00	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.23	0.65	-122.442072	49.130729	
28	0	2400.	2400.	81.00	0.100E-01	0.01	0.00	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.23	0.65	-122.422208	49.130701	
0	1	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.374509	49.141990	
1	1	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.354640	49.142053	
2	1	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.334771	49.142113	
3	1	2400.	2400.	0.00	0.100E-01	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-123.314902	49.142169	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
26	46	2400.	2400.	2197.00	0.100E-01	0.40	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.06	0.46	-122.460246	50.124229	
27	46	2400.	2400.	2197.00	0.100E-01	0.40	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.06	0.46	-122.440137	50.124203	
28	46	2400.	2400.	2197.00	0.100E-01	0.40	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.06	0.46	-122.420028	50.124173	