WIND RESOURCE ASSESSMENT IN AUSTRALIA – A PLANNERS GUIDE

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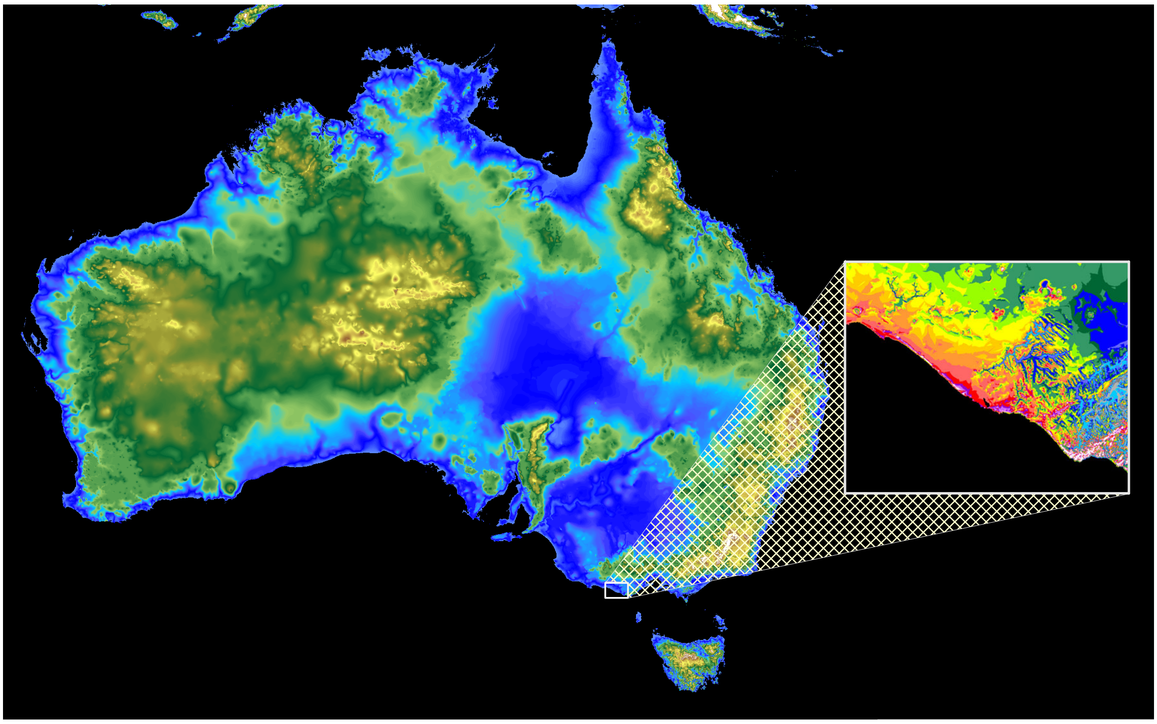

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1 INTRODUCTION

This guide seeks to give a background to the many aspects of wind resource assessment for the utilisation of wind energy. While the wind resource is the fundamental input to any consideration of a wind farm prospect, it is only one of the many factors which must be considered in siting and constructing the wind farm. The Australian Wind Energy Association has produced a Best Practice Guidelines (AusWEA, 2002) which details the many steps involved. State Government agencies have also released planning policies or other information; the NSW Sustainable Energy Development Authority have released "The NSW Wind Energy Handbook" (SEDA, 2001), the Victoria Governments have released "Policy and Planning Guidelines for Development of Wind Energy Facilities in Victoria" and Planning South Australia who have released a "Wind Farms Planning Bulletin for consultation" (Planning SA, 2002).

The wind industry in Australia has seen a rapid expansion phase since the introduction of the Mandatory Renewable Energy Targets (MRET) in 2001. Prior to this, developers were working on small projects such as the Crookwell, Blayney and Esperance wind farms. As the prospect of commercially viable wind farms appeared more likely many additional feasibility studies were under taken. A feature of much, if not all of this activity was that the wind resource studies were generally funded by the potential developers who closely guarded the data and results. Many of these studies took their starting point from the only publicly available studies, mostly conducted at widely separated stations with low monitoring heights, typically 10m. Several of these have been summarised in Blakers et al. (1991) and included wind atlases of Western Australia, Victoria and South Australia. Due to the scarcity of publicly available data sets this has resulted in a concentration of proposals around the windier of the stations described in these studies, for example Cape Bridgewater and Cape Liptrap in Victoria and Lake Bonney and Tungketta Hill in South Australia.

As we will see in this guide the wind varies substantially over short distances and measurement campaigns to map wind resources in high detail are costly and time-consuming. More recently high resolution wind maps generated by computer-model-based systems have become available for NSW and Victoria and can be produced for other areas. Together with the MRET requirement, this has facilitated the rapid entry into the Australian wind industry of a range of new players, many from overseas, who wish to secure development opportunities, short-cutting many of the traditional prospecting methods.

The quantification of wind farm energy yields, especially over the projected lifetime of the wind farm remains an exercise based on precision on-site measurements, using quality, well-calibrated instruments. Particular attention must be paid to converting these, usually short-term measurements, into lifetime average estimates, using quality controlled long-term data sets. The following sections provide a guide to the many steps in this process, from the fundamental wind resource to the precise calculations necessary to determine long-term output of a wind farm.

2 THE KEY STEPS TO WIND FARM RESOURCE CALCULATIONS

The selection of windy sites, the location and arrangement of wind turbines in a wind farm can be broken down into a number of logical steps.

1. Initial selection of a region of interest by utilising knowledge of climatology and any existing background wind data or available broad-scale regional maps and application of basic constraints to development.

2. Initial wind prospecting to choose possible sites, using regional climatology based wind prospecting modelling tools or wind measurements at several locations in the region containing prospective sites, combined with local wind resource mapping.

3. Selection of exact wind farm location based on local wind resource map and a wide range of additional planning issues and constraints (amenity of area, proximity to power line infrastructure etc).

4. Monitoring of the wind at or near hub height (50-80m) with quality, calibrated instruments to confirm the level of wind resource, ensuring that a full year of measurements is considered to capture the seasonal variations. Adjustment of data to reflect long-term wind statistics. Supplementary measurements at other locations in wind farm area which may be important (eg. steep terrain with enhanced turbulence levels).

5. Production of a high-resolution (25m) wind resource map of the immediate wind farm area, to take account of the local variations in wind using a numerical model such as WA^{S}P (Troen and Petersen, 1989), which includes wind speed changes with height, effect of local roughness.

6. Detailed turbine layout design (micro siting), utilising above numerical wind resource map. This takes into account many factors in addition to the location and strength of the wind resource, including noise propagation, visual impact, foundation engineering issues and ease of turbine erection. It will also allow for interference between turbines. The wind data used for these calculations are subject to long-term adjustments to enable a 20-year average energy yield prediction for the farm (to form the basis of energy pricing).

Figure 1 illustrates the alternative strategies to wind farm site identification and energy yield quantification. The only principal differences in the two strategies is the alternative use of modelling approaches or measurement campaigns to identify specific wind farm locations and the timing of when constraints can be applied at steps 2 and 3 above. The detailed application is discussed though this document.

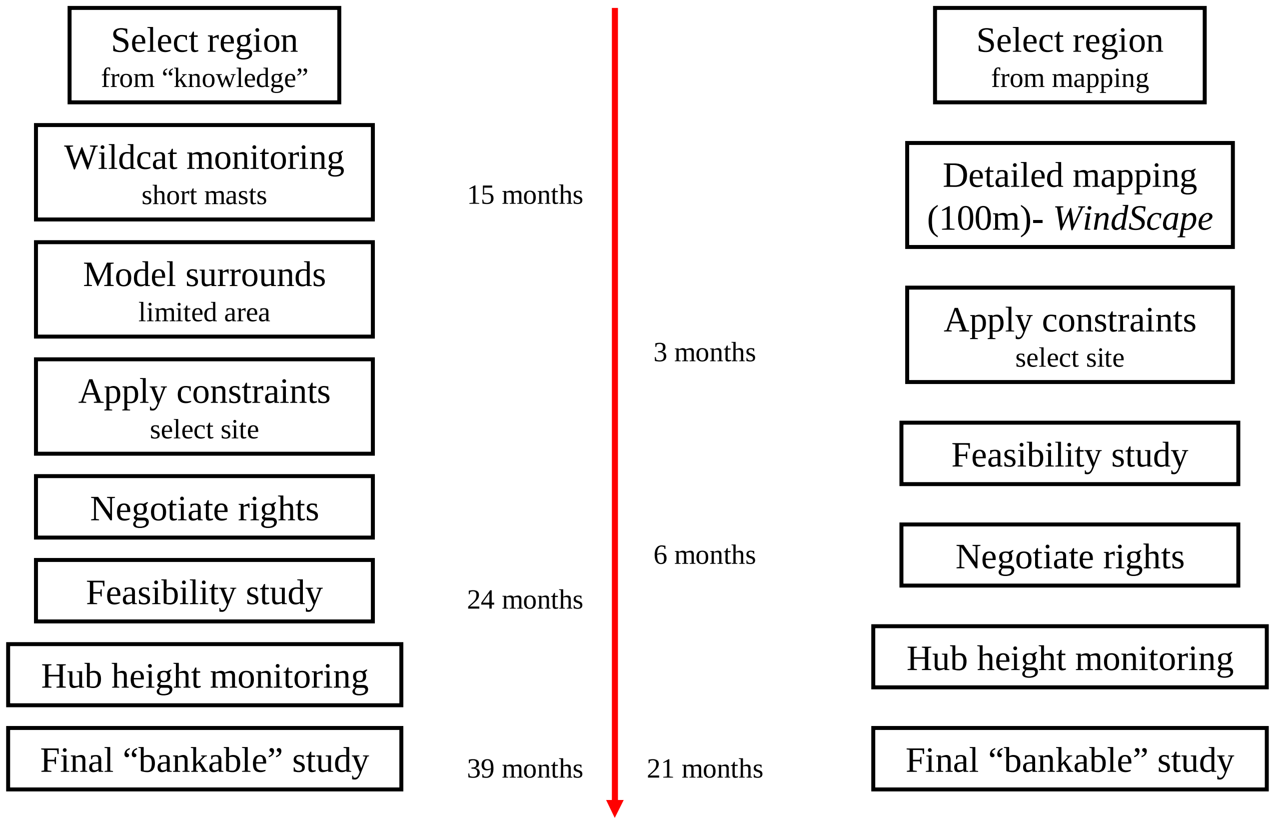


Figure 1 Alternative strategies for wind resource assessment

3 CLIMATOLOGY -WIND CHARACTERISTICS IN AUSTRALIA

3.1 Geographic Distribution

The general climatology of the winds in Australia has been well described in such publications as Gentilli (1971) and DNM (1986). These general descriptions are a very useful guide to the driving forces for the winds in Australia. They are not useful in a quantitative sense except where specific examples are given (eg DNM, 1986).

Australia does have significant wind resources. The southern section of the continent lies in the path of the westerly flow, south of the anticyclone mid-latitude weather systems in a zone known as the roaring 40's (named after the latitude zone it occupies). These winds reach a maximum around Bass Strait. The passage of low-pressure and associated frontal systems brings most of the wind resource to southern Australia. The position of the weather systems and the strength of the fronts determine how far north these frontal systems penetrate. Strong systems may immerse the entire southern half of the continent, while weaker systems skim the southern coasts. Northern Australia also experience monsoon and trade wind systems (southeast trades).

3.2 Large–scale Effects

Large-scale topography such as the Great Divide along the eastern fringe of the continent can have significant steering effects on the winds, sometimes concentrating them through major valleys or blocking them from certain areas. Weaker fronts can be subject to frontal refraction around the ranges of the Divide on the south-eastern corner of Australia – westerlies are deflected to a more southerly component and form the well known "southerly busters" along the east coast.

In northern parts of Western Australia there is refraction of south-east trades around the heat low in the north to become northwest winds. The same heat low can cause the southeast trades on the central coast of Queensland to be deflected to become easterly or north-easterly.

In the hotter months continental sea breezes can extend several hundred kilometres inland, but can be limited by mountain ranges and escarpments. Catabatic winds - large scale down-slope drainage flows from escarpments at night can generate significant winds.

Figure 2 illustrates the general background winds in Australia. The wind strengths indicated are only a guide as local effects; especially topography in the hilly regions will have a significant effect on the local wind strengths (see Section 4).

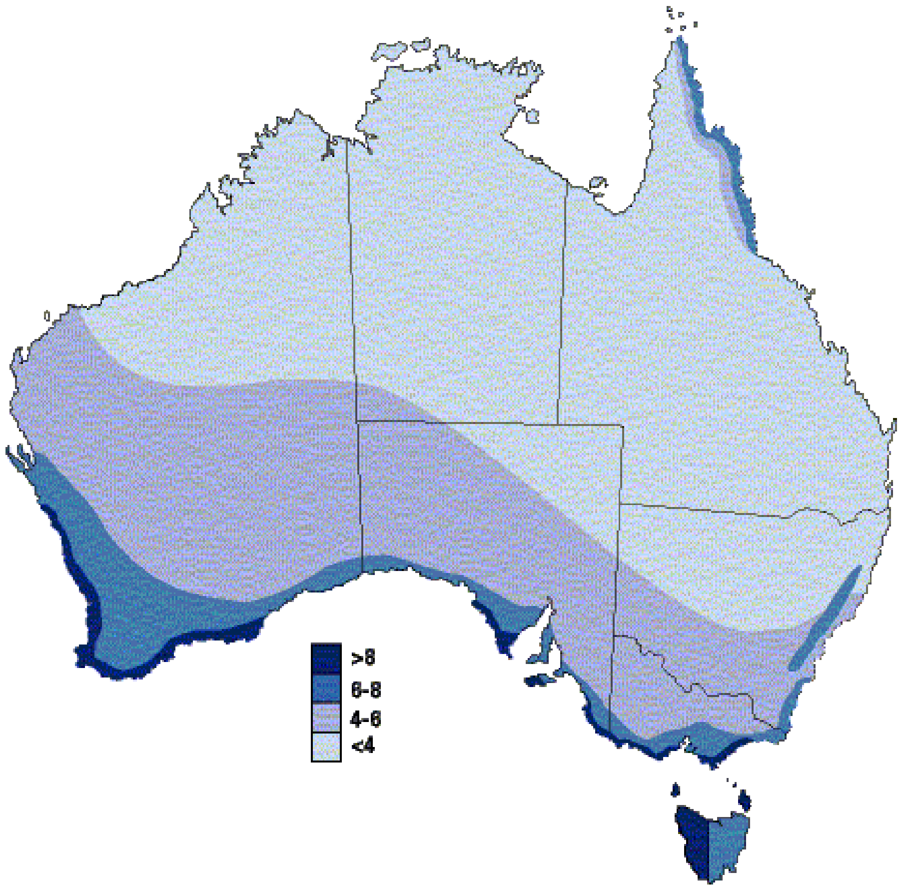


Figure 2 AGO simple picture of background winds in Australia

3.3 Design Implications

The wide range of climatic conditions experienced in Australia creates a wide range of potential wind regimes which must be taken into account when specifying suitable turbines. For example maximum survival gust speeds vary significantly across the continent with additional modifications due to terrain type and topography. This is embodied in the Australia Wind loading code for structures AS1170.2-1989 (see Section 6.3), which specifies various geographic zones and adjustment factors. These must be matched to the relevant standards under which the turbines are constructed which will each have survival wind speed values. The cyclones experienced in the northern parts bring irregular and unpredictable wind strengths which, while having little impact on wind statistics, will determine maximum design wind speeds. Maximum gusts can exceed 85ms^{-1} according to AS1170.2 which exceeds the maximum design specification of most commercially available wind turbines (IEC class 1).

3.4 Time of Year and Time of Day Variations

The average wind speed varies throughout the year with distinctive seasonal patterns. In southern regions winter-spring brings strongest winds. Figure 3 shows the monthly average winds recorded at Adelaide Airport. In this region there is a distinctive minimum in the wind speeds in autumn, when the average of the track of the stable high pressure systems in centred over the latitude of Adelaide. The monthly behaviour will be different for each region. The energy yield variations will be about double that of the wind speed (see Section 6.2).

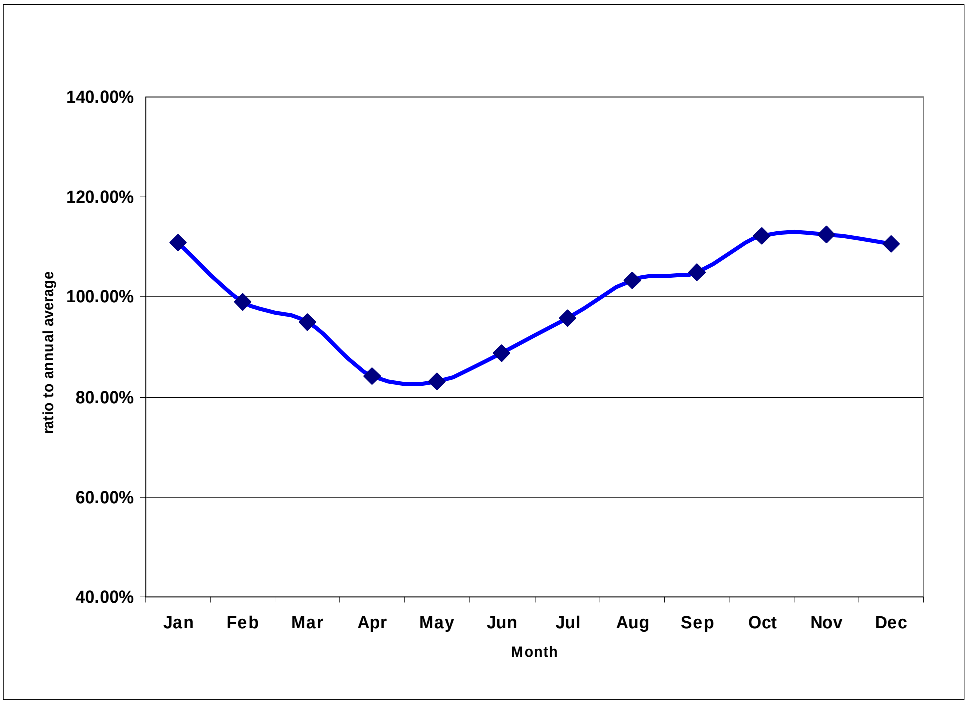


Figure 3 Monthly variation in wind speed from 20 years of data at Adelaide Airport (percentage relative to annual average)

In addition to the monthly variations in wind speed there is usually a daily cycle in the wind speeds. Figure 4 shows examples of daily variations (averaged over 12 months) at three different sites. Typically there is an increase in wind speeds in the afternoon. This is due to increased atmospheric mixing in the latter part of the day, bringing higher speed air down from aloft, and in warmer months, sea breezes near the coast. There is obviously a lot of variation with type of site, whether it is inland or coastal and the distance from coast.

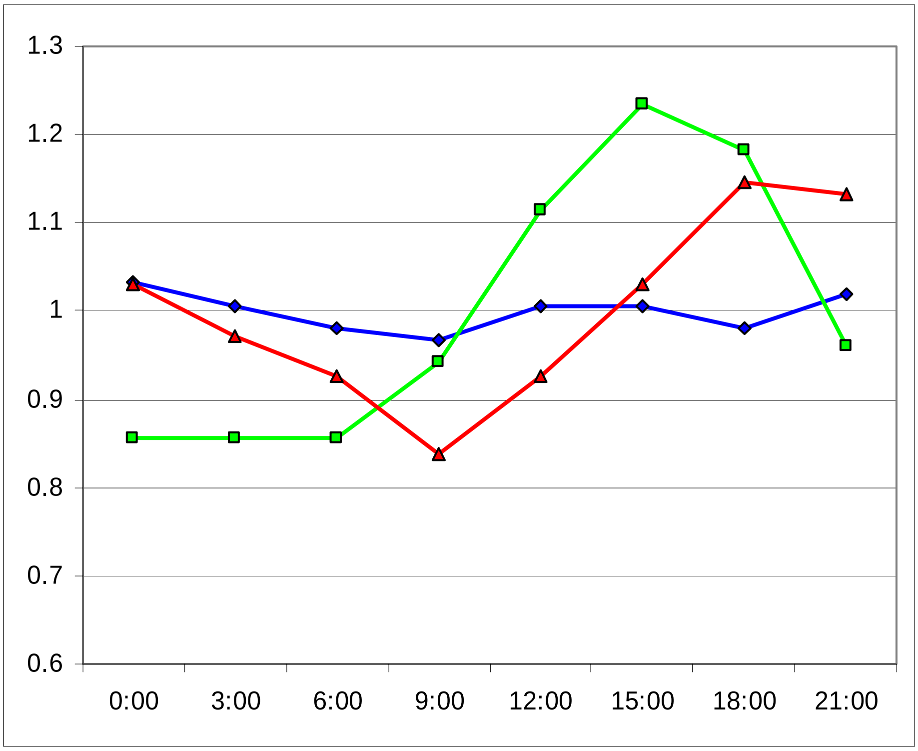


Figure 4 Example daily variation of wind speed at 3 potential wind farm sites (ratio of each hour to daily average)

3.5 Inter-annual Variability & Variation with Location

The weather systems also vary considerably from year to year and with them the wind speed. The familiar cycles such as El Nino/ La Nina also produce variations in wind speed. Like the weather, the annual averages in the wind speed are essentially unpredictable. Historically the range of variations can be described and this gives a good guide to the future range of variations which must be allowed for in energy production sales.

Figure 5 shows the variation of the annual variation of mean annual wind speed at Canberra Airport for a 20 year period. The magnitude of variability is about ±15%. Of course the variability of annual energy yield will be at least twice these figures. In some cases the lowest years can be up to half the energy yield of the best years. The degree of variability can be a function of a number of climatic factors including the whether the location in on coastal flat ground or on a hill top. Figure 6 shows the variation in average wind speeds at a well-exposed hill-top location. The variability is much less than at the Canberra site, about +/-5%.

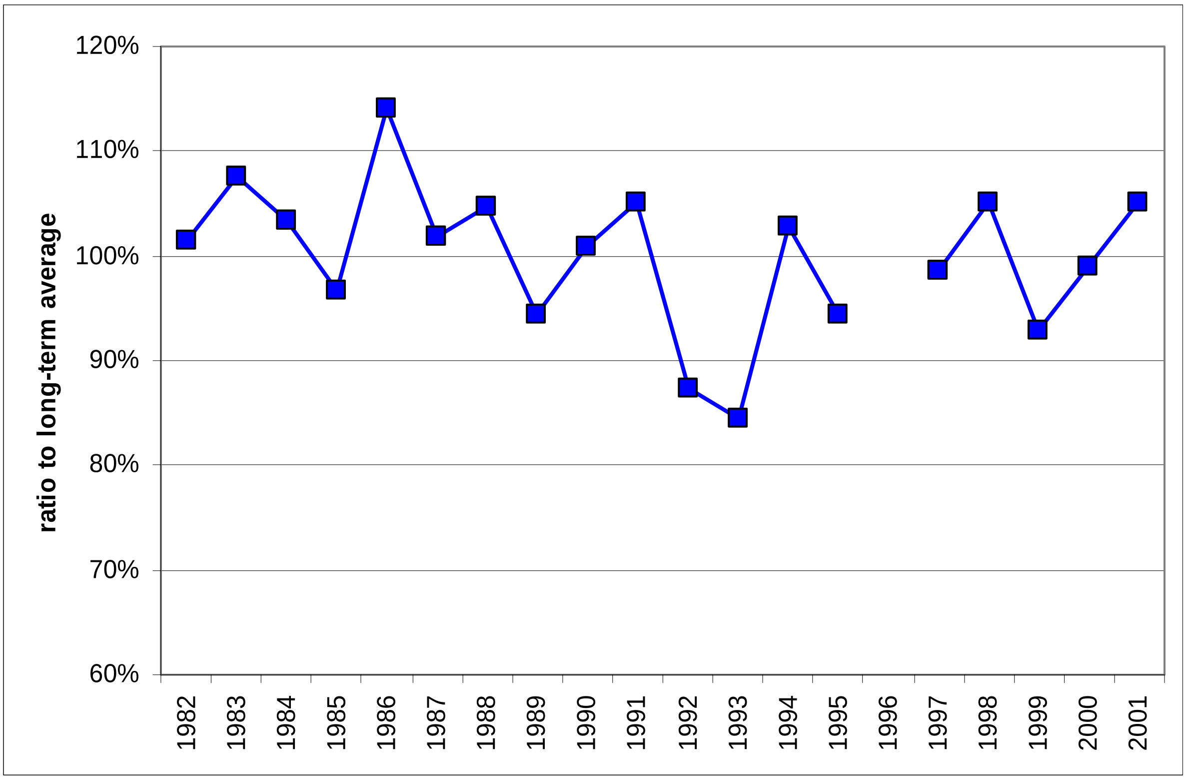


Figure 5 Example annual wind speed variation in wind speed from the Bureau of Meteorology long-term station at Canberra Airport (percentage relative to long-term average)

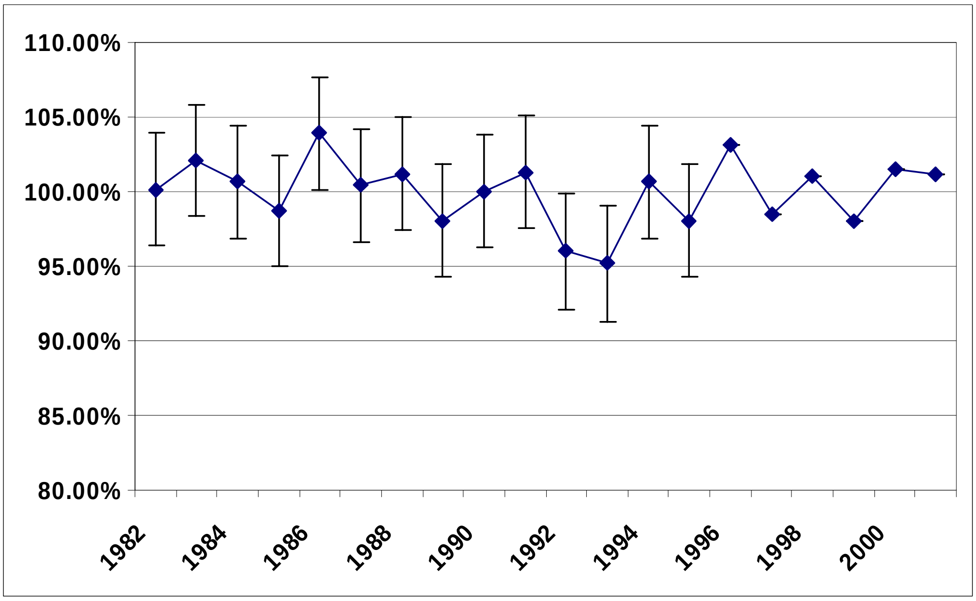


Figure 6 Example annual wind speed variation in wind speed from a well exposed wind farm site (percentage relative to long-term average)

3.6 Available Data Sources

3.6.1 Bureau of meteorology data

The Australian Bureau of Meteorology maintains an archive of wind data recorded for a number of purposes. In the last 10 years it has embarked on a substantial upgrade to its wind monitoring facilities. It has installed more than 500 Automatic Weather Stations (AWS) which feature 10m wind speed and direction readings, often available as hourly data. Prior to this the data availability was highly variable, both in location and quality. A further discussion of this can be found in Section 5.11, which deals with the issue of data quality.

While many of the AWS stations are not located in likely wind farm areas, they are often essential in transforming recent short-term on-site data measurements into long-term statistics. The typical 10m height of the measurement renders the AWS stations susceptible to interference from local obstacles (buildings, trees, etc) with some stations also showing long-term trends produced by surrounding urbanisation or forest growth which is not documented. Care must be taken in transforming this data to hub height. To be fair, the AWS program was implemented before demanding wind energy related applications arose. The archived data is available from the Bureau of Meteorology National Climate Centre in Melbourne.

3.6.2 Historical surveys and wind atlases

In the 1980's Wind Atlases were produced for Victoria (Dear, 1991) and Western Australia (Dear et al., 1990) based on a network of measurements and the application of the European Wind Atlas methodology (see Section 7). These maps are not very useful today as the wind measurements were a very long way apart (typically 200km) and the data was generally taken at a low level of 10m. However they did provide a beachhead into the resource levels to be found at these locations which were often representative of the region. Unfortunately these efforts were not followed up with studies whose results are publicly available.

Surveys were also taken in other states, such as in South Australia (ETSA 1989); many early ones are summarised in Blakers et al. (1991).

Mills (2001) produced an atlas of wind resources for Australia based on coarse resolution wind modelling output (75km), combined with empirical relationships to allow for surface features (Figure 7). The general features are similar to those in Figure 2.

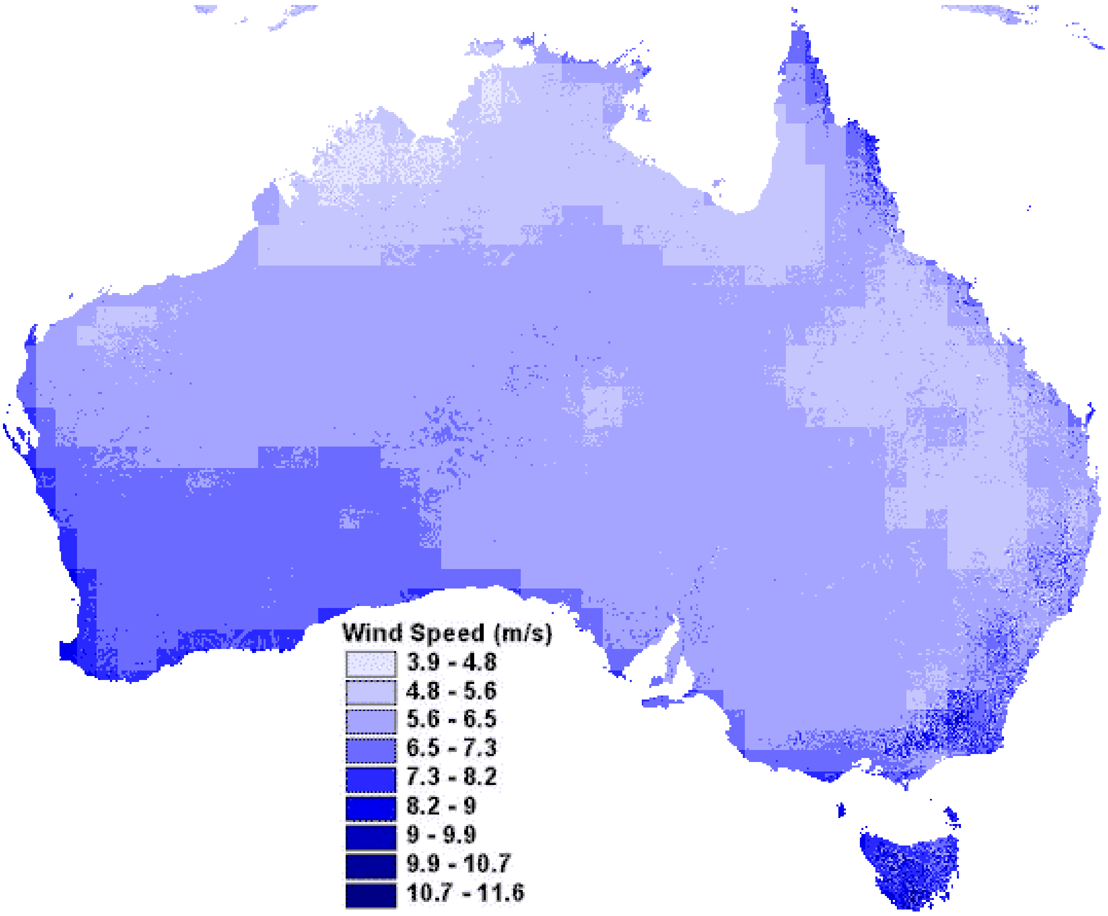


Figure 7 70m wind speeds for the period May 1997 – April 1999 (from Mills, 2001)

3.6.3 High resolution maps and on site data

High resolution wind mapping has recently become available using techniques outlined in Section 8.3. The Sustainable Energy Development Authority of NSW (SEDA) has published a 8km resolution Wind atlas of NSW (Figure 8). They have 100m resolution WindScape® wind maps available for much of the Great Divide area of NSW in the form of regional Wind Reports which feature a series of infrastructure and constraint overlays (availability key is shown in Figure 9). The reports are based on the National 1:100,000 map sheet series. They also have a Wind Synopsis available which features a wind map and various infrastructure and constraint overlays at 3km resolution. SEDA also maintains a substantial network of reference wind monitoring stations in NSW (see Figure 10). These towers are mostly 40m in height and have more than 2 years of data available. For more information on use of these data see http://www.seda.nsw.gov.au

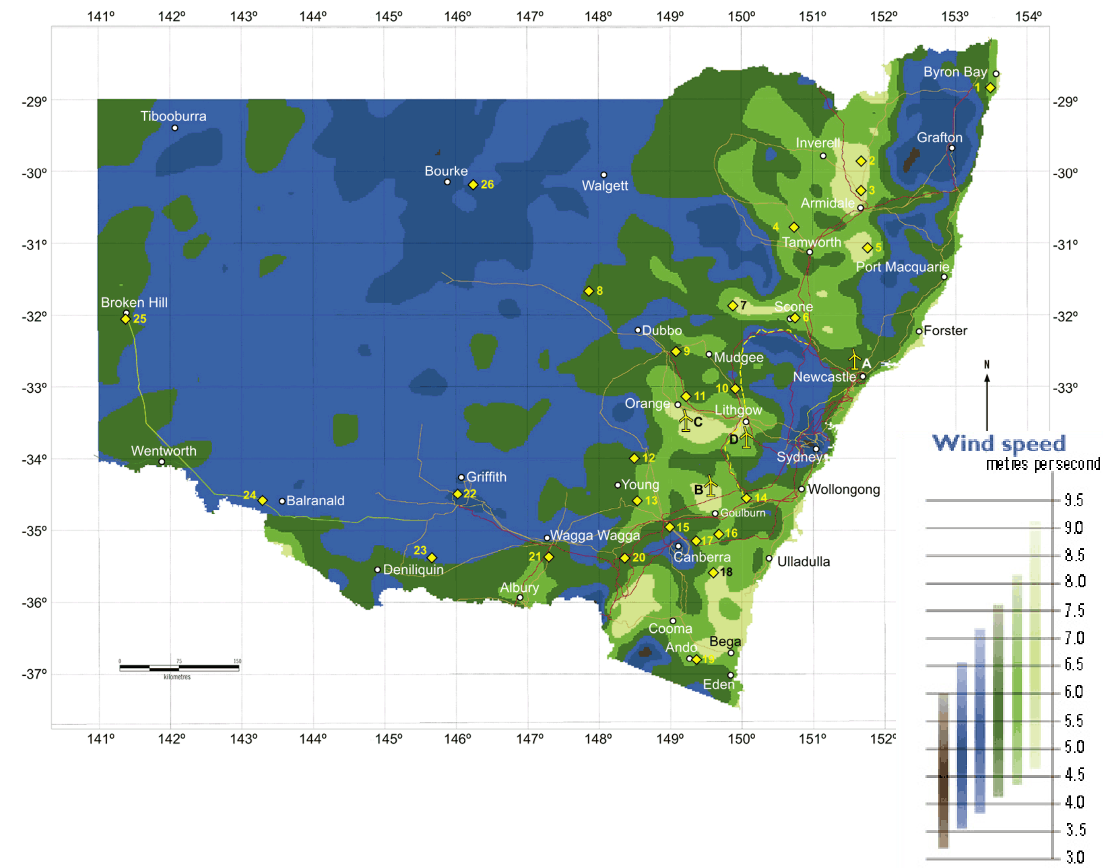


Figure 8 NSW Wind Atlas (8km resolution)

The Sustainable Energy Authority of Victoria is developing a Victorian Wind Atlas.

WindScape® 100m resolution maps for any area can be commissioned from Windlab Systems (www.windlabsystems.com).

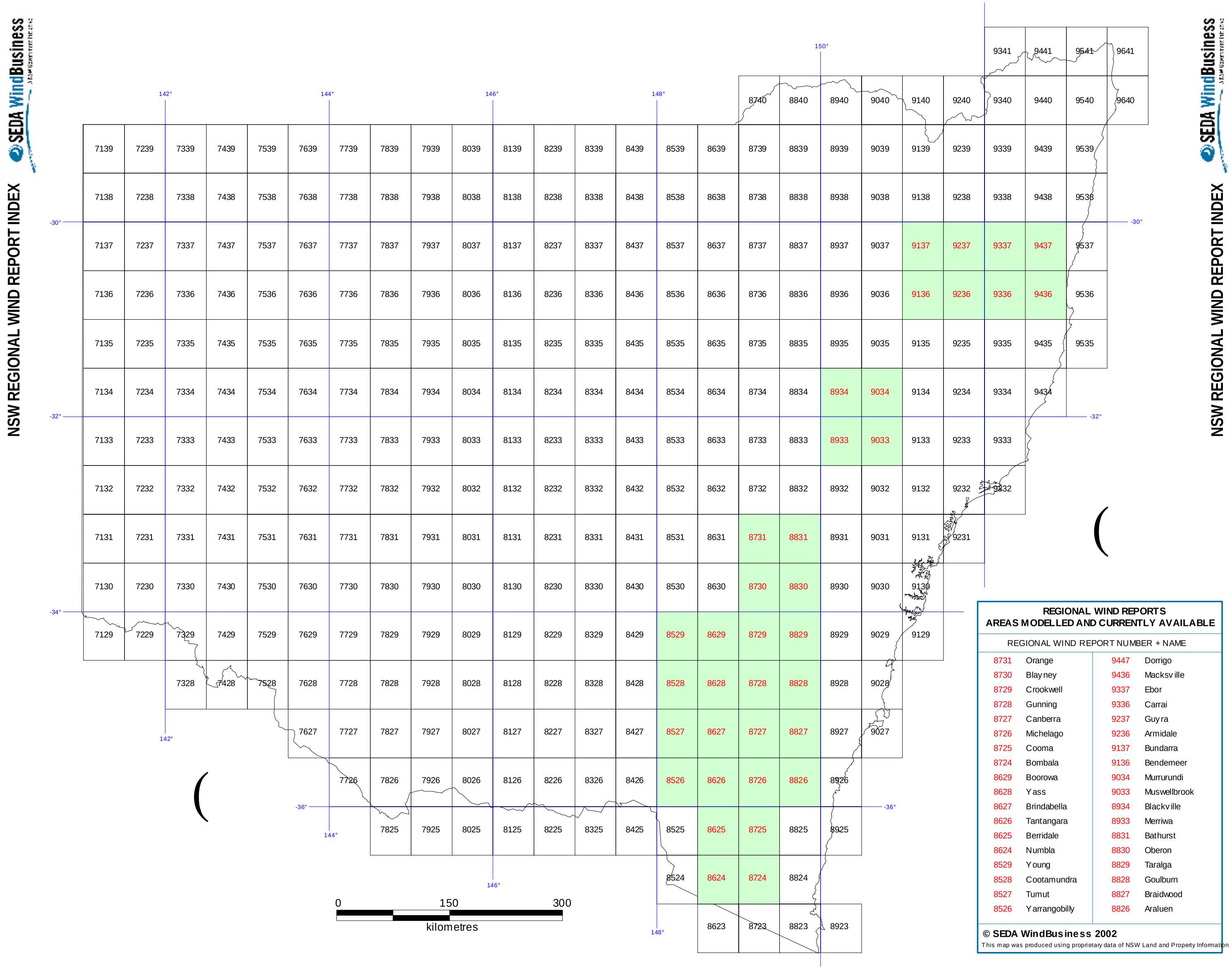


Figure 9 Key to high-resolution Regional Wind Reports available from SEDA NSW

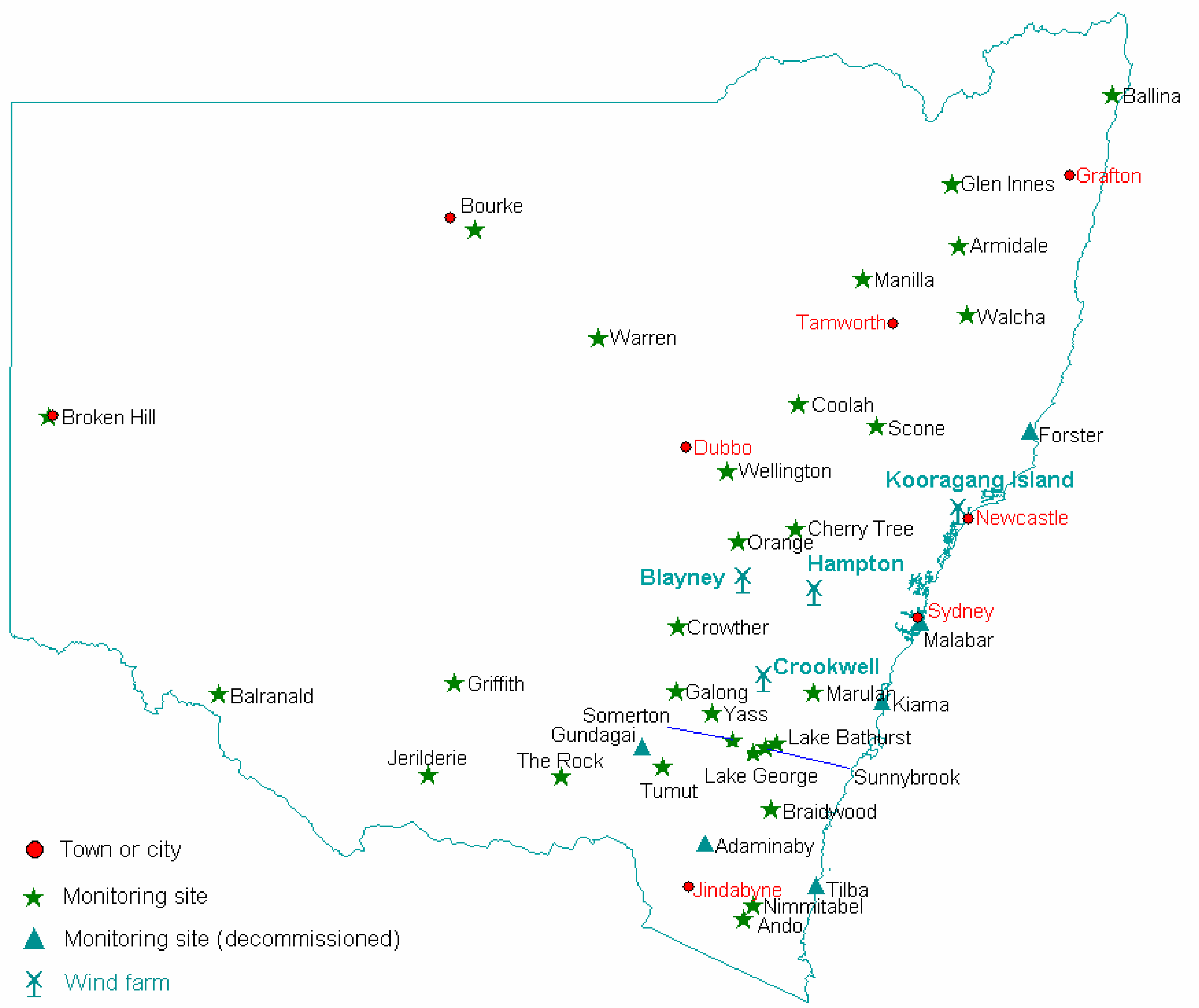


Figure 10 Locations of SEDA monitoring network sites

4 LOCAL EFFECTS ON THE WIND

The effect of local terrain and surface features on the wind is a vast topic which has occupied many text books. This section can only be a short guide to the basic principles relevant to wind energy applications. The interested reader is referred to books such as Kaimal and Finnigan (1994) or Stull (1988). The articles on wind power meteorology (Petersen et al, 1998a, b) also provide a more technical description.

4.1 Variation with Height and Surface Cover –the Wind Profile

The variation of wind speed, U with height, z close to the surface over flat land is conventionally described by a logarithmic relationship with height (often known as the log law):

$$U(z) = \frac{u_*}{k} \ln(\frac{z}{z_0}) \qquad (1)$$

where u_* = a scaling velocity

k = VonKarman's constant

z_0 = the roughness length

All else being equal, the important parameter here is the roughness length which is determined by the type of surface cover. It ranges in value from a fraction of a millimetre over water to a metre or so in urban areas. The above relationship is sometime simplified into a power law which incorporates the roughness in the exponent. The log law also changes if there are significant thermal effects which affect the shear (very stable conditions or convection in low winds). Fortunately, once the wind is blowing hard these thermal shear effects mostly become negligible.

At any given height, the wind speed will drop off with increasingly rough surface cover. The change in wind speed with height known as the wind *shear* and will be proportional to $\ln(z_2/z_0)/\ln(z_1/z_0)$. Hence at a hub height of 65m over grass (with $z_0 = 0.05m$) the shear is quite small at about 0.2% per metre. The swept area of a large turbine may extend from 35m to 100m above ground; in this case the speed at the bottom of the blade area will be 14% lower than at the top, on average. Turbine manufacturers will allow for this in their designs.

At any location the air reaching a given height may have traversed a number of surface types in its journey. Each change in surface type (eg water to land) will generate a new wind profile. The new profile will first be seen at the surface and will propagate upwards at a known rate as the air traverses the new surface. If the air has traversed a number of surfaces it may carry the “memory” of a number of wind profiles with it. Each wind direction will bring a different “memory”. This is one of the most important calculations included in all of the atmospheric flow models used for wind energy calculations (see Section 7).

4.2 Topographic Speedup

The presence of hill and mountain ranges can have a number of effects at different scales. Large ranges which extend a significant height above the surrounds (approaching 1000m) can simply block or steer the wind flow around them due to the inherent stability of the bottom layers of the atmosphere. Smaller scale hills can act as an aerodynamic object, much like an aircraft wing. Here the wind will generally be accelerated over the hill, the magnitude of which will depend on the size, shape and orientation of the hill to the wind. Figure 11 shows the general features of flow over an isolated steep hill. For hills of moderate slope the wind will be accelerated in a zone near the ground, and the normally logarithmic wind profile will be distorted at the crest of the hill, generally straightening it at the heights of the turbine blades.

As the steepness of the hill increases the flow may begin to separate (at a slope of about 0.3 or 17°). Here the picture becomes more complex as the wind flow aloft begins to pass over the separated region which is somewhat chaotic. The separation zone will create a wake of highly turbulent air which can be detrimental to the fatigue life of turbine blades. In the extreme limit of slope, cliffs can be significant sources of turbulence and distorted wind shear.

In the case of steep hills and cliffs, as the zone of enhanced turbulence grows in thickness the strength of the turbulence also weakens. Turbines can generally be sited on the very top of isolated steep hills with some immunity. Turbines which are placed on spurs running down from a steep ridge may find themselves in the turbulent lee of the hill for some wind directions. In the case of a well defined cliff turbines may be located so that they are tall enough to be located above the zone of enhanced turbulence. However all wind directions must be taken into account and the turbines may be exposed to enhanced turbulence from flow from directions other than normal to the cliff line.

Mathematical modelling has done a good job of describing the flow over hills of moderate slope (the linear models) and forms the basis of the tools used in the wind energy industry (Section 7). For steeper terrain, very much more complex mathematics is required (non-linear models) of which very few exist. As will be shown, if simpler linear models are used in steep terrain cases, significant errors can be made. These issues are dealt with in more detail in Section 7.

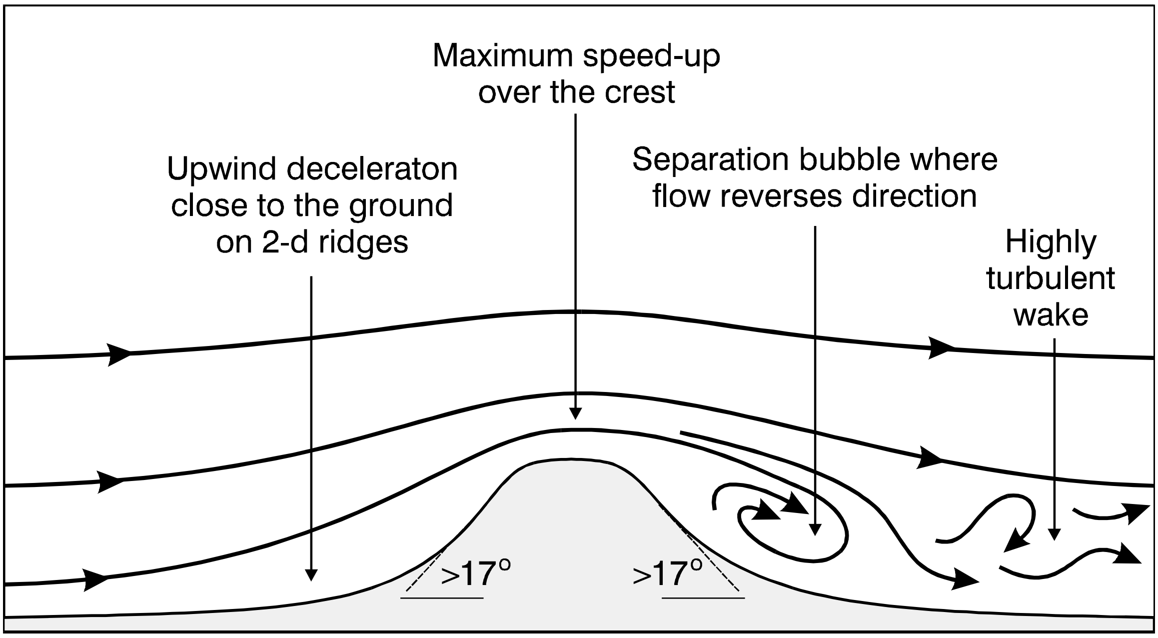


Figure 11 Diagram of wind flow over a steep hill

4.3 Thermal Effects and Funnelling

While the weather systems themselves (and their accompanying synoptic winds) are the product of different amounts of heating across the globe, there are thermal effects at a smaller scale which have a significant effect on the local winds. The best known of these are the sea breezes which are a feature of the coastal areas in the warmer months. While not usually very strong unless backed by the synoptics winds, they are quite regular, as long as the land surface receives heating during the day (eg Fremantle Doctor in Perth). Their strength and extent of their penetration inland is determined by a range of factors. Obviously the degree of heating and any opposing winds have a primary effect. The opposite can occur at night with land breezes.

The breezes can be blocked by topography, such as in the case of the Adelaide Hills. On a large scale their can be “continental” sea breezes which can extend hundreds of kilometres inland by the end of the day. Such winds are experienced in the Riverland of South Australia. In the Great Divide Area of NSW, with the backing of a general easterly flow there can be a significant amplification during the day due to the continental sea breeze, accounting for substantial extra wind energy potential during the summer months.

In conditions with stable high pressure systems there is often a capping inversion at about 1000m above ground, caused by the generally sinking air in the middle of the system, which forms an effective lid on the boundary layer. If there is a constriction through which the thermally driven flows must pass, then this lid can cause a major amplification to the flow. This is seen on a major scale in the mountain passes in California where significant wind resource is handled in Altamont and Tehachapi Passes and the in Colombia Gorge in Oregon. On a small scale the land breezes in easterly flow conditions in the Adelaide Hills are concentrated into the "Gully Winds".

At night the cooling of air at the top of hill at night can flow down hill (catabatic winds) reaching considerable strength with large escarpments.

All of the effects where there is thermal amplification tend to very localised and difficult to resolve in numerical models. Small-scale models, such as WA^{S}P do not have thermal effects in their mathematics and so must be used with great caution where there are strong gradients in wind flow caused by thermal effects. (See section 7)

4.4 Turbulence Generation and Gusts

As outlined above, steep terrain, cliff edges etc can be significant sources of increased turbulence, potentially exceeding the design limits of the turbine. Large areas of rough surface upstream such as forests and urban areas can also cause turbulence which is above design limits. It is difficult to generalise the magnitude of these effects as very few situations resemble the simple cases which can be calculated. Measurements must be taken to determine the level of turbulence for a particular development where there may be a problem.

Extreme wind gusts are generally caused by factors other than steady flow over rough or steep surfaces. They are usually the result of downbursts from strong storm systems or tornado-like phenomena. They can only be described in a statistical fashion from past measurements. The likely strongest gusts in a particular location are incorporated in the Australian Wind Loading Code AS1170.2 (Section 6.3) which calculations allow for height above ground, terrain roughness and topographic enhancement effects. The ability of a turbine to withstand both turbulence and extreme gusts is incorporated in the IEC design standard classes for wind turbines (Section 6.3).

4.5 Shelter and Obstacles

On a local scale some isolated features such as buildings, wind breaks and large isolated trees do not resemble uniform roughness but discreet obstacles to the flow. This is especially important when measurements are made at 10m or below which can be greatly influenced by such obstacles. The effect of a solid obstacle can be felt for a considerable distance downstream, up to 10 times the dimension of the obstacle (Taylor and Salmon, 1993). The amount of turbulence generated will depend on the porosity of the feature (especially in the case of trees) and the angle of the wind to the obstacle. Simple relationships for the effect of obstacles are included in WA^{S}P to enable low-level measurements to be used for resource calculations. Obstacles can often affect AWS sites; the Bureau of Meteorology has available simple diagrams of the surroundings for all its sites to allow these effects to be assessed.

4.6 Example of Local Effects

Figure 12 shows and example of wind energy potential in a wind flow coming onto the land from the ocean (from left to right). This shows several of the effects outlined above. The energy potential drops as the first rough surface is encountered over the island. The potential recovers somewhat over the water again before encountering the disturbed flow in the areas of the cliffs. There is some enhancement over the cliffs but note the no-go zone lower down where enhanced turbulence is likely. The energy potential reduces inland again as the flow encounters the rough land surface. The large hill creates a major boost to the energy potential, enhancing it to values above those available over the flat water surface. However the hill is steep enough to cause flow separation and excessive turbulence behind the hill. In this simple case wind turbines could be placed safely on top of the hill but not behind. Section 8.3.2 shows example cross-sections of wind speed for this type of land feature in Gippsland. Although an average of all wind directions, they clearly show the slowdown and enhancement over the hills, often to values above that over the ocean.

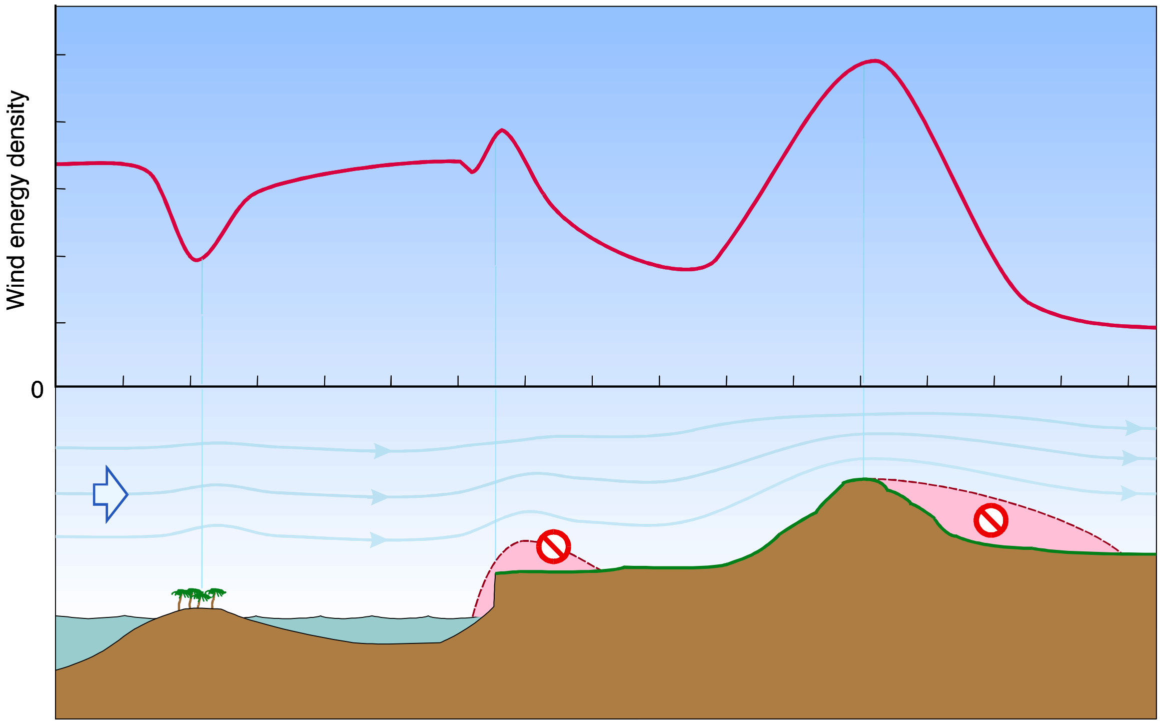


Figure 12 Diagrammatic cross-section of wind energy yield changes across the landscape

4.7 The Area of Wind Available at a Given Resource Level

The amount of land area available at a given satisfactory resource level will, of course be a function of the how much exposed coastline is available and the amount of topographic enhancement available. Using wind resource modelling data over large areas it is possible to estimate the land area available at each wind speed resource level.

It is useful to look at an example for an inland hilly area where it is most difficult to estimate resource levels. The following example is taken from NSW where a section of 80,000km^2 in the Great Divide area has been modelled using the WindScape™ system (see Section 8.6) at a resolution of 100m. Wooded areas have been excluded. Table 1 and Figure 13 show the results. There is a clear exponential relationship (indicated by the straight line on the logarithmic plot) between the land area and the mean annual wind speed. If the economic threshold for wind power production were lowered from 8ms^{-1} to 7 ms^{-1} for example, there would be about 20 times more land area available for economic production.

The exact nature of this wind speed/land area relationship will naturally depend on the particular landforms in the area but it will be typical of the hilly areas of Australia.

Table 1 Land area available as a function of mean annual wind speed - from 80,000 sq km - wooded areas excluded

Mean annual wind speed exceeded	Percentage land area	Land area km^2
9	0.02%	19
8.5	0.08%	71
8	0.16%	134
7.5	0.54%	460
7	3.07%	2,635
6.5	12.13%	10,396
6	28.60%	24,500

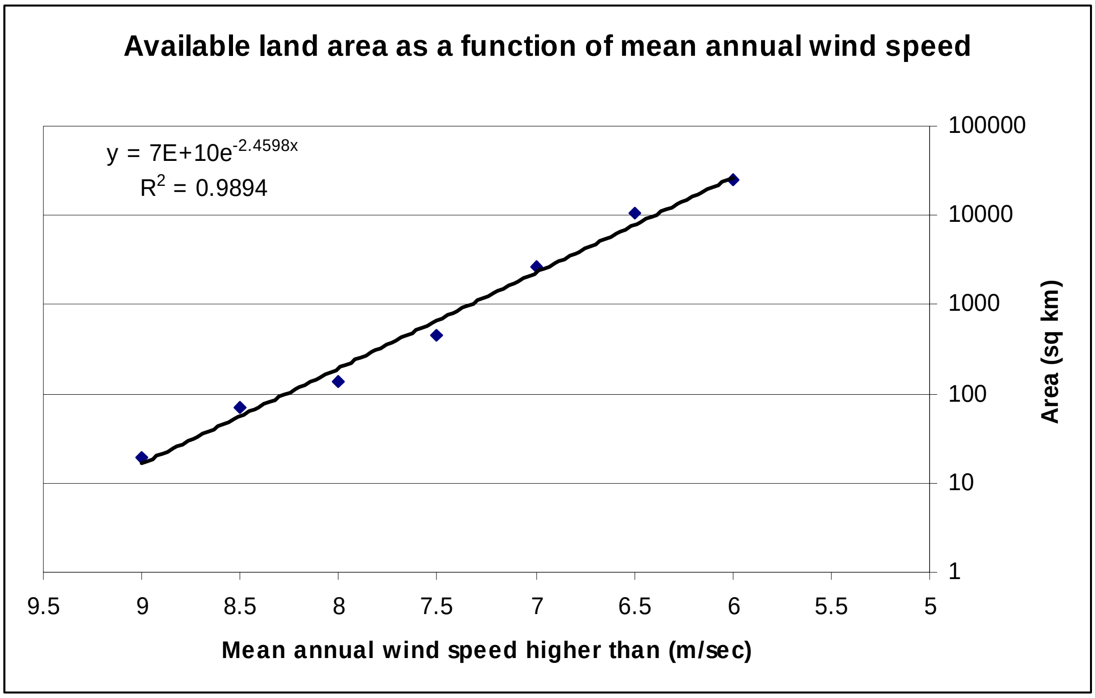


Figure 13 Land area available as a function of mean annual wind speed - from 80,000 sq km - wooded areas excluded

5 MEASURING THE WIND

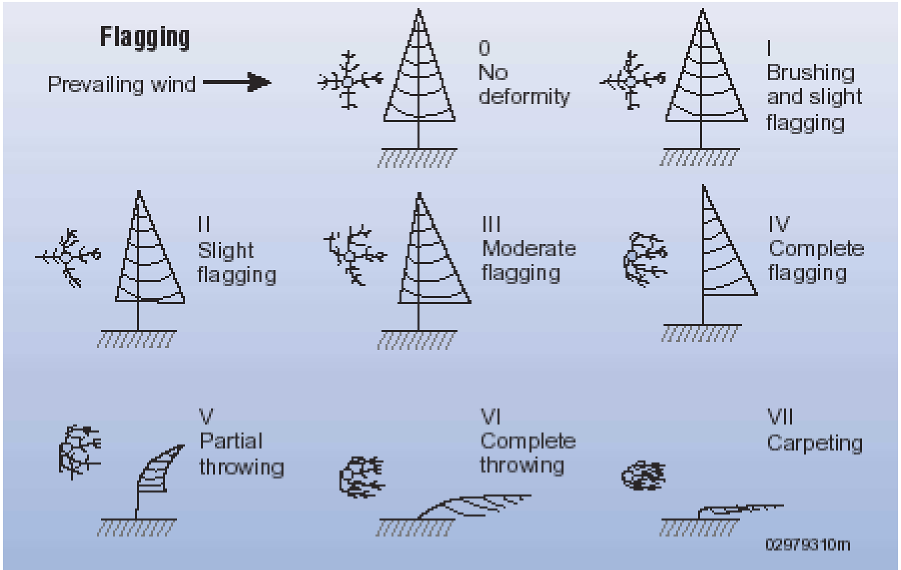
5.1 Introduction

Wind measurements are the key input to all phases of wind resource assessment, whether initial surveys, on-site verification of modelling predictions, providing final dataset for "bankable" energy yield or for validation of wind farm production and turbine performance verification after the wind farm is constructed.

5.2 Indirect Indicators

Simple indicators of wind speed are often mentioned, such as the Beaufort Scale, but these usually refer to short-term or "spot" observations. Weight is sometimes given to anecdotal evidence from landholders. This can range from quite reliable, where indicators such as stock behaviour or vegetation characteristics are noticed, through to quite unreliable where only regular extreme events are recalled. The human mind is not a good integrator of wind speed data 24 hr per day, 365 days per year.

Some indirect methods have been shown to be good indicators of broad wind speed categories. Tree flagging is perhaps the best known of these; the Griggs Puttnam Index is shown in Figure 14. The vegetation growth is biased towards the downwind side of the tree or bush. Care should be taken as in coastal regions salt laden air can grossly exaggerate this effect, such as in Figure 15.



Griggs-Putnam Index of Deformity

Index	I	II	III	IV	V	VI	VII
Wind mph	7-9	9-11	11-13	13-16	15-18	16-21	22+
Speed m/s	3-4	4-5	5-6	6-7	7-8	8-9	10

Figure 14 Griggs-Putnam Index of Deformity (from US Dept of Energy)

Figure 15 Tree flagging with significant amplification from salt air

5.3 Direct Measurements

Direct measurements of the wind are often taken for a variety of non-wind-energy purposes, including the substantial network of Bureau of Meteorology automatic weather stations (AWS). These will discussed in some detail in Section 5.11, but it should be borne in mind that these stations are not always in locations which can be related to sites of interest to wind energy developers. While being a very valuable resource great care should be taken in selecting and qualifying these data sets, especially data series which extend further back than the installation of the AWS equipment.

On-site measurement of wind for the wind energy industry has been the subject of considerable research which is embodied in a number of standards, either for resource assessment or turbine validation purposes. Good guides are Petersen et al, 1998b, and IEA (1999) which contain recommendations for siting measurements, mounting instruments on masts, instrumentation selection and measurement schedules. Somewhat more stringent standards exist for Wind Turbine calibration (IEC, 1998). These can be summarized as follows.

5.4 Location

If not using a model-based approach (see Section 8 for a comparison of approaches), general prospecting studies can be achieved with arrays of tower-based measurements. These should be carefully located to be representative of typical wind farm locations. They should be on well cleared areas with no steep terrain nearby, increasing the chances of being able to incorporate the data into a model based mapping program to interpolate between the stations such as the European Wind Atlas approach or for validation of a WindScape type study.

Measurements on wind farm sites should be made at one or more locations, depending on the extent and nature of the site. A main monitoring site should be chosen which is in a location near the centre of the turbine array, to minimize errors when extrapolating the data to other parts of the farm. This is particularly important with steep terrain where the measurement site should be representative of the complexity of the site. As with the prospecting measurements, the measurement site should be well clear of any surface features which cannot be incorporated into the analysis. If the site is very extensive, there are areas of steep terrain or any other features which will make it difficult to relate the measurements at the main site to these areas of special interest, supplementary measurements at additional sites should be added, even if only for shorter periods. The exact spacing of the extra measurements will depend on the extent of the terrain changes and the ability of the modelling to cope with these. If cup anemometers are used, the terrain slope at the measurement site should not exceed 10° (see Section 5.8.2).

5.5 Height of Measurement

For all types of studies the masts should be tall enough to avoid the influence of local features (trees, bushes, buildings, windbreaks, small-scale topography) which do not appear on topographic mapping products or as readily identified obstacles - measurements at 10m often suffer from this problem. This is essential for the process of extrapolating the data away from the measurement site, most importantly when using topographic flow models. As a rule, for topography, if the feature influencing the flow at the measurement height is not visible on the contour mapping (typically 1:25,000 scale) there will be a problem. Additional surveys of the surrounds should be undertaken if the mapping is possibly out of date and clearing or vegetation growth may have occurred.

For general prospecting studies on well cleared sites the measurements should be at 30m or higher. For wind farm energy yield calculations on-site instrumentation should be mounted on a mast which is as tall as possible, ideally at hub height, but with hub heights approaching 80m, this may not be justified in the initial stages of a study, and so it should be at least 2/3 of this height. For turbine calibration (and for wind farm energy yield certification) the measurements should be within +/-2.5% of hub height, within 2.5 blade diameters from the turbine and not sited near steep terrain (IEC 1998).

The greater the difference between the measurement and hub heights, the greater the reliance on extrapolation techniques (eg flow modelling) and the greater the additional error which must be assigned to any energy yield estimates. Indeed the cost of a taller tower will easily be recouped in the economic benefit of a reduced uncertainty in the yield estimates (see Section 7).

Measurements at a number of heights are often made to determine any wind shear problem (for example in steep terrain), for comparison with nearby studies at similar heights or to provide information at a standard height such as at 10m for background noise studies. Heights are sometimes arranged with a logarithmic spacing from the top, to approximate the logarithmic shear, and a height is often chosen to match the bottom of the typical turbine blade swept area (typically about 40m above ground).

For supplementary studies (eg of steep terrain) in may not be practical to make measurements at the maximum height of the main mast but should match a corresponding additional measurement height on the main mast.

5.6 Type of Masts

A guyed, tube-type tilt-up mast is often used for initial prospecting, feasibility and special purpose studies. They are relatively inexpensive to purchase, do not require concrete foundations and do not require climbing. They are available in a variety of heights, with locally made versions available to 50m. The instruments are placed on the mast before erection and the whole constructed tilted into place with a supplementary pole acting as a fulcrum. This is rather labour intensive, typically requiring 3-4 people for the erection phase. If instruments need to be accessed the erection procedure must be reversed, the instruments serviced and the mast re-erected. If the deployment encounters problems or extends for some time with scheduled instrument checks, the economy of this type of mast can be rapidly eroded. However these masts are ideal for short-term studies, such as steep terrain studies as they can be readily moved between several locations.

For hub height monitoring, and long-term deployment a guyed lattice is used. The tower is typically 300mm in width, equipped with a safety cable system (eg LadsSaf) and easily climbed by qualified personnel. A typical lattice mast is shown in Figure 16 for Lord Howe Island (SEDA NSW network) – note the aviation safety markers. Heights of 65m are common for these towers with some as high as 90m.

Figure 16 40m guyed lattice mast at the SEDA (NSW) monitoring site at Lord Howe Island

5.7 Instrument Placement

Instrument placement is very important as the wind readings can be affected by interference from the tower, the mounting arm and other instruments such as the wind vane. The IEA recommendations for this are laid out in IEA 1999.

The most effective way of ensuring a quality wind readings at the mast height is to attaching the instruments on to a mount protruding vertically from the top of the mast. This should place the instruments at least 2 tower diameter above the top, well clear (horizontally) of any lightning arrestor. The anemometer should be minimum of 100mm above the top of the wind vane or the horizontal separation at least 10 times the largest horizontal dimension of the instruments.

Lower down the instruments should be mounted on booms which place them well clear of the mast structure. IEA 1999 indicate distances of 3.7 tower diameters from the centre of the tower for open lattice construction and about 6 diameters for tube masts. Petersen et al. 1998b indicate a minimum of 3 tower diameters for lattice masts. A compliant arrangement is shown in Figure 17. These requirements can be quite challenging for tall lattice masts with 450mm diameters. At lower levels the inter-instrument spacing can also be achieved by using a double sided boom. The mounting hardware should be arranged at all levels so that wind speed instrument is placed on the prevailing wind side of the mast.

The anemometer can experience flow distortion from the mounting boom itself and IEA 1999 recommends that the anemometer rotor be at least 12 boom heights (the diameter of the mounting boom) above the boom.

These requirements will negate the use of existing communications towers for opportunistic mounting of wind instruments. Such towers are invariably too large and bulky to achieve accurate measurements.

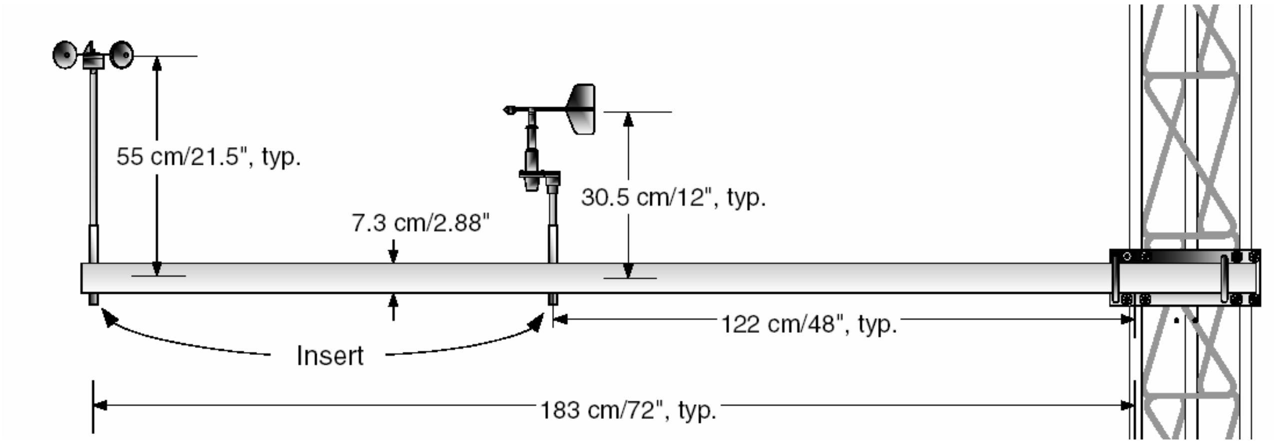


Figure 17 IEA compliant lower mounting boom and instrument arrangement (from Second Wind Inc)

5.8 Instrumentation

5.8.1 Types of instruments

The most universal instrument in use is the cup anemometer. Although a simple device, when quality, well calibrated units are used they can produce very accurate results. As with any instrumentation a variety of quality levels are available. Care should be taken in selecting units which are capable of surviving exposure to very strong wind and which have well understood response characteristics. Calibration before and after deployment is essential (see below), an instrument can be destroyed by lightning and if no pre calibration is available than the quality data is impaired.

The other wind instrument in regular use is the sonic anemometer. These instruments are becoming more affordable in their simplest form and have superior performance in some areas than the cup anemometer. Unfortunately the differences in response characteristics (see below), often causes them to read lower than a cup anemometer in similar circumstances (up to 10%). Most wind turbine power curves are certified against cup anemometers and so it is recommended that sonic anemometers be used with caution. Remote sensing instruments such as SODARs are not accurate enough for wind energy resource assessment measurements. They are sometimes used for brief investigations of excessive shear or turbulence.

5.8.2 Response characteristics

Several characteristics of the cup anemometer affect its ability to measure the wind accurately. The first is the starting speed of the instrument, this being mainly determined by the internal friction the bearing system. The starting speed should be well below 1 ms^{-1}, ideally 0.5ms^{-1} or less. Although most wind generators do not produce energy below about 3 ms^{-1}, it is important to maintain the lower end values of the probability distribution of wind speeds (see Figure 23). When the data is used to produce energy estimates over the surrounding area, wind flow models such as WA^{S}P fit a Weibull curve to the probability distribution as shown in Figure 23, to enable the necessary mathematical manipulations. If the lower wind speeds are not correctly represented then the curve fit will not be correct and errors in energy estimates (usually too high) of 10% or more can occur.

The design of the cup assembly influences the response of the system in two ways. Firstly the time taken to respond to changes in wind speed, as described by the "response length" of the instrument. This should be a few metres at worst to allow gusts to be adequately captured. Secondly the change in instrument output with the vertical angle of attack (or tilt angle) of the wind to the horizontal. Cup anemometers fall into two categories. Most have a uniform response, i.e. they read the same until the tilt in the wind flow approaches 30°, but some are deliberately designed to have a cosine response where the output of the instrument drops off with the cosine of the tilt angle. Wind turbines do not generally have a cosine response so the type with uniform response is recommended for speed measurements (Dahlberg et al, 2001). The uniform angular response is one of the reasons for the observed disagreement between cup anemometers and sonic anemometers which generally have a cosine response. Also the slope of the terrain at the measurement site should not exceed 10° (IEA, 1999).

The performance of the cup anemometers must obviously be maintained to ensure accuracy of the data. The bearings in particular degrade with time and can significantly increase the starting speed of the instrument. This can occur in two years or less with commonly used instruments. The safest practice is to exchange the anemometers annually with freshly calibrated units, refurbishing the instruments with new bearings. The calibration of a cup anemometer will be maintained as long as the bearings are in good condition and the cup assembly is undamaged.

5.8.3 Calibrations

Much effort has gone into the calibration procedures for wind measuring instruments. The best outline of this is provided by MEASNET, a European standards grouping (MEASNET, 1997). Calibrations are carried out against a certified reference instrument in a wind tunnel over a wide range of wind speeds, from starting speed to close to the cut-out speed of the wind turbines (usually 25 ms^{-1}).

If calibrations need to be certified, the relevant Australian standards body (NATA -Australia's Government-endorsed provider of accreditation for laboratories and similar testing facilities) has certified the wind tunnel facilities at CSIRO Atmospheric Research, Aspendale and at WERU in Canberra, calibrating to MEASNET procedures. Calibrations are normally to 1% accuracy.

5.9 Measurement Schemes

The recommended scheme for logging the data from the instruments is to sample frequently enough to capture the wind gusts which are important to wind turbines, at least every 3 secs. These should be formed into statistics at least every 10 mins (IEC, 1998). Pulse output cup anemometers should have a high enough pulse rate to give a meaningful count every 3 secs; one count per revolution is usually not enough. The data logger should be capable of calculating a true average for the wind direction or recording vector components to enable this calculation. Raw output from a wind vane cannot be directly averaged (eg the average of 359° and 1° is 360° not 180°).

Statistics to be collected every 10 min are average wind speed, average wind direction, standard deviation of wind speed, maximum wind speed and optionally standard deviation of wind direction. The turbulence intensity is the standard deviation of wind speed divided by the mean wind speed. If the data is to be used for very accurate energy yield calculations over daily cycles (for example) or for turbine performance verification then air density must be calculated every 10 mins by measuring air pressure and temperature. For annual yield calculations the mean air density can be calculated from the altitude of the station. Over the course of a year the air density, and hence the turbine output at a given wind speed; can vary by 10% (see Equation 2).

The data must be taken for at least one year before any meaningful energy calculations can be undertaken (Petersen et al, 1998b). This enables the full annual cycle of wind conditions to be captured. This is clear from the monthly values shown in Figure 3.

Also apparent from the sequence of annual averages shown in Figure 3 is the need to adjust any annual averages for the year-to-year variation. This is necessary to produce a long-term average energy production over the lifetime of the wind farm, typically 20 years. This is normally performed by correlation analysis with a suitable long-term wind monitoring station nearby (see Section 5.11). Similar techniques are used to extend data sets, for example where a tall tower has been running for a shorter period than a nearby shorter tower, or a tower on another site in the region.

5.10 Data Series Extension (MCP)

The data from a longer-term tower can be used to extend the data from a shorter-term tower using correlation analysis, often known as the Measure-Correlate-Predict (MCP) method (eg. Wamsley and Bagg, 1978). Here a series of linear relationships (hence correlations) are formed from the overlapping data period. This is done for each of a number of wind direction and wind speed classes. The success of this method depends on the amount of overlapping data available (hence how much data in each of the direction and speed classes) and the degree of correlation (often determined by distance) between the sites. This will determine the ultimate accuracy of the exercise.

The question of how long a short term series must be to correlate with a long-term data series has been studied by Salmon and Wamsley (1999). They employed the MCP technique for pairs of stations in Canada. Figure 18 shows the standard deviation of the long-term estimates as a function of the overlap period employed. It is clear that the estimates only begin to stabilize after 12 months of data overlap. This is most probably because the correlation between the stations has a seasonal component to it, which is only fully captured after 12 months.

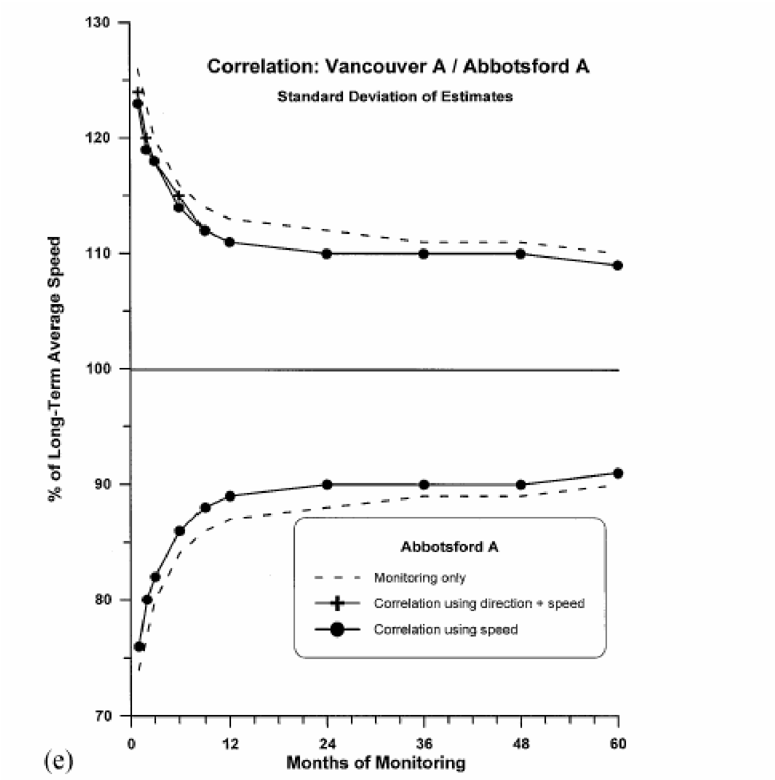


Figure 18 Standard deviation of long-term wind speed estimates vs overlap time at two wind monitoring stations (from Salmon and Wamsley, 1999)

The MCP method is sometimes used within a wind farm site to predict the energy yield at a number of locations within the site by referring short-term measurements back to a central long-term mast. This technique may require less overlap than discussed above due to the proximity of the site. If this is used instead of a flow model to form an energy yield map of the site it will require a high density of measurements for a large complex site.

5.11 Long-term Projection of Energy Yields

An estimate is needed for wind speeds at hub height for the next 20 years, or the design lifetime of the wind farm. No forecasting system can deliver this to sufficient accuracy. Quality, hub height on-site observations are usually only available for a short period. The only alternative is to look at information recorded in the past and try to relate available long-term data to the shorter period of on-site observations. This is usually accomplished using various modifications of the MCP analysis described above.

Several major factors influence the success and accuracy of this process.

1. The availability and proximity in both distance and climatic similarity terms of the long-term data set to the local data.
2. The nature and quality of the long-term observations
3. The length of the long-term record

4. The length of common record between the two stations available for correlation analysis
5. The assumption that the future will resemble the past, especially with climate change possible effecting wind speeds

5.11.1 Data integrity

The only widely available long-term wind data sets available in Australia are from the Bureau of Meteorology. These data sets differ widely in regional availability and quality. Miurhead (2000) discusses some of the features of the available data. The Bureau currently operates a network of over 500 Automatic Weather station (AWS) which deliver wind data from a 10m level, in many cases in hourly average form. Unfortunately the AWS program has only been progressing for the past 10 years or so with many stations available for a shorter period. Prior to this the availability of good wind data is very sparse. At some centres daily wind run data are available for a considerable period. At others only manual observations or infrequent observations are available.

One of the major problems in using a long-term data set is ensuring the quality and consistency of the data over the entire period. Miurhead (2000) illustrated several problems with the Bureau data sets which incorporate pre-AWS observations. Over a period of decades there may have been significant and repeated changes to instrumentation, observation frequency and even location of a site. The station number can often remain the same. This will render the data set unusable. Every data set must be quality controlled. Some examples from our own experience follow.

Figure 19 show the daily average wind speed for Mt Gambier Airport over a 20 year period. The AWS station was installed in late 1993. It is obvious that the data from the AWS has completely different character to the previous observations. The previous instrumentation was not of the same quality as the AWS system. This data set is not useable as long-term series. Figure 20 shows a similar picture at Armidale Airport. Although harder to detect, enquires to the airport management revealed that a Bureau AWS system had replaced a private, uncalibrated system in a different location in 2001. This renders the data set unusable. Figure 21 shows the daily wind run from a station near Orange (NSW). There is a distinct downward trend in the data series. Investigations revealed that this is probably due to urbanization, or vegetation growth in the region immediately surrounding the station. This data can be used with some detrending.

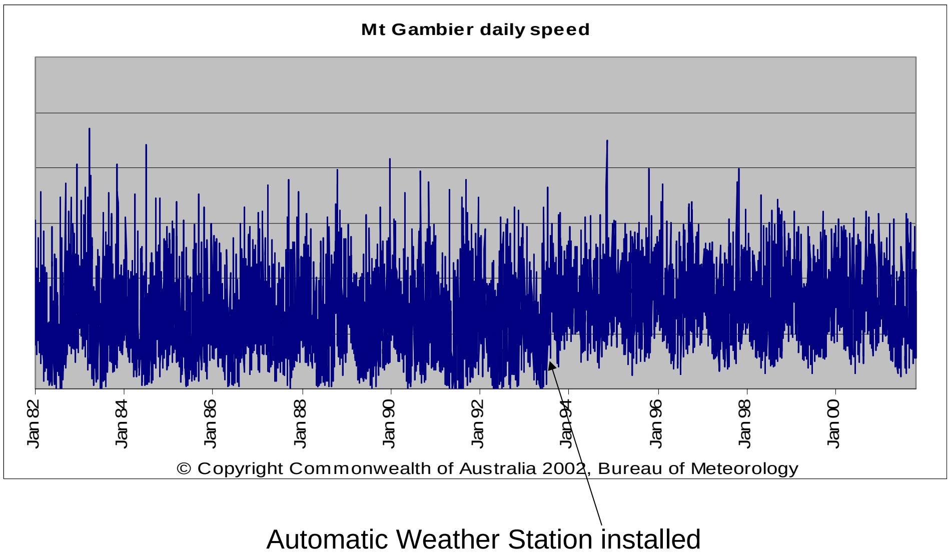


Figure 19 Daily average wind speed at Mt Gambier Airport showing installation of AWS

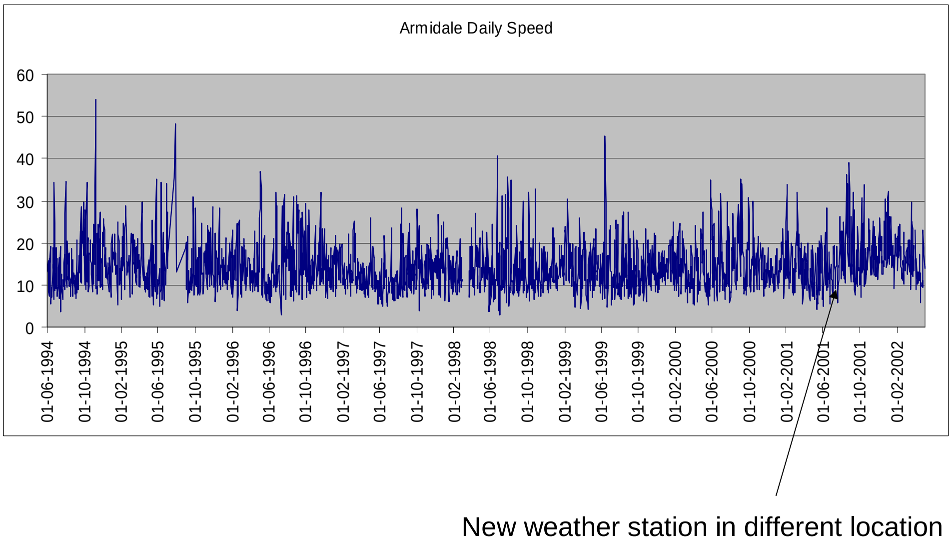


Figure 20 Daily average wind speed at Armidale Airport showing installation of AWS

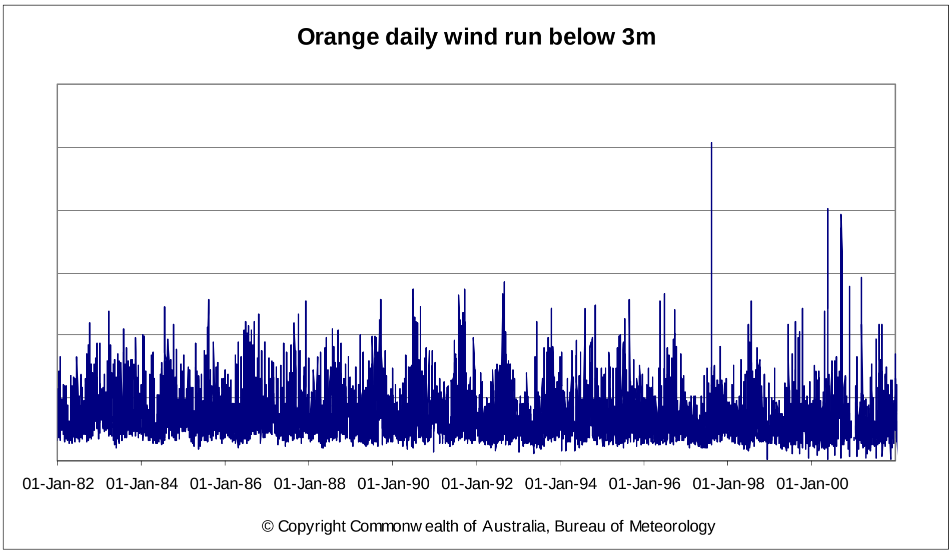


Figure 21 Daily average wind speed at Orange showing long-term trend

In some wind farm areas the most obvious Bureau data sources of sufficient quality are AWS stations with relatively short record, eg 6-8 years. Although successful correlations can be made with a year or two of on-site data, the long-term energy yield estimate will have an added uncertainty. Figure 22 shows an example of average wind speed at a well exposed airport site over a 20 year period. The plot shows the average wind speed starting with just one month of data. Even after accumulating several years of data the average is biased by a sequence of high years. The annual cycle is clearly visible, indicating that only whole years should be considered.

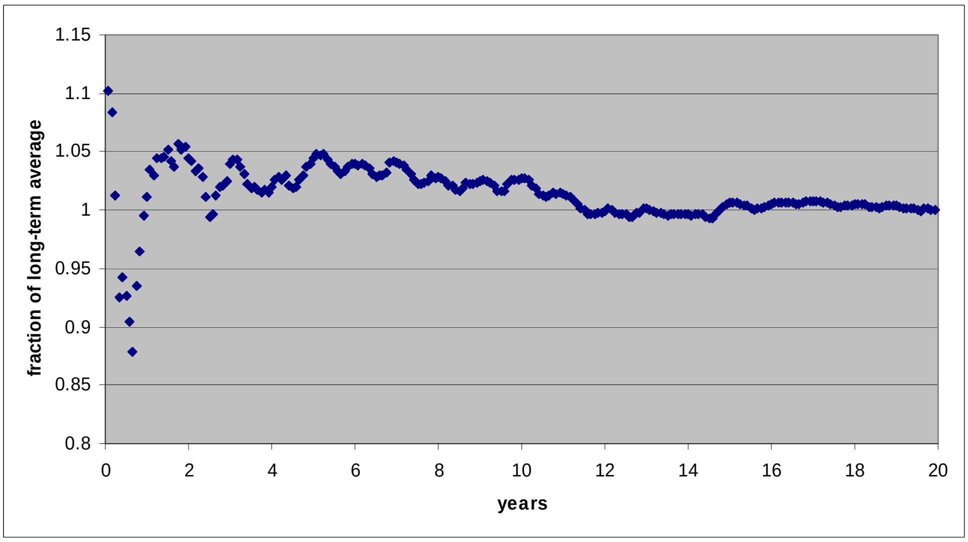


Figure 22 Cumulative average wind speed over 20 years based on monthly averages at an airport site

5.11.2 Correlation techniques and quantification of accuracy

The most common technique for adjusting local data for long-term is to first perform a correlation analysis between the long-term data source and the target site for the time both were operating. This procedure produces a relationship and confidence interval for predicting the wind speed at the target site from the long-term site. This relationship is then applied to the long-term data set when the target site was not in operation and the result is combined with the known data at the target site to produce an estimate for the entire twenty year period.

The type of relationship used depends on the long-term data source and its correlation with the target site. Often only daily wind run data with no directional information is available. Hence a linear relationship is the only option. If hourly wind data is available then it is often advantageous to break the analysis down into wind direction sectors (typically 12) with a linear relationship defined for each sector. The distance apart or climatic differences between the stations can degrade the correlation between the stations (Ayotte et al 2001), e.g. if one site on an escarpment and the other on the coast. This can introduce significant uncertainty into the calculations. Averaging times greater than one hour must sometimes be used and/or light winds excluded and some techniques force the intercept of the linear relationships though zero.

Confidence intervals for the predicted average wind speed can be obtained using the standard errors for the regression coefficients and residuals. These confidence intervals are only valid if the assumptions of the linear regression model are met. Briefly, the residuals should represent a random, independent, normally distributed deviate with constant variance. In practice these conditions are difficult to satisfy completely, so confidence intervals developed in this way are often approximate.

If the length of the long term data set is less than 20 years, there is likely to be additional uncertainty due to the variation in wind speeds on time scales of decades. This may add several percent to the uncertainty. These are complex procedures and the total error can have a very significant bearing on the uncertainties in the long-term average energy yield estimates, especially if there are no satisfactory long-term data sources nearby.

6 GENERATING THE POWER – TURBINES INTERACTING WITH THE WIND

The interaction between a given turbine and the wind is complex and of course fundamental to the determination of the amount of energy extracted. Here we deal with the matters of energy yield prediction. The topics of wind farm yield validation and the verification of turbine power curves (for which there is an International standard - IEC 1998) is beyond the scope of this document.

6.1 Turbine Response Relationship

The response of typical large-scale wind turbine to the wind speed can be described in the following equation

$$P = \frac{1}{2}\rho A U^3 C_p \qquad (2)$$

where $P =$ power
$\rho =$ air density
$A =$ swept area of turbine
$U =$ wind speed
$C_p =$ turbine power coefficient (maximum of 35-40%)

The combination of the aerodynamics of the blades and the control system of the turbine (often including blade pitch) is used to stop, start and maintain turbine output once the generator rated output is reached. A typical wind turbine power curve is shown in Figure 23, together with a wind speed probability distribution curve and resultant power yield as a function of wind speed. The turbine is started at about 4 ms^{-1} and increases output in an approximately linear fashion until the rated output is reached at about 14 ms^{-1}. The machine shuts down above 25 ms^{-1}. At windier sites as more and more of the wind occurs above the constant rated output of the turbine where the machine is limiting, more and more energy is lost. This ensures that the power output does not strictly follow the cubic relationship between the wind speed and the available power in the wind.

6.2 Energy Yields

The example annual wind speed probability distribution (shown here with a Weibull curve fitted) indicates that the turbine is most often operating at less than its rated output. The resultant annual energy production curve shows that most of the energy is also generated at wind speeds below the turbine's maximum output. Over a year the average energy output may be 30-40% of the output that would be obtained if the generator were running at its rated output all year. This percentage is known as the capacity factor.

If the turbine is located at a windier site, the wind speed probability will shift to the right and energy production will increase. The converse occurs at a lower wind speed site. The magnitude of this change will depend on the power curve of the turbine and the shape of the wind distribution. Typical changes are shown in Figure 24. Here some turbines are shown to increase their output by 2-3% for every 1% increase in wind speed at an average of about 7 ms^{-1}. This is an important relationship as locating slightly higher wind speed sites can have major economic benefits. Similarly, uncertainties in wind speed estimates are magnified in terms of energy production.

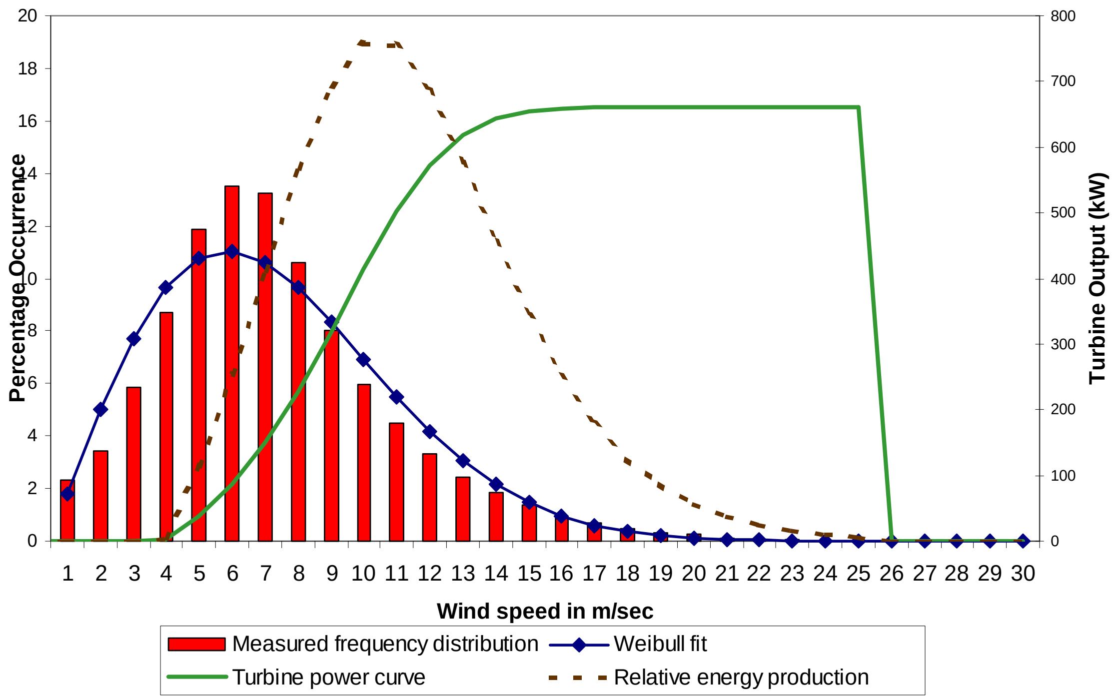


Figure 23 Typical 660kW wind turbine, power curve, wind speed probability distribution curve and resultant power yield as a function of wind speed

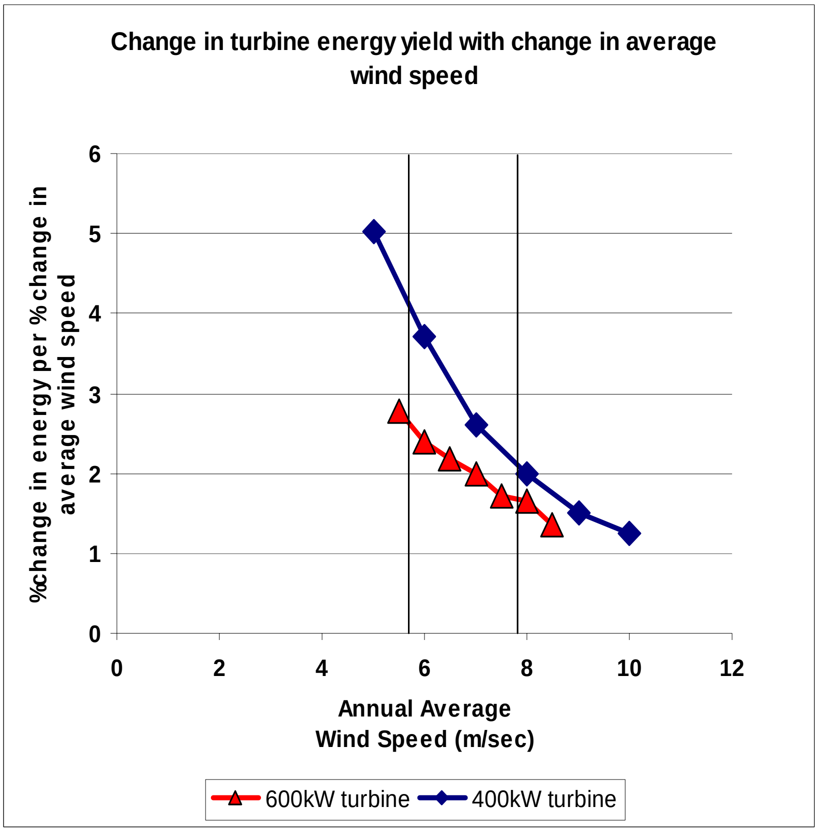


Figure 24 Changes in turbine output as a function of mean annual wind speed

A range of hub heights is often available from turbine manufacturers. The higher hub heights can be utilised to benefit from the increase in wind speed with height (Section 4.1). This comes at a cost for the extract height of the supporting structure and the trade-off can be calculated by estimating the energy yield at the alternative hub heights. This can be most easily done with the flow model and wind farm packages (see Section 9).

6.3 Turbulence and Gusts

Turbine manufacturers will be interested in a range of wind characteristics when specifying a suitable turbine for a site. This is to ensure the safe operating and design-lifetime conformance of the turbines (IEC 1999). The mean annual wind speed will be a first guide.

The average turbulence intensity will have a significant bearing on the fatigue of the turbine structures, particularly blades. The IEC standard (IEC 1999) specifies a design average turbulence intensity of 18%; above this a 3% increase can increase blade fatigue by 20% (Dekker and Pierek, 1998). Hence manufacturers are very interested in the turbulence intensity at a site and will want to know of any steep terrain etc which may lead to enhanced values. Unusual or excessive wind shear caused by steep terrain will also be of vital interest.

Maximum wind gusts are specified in the IEC design standard (IEC 1999), based on a 50 year return period gust with a modifier for the particular turbine hub height. This leads to a typical maximum gust specification of 75ms^{-1} for the Type I turbine class (the most robust). The Australian wind loading code for structures must be taken into account. The current standard (AS-1170.2-1989) specifies maximum survival gusts for various geographic regions. Modifiers are specified for height and terrain type, including relationships for hills. For most of south-eastern Australia the type I turbine with a hub height of about 70m can be placed on hill of slopes not exceeding about 0.2. Steep hills can produce amplified gusts amplified and can special measurements may need to be undertaken. Under this standard parts of the northwest coast of WA will have wind gusts exceeding the Class I specification.

6.4 Wakes

The role of a wind turbine is to extract energy from the passing air. In doing so it leaves behind it a wake consisting of slower, more turbulent air. This obviously will have an effect on any other turbine placed nearby when the wind is blowing directly in a line between the two. The study of such wakes is a whole area of research. The characterisation of wakes is very important for not only for the prediction of wind farm energy yields but also for the assessment of any enhanced turbine blade fatigue possibilities.

Depending on the prevailing conditions the deficit in velocity can persist for a considerable distance downwind of the turbine, more than 10 blade diameters (Magnusson and Smedman, 1999). Models for describing the wake effects have been developed (eg Ainslie,1988) and are included in wind farm design packages (See Section 9), where the wake losses from multiple wind turbines must be taken into account. It is often the primary driver of wind farm optimisation (squeezing turbines onto the best spots vs reducing wake interference). If the wind blows from a narrow range of wind directions (e.g. west and east) the rule-of-thumb is for spacing to be at least 2 blade diameters across wind between rows and 10 diameters downwind between rows. The across wind spacing of 2 is visually very close and 4 seems to be an accepted value (250m for a 66m blade diameter). For a more uniform wind rose the optimum seems to be about 6 diameters in all directions. The net wake loss for a wind farm with poor optimisation can be 7-10%, but well optimised spacings can reduce the wake losses to 3-4%. This represents a very significant and valuable improvement in yield.

7 MODELING THE WIND – LOCAL AREA

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7.1 A Historical View – The European Wind Atlas Analysis and Application Program - WASP

Many of the practices we currently consider to be industry standard have originated from the tools and methodology used to create the European Wind Atlas (see Troen and Petersen, 1989)[1]. This methodology uses WA^{S}P (The European Wind Atlas Analysis and Application Program – a model of flow over topography and roughness changes) to remove the local roughness and topographic effects from measurements. This is done to make them representative of the broader background wind resource. Simply stated, this methodology is based on modeling the effects of topography at a tower location and at a chosen location some distance from the location at which the measurements have been taken (see Figure 25). For example, as is often the case, where a measurement mast is located in accelerated flow at the crest of a hill, measurements will give wind speeds that reflect that acceleration and are not therefore representative of flow over the surrounding topography even a short distance away. In order to make the measurements representative of an area broader than just the tower location, the acceleration of the flow due to the hill at the tower location is calculated and subtracted from the measurements to give a wind resource representative of a broader area. Once this background wind resource is calculated, that wind resource can be translated and applied to other locations on the landscape or to a different height at the same location. Using this method essentially in reverse, the wind resource is calculated at another point on the landscape by again modeling the flow at that point and adding any local affects to the background wind resource to yield a wind resource that is specific to the local topography and roughness. Typical results of this process are shown in Figure 26.

There are two intrinsic and sometimes ignored assumptions in this methodology. The first is that the background wind resource does not vary over the distance between the point for which measurements are available and that where the wind resource is to be calculated. This assumption is normally valid over a few kilometres where no strong gradients of thermal characteristics of the surface (for example land/water boundaries) are present. The second assumption is that the model accurately accounts for any differences in the flow between where the

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

measurements have been made and the location of interest. This requirement, though seemingly obvious and simple, is somewhat onerous in that the model must be capable of reproducing the effect of underlying topographic features and roughness changes. Further it requires that the model is used under the limited conditions for which it was designed. There is great scope for violating these assumptions. However, it is possible to test for conditions that violate these assumptions, and tools of a more advanced nature than the WA^{S}P model are becoming available.

The above description involves the use of the WA^{S}P model. This model has been used extensively and been shown to produce accurate results when used in conditions for which it was designed. However, it is well known that this model has limitations (see Bowen and Mortensen, 1996)[2], such as its limited accuracy when used in steep terrain. The WA^{S}P model has a strong history, leading to its adoption as a de facto industry standard. There is no reason that other models cannot be used within this methodology to overcome the identified limitations in WA^{S}P.

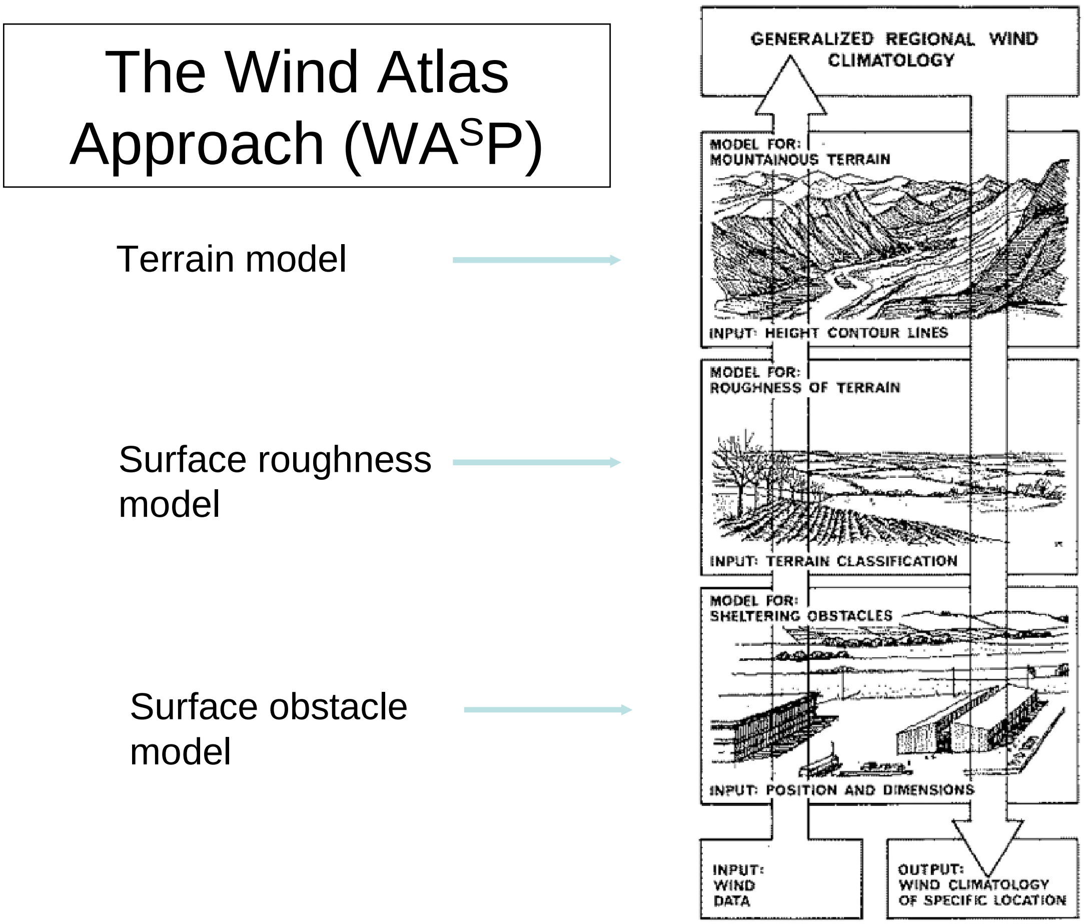

Figure 25 Schematic of European Wind Atlas methodology

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[2] Bowen, A.J. and Mortensen, N.G.: 1996, 'Exploring the Limits of WAsP: The European Wind Atlas Analysis and Application Program', in *Proceedings of the 1996 European Union Wind Energy Conference*, 20-24 May, 1996, Goteborg, Sweden

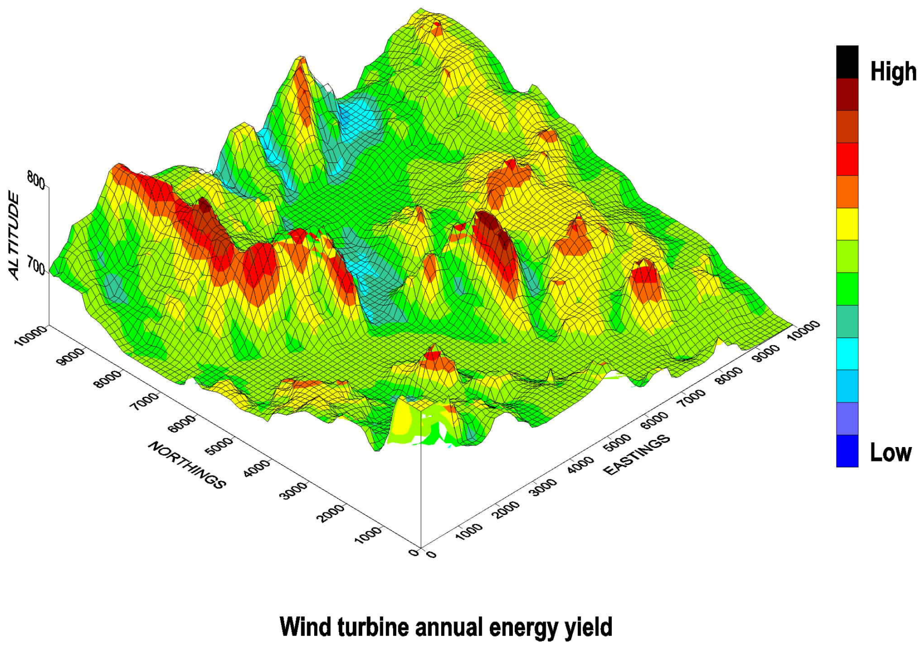

Figure 26 Typical small area wind resource map produced by WA^{S}P.

Obtaining the best available wind resource predictions over a local area is strongly dependent upon understanding the errors that can be made in making the predictions. We begin by giving a description of the statistical nature of the wind as a background upon which a structured view of modelling error can be based.

7.2 The Statistical Nature of the Wind

When we think of wind flow, we often envision streams of air traversing the landscape in smooth streamlines much like we would expect to see in a streambed or as indicated by the heavy near-surface lines shown in Figure 27. The idealized smooth flowing nature of the wind is only true in an average sense. At any one time, the flow is made up of a nearly infinite number of eddies, each oriented differently in the mean flow. The real turbulent nature of the flow is also shown in Figure 27 and originates primarily in shearing motions and buoyancy forces caused by heating in the lower part of atmosphere. These eddies exist at scales ranging from a few millimetres to a few kilometres and fractions of seconds to several minutes.

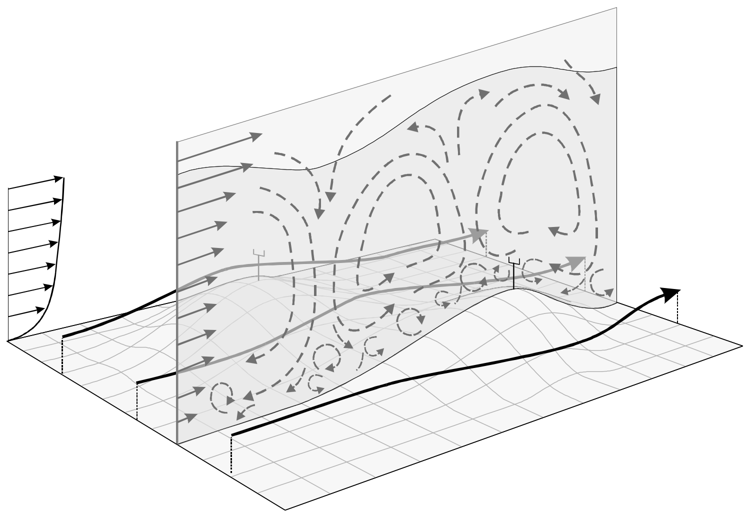

Figure 27 The turbulent nature of flow over the landscape.

Given the turbulent nature of the flow near the surface, it can often be observed that the wind speed and direction measured at two points are nearly unrelated at any instant in time and only begin to behave in a more coherent fashion when averaged for several minutes or longer. Another important aspect of this type of behaviour is that the further two points are apart, the less likely instantaneous (or averages over short periods) wind speed and direction measurements are to be similar between the two points. As averaging periods grow in length and/or measurements are taken closer together, the more correlated the observations become.

7.3 A View of Error in Modelling Wind Flow

As described above, the process of modelling the local wind resource is somewhat standardised in terms of methodology. When the available tools are used within the bounds of their design, accurate results can be expected. However, in practice, many situations are beyond the capabilities of current tools such as WA^{S}P. As with many things, the best defense against making errors of this nature is to understand their origin. Toward this end, the following gives a view of modelling error and highlights the most common and potentially most problematic of them.

One way of viewing the limitations on model accuracy is to look more closely at the sources of error in comparison of model output to field or wind-tunnel measurements. Figure 28 shows model error attributed to increasingly more specific categories moving from the top layer downward. The middle layer shows a division of the error into *statistical* and *model physical* error. In a general sense, this divides error into that which is attributable to the model and that which is due to the statistical framework within which the measurements are examined and processed. The statistical error is further divided into *data input* and *sampling* error.

The first is due actual errors in instrumentation that might arise, such as misalignment or equipment failure. These and other errors are outlined in Petersen et al. (1996). With care, this error can be eliminated to the extent that the instrumentation is performing to its specification. Sampling errors are associated with the frequency and duration of the measurements, including any averaging intervals used. An example of this type of disagreement might arise in comparing an ensemble mean from model output to data that have not been averaged long enough to give a stable mean of the variable in question.

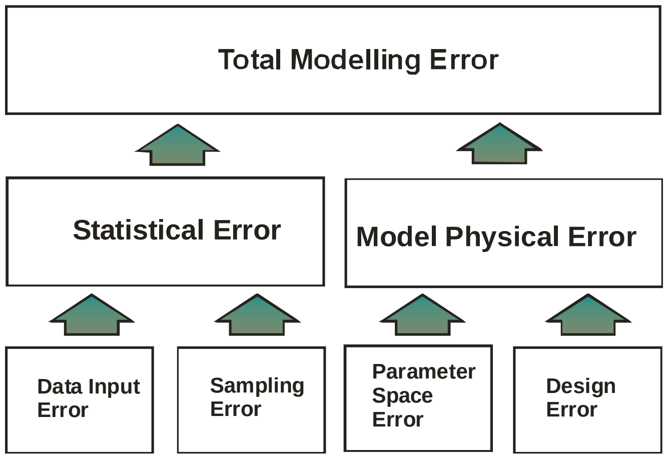

Figure 28 Composition of error in comparison between modelled and measured flow. (from Ayotte et al. (2001)

The model physical error is divided into *parameter space* and *design* error. The first comes from using a model beyond its design limits, for example a linear model in steep terrain where the assumptions used in the linearisation are violated or using a hydrostatic model where vertical acceleration is significant. These are referred to as operational errors by Bowen and Mortensen (1996). Design error is a result of limitations of the model itself. Examples of this are the errors associated with various discretisation methods or the (often many) simplifying assumptions that exclude processes or scales that exist in the measured flow, the real atmosphere in this case.

7.4 Coherence

By the nature of the formulations used in computer models of wind flow over terrain, only the averaged flow is represented. That is, modeled wind flow matches the smooth streamlines shown in Figure 27 and does not explicitly represent the turbulent nature of the flow. As such the turbulent nature of the atmosphere is often unaccounted for and can cause a lack of agreement between measurements and output from flow models – particularly when attempting to model observations that are some distance apart or have been averaged for only a brief period. In the framework presented in Figure 28, this type of error straddles *Sampling Error* and to a lesser degree, *Parameter Space Error*.

If two measurements vary together they are referred to as coherent or strongly correlated. As noted above the level of coherence is dependent on a number of characteristics of the atmospheric flow but is most strongly dependent upon the averaging time of the observations and the distance between the observations. For example one could expect observations of wind speed and direction to vary in a strongly correlated way when averaged over ten minutes at a separation of, say, one kilometer. Using the same averaging period the wind speed and direction observations from points separated by five to ten kilometers will show far less of a tendency to vary together (coherently).

The impact this has on the ability of models like WA^{S}P and others to accurately model flow originates in the sector-wise way in which the calculations are carried out (see the first section of this chapter). In calculating the background wind resource (wind atlas or wind resource grid) the winds from each sector are modified by a speedup specific to that sector. This comes as a natural consequence of the local terrain affecting the flow differently from each direction. A fundamental assumption in using this method is that the distribution of wind directions is constant across the distance from the point where the observations are taken to the location of interest. If the wind at these two locations does not vary in a coherent fashion, the wind direction distributions will not be similar, invalidating the assumption of coherence and introducing error into the calculation. Violation of this assumption is seen most easily in correlation coefficients between the two stations of less than 1.0.

To see this more clearly, Figure 29 shows correlation coefficients plotted against separation between locations from which several year-long measurement sets were taken. The correlation between the two sets of measurement clearly diminishes with distance as expected. As a natural consequence of this, the error associated with modelling between the sets of measurements using the WA^{S}P model increase with decreasing correlation (increasing separation). This is shown in Figure 30. Here modeling errors are normalised (made relative to) the error from modeling over a distance of 104 km (the greatest separation between the locations from which the measurements were taken). Here it is important to note that although the model used is WA^{S}P, these results are more a reflection of the statistical problems associated with modeling wind flow than the WA^{S}P model itself, with comparable results expected from any model which makes similar assumptions.

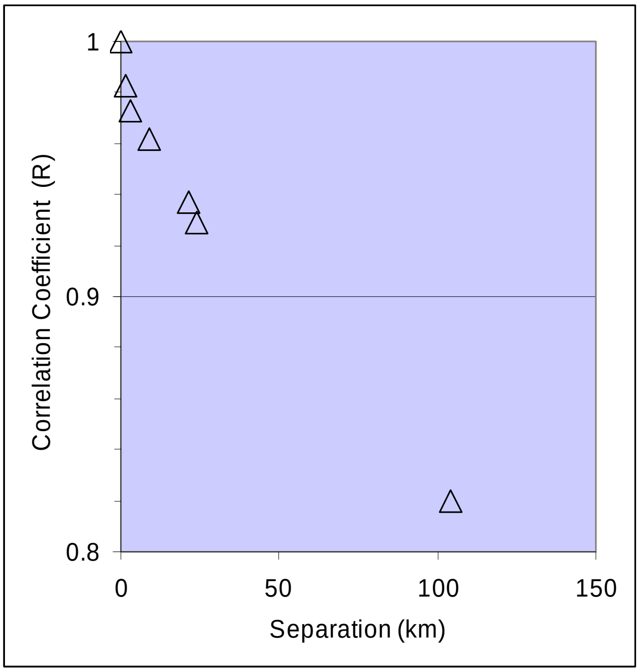

Figure 29 Correlation coefficient plotted against separation between measurements.

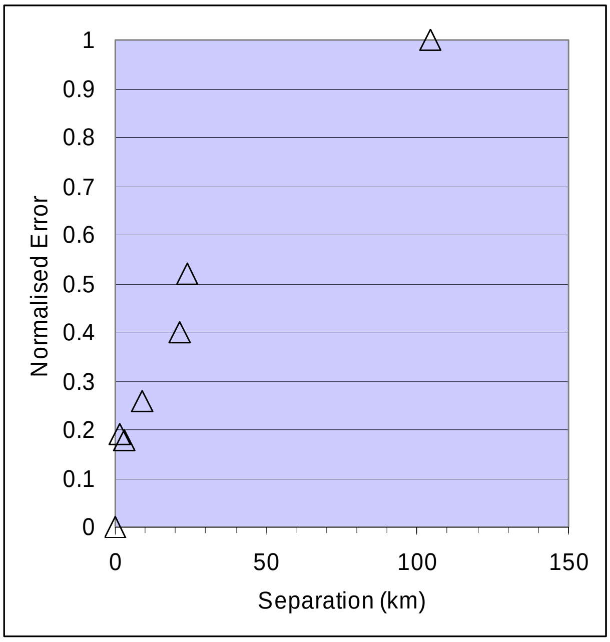

Figure 30 Normalised error using the WA^{S}P model plotted against separation between measurements. Error is normalized by error from greatest separation.

7.5 Flow in Steep Terrain

Flow accelerates over and around topographic features in response to pressure perturbations as streamlines converge at the crest of a hill as shown in Figure 31. The pressure pattern in flow over a simple hill has a minimum at the crest of the hill with maxima on the windward and leeward hill faces. Relative to the background wind profile (the dashed line in Figure 31, the flow accelerates toward the pressure minimum at the hill-crest, with an associated deceleration in the adverse pressure gradient on the lee side of the hill.

$$U_j \frac{\partial U_i}{\partial x_j} = \frac{-1}{\rho} \frac{\partial P}{\partial x_i} - \frac{\partial \overline{u_i u_j}}{\partial x_j} \qquad (3)$$

In steady flow over a hill, the balance of forces is essentially one between advection, pressure gradient and turbulent flux divergence - the terms appearing in Equation 3 in order from left to right. In the outer layer of the flow, the balance is mainly between advection and the pressure gradient - the first two terms in Equation 3. Closer to the surface, the turbulent stress divergence becomes more important, giving a more even balance between all three terms. However, advection plays a significant role nearly everywhere in the flow.

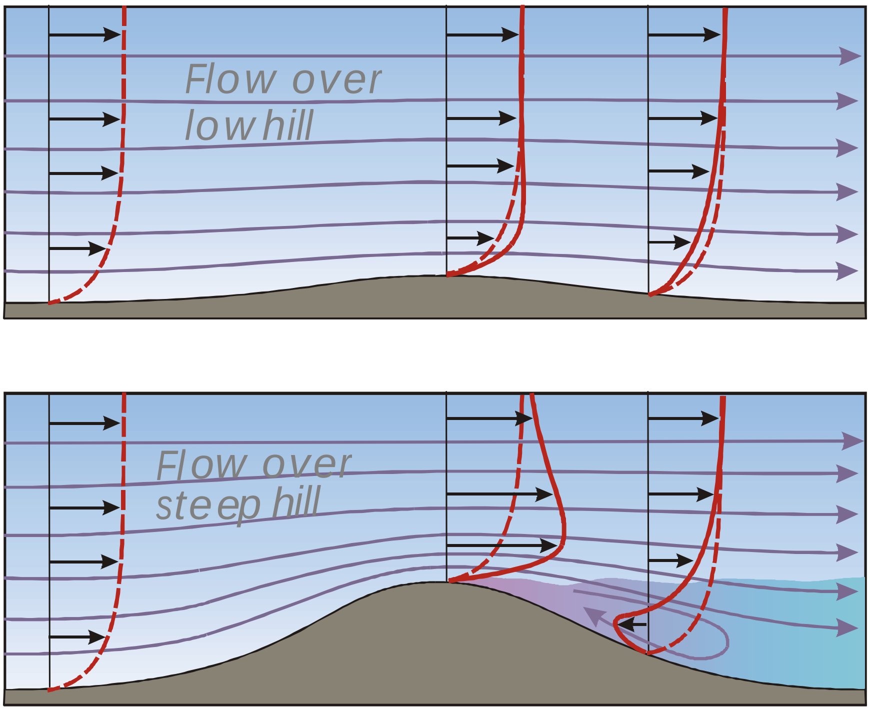

Figure 31 Idealised accelerated flow over low and steep hills. The solid line is accelerated flow and the dashed line represents unperturbed upstream flow.

In linear models (like WA^{S}P) of flow of this type, the nonlinear advection term is linearised by separating the velocity into a zero-order background part (the dashed line in Figure 31) and a perturbation part: $U_i = U_i^{(0)} + U_i^{(1)}$ The equations are then rewritten with higher order terms neglected yielding a greatly simplified (linear) system of equations to solve. In order for this approximation to be accurate, the size of the perturbation part must be small compared to the zero-order part, as in the upper frame of Figure 31. Conversely, as in the lower frame of Figure 31, over steep terrain the size of the perturbation part can be of the same order or even greater than the zero-order part, leading to significant errors in the modeled flow. In addition, on the leeward side of the hill in the area of strong adverse pressure gradient, the mean flow may reverse. In this situation, the validity of the model solution will be strongly dependent upon the accuracy of the balance between all three terms in Equation 3, particularly the flux divergence.

Though linear flow models are fast and efficient, they lack accuracy when used outside of the parameter space for which they were designed – most notably over steep terrain. To see this more clearly, maximum speedup $\Delta S=((U-U^{(0)})/U^{(0)})$ has been plotted against slope in Figure 32. The measurements are from flow over two dimensional ridges in the boundary layer wind tunnel at the CSIRO Division of Land and Water Pye Laboratory (Ayotte and Hughes, 2003)[3]. Here values superscripted with a zero represent undisturbed upstream values. The lines are projections from the origin through the ΔS values at 0.2 for both the rough and smooth surfaces. If, as is often assumed, the flow can be modeled to a high level of accuracy over topography with a slope of 0.2 using a linear assumption, then the maximum speedup modeled using a linear model will lie along these lines for slopes greater than 0.2. As can be seen in the figure, this would clearly result in a substantial over-prediction by a linear model at slopes greater than 0.2. In reality, validation of linear models suggest that accuracy diminishes even before an upper limit of 0.2, making the situation even less optimistic than presented in Figure 32.

[3] Ayotte, K.W. and Hughes, D.E.: 2003, 'Observations of Boundary Layer Wind Tunnel Flow over Isolated Ridges of Varying Steepness and Roughness', *Boundary Layer Meteorology*, in press.

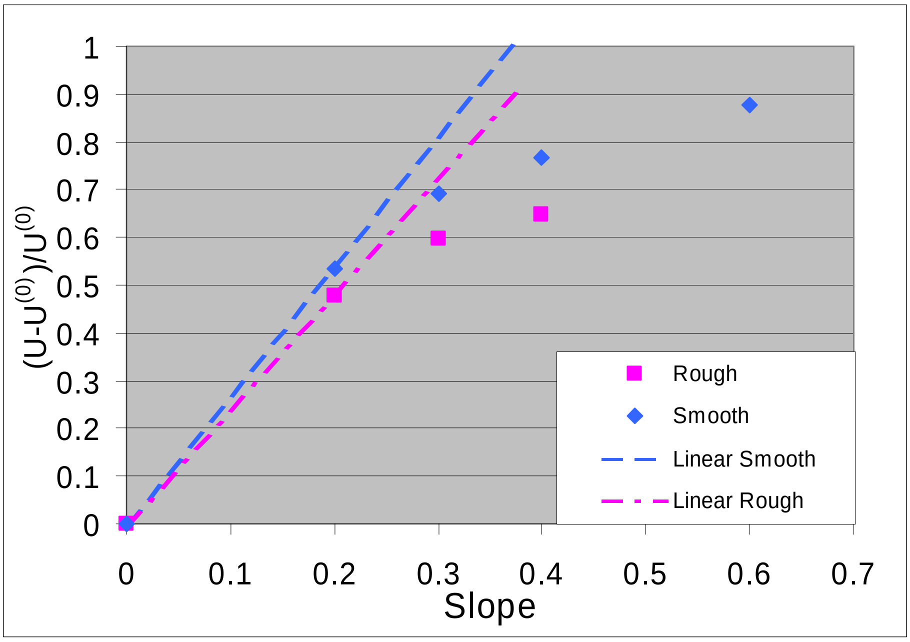

Figure 32 Maximum speedup over hills of varying slope and roughness. Measurements from wind tunnel flow over isolated sinusoidal ridges. Dashed lines are projections through speedup at slope of 0.2

7.6 Thermal Stratification

The complexity and difficulty associated with dealing with flows in and over complex terrain is increased significantly by the presence of buoyancy effects. Evidence for this is in the vast number of atmospheric phenomena that can be present in a stratified atmosphere that are not physically possible in a neutrally stratified atmosphere. Drainage flows and mountain waves are two examples that can be observed on a nearly continuous basis. A detailed overview is presented in Blumen (1990)[4] and the reader is encouraged to access the broad range of material available in the literature for a more in-depth understanding. However, in this chapter we will simply note that in the current context the main effect of stratification on flow over hills is to modify the way in which air flow is deflected by topography.

In neutral flow a parcel of air approaching a hill is forced to deflect around the hill by the dynamic pressure forces associated with the vertical acceleration of the air parcel as it rises on the windward side of the hill. This pressure maximum on the windward face of the hill tends to deflect the flow around the hill. This directional deflection is dependent upon the size and shape of the hill but tends to be small under neutral conditions, where buoyancy forces are small or nonexistent. In the presence of

[4] Blumen, W. Editor, 1990, `*Atmospheric Processes over Complex Terrain*', Meteorological Monographs, Volume 23, Number 45, American Meteorological Society, Boston, MA

thermal stratification, buoyancy forces act to resist the rise of the parcel as it moves upward over the windward face of the hill. The path of least resistance has the parcel moving around the hill more easily than over the hill crest. This has the effect of increasing the amount of deflection around the hill. The overall result is the reduction of the speed at the hill crest relative to otherwise similar but neutrally stratified flow.

Reflecting on the limited ability of flow models to deal with thermal stratification, it is clear that many times during a yearly wind record, the flow is likely to be affected by stratification. As such, it is expected that these models that do not account for thermal stratification will do a poor job of predicting speedup over topographic feature, resulting therefore in errors in the predicted wind speed. To some degree, this problem is made less important by the fact that the times during which the atmosphere is strongly stratified are times of low wind speed. This is so because as the wind speed increases, the shear generated turbulence tends to mix out any temperature gradient and thereby the stratification. Therefore the largest errors of this nature are likely to be in times of low wind speed.

In looking for ways to address this problem, it appears the most fruitful avenue to pursue is one of using meso-scale models, noting that tools of this nature do account for stratification. If used at a high enough resolution so that the important topographic features and therefore their affect on the flow are resolved, it could be expected that the accuracy of wind speed predictions would be increased. However, is should also be noted that this would be a very computationally expensive pursuit. Therefore, for the foreseeable future it appears we will be limited to living with the errors associated with stratification.

7.7 Summary

In this chapter, the methodology used to predict the local wind resource as modified by local topography and roughness changes has been outlined. The tools for modelling these changes are somewhat limited with regard to the situations in which they will give accurate answers. Two clear examples presented here are modelling flow in steep terrain and modeling flow in situations where thermal stratification is significantly affecting the flow. This must all be considered against the backdrop of the statistical nature of turbulent air flow and its affect on the ability to model over significant distances. Though it is difficult to be specific with regard to the magnitude of any of these errors, it is not uncommon to encounter errors well in excess of 15% in mean annual wind speed in any linear model, which translates to an even greater error in energy yield.

To some degree, some of these problems or limitations are being tackled by advances in computational fluid dynamics (CFD) methods and significantly increased computing power available on the desktop. For example, nonlinear model calculations are now available for calculating flow in steep terrain, significantly increasing the accuracy of the wind energy estimates and lowering the risk to developers. In addition, methods of assessing wind resource over broad areas that account for regional-scale variability in wind climate are also now available (see the next chapter). Though the future looks promising in terms of the availability of computational tools, knowledge of the underlying physical and mathematical principles is essential to use these or any other flow modelling tools effectively. Here we have provided a very broad overview of the methods and tools for modelling local wind flow on a local scale. The reader is strongly encouraged to explore more deeply the significant body of information available on the subject.

8 MODELLING THE WIND – LARGE AREA

8.1 Introduction

The traditional technique for modelling the wind over large areas is to combine high-quality measurements with a microscale model (such as WA^{S}P) – the wind-atlas approach – pioneered by RISØ (see Section 7). This approach works well when the measurement network is quite dense and where the terrain is fairly uniform and flat – such as in Denmark and Northern Germany. However, as noted, with a sparse measurement network and/or in complex terrain this approach should only be used within a few kilometres (~5-10km) of the measurement location.

The main reason for the errors in the wind-atlas approach is that microscale models make certain assumptions in order to make them computationally efficient. They assume that the flow is stationary (i.e. not time dependant) and normally neglect thermal effects. Where thermal effects are included in microscale models horizontal homogeneity is assumed such that the model only accounts for the effects of atmospheric stability on the boundary layer profile. This implies that microscale models are limited to modelling the effects of roughness changes and topographical changes on the flow. They cannot account for thermally forced flows such as sea-breezes and downslope winds.

In recent years a number of institutions and companies have begun using mesoscale models for wind energy applications such as forecasting and wind-mapping. Mesoscale models do include thermal effects and by their nature model unsteady phenomena such as the evolution of sea breezes and mountain waves. As such they are suitable for modelling the horizontal variations in climatology not accounted for by linear microscale models.

There follows a short description of mesoscale models and their application to wind mapping studies. The *WindScape* combined mesoscale/microscale approach is described in some detail and an example is given in the Appendix. Further comments are made on the competing approaches of MesoMap & KAMM/WA^{S}P.

8.2 Mesoscale Models

Mesoscale models were developed for general weather prediction purposes at finer resolution (1-10km) than standard Numerical Weather Prediction Models. In particular they were developed for air pollution studies and aviation purposes. Most of these models can be run in both historical and forecast modes. Many organisations have developed their own Mesoscale models including the National Center for Atmospheric Research, Environment Canada and CSIRO Atmospheric Research – details on these models are available at the websites provided in Table 2.

Table 2 Selected mesoscale model websites

Organisation	Model	Website
NCAR	MM5	http://www.mmm.ucar.edu/mm5/mm5-home.html
CSIRO	TAPM	http://www.dar.csiro.au/tapm/index.html
Environment Canada	MC2	http://www.cmc.ec.gc.ca/rpn/modcom/en/mc2v4.95.html

The boundary conditions or forcing of mesoscale models is normally done by the use of synoptic reanalysis datasets. These reanalysis datasets are essentially historical weather databases prepared by various weather bureaus and atmospheric institutions across the globe and at a variety of temporal and spatial resolutions. For example GASP reanalysis data is used to drive the TAPM model. GASP (Global Atmospheric Sampling Program) datasets consist of six-hourly data on a 0.75° grid across most of the globe. At each grid point data are provided for wind speed, wind direction, humidity and temperature at a number of pressure levels. The datasets are derived by compiling weather information from various measurement sources, typically weather balloons, incorporating the measurements into a numerical model which ensures certain conditions are met such as continuity and conservation of momentum before outputting the data on a regular grid. This reanalysis dataset can then be used more readily to drive finer scale meteorological models.

The mesoscale model solves numerical equations for the conservation of momentum, heat and moisture together with a continuity equation. Parameterisations are made for the behaviour and interactions of clouds, radiation processes and surface properties. Output normally consists of hourly averages of meteorological variables at each model grid point.

Wind mapping or prospecting applications normally involve running a mesoscale model historically over a number of years down to a resolution of 3km or less and combining the output with some sort of microscale model in order to account for the fine-scale effects

8.3 Combined Meso/Microscale Model Approaches

8.3.1 WindScape system

Several modelling systems have become available which are based on the complementary matching of a regional scale modelwith a fine scale flow model as described in Section 7. The systems make use of data and model predictions from global/continental-scale analysis down through to very fine scale calculations on the scale of individual topographic features with length scales from tens to hundreds of metres. They combine the abilities of mesoscale models to describe the background wind resource in some detail with the type of microscale modelling.

Three of these approaches, KAMM/WA^{S}P from RISØ, MesoMap from Truewind and *WindScape®* from CSIRO are described in Section 8.4. A schematic describing the principles of these techniques (*WindScape* in this case) is shown in Figure 33. With the global/continental-scale analysis driving the regional-scale model the remaining fine-scale variations in the wind flow patterns are accounted for using a fine-scale model nested within the regional-scale model. Where the regional-scale model operates at larger scales and is driven primarily by hydrostatic forces created by thermal contrasts (variations in land surface heating, cloud microphysical processes, *etc.*), the fine-scale model lacks this level of sophistication in terms of the processes it models. Instead, the fine-scale model assumes a neutrally stratified atmosphere and focuses on the dynamic pressure forces created over topographic features as air accelerates and decelerates over uneven terrain. This coupling of the models makes use of the underlying assumption that there exists a similar separation of scales and physical processes within the real atmosphere and that this separation is well represented in the two models.

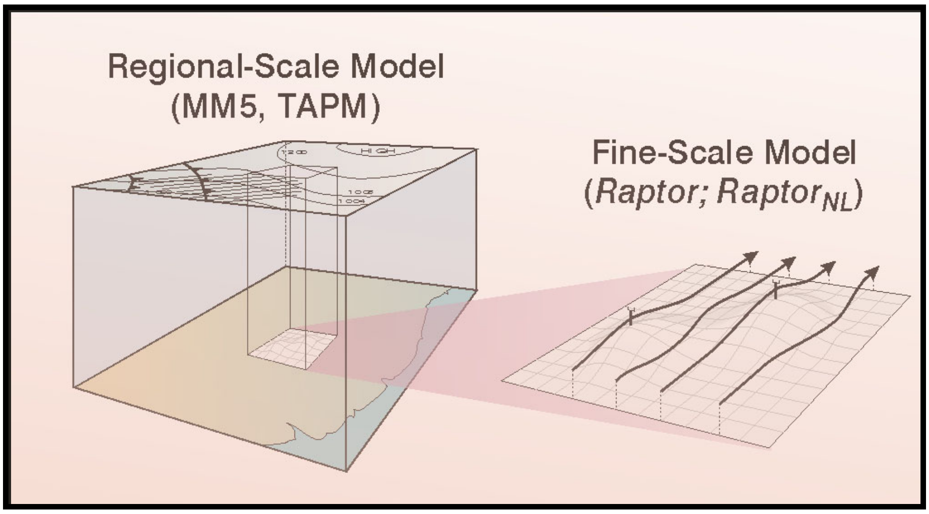

Figure 33 Schematic of *WindScape* system.

8.3.2 Example wind mapping output

The wind maps generated by these systems can be used in the initial stages of wind resource assessment, to identify areas or specific locations suitable for possible wind farm development. Output from the model consists of maps of mean annual wind speed (see example in Figure 34). This example map covers an area 100km*100km (1 degree by 1 degree) at a resolution of 100 metres. These maps can be combined within a GIS environment with maps of transmission lines, road layouts, topography contours, vegetation and other quantities to facilitate the wind prospecting process. In addition, hourly predictions of wind speed and direction can be calculated at "virtual tower" locations. These allow preliminary turbine layouts to be determined before the availability of measurements. Once strong candidate locations are identified, a measurement program is typically initiated and the development process proceeds in a standard manner. However it is also possible to calculate energy yields based on output from such systems in order to make preliminary assessments of project viability before a measurement campaign is initiated.

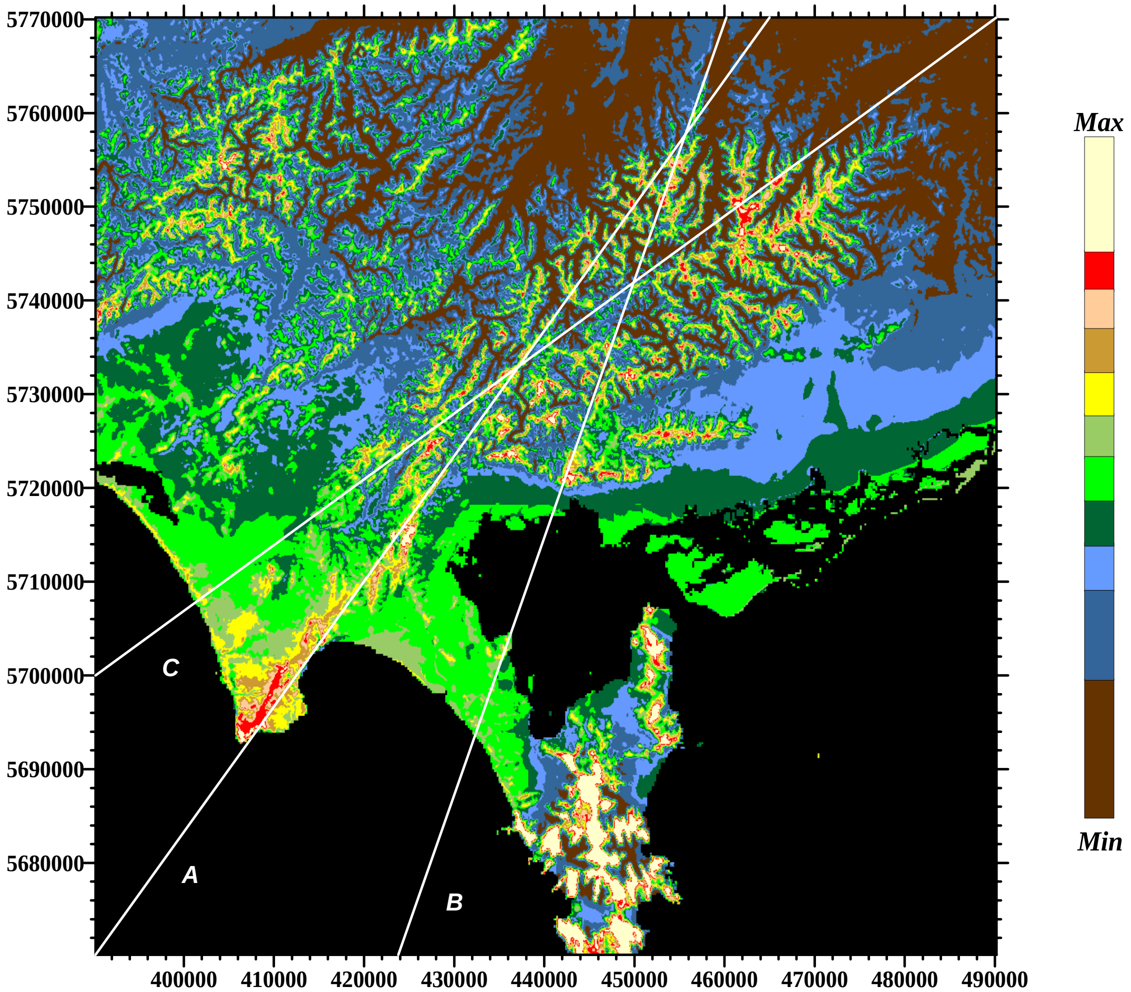

Figure 34 Example *WindScape* map of mean annual wind speed in the South Gippsland region.

To help understand the advantages offered by such wind speed maps three cross -sections have been taken from the example map, Figure 34. Mean annual wind speeds along these cross-sections are indicated in Figure 35. It should be noted that the annual average wind speeds reflect flow from all wind directions, for example locations just offshore will be affected by both onshore and offshore winds.

The main features of interest can be summarised:

- As expected the mean trend is a gradual drop in the wind speed moving inland from the ocean
- However, some of the inland hills and ranges have wind speeds similar to those at the coast, even as far as the Strzelecki Ranges
- Wind speeds in the Latrobe valley are relatively low

Of course the provision of such maps in only the first step in deciding the feasibility of wind farm development. The maps can form the basis of a GIS which can include many other factors such as land-use boundaries, vegetation, power line locations. Figure 36 shows an enlargement of the Cape Liptrap area with a vegetation mask blocking out forested areas.

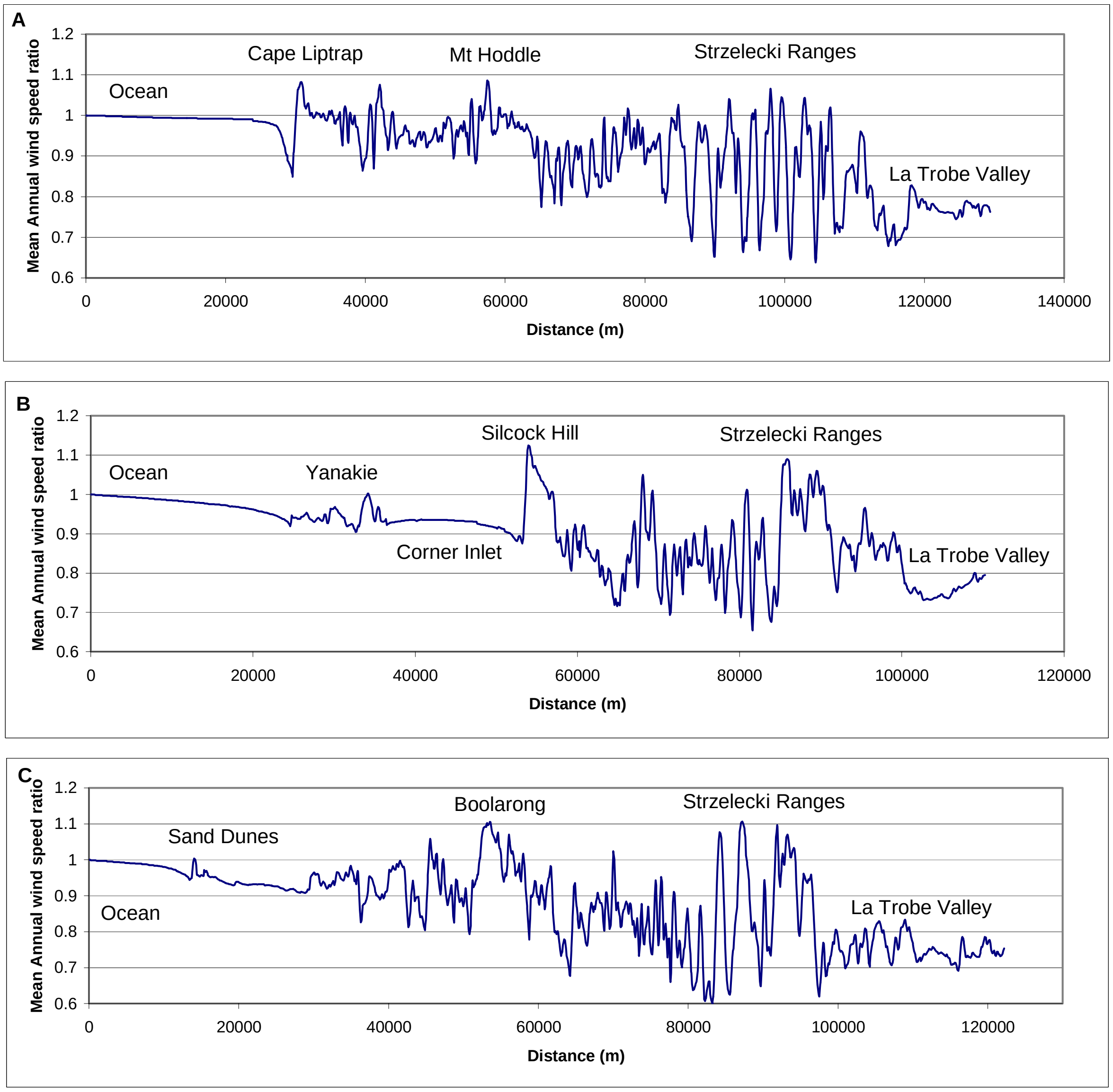

Figure 35 Cross-sections of mean annual wind speed - ratio with reference to start of cross-section at the ocean end. See Figure 34 for cross-section references.

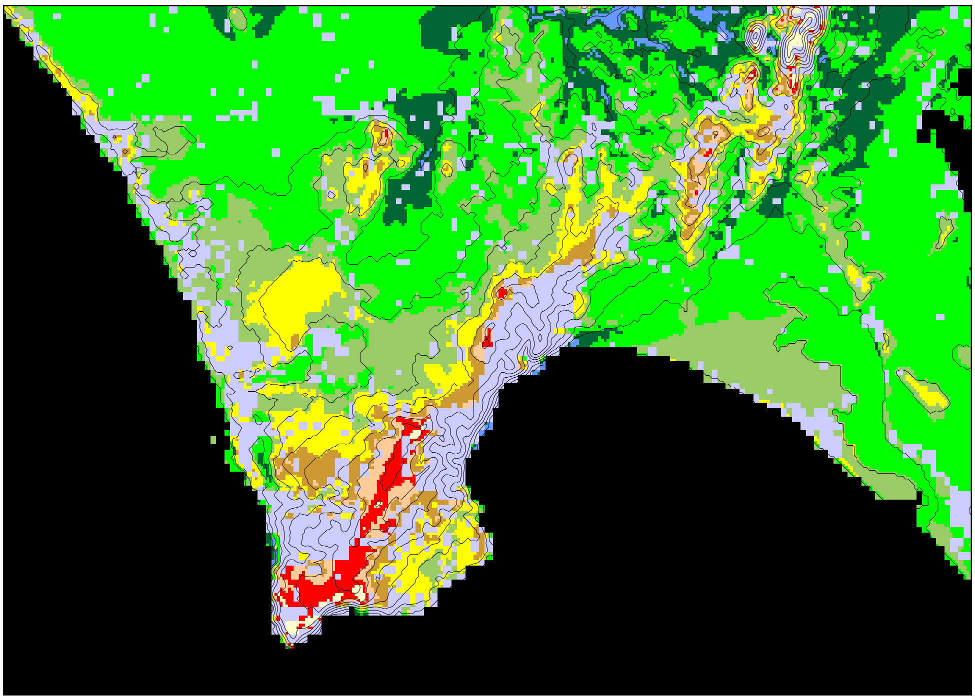

Figure 36 *WindScape* results for Cape Liptrap area with a grey vegetation mask blocking out forested areas

8.4 Summary of Example Combined Mesoscale/Microscale Systems

8.4.1 RISØ - KAMM/WA^{S}P

Methodology

- Combination of mesoscale model (KAMM) and microscale model (WA^{S}P)
- Statistical cluster analysis of different climactic situations

Output

- Maps of mean annual wind speed at set heights above ground level and at a resolution of 1-3km.
- WA^{S}P format Wind atlas files.

Validation

- Validation undertaken across Ireland[5]

Features

- Representative of climate in a long-term statistical sense
- Uses industry standard model - WA^{S}P - for microscale calculations – compatible with wind atlas approach

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[5] Frank, H.P. and Landberg, L., (1997) Modelling the Wind Climate of Ireland, *Boundary-Layer Meteorology*, **85**, pp359-377.

8.4.2 Truewind - MesoMap

Methodology
- Mesoscale model (MASS)
- Random statistical representation of long-term climate

Output
- Maps of mean annual wind speed at set heights above ground level and at resolutions of 400 -1000 metres.

Validation
- Validation demonstrated in USA[6] and Brazil

Features
- Representative of climate in a long-term statistical sense
- Covers large areas such as South East Asia[7]
- Extensively used across the globe

8.4.3 CSIRO/WERU - *WindScape®*

Methodology
- Combination of mesoscale model and microscale model
- Run for distinct historical time periods of a year or more

Output
- Maps of mean annual wind speed at set heights above ground level and at a resolution of 100 metres
- "Virtual-Tower" time series at any location and height within the mapped area
- Wasp format Wind Resource Grids for input into industry standard wind farm design software

Validation
- Validation of the model performance at sites across Australia has been demonstrated [8,9]
- More limited validation studies have been undertaken in Ireland, Scotland, Pacific Islands and Spain

Features
- Modular modelling system – allows the choice of a mesoscale or microscale model appropriate to the complexity of the terrain
- "Virtual-Tower" output allows detailed model validation or wind farm feasibility studies to be undertaken
- Wind Resource Grids are compatible with industry standard wind farm design software

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6 Brower, M.C., Zack, J.W. and Bailey, B.H. (2000) Validation and application of MesoMap, *Proceedings WindPower 2000, American Wind Energy Association*.

7 Wind Energy Resource Atlas of Southeast Asia (September 2001), Prepared for the World Bank Asia Alternative Energy Program, Prepared by TrueWind Solutions , LLC.

8 Steggel, N, Ayotte, K.A., Davy, R.J. and Coppin, P.A. (2002) Wind Prospecting with *WindScape* in Australia, in Proceedings of Global WindPower 2002.

9 Steggel, N. (2003) *WindScape* assessment in the State of Victoria, Australia – PRICING & TECHNICAL SPECIFICATIONS, Internal report, CSIRO Land & Water.

8.5 Recommended Usage of Model Output

WERU recommend the following procedure for usage of combined mesoscale/microscale wind maps and virtual tower output.

- Determine broad area of interest for possible wind-farm location.
- Obtain wind maps for appropriate areas and at high resolution (preferably at least 200m) - the importance of obtaining maps at high resolution is demonstrated in Section 8.6.
- Combine wind maps in a GIS system with other layers such as vegetation, access routes and transmission lines – alternatively overlay wind-maps as transparencies – identify potential wind-farm sites.
- Examine validation details for nearest Automatic Weather Stations – if additional tall-tower datasets are available obtain "virtual-tower" output or equivalent at these locations and test model performance at these locations.
- Examine local terrain slopes and vegetation and assess capabilities of mesoscale and microscale models at chosen site(s)
- Pre-feasibility assessment of each wind-farm location (e.g. WA^{S}P,WindFarmer, Financial modelling).
- Obtain land options to develop and initiate measurement campaign.

Figure 37 illustrates the process of site identification using high resolution wind mapping data. The "virtual tower" data at the suitable site can be used for pre-feasibility studies.

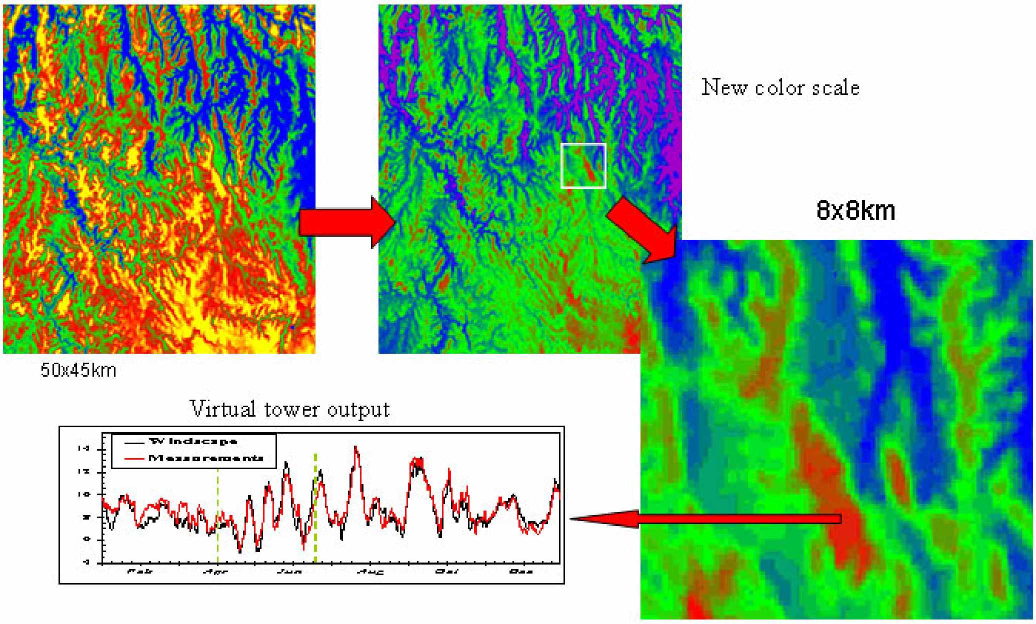

Figure 37 Selection of wind farm sites from high resolution wind mapping and Virtual Tower output

It should be stressed that a viable wind farm development is dependent on high-quality measurements and that although models such as *WindScape,* MesoMap & KAMM/WA^{S}P are useful wind prospecting tools, they will not replace measurements in the foreseeable future.

8.6 Mapping Scale Issues

It is important to consider the scale at which mapping is calculated and published. From Section 4.7 it is clear there is an exponential relationship between the area of land available and the wind speed resource. Figure 38 shows the effect of changing resolution on the features visible in a hilly area of the NSW Great Dividing Range. These results are taken from *WindScape* model results. At a resolution of 8km or even 3km only the broad features are apparent. With the finer resolution of 100km it is evident that a) the 3km maps may overestimate the land area available at a given resource level and b) it will miss a significant number of smaller features with good resource. This latter point can be clearly seen in the two areas on the right of the Figure which show features with good resource present in an area which indicates lower resources via its green colouring. In general good features will always be found in areas which indicate well at coarse resolution but many others will be missed unless adequate resolution mapping is used.

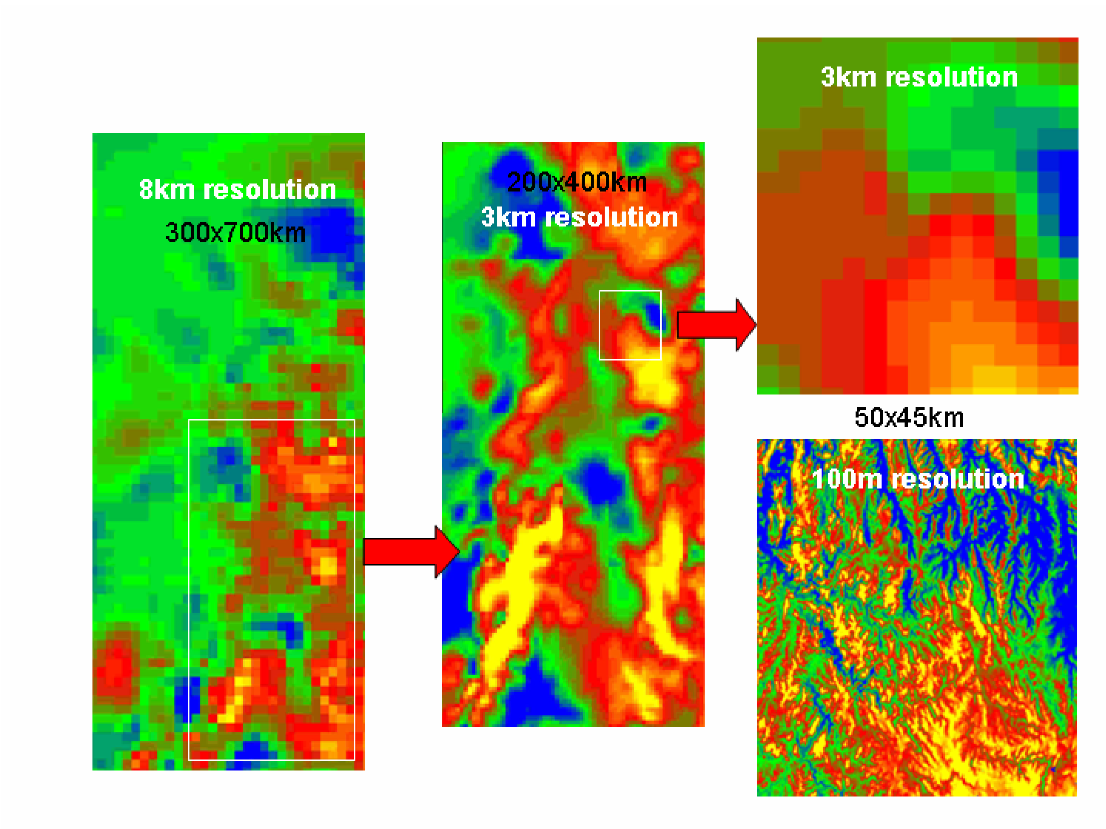

Figure 38 Changes in wind speed maps with resolution (same wind speed scale in each case – yellow/red indicate better resource)

9 WIND FARM LAYOUT DESIGN

9.1 Principles

There are a number of software packages which assist in the design of a wind farm, taking into account a range of constraints and design parameters which extend beyond the consideration of energy yield alone.

The wind resource component of these packages all require the input of a map of potential energy yield for the desired location. This is generated in the fashion described in Section 7. The packages require or can use input from WA^{S}P (WindFarm also supplies MS-Micro as an alternative). Hard constraints are then applied in terms of permitted areas for placement of turbines, distance to boundaries, minimum turbine spacings are also applied. Depending on the particular package, an optimisation process which balances wake losses against maximum utilisation of the best yielding areas is provided. Some packages can also apply series of computed constraints in this process which take into account noise emissions and visual influence parameters. (e.g. where noise must not exceed a nominated level at a particular location or turbines must not be visible from a certain spot). The packages vary in the sophistication of this process.

Beyond having a predicted wind farm energy yield, the packages can produce photomontages where resulting turbine array can be overlayed over images of the site, some even producing animations. Economic and electrical calculations are also available in some cases.

9.2 Limitations

Care must be taken with specifying parameters which influence the look of a wind farm (primarily spacing and zones of visual influence), the optimiser will always place turbines in the highest yielding locations within the constraints which may result in an aesthetically displeasing array. This can be seen where the available land area is quite large but the resource is biased to one side (eg nearest the sea) in which case the turbines will all end up “crowded” to one side. While this may seem obvious, it may not have been what was foreseen.

The packages work from the supplied energy yield map which carries all the limitations inherent in the linear modelling described in Section 7, including steep terrain. These energy maps, of course, are in turn dependent on the wind data from which they were calculated and so issues such as long-term corrections and location of the data set must be considered.

9.3 Available systems

9.3.1 WA^{S}P – Basic wind energy yield calculations

The WA^{S}P program has been described in Section 7 and provides the underpinning for all the wind farm design packages (except for WindFarm which has a similar model included as an alternative). The wind resource maps which WA^{S}P can produce in mean annual wind speed or potential wind energy forms are used to calculate the energy yield of wind turbines placed in certain positions by the user or the optimiser software as described above.

WA^{S}P also has the ability to calculate the energy yield from a wind farm consisting of turbines placed at user supplied coordinates. It contains no optimiser or additional modules. A chosen power curve is applied at a fixed hub height and energy yields calculated, allowing for wake interference between units (using the PARK module). This is quite useful where constraints have been applied manually and turbine positions are known, often in the feasibility study stages. It has limitations in the simplicity of the wake modelling and the inability to apply variable air density over sites with significant altitude changes. More information can be obtained from www.wasp.dk

9.3.2 WindFarmer

WindFarmer is comprehensive design package which includes modules for wind statistics and turbine characteristics, optimisation, visualisation, turbulence intensity, financial, electrical and shadow flicker. It requires wind resource grid information from WA^{S}P but includes a selection of wake effect options, including PARK. More information can be found at www.garradhassan.com/windfarmer

Figure 39 Example WindFarmer photomontage

9.3.3 WindFarm

WindFarm is a comprehensive design package which includes modules for wind flow across the terrain and energy yield, wind analysis, optimisation, noise calculation, turbine characteristics, photomontage and landscape view, zone-of-visual-influence, shadow flicker. It uses either energy yield maps sourced externally from WA^{S}P or from running the built in MSMicro micro program which has similar performance. More information can be found at members.aol.com/resoft/homepage.htm

9.3.4 WindPro

WindPRO is a comprehensive design package which contains a series of modules which is illustrated in Figure 40. It also requires energy yield maps from WA^{S}P and uses the PARK wake model. More information can be found at www.emd.dk/windpro

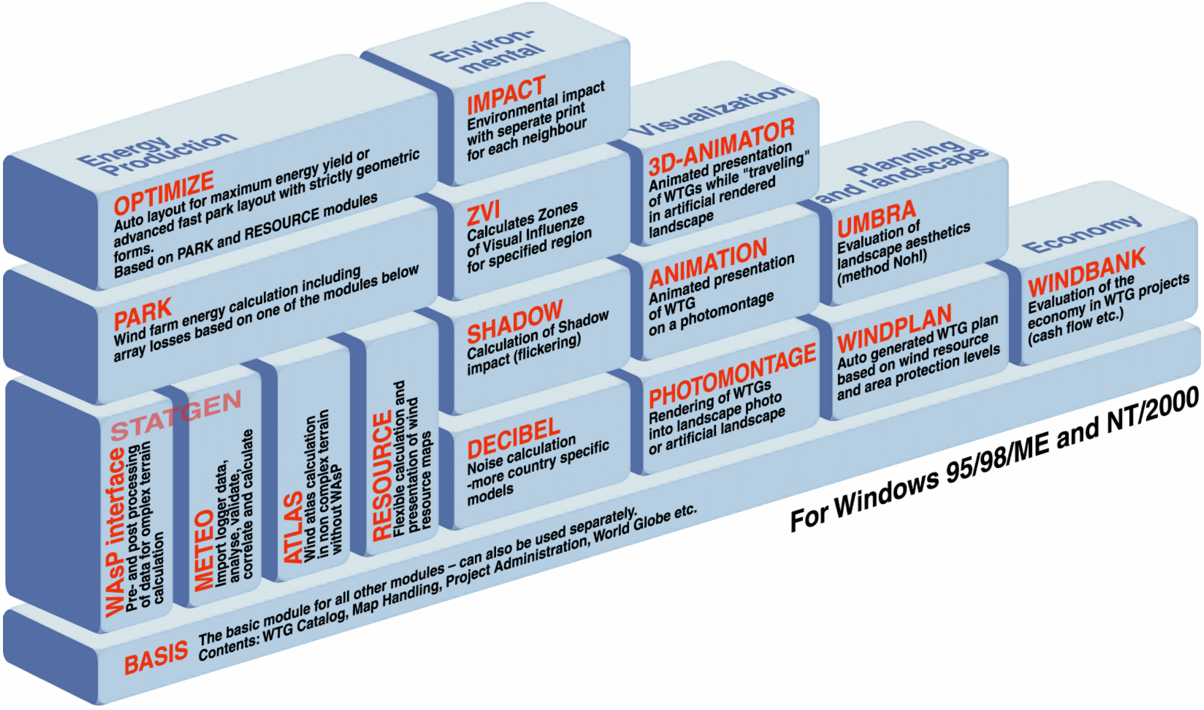

Figure 40 Example of wind farm design system modules – WindPro

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11 APPENDIX A - *WINDSCAPE®* ASSESSMENT OF POTENTIAL WIND ENERGY YIELD IN THE FOSTER REGION

Summary

The *WindScape®* wind resource modelling technique was used to investigate the wind resource in the Foster area of Victoria to provide a comprehensive example of the application of fine-scale wind resource mapping. The area computed comprised a rectangle 100km by 100km having SW and NE corners located at (392000E, 5672000N) and (492000E, 5772000N) respectively. *WindScape* was used to provide estimates of wind speed over this area at a resolution of 100 metres. The year 2000 was used for the simulations. The *WindScape* results showed numerous hills and ridges within these bounds to have annual average wind speeds in excess of 8.4m/s at 67m above the terrain. This translates into a wind turbine yield of approximately 3.0 GWh/annum per installed MW. The absolute accuracy of the wind speed estimates is about ±10%.

The areas of highest yield are located in two main regions. The largest of these is found in the vicinity of Cape Liptrap. Further windy areas are located along hills and ridges stretching from Mount Hoddle to Silcocks Hill.

11.1 Background

This report describes a detailed wind resource assessment carried out for an area of Victoria approximately centred on the town of Foster. The assessment is required to enable the identification of wind "hot-spots" suitable for further investigation and possible wind farm development. The regional wind mapping tool *WindScape* has been used to create the wind resource map. Once prospective sites have been identified it is recommended that actual on-site monitoring should be carried out by measuring the wind at the anticipated hub height for a period of at least one year. Then modelling of the proposed site can be carried out using WA^{S}P or other programs.

The aims of the *WindScape* modelling were twofold:

1. Provide an assessment of the wind energy potential for the region in absolute terms. This can be used as a guide for determining the potential viability of any wind development project, and
2. Identify suitable wind hotspots in a relative sense to enable a wind measurement program to be initiated at selected sites.

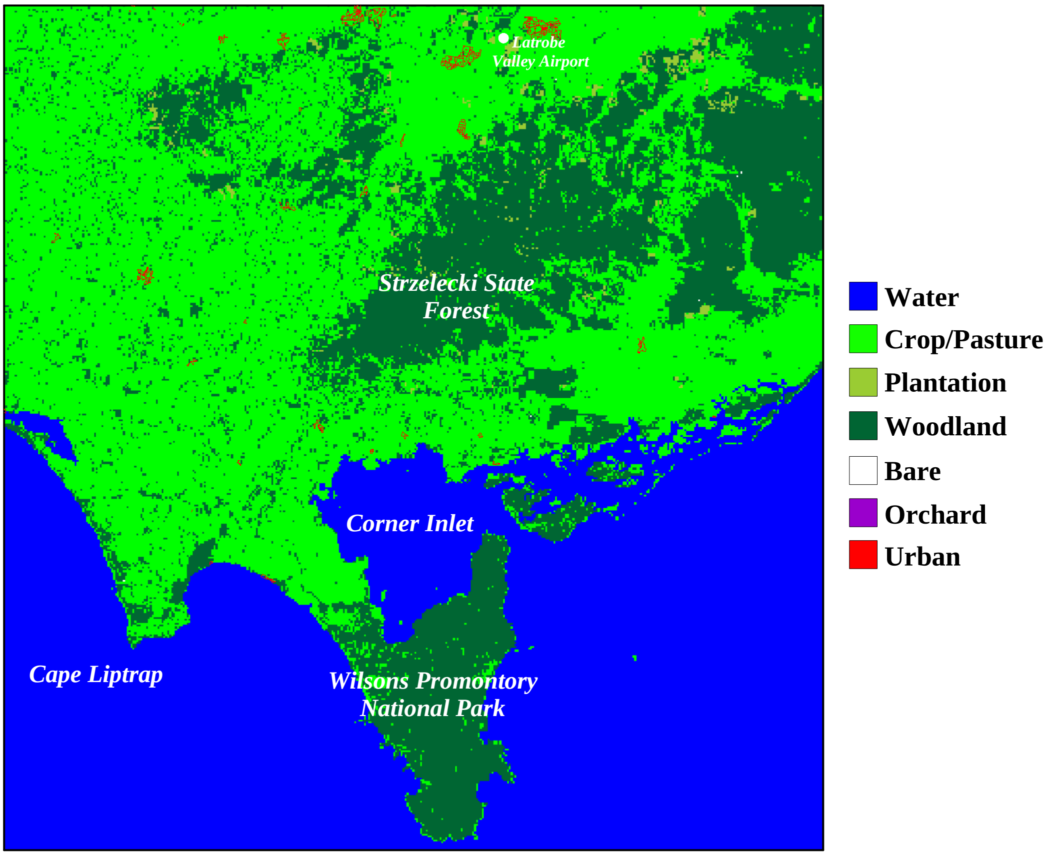

Figure 41 Fine scale vegetation across Foster region

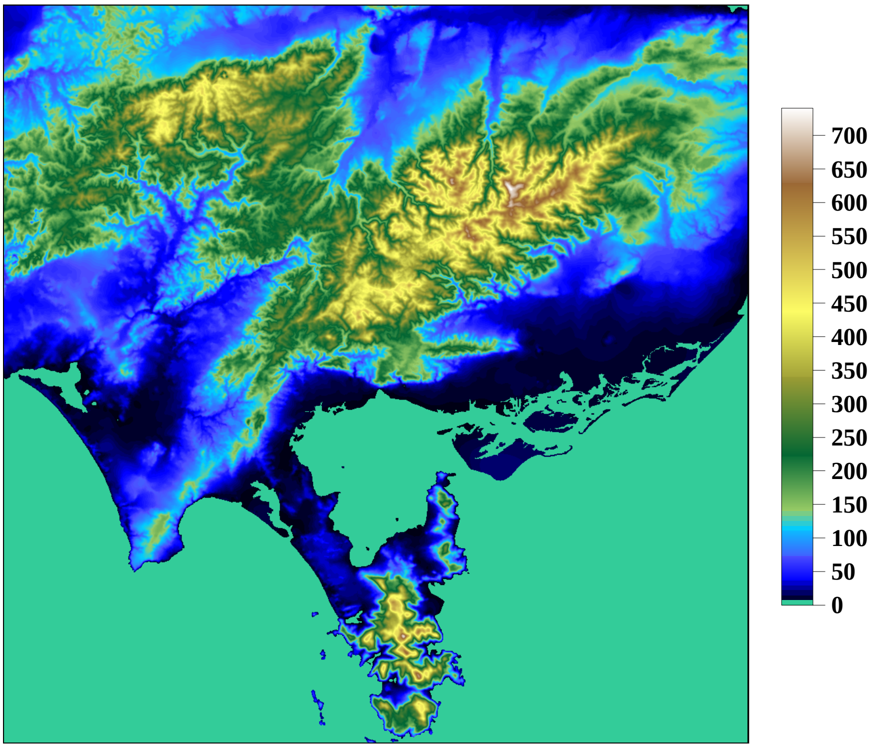

Figure 42 Fine scale topography covering Foster region (units are metres)

11.2 Description of the area

Fine scale vegetation and topography maps of the region of interest are provided in Figure 41 and Figure 42 while broad scale maps are given in Figure 45 and Figure 46 respectively. There are several small towns in the area – Toora, Inverloch and Foster in the south and Warragul, Moe and Morwell in the north – and scattered forests are observed across the region together with the more densely vegetated Strzelecki State Forest and Wilson's Promontory National Park. The topography of the region is dominated by two main ridge features – one stretches inland from the Foster area and incorporates Strzelecki State Forest, the other stretches inland from the Foster area to the region around the town of Moe.

11.3 *The WindScape®* Approach

11.3.1 WindScape system

A described in Section 8, the *WindScape*[10] system is a regional wind resource mapping tool based on the complementary matching of a regional scale model with a fine scale flow model.

The modelling system produces detailed spatial estimates of wind energy resource at high resolution (50-100m) over broad regions, typically 100km square. These modelled regions can be located in areas where there are no existing tower measurements and when used in the initial, exploratory stages of defining the wind resource over a large area, the system can provide information to optimise the location of measurement towers. Where measurements have already been collected *WindScape* can be used to model the wind statistics to distances of order 100km from the measurement location. This is a significant improvement over current industry standard fine-scale models which do not account for regional-scale variations in wind climatology and thus become unreliable at much shorter distances from the measurement tower. This greatly increases the value of existing measurements by expanding the area over which they are representative of the wind climate.

The system makes use of data and model predictions from global/continental-scale analysis down through to very fine scale calculations on the scale of individual topographic features with length scales from tens to hundreds of metres. The system does this by nesting progressively finer scale calculations, one within the other, beginning with continental-scale analyses provided by a global measurement network.

With the global/continental-scale analysis driving the regional-scale model the remaining fine-scale variations in the wind flow patterns are accounted for using a fine-scale model (*Raptor* or *RaptorNL*) nested within the regional-scale model (See Figure 33). Where the regional scale model operates at larger scales and is driven primarily by hydrostatic forces created by thermal contrasts (variations in land surface heating, cloud microphysical processes, *etc.*), the fine scale model lacks this level of sophistication in terms of the processes it models. Instead, the fine-scale model assumes a neutrally stratified atmosphere and focuses on the dynamic pressure forces created over topographic features as air accelerates and decelerates over uneven terrain. This coupling of the models makes use of the underlying assumption that there exists a similar

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[10] Steggel, N, Ayotte, K.A., Davy, R.J. and Coppin, P.A. (2002) Wind Prospecting with *WindScape* in Australia, in Proceedings of Global WindPower 2002.

separation of scales and physical processes within the real atmosphere and that this separation is well represented in the two models.

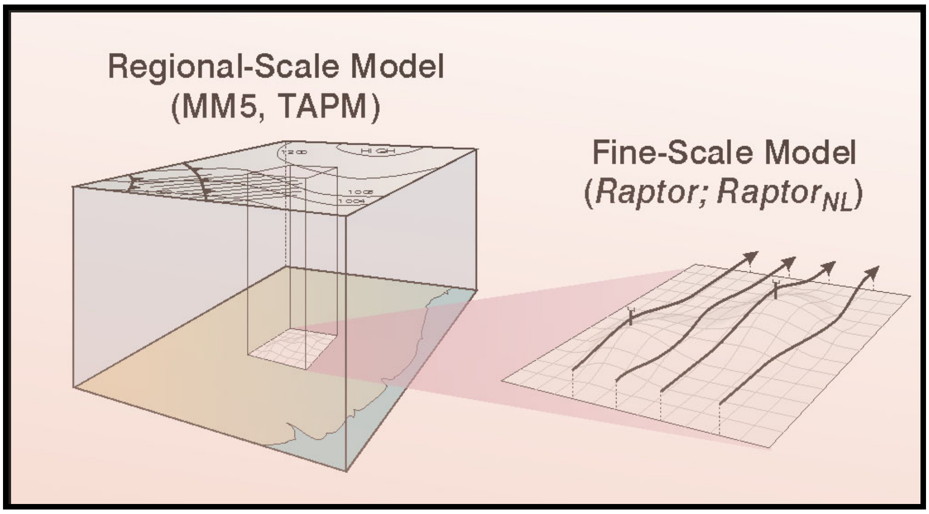

Figure 43 Schematic of *WindScape* system.

11.3.2 Validating *WindScape*

Validation tests of *WindScape* within Australia and overseas show a high level of skill in calculating wind energy potential over broad areas (see **Error! Reference source not found.**).

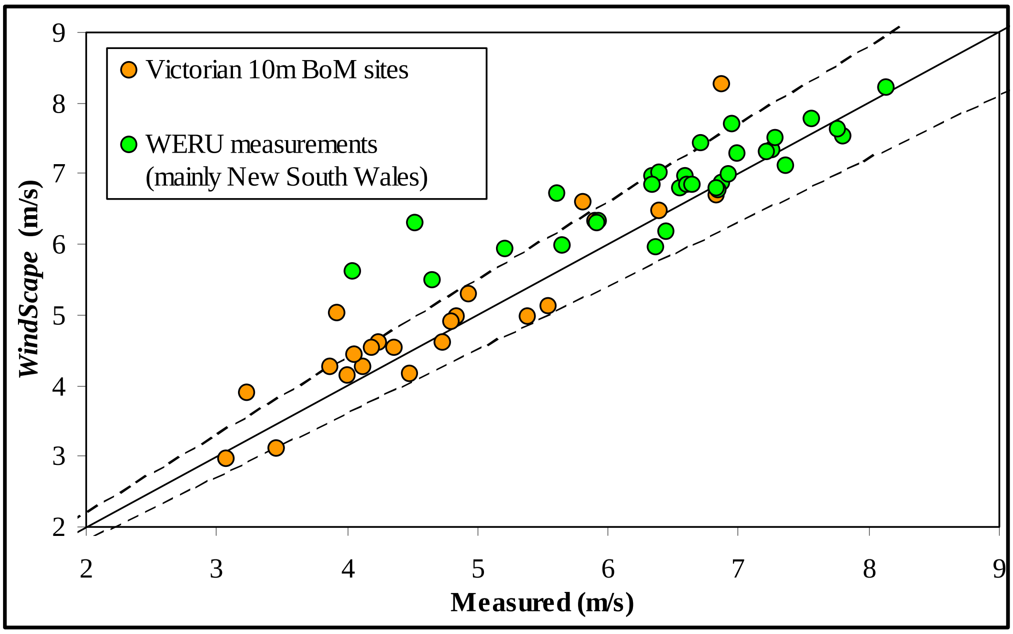

Figure 44 WindScape performance across Australia, mean annual wind speed, Orange Circles are Bureau of Meteorology Sites in Victoria with greater than 90% data availability, Green Circles are WERU tall-towers mainly located within New South Wales.

11.4 Application of *WindScape* to the Foster region

In the following sections a description of the *WindScape* application to the Foster region is given. Results are presented for the mean annual wind speeds predicted by *WindScape* for this region during the year 2000 as well as a description of some of the limitations relevant to the *WindScape* methodology. In an attempt to further pinpoint reliable wind hot-spots a vegetation masking map is provided covering those areas that are urban or forested and thus unsuitable for wind development.

11.4.1 Regional scale modelling

Area of interest for modelling purposes centred at:

Latitude 38 degrees 39 minutes;
Longitude 146 degrees 20 minutes.

Eastings 441988;
Northings 5721837.

All coordinates are given in:
Longitude and Latitude: AGD66 (Australian Geodetic Datum 1966)
Eastings and Northings: AMG66 (Australian Map Grid 1966, zone 55)

Time span for regional scale run is the year 2000.

A standard nesting with horizontal grid spacings has been employed for the regional scale calculations:

Outer nesting	20 km
Middle nesting	8 km
Inner nesting	3 km

The inner nesting covers an area bounded by:
Eastings:- 383488 – 500488
Northings:- 5663336 – 5780336

TAPM[11] version 1.8 was used for the model run.

[11] Hurley, P.J. (1999) The Air Pollution Model (TAPM) Version 1: Technical Description and Examples, CSIRO Atmospheric Research Technical Paper No.43

A map of the vegetation type as seen by the regional scale model is provided in Figure 45. Note that the regional scale model actually utilises something rather more complex than this map as each of the broadly defined vegetation types are further subdivided according to vegetation height and density.

In Figure 46 the 3km and 8km nesting areas are shown superimposed on the topography (the topography also shows the appropriate resolution at each nesting level). At each nesting there are 40*40 grid points in the horizontal directions and 20 vertical grid points. The inner nesting therefore models a region of 120 km by 120 km.

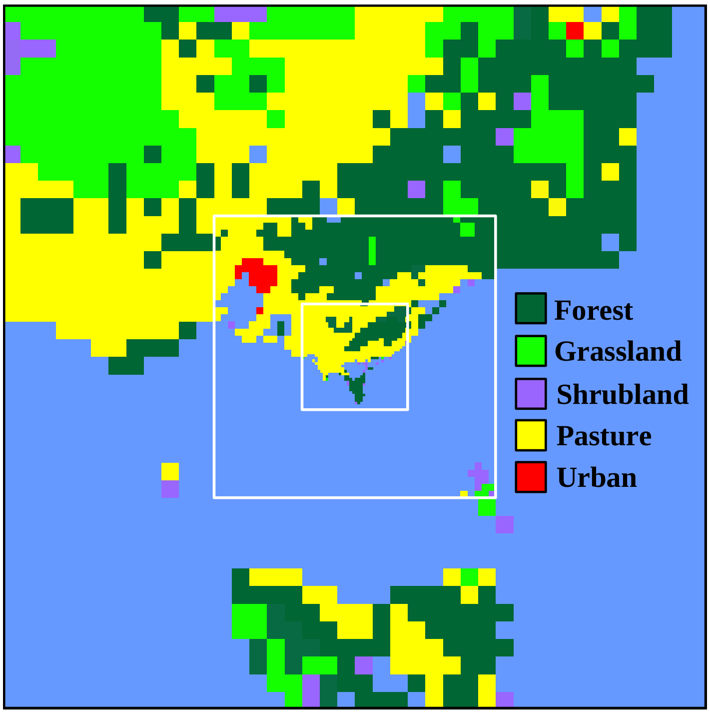

Figure 45 Vegetation as represented by regional scale model - 20km, 8km and 3km nesting arrangement

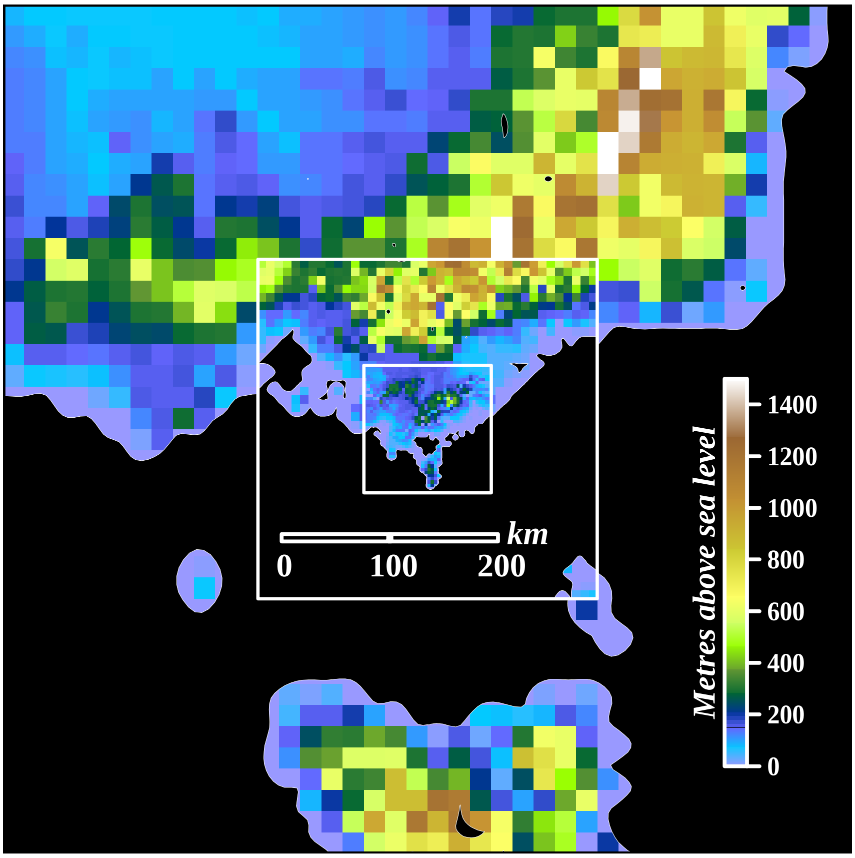

Figure 46 Regional scale topography as seen by regional scale model -20km, 8km and 3km nesting arrangement.

At each of the grid points within each of the three nesting resolutions, output from the regional scale model is obtained at hourly intervals. Wind statistics are compiled from this information at a suitable height. The chosen height for this application is 67 metres above ground level which is representative of the hub height of currently available turbines. Figure 47 shows the mean annual wind speed at 67m above ground level for all three of the nesting resolutions.

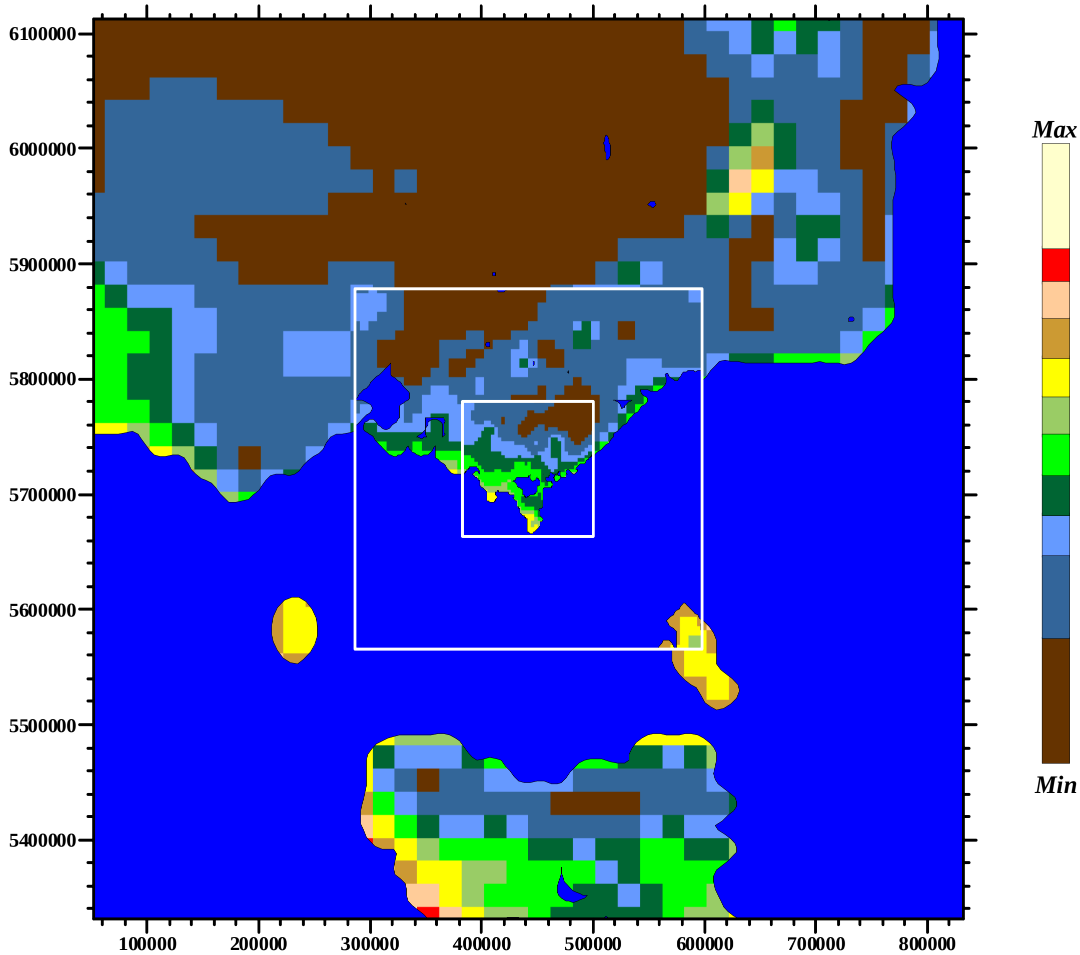

Figure 47 Mean annual wind speed at 67m above ground level. Predictions from regional scale model run for year 2000

11.4.2 Fine scale modelling

The Raptor model has been used for the fine scale modelling. The model uses a mixed spectral and finite difference formulation to calculate the linear topographic perturbation to a background wind flow[12] (See Ayotte and Taylor, 1995). As the model is linear, the slopes over which the model will reliably predict speedup/slowdown of the flow are limited to approximately 0.3 (17 degrees). For steeper slopes, model solutions become less accurate. Where slopes exceed this limit a linear model will tend to over-predict the speedup of the flow over the topography. For this reason the speedup has been limited to 30% (at a height of 67m) within the *WindScape* technology. This reduces the risk of over-predicting wind speeds in steep areas.

[12] Ayotte, K.W. & Taylor, P.A. (1995) A simple linear three-dimensional model of planetary boundary layer flow over topography, *Journal of Atmospheric Sciences*, **52**, 3523-3537.

The region covered by the fine scale modelling extends from: Eastings 360000 to 460000, Northings 5680000 to 5780000, an area 100km by 100km in size. Fine scale topographical maps covering this area were obtained from the Victorian company Geomatic Technologies in ArcInfo format. The topography was provided in a mixture of 1:25000 and 1:50000 scale 10 metre contour maps. These contour maps were combined and converted to a 100m grid map using the package ANUDEM. The topography, in 100m gridded form, is shown for the Foster region in Figure 3.

Output from the fine scale model is the value of speedup/slowdown at each grid point (100m resolution) for each of twelve sectors. These perturbations are then applied to the wind speed values obtained from the regional scale model interpolated to the 100m resolution fine scale model grid from the 3km regional scale model grid.

11.4.3 Predictions of wind resource

The *WindScape* system provides hourly estimates of wind speed at a chosen height above the surface. These estimates include the effects of regional scale variations in wind climate that arise from large scale surface features, for example the roughness change from sea to land, as well as the regional variation in weather patterns caused by atmospheric phenomena such as sea breezes, katabatic and anabatic winds. Superimposed upon this is the fine scale perturbation to the flow (speedup/slowdown) caused by smaller scale topographic features that have horizontal length scales from a few hundred metres to a few kilometres.

Statistical measures of the wind resource such as mean annual wind speed can be derived from these wind speeds. Maps of these statistical measures can be prepared giving a geographical distribution showing the fine detail of the wind resource over a broad area. The wind speed statistics at each point can be combined with the power curve of a chosen wind turbine to yield a map of the predicted annual turbine energy yield over the region. In addition, a number of overlays such as vegetation cover and prediction confidence can be used to further qualify the wind resource map. In the work presented here a vegetation overlay has been prepared.

The vegetation overlay is derived from the Bureau of Rural Sciences land cover analysis completed in 1995. This analysis is derived from satellite information and classifies the Australian landscape into several classes, including, plantation and native forest, pasture/crops, bare, urban, water, etc. at a resolution of roughly 200m. The overlay shades all areas that are not classified as pasture/crops or bare, and hence represents areas unsuitable for wind turbine placement.

11.5 Results

11.5.1 Regional scale results

Mean annual wind speed predictions from the inner (finest) grid of the regional scale model for the year 2000 are plotted in Figure 48. The decelerating effect of the land on the wind speeds can be clearly observed. The regional scale model results indicate that the most favourable wind speeds are likely to be found close to the coast particularly in the vicinity of Cape Liptrap. However, since there are substantial topographic features in this region the *WindScape* results are likely to show up wind hot-spots in far more detail.

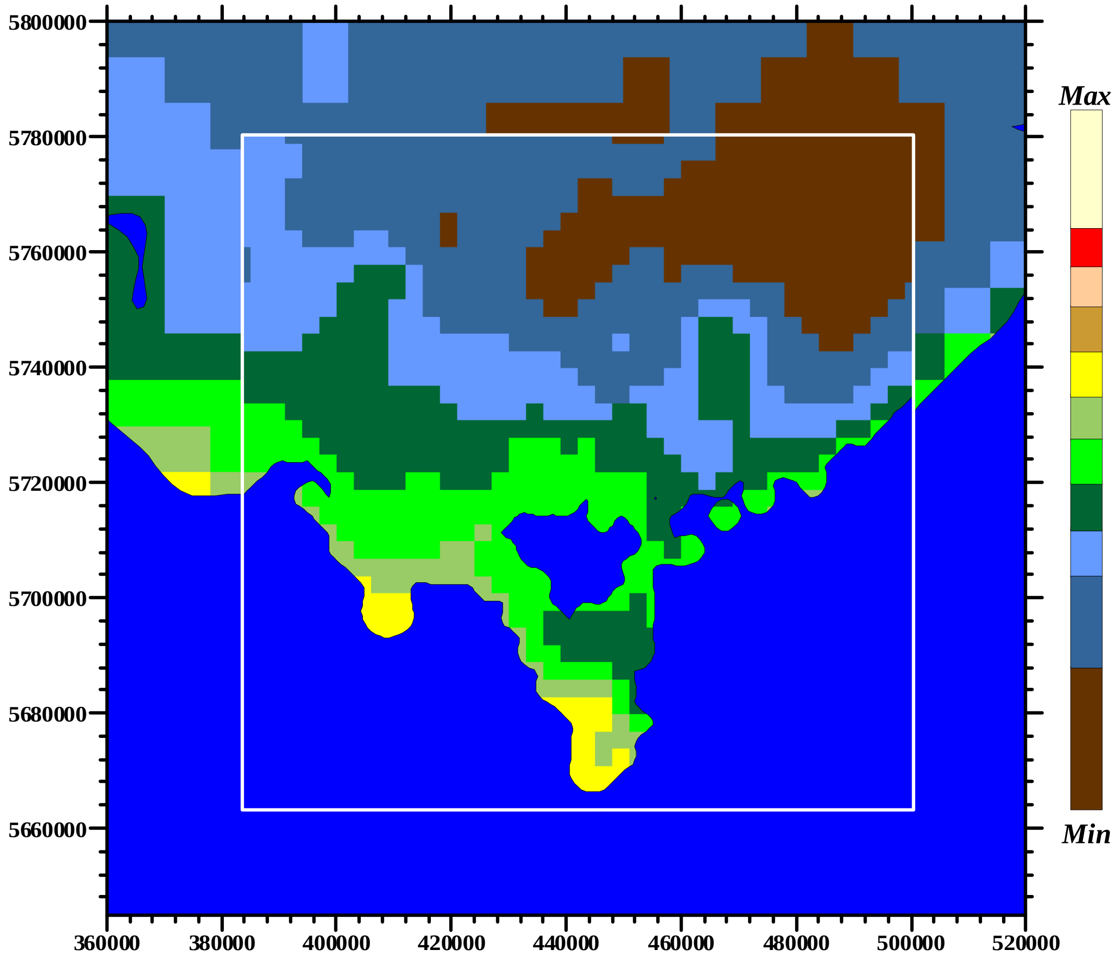

Figure 48 Mean annual wind speeds at 67m AGL from regional scale model over Foster region for the year 2000

11.5.2 Combined regional and fine scale predictions

WindScape predictions of the mean annual wind speed are given in Figure 49. There are two notable areas of high wind – Wilson's Promontory and Cape Liptrap. In Figure 50 the *WindScape* results are blanked of urban and forested areas. We note that significant portions of the windiest areas are forested or conservation areas and thus unsuitable for wind farm development. However there are numerous other smaller windy features which are worth investigating in more detail.

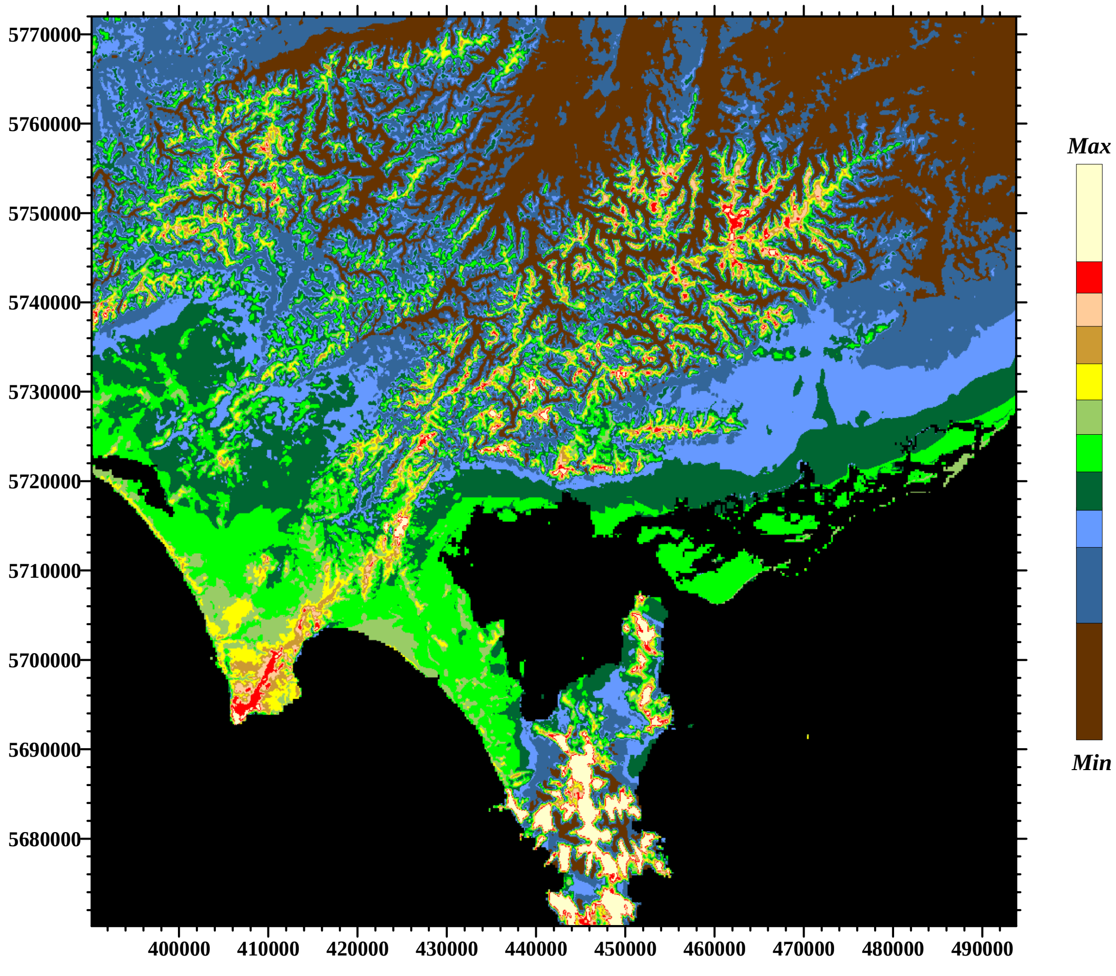

Figure 49 *WindScape* predictions of mean annual wind speed (m/s) across the Foster region for the year 2000 - 67m AGL

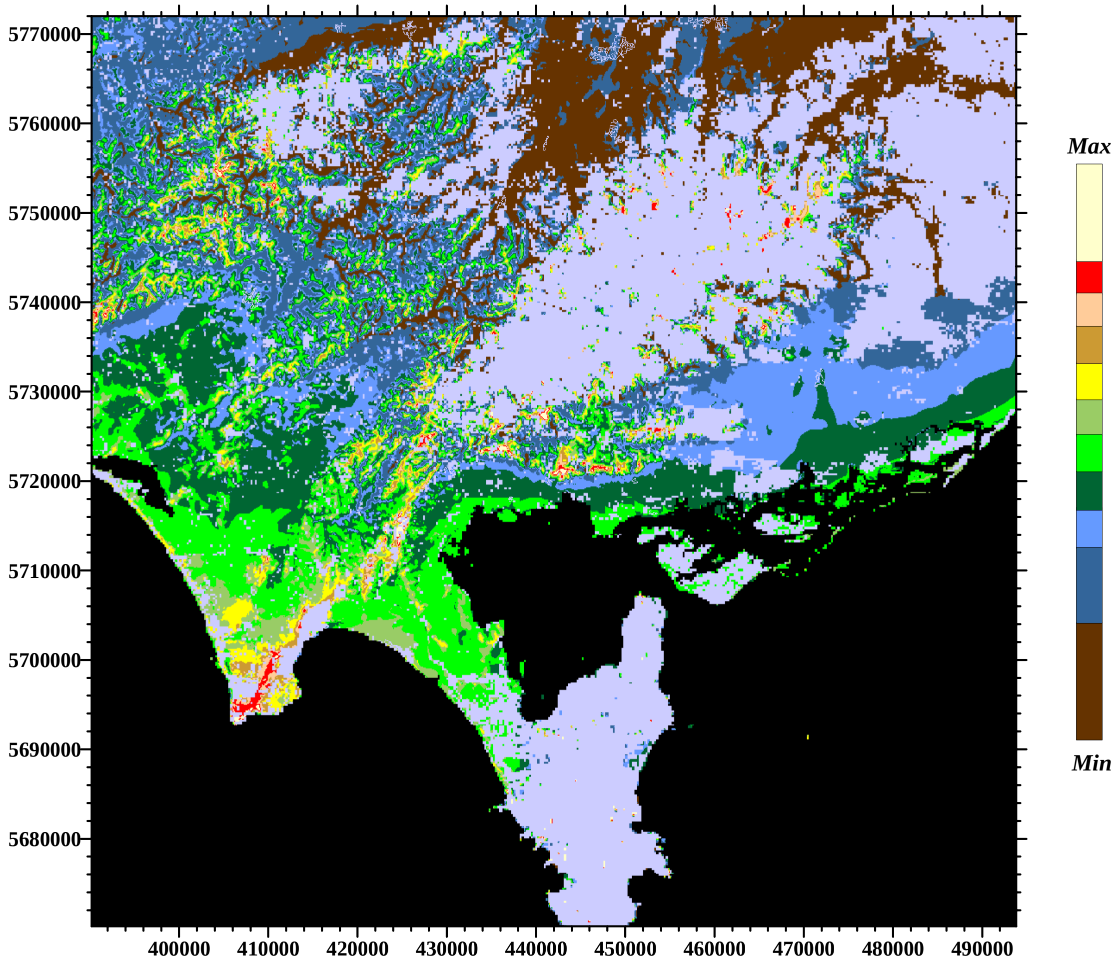

Figure 50 *WindScape* predictions of mean annual wind speed (m/s) at 67m AGL across the Foster region for the year September 2000 to August 2001. Including vegetation mask

Figure 51 indicates the areas for which enlargements of the mean annual wind speeds have been provided. While the areas selected generally cover the areas of highest wind speed they do not represent all areas in which wind farms could be potentially developed. Despite having lower annual average wind speeds, other areas may contain more viable sites when development and environmental constraints are taken into consideration. The enlargements are Figure 52- Cape Liptrap and Figure 53 – Mt Misery.

It is important to note at this point that the vegetation mask has been provided merely as a guide and each of the locations identified above would require a site visit to determine the true nature of the vegetation at and surrounding the potential site.

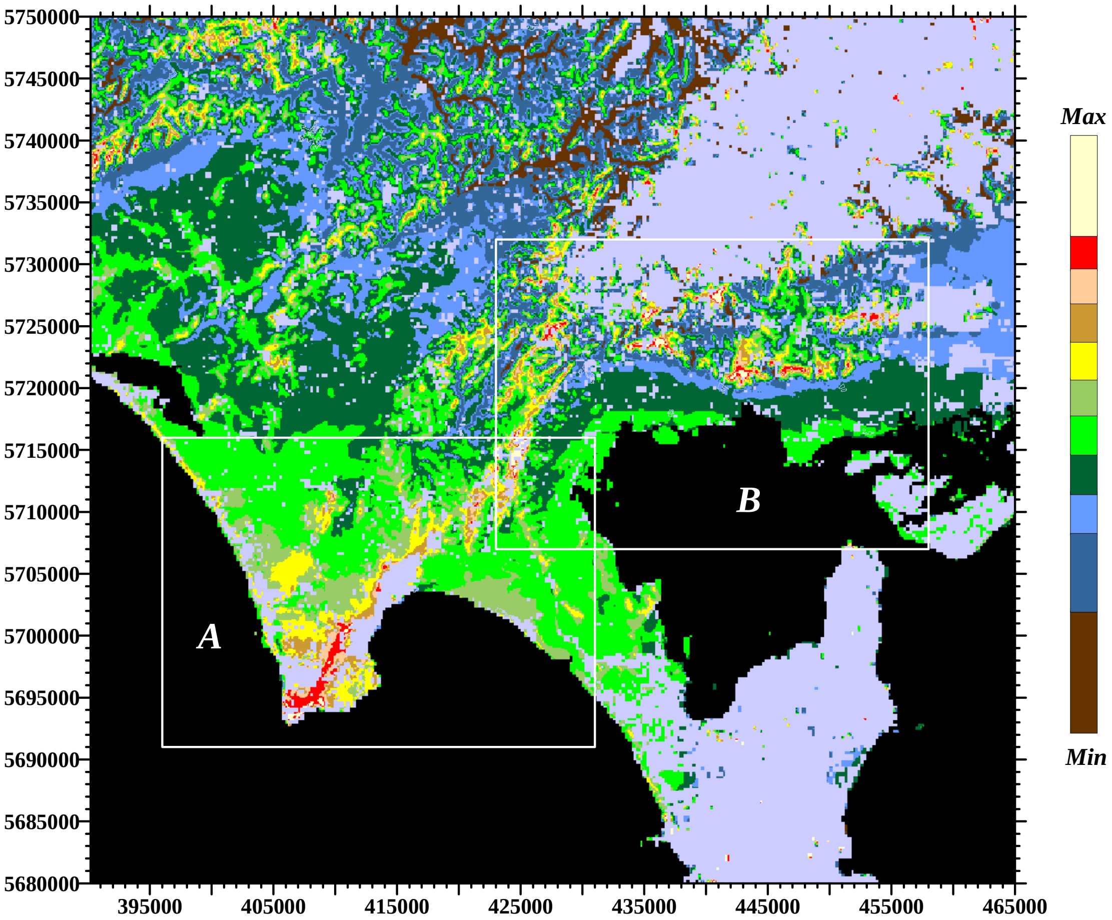

Figure 51 *WindScape* predictions of mean annual wind speed (m/s) at 67m AGL across the Foster region for the year 2000. Including vegetation mask and showing areas covered by enlargements in Figures 12 and 13

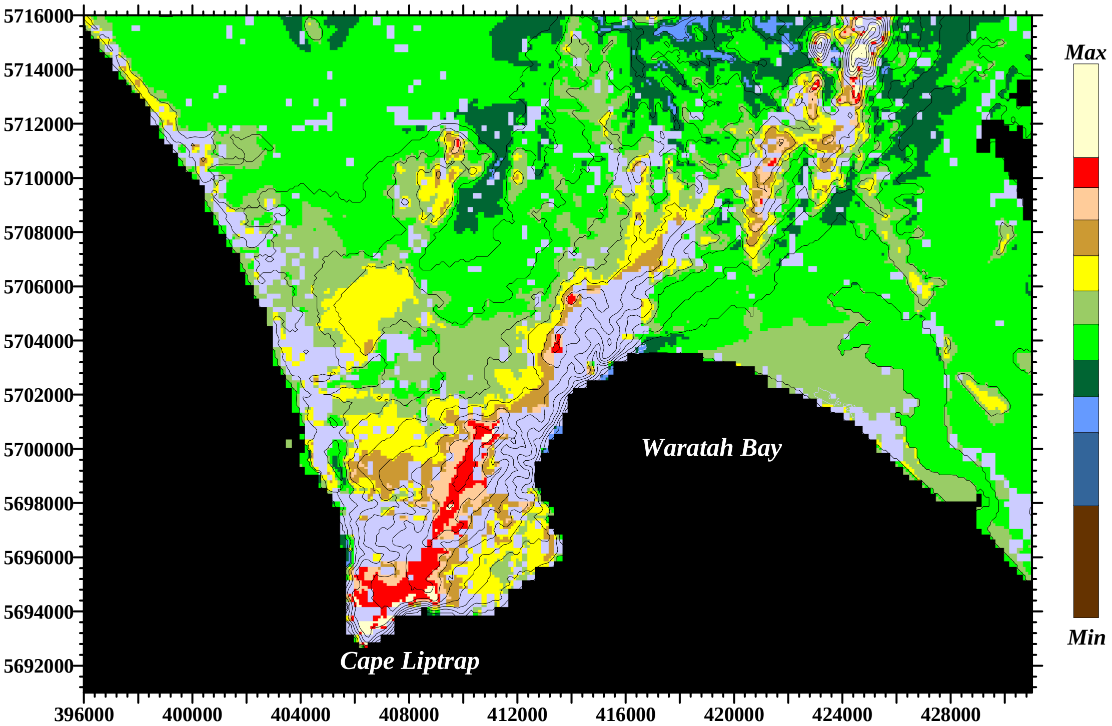

Figure 52 Enlarged view – Bass Hill. *WindScape* predictions of mean annual wind speed (m/s) at 67m AGL across the Foster region for the year 2000 with vegetation mask

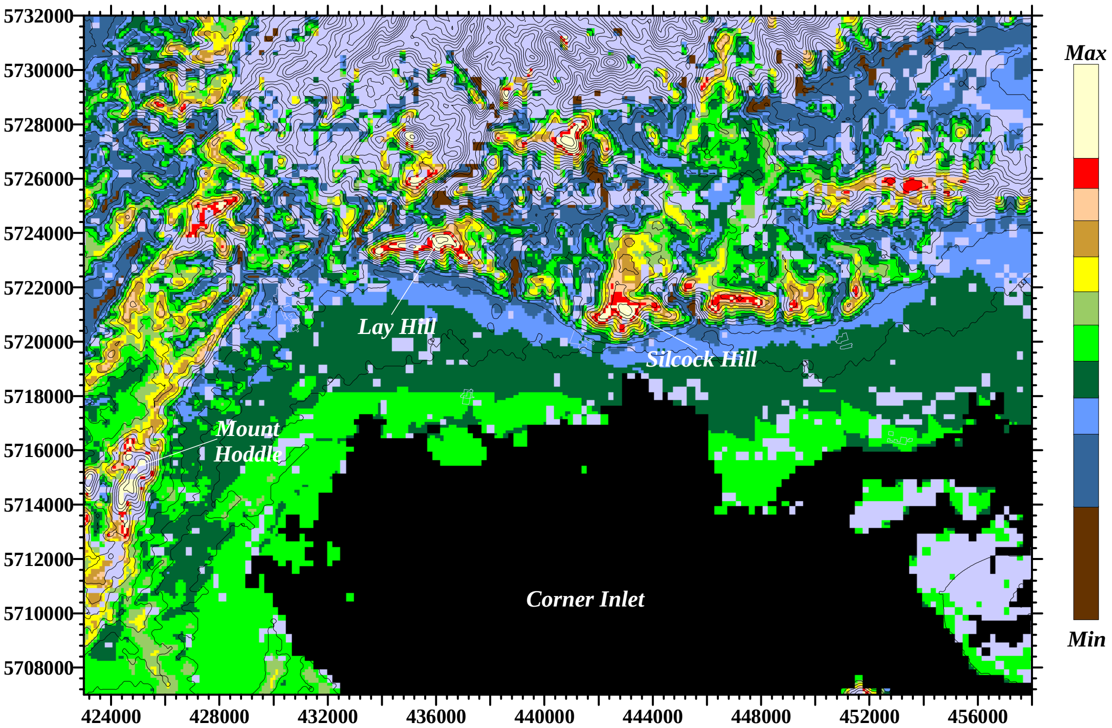

Figure 53 Enlarged view – Mount Misery. *WindScape* predictions of mean annual wind speed (m/s) at 67m AGL across the Foster region for the year 2000 with vegetation mask

11.5.3 *WindScape* predictions at monitoring towers

The *WindScape* predictions have been validated against tall tower data in the modelled region and found to be well within the stated accuracy of approximately ±10%. The exact details of the validation can not be revealed as the data sources are proprietary. There is a weather station at Latrobe Valley Airport which registers wind speeds and direction every 3 hours at 10m above ground level – although the data availability for the year of interest is only 85% a comparison has been made with the *WindScape* "virtual tower" output at this location. A long-term (10 year) wind measurement dataset is included in the comparison for interest.

In Figure 54the overall wind speed pdf is shown. Figure 55 shows the wind speed pdf segmented into North, South, East & West sectors. *WindScape* predicts an overall mean annual wind speed of 4.15m/s around 7% lower than the measured value of 4.48m/s.

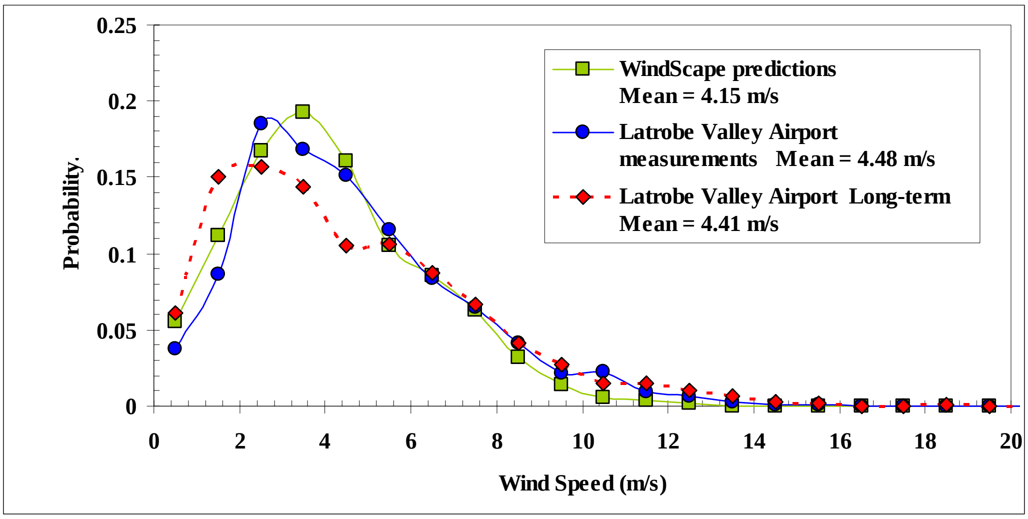

Figure 54 Wind speed probability distribution function (pdf) at Latrobe Valley Airport. Eastings 454037, Northings 5770806, Zone 55. 10 metres above ground level. Year 2001

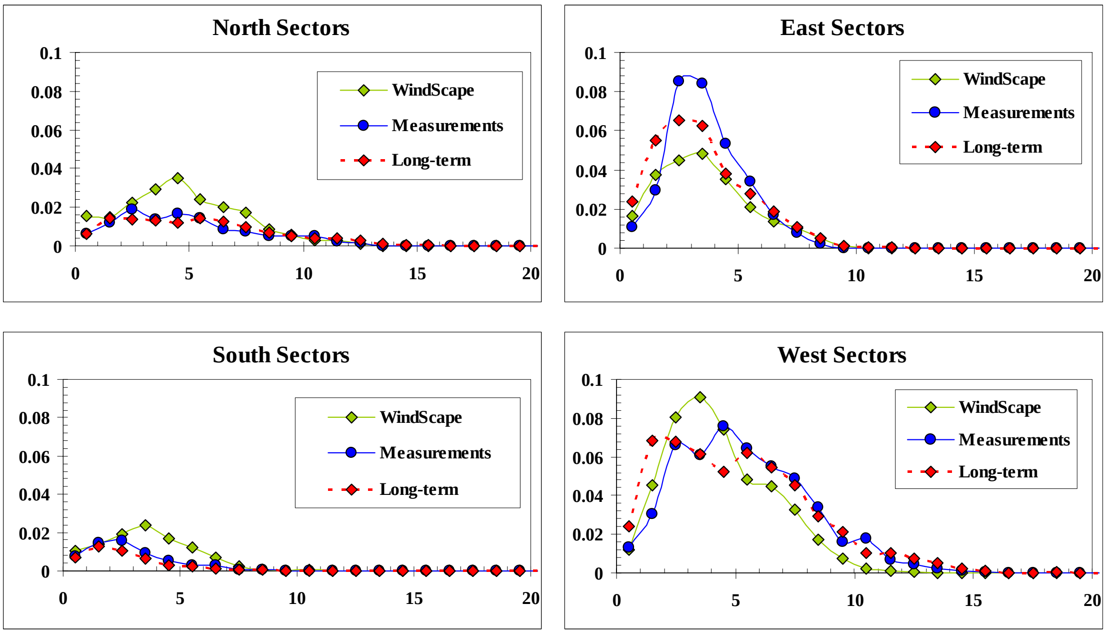

Figure 55 Wind speed probability distribution functions from North, South, East, West directions at Latrobe Valley Airport

The directional statistics, mean wind speed from each wind sector and mean wind speed by time of day are presented in Figure 56 (a), (b) and (c) respectively – a satisfactory agreement between *WindScape* and measurements is observed in all Figures.

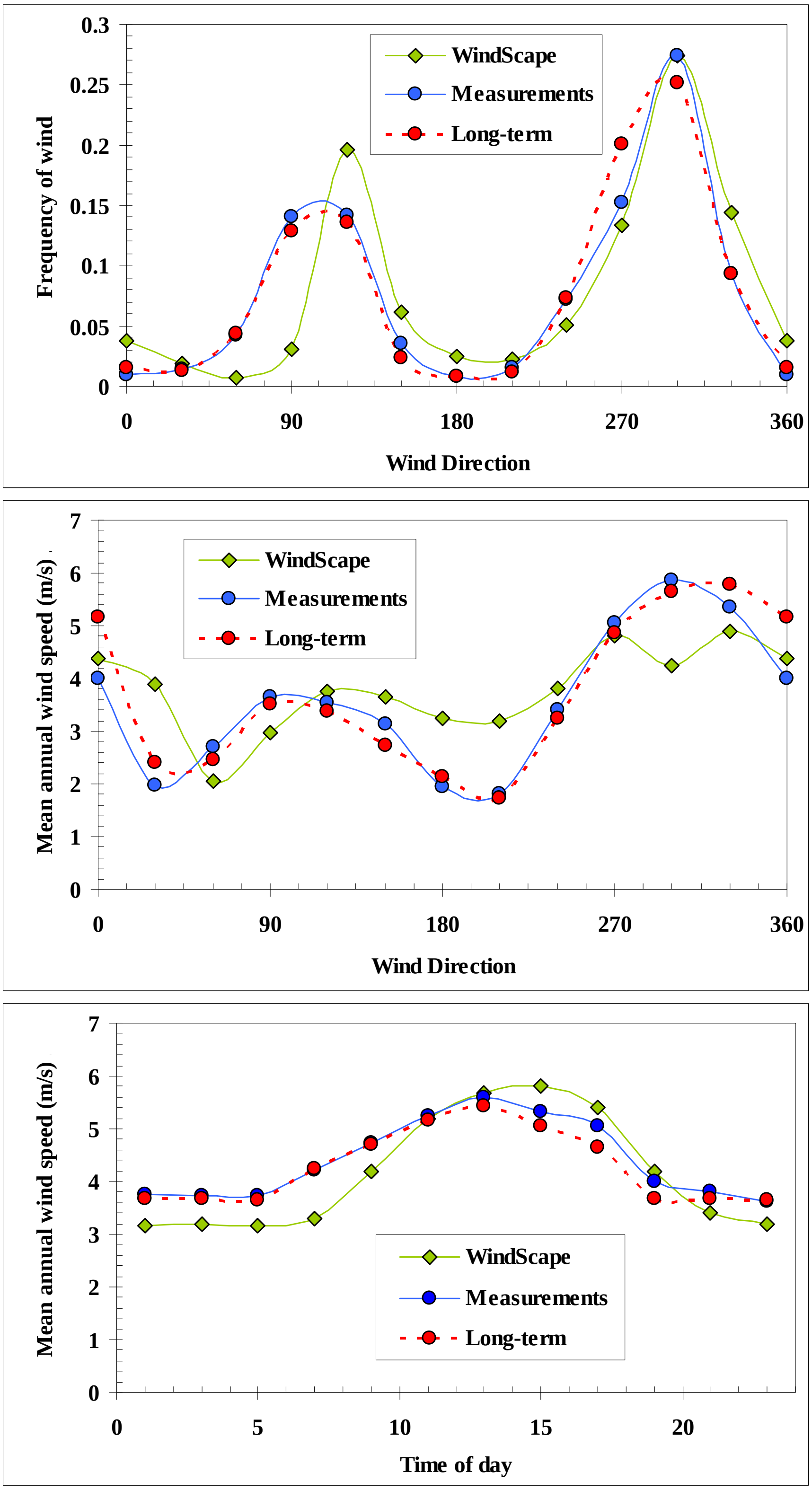

Figure 56 (a) Wind direction pdf, (b) Mean wind speed in each sector, (b) Mean wind speed by time-of-day at Latrobe Valley Airport

11.6 Concluding remarks

Work presented in this report represents the combined implementation of two recent developments in modelling technology. We expect the results given here to be of a high degree of accuracy. Where there is some question concerning the accuracy of the results, the uncertainties and the reasons for their existence have been noted.

A number of areas in which the wind resource appears promising for wind farm development have been identified. The WindScape results showed numerous hills and ridges within the bounds of the modelling domain to have annual average wind speeds in excess of 8.4m/s at 67m above the terrain. This translates into a wind turbine yield of approximately 3.0 GWh/annum per installed MW. The areas of highest yield are scattered across the region. The largest exposed area is found in the vicinity of Cape Liptrap. Numerous exposed and windy hills and ridges are found close to Silcock Hill. Further windy sites are located on hills and ridges north of Foster and on a feature that stretches eastwards from Moe.

Model validation was conducted at the weather station at Latrobe Valley Airport. The agreement between predictions and measurements was good with a 7% under-prediction of mean annual wind speed. The wind climatology as indicated by directional and wind speed probability distribution functions was modelled to a satisfactory degree.