ASSESSING WIND ENERGY POTENTIAL IN ANTARCTICA

“Assessing wind energy potential In Antarctica”-Marianna Imbimbo, student number:s061762
Danish Technical University, 2006-2008
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References
Introduction

The project consists of investigating the siting of wind turbine generators in the Antarctica area, with respect to energy yield, life time of wind turbines, impact on the scientific stations (radio disturbance, disturbance of the measurements), and environmental impact. The motivation of wind energy exploitation in Antarctica is to supply electric energy to the scientific stations located in Antarctica, as for instance Baia Terranova-Mario Zucchelli and Dome C Concordia, using renewable energy sources, in this case wind energy, in order to substitute the diesel generators which are in use nowadays.

The methodology of analysis is based on the accurate assessment of wind power potential, concerning the area of Antarctica, more in detail the area of Baia Terranova and Dome C, which is a non-conventional site. This is because the area analysed is a hostile climate site, in the sense that it makes the turbine operate in extreme conditions. These sites present:

1. air temperature $T_a < 0$ degree centigrade for large periods during the year;
2. complex terrain;
3. site elevation in some area;
4. extreme conditions (high turbulence, extreme gusts, extreme wind speed);
5. A systematic analysis of Antarctica can be made grouping the characters of the site as follows:

1. GROUP 1 Micro-climate factors:
   - Temperature distribution;
   - Three dimensional wind speed distribution;
   - Air liquid content distribution;
   - Icing and snowing probability;

2. GROUP 2 Landscape Factors
   - Territory utilisation;
   - Morphological and geological characteristics;
   - Elevation;

3. GROUP 3 Logistic
   - Distance from the electric grid
   - Access to road

For siting of Antarctica and yield estimation, the following information is available:

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1. Time series of wind speed and wind direction (hourly), measured from only one mast for each scientific station present in the Italian base of Antarctica. The time series goes from 1987 to 2006, and the number of the scientific stations present is 16.

2. Temperature and humidity time series, in order to estimate ice accretion;

3. Maximum winds or gustiness.

4. Orographic maps of the area, for use in WAsP engineering

Antarctica is a continent with 98% of its area covered with snow and ice. The Antarctic continent reflects most of the sun's light rather than absorbing it (high albedo). The extreme dryness of the air causes any heat that is radiated back into the atmosphere to be lost instead of being absorbed by the water vapour in the atmosphere.

Antarctic winds are strongly influenced by the ice covering the surface and topography. The unwavering directional constancy on the surface winds observed at many Antarctic stations suggests that topography plays an important role in governing the local wind field. The surface wind pattern is primarily driven by a long-wave radiative cooling of the continental snow surface. This cools down the overlying atmospheric surface layer and induces a downslope pressure gradient force, for example the katabatic force, these katabatic winds which flow down the slopes of the Antarctic ice sheet, and can reach in the coastal areas very high wind speeds.

Surface winds over Antarctica are driven both by katabatic and synoptic-scale forcing mechanisms.

It is estimated that the surface flow is primarily katabatic ~40%–50% of the time, but it “appears” katabatic ~60%–70% of the time. This work on katabatic winds has been done in Coats Land where the katabatic flow has been proven to be relatively shallow, leading to strong vertical shear with consequences on turbine lifetime. Katabatic winds tend to last for ten or hundred hours, with a short interruption before a shift to non-katabatic winds.

In the Antarctic area the wind speed distribution are not close to the Gaussian but they are approximated by the two parameters Weibull distributions (e.g. Justus et al.1978, Pavia and O’Brien, 1986). The distribution suggests many periods of calm and low wind speeds, interrupted by strong wind events, due to the passage of low pressure system. For what concerning the wind measured at the Italian stations, the wind speeds at Dome C are very light compared with other inland stations. The mean value is around 3ms-1 with no
important annual cycle, while all slope stations show constancy in the wind direction, due to the downslope gravitational flow. Only at Dome C where gravitational flow cannot take place, there is a large variation in wind direction observations.

The Antarctic raw data will be analysed with the software called WAsP and WAsP Engineering which are meteorological models used to calculate the regional wind climatologies from the raw data.

The application of wind speed statistics to wind energy resource calculations in a region requires methods for the transformation of the wind speed statistics resulting in a comprehensive set of models for the extrapolation of meteorological data and estimation of wind resources.

WAsP (Wind Data Analysis and Application Program) and WAsP Eng2
WAsP is a program characterized by these features:
- hills treated as first order perturbation
- first order closure
- varying surface roughness
- shelter effects of obstacles

WAsP eng. is a program to support load calculations on wind turbines. Such as:
- turbulence
- wind shear and profiles
- extreme wind climatologies

Extreme wind climate files are based on reduced geostrophic winds. The reduced geostrophic wind is the wind speed at 10 m above the ground level, in an ideal homogeneous terrain.

The present work is divided in four chapters:

In the first chapter the pristine Antarctic environment has been described, in order to understand the morphology and characteristic of the territory in which the scientific Italian bases are located. The main part of the first chapter is the calculation of the snow roughness at Terra Nova bay. The data have been acquired from two sonic anemometers located in Terra Nova Bay, during two consecutive summer expedition occurred in 1995-96 and 1999-2000.
The second chapter provides an overview of the scientific community who work in the two Italian bases in Antarctica and the legal, environmental and operational parameters that apply to their activities. The overview indicates that several possible motivations which subsists for the Antarctic communities to incentive and promote more sustainable energy solutions than the fossil fuels that are currently present. Moreover a description of the meteorological data for the wind energy resource analysis has been carried out.

Chapter 3 describes the methodology of the wind resource analysis for the two Italian scientific stations, based on two standards programs WAsP and WAsP Engineering2, considering their limitation in the extreme environment.

Chapter 4 summarises the environmental monitoring activities that have been conducted in Antarctica during recent years. It aims to demonstrate the existing level of Antarctic monitoring, to increase awareness of monitoring activities. The environmental impact assessment in Antarctica for the introduction of wind turbines in the two Italian bases, has been carried out according to the principle of the PROTOCOL ON ENVIRONMENTAL PROTECTION TO THE ANTARCTIC TREATY, which states that activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependent and associated ecosystems.
Chapter 1: The Antarctic Environment

1.1 Site description

Antarctica is the fifth largest of the seven continents of the Planet. It is a region of extreme features – the coldest, driest, windiest, highest, and most remote continent on Earth (Coldest Temp: -89°C / -129°F (Recorded at Vostok) Highest Altitude: Antarctic has the highest mean Altitude (2500m). Windiest: 375km/h recorded at D'Urville. Iciest: Antarctica has over 90% of the planets ice).

Figure 1.1.1 Antarctica, with cutaway showing ice sheet and bedrock. Source: http://www.nsf.gov/pubs/1997/antpanel/3enviro.htm

Antarctica is situated over the South Pole almost entirely south of latitude 66°30' S (the Antarctic Circle). It has a very rough circular shape with the long arm of the Antarctic Peninsula stretching towards South America. There are two large indentations, the Ross and Weddell seas and their ice shelves.

Antarctica is characterized by two major, geologically distinct parts bridged by a vast ice sheet (see figure 1.1.1).

East Antarctica, the larger of the two, is composed of a continental crust covered by an ice sheet that averages 2.6 km thick. Rock exposures are limited to coastal regions and to alpine elevations in the 3218-km long Trans-Antarctic Mountains. West Antarctica, the smaller portion, is constituted by small blocks of continental crust covered by the West Antarctic Ice Sheet, similar to a mountain chain forming the Antarctic Peninsula. Most of the West Antarctic Ice Sheet is grounded below sea level, in places over around 2.4 km below sea level.

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The Antarctic continent is a dome of ice, with a high plateau in its interior of 4000 m elevation, and sloping towards its perimeter at sea level. Over the ice sheet of Antarctica the snow surface is highly reflective for shortwave radiation, while it loses heat in the form of longwave radiation to the cold and clear overlying atmosphere. As results, the surface is generally colder than the air, for most of the year. This leads to a development of a strong inversion conditions which are persistent and can be seen over nearly the entire continent for much of the year. Over the coastal slopes of the ice sheet, cooling of near-surface air forces strong and persistent katabatic winds. These winds provide the shear necessary to maintain turbulence exchange in the very stable stratified surface layer, especially in winter (see figure 1.1.3).
For the reason described above, the gravity flow dominates the surface wind regime of Antarctica, which has an enormous influence on the climate of the entire continent; Parish and Bromwich (1987) indicate the presence of confluence zones of katabatic winds in regions above the major glacier valleys in the Transantarctic Mountains as well as the Siple Coast of West Antarctica. The confluence zones are locations of enhanced katabatic winds due to the pattern of the underlying topography of the Antarctic plateau. The dominance of this pattern implies that the surface flow plays an important role in the tropospheric circulation of the Southern Hemisphere, as well as the climate system.

In fact there is a formation of a tropospheric convergence which generates cyclonic vorticity via conservation of angular momentum, which has a key role in centering the circumpolar vortex over the crest of East Antarctica [James, 1989, Parish and Bromwich 1991].

As air flows away from the summit of the ice sheet, it converges into a limited number of “confluence zones” (see figure 1.1.3). In these zones, very strong winds have been observed. The observations show that katabatic winds, which are driven by the katabatic force, derived from a downslope pressure gradient force, are not constant in strength all
over the entire year. In fact, because in summertime the radiation balance is not one constant radiative cooling, in this period of the year katabatic force is often small or not existing, but this is not valid for the wind direction. This is due to the adjustment of the synoptic pressure distribution to the Antarctic topography, which causes a high degree of directional constancy in the surface wind field. [A. Renfrew, P. Anderson, 2002]. The directional constancy of the katabatic wind, which originates on the interior plateau of Antarctica, is, anyway, closely related to the direction of the slope of the terrain; when the gravity driven flow arrives at the coastal escarpment, there is an increase in the intensity of the wind velocity, which can reach 250 km/h.

Figure 1.1.4 Cross sections at time t=24 hours of (a) Potential temperature; (b) wind component u. Source: I. Renfrew “The dynamics of idealized katabatic flow over a moderate slope ice” British Antarctic Survey, 2003

Figure 1.1.5 sections at time t=24 hours of (c) wind component v; (d) turbulent kinetic energy TKE. Source: I. Renfrew “The dynamics of idealized katabatic flow over a moderate slope ice” British Antarctic Survey, 2003

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According to the study done by I. Renfrew of the British Antarctic Survey, on “The Dynamics of idealized katabatic winds over a moderate slope and ice shelf”, in which a non-hydrostatic numerical weather prediction model has been used to simulate katabatic winds over Antarctica, the potential temperature profile of a katabatic wind show the development of a strongly stable surface layer, which is formed as a result of downward sensible-heat flux into the snow surface. This leads to a development of a well defined jet in u, fading in 36 hours.

Figure 1.1.4 and figure 1.1.5 show an example of the potential temperature, the downslope velocity, the cross slope velocity, and the turbulent kinetic energy (TKE) of a katabatic flow after 24 hours of model simulation.

The model shows that after the 24 hours simulation, there is a formation of a strongly stable surface layer, due to the strong surface cooling, while in the first 12 hours there is a formation of a shallow katabatic flow. Also the presence of the slope generates a buoyancy force, which can be identified with the katabatic force, and the development of a shallow downslope flow. From the model it can be seen that the katabatic flow goes from the crest of the slope to the foot of the slope, with a layer depth around 100m height. Also, from the model, it is seen that there is a positive v component due to the Coriolis force, and the strongest cross-slope winds are collocated with the strongest downslope winds.

1.2 Antarctic Boundary Layer

Generally speaking, the atmospheric boundary layer is classified in:

1. Convective (potential temperature decreasing with increasing height above the ground)
2. Neutral (potential temperature constant with height)
3. Stable (potential temperature increasing with height)

For what concerning the case of The Stable Boundary Layer, it is considered as steady state, when the turbulent fluxes are stationary. Furthermore, the atmosphere is assumed as dry and the divergence of radiation fluxes is neglected in the energy equation in the boundary layer. Both assumptions are confirmed in the Antarctic atmosphere as a consequence of the low temperature and the high longwave emissivity of ice and snow surfaces (Garratt and Brost, 1981).

The stable boundary layer can be classified in weakly stable boundary layer and strongly stable boundary layer (Mahrt 1998). The weakly stable case forms when the “Assessing wind energy potential In Antarctica”-Marianna Imbimbo, student number:s061762

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sensible heat flux increases with stability. A sudden increase in stratification leads to a larger heat flux, opposing the increased stratification (negative feedback). This kind of SBL has the shape of the nocturnal boundary layer.

In the strongly stable case, there is an increase in stratification which leads to a reduction of the sensible heat flux and therefore intensifying the increased stratification (positive feedback). This may lead to a collapse of turbulence so that the actual SBL decouples from the surface.

For the case of Antarctica, we talk about the strongly or very stable boundary layer, due to the fact that a ubiquitous feature of very stable boundary layer is the presence of katabatic flow. In fact katabatic winds are formed when air, closed to a sloping surface, is cooled compared with the surrounding atmosphere. The difference in temperature, between the surface and the adjacent air can be large enough to sustain continuously the katabatic flow. Also it generates buoyancy forces, because of the sloping surface, act along the slope.

A simple description of glacier wind (or katabatic winds), is the Prandtl model for the gravity driven flow, down a cooled sloping surface. Probably the Prandtl model is the best model for studying simple katabatic flows. Hence the Prandtl model is a tempting way of treating long cool sub polar slopes that generates katabatic flows in the strongly stable atmospheric boundary layer.

The model equates divergence of the turbulent fluxes of momentum and heat to the advected background temperature lapse rate and the buoyancy acceleration:
\[ \frac{\partial \theta}{\partial t} = -\gamma \sin(\alpha) - \frac{\partial (\overline{w'\theta'})}{\partial z} \]  

\[ \frac{\partial u}{\partial t} = g \frac{\theta}{\theta_0} \sin(\alpha) - \frac{\partial (\overline{w'u'})}{\partial z} \]  

Where, according the parameterization to the K-theory

\[ \overline{w'\theta'} = -K_h \frac{\partial \theta}{\partial z}, \overline{w'u'} = -K_h Pr \frac{\partial u}{\partial z} \]  

Pr is the Prandtl number and it is equal to Pr=Km/Kh, where Km is the eddy diffusivity for momentum, and Kh is the eddy diffusivity for heat. Considering steady conditions and considering Kh and Pr as constants, the resulting governing equation is:

\[ \frac{\partial^2 \theta}{\partial z^2} + N^2 \frac{\sin^2(\alpha)}{Pr K_h^2} \theta = 0; N = \sqrt{\frac{g\gamma}{\theta_0}} \]  

It is assumed that in the coordinate systems, the x-axis is aligned with the slope. In the previous equations, \( \theta \) is the potential temperature perturbation and \( \theta_0 \) is a reference temperature, which in this case is the temperature of the melting point of ice, \( \gamma \) is the background potential temperature lapse rate, \( g \) is the gravity force, \( z \) is the vertical coordinate, perpendicular to the slope is the slope of the surface and \( \overline{w'\theta'} \) and \( \overline{w'u'} \) are turbulent heat and momentum fluxes parameterized.
The solution to equation 4 is:

\[ u = -C\mu e^{\lambda z} \sin(\lambda z) \]  

\[ \theta = C e^{\lambda z} \cos(\lambda z) \]

with

\[ \mu = \sqrt{\frac{g}{\theta_0 \Pr \gamma}} \lambda = \sqrt{\frac{g\lambda \sin^2(\alpha)}{4 \Pr \theta_0 K^2}} \]

Figure 1.2.1 shows a Prandtl model profiles for katabatic boundary layer.

Figure 1.2.1 Numerical solution for the Prandtl model (a) \( \theta_{tot} = \theta + \gamma z \), (b) \( U \) and (c) \( V \). Here \( f = 1.1 \times 10^{-4} \) s\(^{-1} \); other parameters are \((\alpha, \gamma, K, \Pr, C) = (-4^\circ, 4 \times 10^{-3} \) K m\(^{-1}, 1.1 \) m\(^2\) s\(^{-1}, 1.1, -8 \) K). Solutions are displayed at \( t = T = 2.1 \) h (solid) and \( t = 4T \) (dashed). The numerical model top is at 2000 m. Source: Royal Meteorological Society- Q. J. R. Meteorol. Soc. 133: 101–106 (2007) DOI: 10.1002/qj

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An important aspect of the katabatic flow is the presence of a low level jet. The term “low-level jet” has been used in a variety of contexts in atmospheric literature (Bonner 1968; Uccellini and Johnson 1977; Li and Chen 1998). The LLJ is defined as a jet stream that is typically found in the lower 2 – 3 km of the troposphere. A jet stream is defined as relatively strong winds concentrated within a narrow stream in the atmosphere.

The formation of the low level jet is a dynamic response in the lower boundary layer to surface cooling this means that although friction acts on the surface, generating shear stress, the turbulence production is not originated mainly by the surface, but it is strongly influenced by the jet.

The low level jet can be found both in the weakly stable boundary layer (for ex. nocturnal boundary layer) and in the very stable boundary layer. It is characterized by an increase of the wind speed which can be seen in the formation of the typical” nose” of the wind profile component u (figure1.2.1-(b)).

Concerning the Antarctic continent, there are three prominent low-level jet (LLJ) features [M.Seefieldt-J.Cassano, 2008] on the Ross Ice Shelf Region: the largest and the most dominant Low Level jet are along the Transantarctic Mountain, by the Siple coast, and the southern end of the Ross Ice Shelf, the second extends from the base of Byrd Glacier and curves to the north, passing by the eastern extremes of Ross Island, the third LLJ extends from the base of Reeves glacier and curves to the north across the western Ross Sea. An important issue is that a strong seasonability has been found in frequency and intensity of the low level jet, with the highest value of wind speed and size of the LLJ at the maximum during winter and spring month, katabatic forcing, in fact, is related to the strength of the inversion on the polar plateau and it is strongest during the long polar night during the winter months. The temperature contrasts between continental interior and the southern ocean are strongest during the winter months. The summer months are characterized by a minimal minimal katabatic activity due to the limited net radiational cooling on the plateau.

The observations indicated the presence of a low-level jet (LLJ) approximately 200 m above ground level with increasing intensity towards the Transantarctic Mountains.

The Siple LLJ is located at 84°S 110°W to 82°S 170°E. The LLJ of this region is driven by a synoptic force and it could also merge with an additional high wind region along the Western Ross Ice Shelf, and with the Byrd LLJ. The Siple LLJ presents a constant feature through all over the year, with a small seasonability.
The maxima are present in areas characterized by a relatively steep topography. The Byrd LLJ extends to the Byrd Glacier to the northeast and then curves to the north. Flowing to the north it passes to the eastern extremes of the complex terrain of the Ross Ice Shelf. The LLJ of this region is a combination of air flow extending from Byrd Glacier and from the southern Ross Ice Shelf; and then curves around the area of northwest of Byrd Glacier. Due to the presence of a strong inversion indicated in the source region of the LLJ [Mark W. Seefeldt John J. Cassano, March 2008], there is a large katabatic component of the wind blowing towards Byrd Glacier.

The Reeves LLJ is more dependent on the flow down the Reeves Glacier, as strong synoptic forcing makes the narrow stream of air from the base of Reeves Glacier less dependent.

In conclusion it can be said that the LLJ of the three different regions show seasonal frequencies. This can provide events which are comparable to the extreme conditions often seen during the long polar winter.

1.3 Antarctic Roughness Surface Analysis

The Antarctic ice sheet is the major heat sink in the climatic system of the continent. The surface energy balance can be written according to the following equation:

\[ M = \text{SHW}_\downarrow + \text{SHW}_\uparrow + \text{LW}_\downarrow + \text{LW}_\uparrow + \text{SHF} + \text{LHF} + G = \text{Rnet} + \text{SHF} + \text{LHF} + G \]

In the equation above, M is the melting energy, \( \text{SHW}_\downarrow \) and \( \text{SHW}_\uparrow \) are the incoming and emitted shortwave radiation fluxes, \( \text{LW}_\downarrow \) and \( \text{LW}_\uparrow \) are incoming and emitted longwave radiation fluxes, SHF and LHF are the turbulent fluxes of sensible and latent heat, and G is the subsurface conductive heat flux.

Because of the high reflectivity property of the Antarctic snow surface for shortwave radiation (called Albedo), the surface is generally colder than the air above, making SHF positive, and at the same time LHF small, because low temperatures limit the absolute moisture content of the atmosphere.

The surface turbulent flux SHF is equal to
in which \( \rho \) is the air density, \( c_p \) is the heat capacity of dry air at a constant pressure, and \( w' \) and \( \theta' \) are the turbulent fluctuations of vertical velocity and potential temperature and \( u_* \) and \( \theta_* \) are the associated turbulent scales. One important parameter which determines the magnitude of SHF is the roughness length \( z_0 \).

The aerodynamic roughness height, \( z_0 \), is defined as the height where the wind speed becomes zero, and it is measured in meters[Stull, Boundary Layer Meteorology]. The surface roughness length for momentum, \( z_o \), is determined mainly by roughness element shape and distribution since momentum is most efficiently transferred to the surface through pressure fluctuation gradients across roughness elements, the so called ‘form drag’.

The roughness of a surface describes the surface sink strength for momentum as the integrated result of turbulent drag caused by many obstacles, from small to large, and is defined for neutral thermal stratification.

To estimate the mean wind speed as a function of height above the ground level, the roughness length, and the friction velocity are relevant quantities.

The logarithmic relationship between these variables is given in the following equation:

\[
U = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) \quad \text{eq 7}
\]

Where \( k \) is the Von Karman constant, equal to 0.4.

In non neutral conditions, like the case of Antarctica, the buoyancy parameters and the surface heat flux are relevant variables.

When considering stable boundary layer it is necessary to insert a stable correction to equation 7, as written below:

\[
U = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) + \Psi_M \left( \frac{z}{L} \right) \quad \text{eq 8}
\]

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In equation 8, $\Psi_M$ is a function given for stable conditions, $\Psi_M(z/L)=4.7z/L$ [Stull, Boundary Layer Meteorology].

$L$ is the Monin-Obukhov length which is given by the following expression

$$L = \frac{-u_* \bar{\theta}_v}{g \left( \frac{T_w}{\theta_v} \right) \sqrt{\frac{w'T'}{T}}} \quad \text{eq 9}$$

With $g$ the gravitational acceleration, $\bar{\theta}_v$ the virtual potential temperature, and $w'T'$ the virtual heat or buoyancy flux. The length scale $z_0$ scales the total magnitude of shear forces acting on the rough surface. For stable conditions, the dimensionless relation $z/L$ is always positive ($z/L > 0$).

The roughness length for the Antarctic ice sheet can be determined from the logarithmic wind profile, using the following expression:

$$z_0 = \frac{z}{\exp\left(\frac{ku}{u_*}\right)} \quad \text{eq 10}$$
1.3.1 Data acquisition and experimental set up for the roughness analysis

In order to calculate the Antarctic surface roughness, data from onshore measurements, which were collected during three Antarctic summer campaigns, have been used for the analysis.

The first two campaigns were carried out at one location in Hells Gate during two consecutive summers 1995 and 1995-1996. And a third experiment was carried out in the austral summer 1999-2000. (Sempreviva and Lavagnini).

Four meteorological stations were positioned along the direction of the katabatic flow: one station upwind, one above, and two stations downwind the Inexpressible Island. (See figure 1.3.1).

![Figure 1.3.1: Italian base at Terra Nova Bay. Experimental set-up. Source: Sempreviva A.M.I, Lavagnini A. I, Transerici C. and Tagliazzucca M.](image-url)
The data consist in turbulence statistics of the flow under different wind regimes from the first two intensive Antarctic summer campaigns, over the whole range of wind speed, and focus on the high wind regime. Data from the third campaign to compare turbulence statistics, especially heat fluxes during katabatic wind episodes in the four locations.
Data were collected during January-February 1995 and November 1995-January 1996. In this period, time series of wind speed components, temperature and vertical temperature gradients were recorded at one mast in the middle of Hells Gate, 5 km inland from the line of the continental ice, for a total of 73 days.

During the first campaign of 18 day duration, from 20 January 1995 to 9 February 1995, [12] (Sempreviva and Lavagnini, 1997), the following instruments were used:

1.4 An omni-directional Gill sonic anemometer at 10 m to measure fluctuations of wind speed components u, v, w and virtual temperature T at 20 Hz sampling rate.
1.5 Absolute temperature sensor at 10 m connected with its own acquisition system at 1 Hz sampling rate.
1.6 A thermocouple to measure temperature difference ΔT between 10 m and 2 m at 1 Hz sampling rate.

During the second campaign of 57 day duration, from 15 November 1995 to 10 January 1996 (Lavagnini and Sempreviva, 1998), have been used the same set-up as the previous campaign with a different sensor for the absolute temperature and collected the data using one acquisition system. Data were corrected online, and the time series were screened for data spikes, and de-trended before calculating thirty-minute averaged statistics of turbulence parameters such as variance and covariance (i.e. friction velocity u- and mean turbulent virtual kinematic heat flux $w'\overline{T'}$).

The third campaign was carried out from 12 November 1999 to 19 January 2000 (Bortoli et al. 2000) using four meteorological stations.

The first was located over the flat ice surface of the Nansen Ice Sheet, 4 km upstream Inexpressible Island at a distance of 19 km from the Reeves glaciers slope break. The second station was installed at about 315 m a.s.l. on the Inexpressive Island (INX). The third station was installed at Hells Gate (HGW) at a distance of 1.2 km from the base of INX, and the fourth station was installed at a distance of 4.6 km from the base of the INX (HGE). HGE was installed approximately at the same position as in the first two campaigns.

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1.3.2 Results

The data used were collected from two distinct sonic anemometers: the Metek and the Gill, located in two different positions, (see figure 1.3.2).

The data have been analysed with Matlab R-14. Before the calculations, the data have been cleaned according to the near neutral condition, which means that the data utilized were only those which were corresponding to -0.03<z/L<0.03, which show a frequency of 23% of the total data; 4 % of the total data for u > 15 ms\(^{-1}\); 8% of the total data is for u <4 ms\(^{-1}\) and only for z/L < 0.

The figures below show the results obtained from the analysis.

![Figure 1.3.2 1: z/l plotted against z0, for the Metek sonic anemometer.](image)

**Figure 1.3.2 1:** z/l plotted against z0, for the Metek sonic anemometer.
Figure 1.3.2 2: virtual heat flux plotted against $u_{*}/U$, for the Metek sonic anemometer

Figure 1.3.2 3: linear regression of the virtual heat flux plotted against $u_{*}/U$, for the Metek sonic anemometer
Figure 1.3.2 4: z/l plotted against z0, for the Gill sonic anemometer

Figure 1.3.2 5: virtual heat flux plotted against ustar/U, for the Gill sonic anemometer

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In order to calculate the value of the ice roughness around Hell’s Gate, the value at virtual heat flux equal to zero, which is the case of near neutral stability (z/L=0) has been taken.

The values of the roughness for the two sonic anemometers are shown in the following table 1.3.1:

<table>
<thead>
<tr>
<th>Gill</th>
<th>Metek</th>
</tr>
</thead>
<tbody>
<tr>
<td>z₀=0.0508 m</td>
<td>z₀=0.0493 m</td>
</tr>
</tbody>
</table>

Table 1.3.1 roughness values calculated for the Metek and the Gill sonic anemometers.

The Gill shows a higher value of roughness compared to the Metek, for the case of neutral conditions. This can be explained by the fact that the two sonic anemometers show an important difference. In fact when the wind speed is higher, the HGW (Metek) appears to be influenced by low frequency perturbations induced by the presence of the mountain, Inexpressive Island.

The Inexpressive Island appears not to be pertubated by low frequency perturbations as for the sea level stations. (Sempreviva, Lavagnini)
From the results obtain, it can be seen that the roughness values are of the order of the centimeters, which differs from the value reported in the European wind Atlas. (the order of the snow roughness is around $10^3$ m). According to the Alt 1975, *Physics of the glacier*, these values correspond to a snow roughness characterized by fine grained melting snow.

The change in roughness parameter can be correlated with blowing snow. Blowing snow is the transport of snow due to strong winds over a snow surface. During blowing snow effective roughness length, because of the saltation of the snow particles, is dependent on the concentration of the particles near the surface. A manifestation of this transport of snow is to be found in sastrugi, a kind of snow dunes, which cover large part of Antarctica.

![Figure 1.3.2 Example of the structures of a sastrugi taken from a mast at about 3-m height above the surface.](image1)

![Figure 1.3.2 Schematic drawing representing a cross section of the ice surface and the experimental set up of a mast. z the sensor height measured at the site relative to the local ice surface, (z C zc) the height above the displaced zero plane representing the actual measurement height, h is the average roughness element height.](image2)
Around Dome C area there can be present sastrugi (see figure below) of maximum height of 30 cm. They are directed along the resultant wind vector and they are semi-permanent, which means that they can move 4 km per year.
Chapter 2: Italian bases description and Data acquisition

The Antarctic environment is thought to be particularly sensitive to climatic changes: the mechanisms by which Antarctica might have a considerable importance for global changes include, e.g., the ice-albedo feedback and the modification of the mass balance of the Antarctic ice cap. Because numerical climatological models do not simulate correctly these phenomena, it is essential to monitor the effects of climatic variations in Antarctica, on time scales varying from a few years to several decades. This is necessary due to the considerable lack of measurement sites on the mainland and surrounding oceans, while satellite-based measurement need to be calibrated through surface observations. The main goal that the meteorological observatory, positioned on the Italian bases, would like to reach, is the continuity and the accuracy of the measures, in order to produce a data set that might be used for meteo-climatological and atmospheric studies, to the local weather forecasting and for scientific activities using meteorological data as support.

The main goal of the meteorological observatory is the collection of continuous measurements, The Meteo-Climatological Observatory in Antarctica, is a research project funded by the P.N.R.A. (Progetto Nazionale Ricerca Antartide). It started an observing programme in 1987: now, it consists of a network of 21 Automatic Weather Stations, 2 Radio sounding Stations and several instruments; in addition, the Observatory manages all the meteorological instruments used for operational meteorological assistance. Data are acquired according to the WMO/ICAO standards; they are stored, processed, verified, and distributed through a data base. The 21 AWS scattered from the coast of the Ross sea, to the Italian-French station Concordia at Dome C (figure 2.2); 2 radiosounding stations, one in Concordia station in Dome C and one in Mario Zucchelli station in Terra Nova Bay; a series of additional instruments (4 driftometers, 1 celiometer) each instrument produces a series of data that are collected during Antarctic expeditions.
Figure 2.1: Location of the two Italian stations in the Antarctic continent

Figure 2.2: Location of the Italian meteorological stations in Antarctica
2.1 Terra Nova Bay-Mario Zucchelli Station

Terra Nova Bay Station is located on the coast at Terra Nova Bay (Victoria Land) at 74°41'S 164°07'E, at 15 m above the sea level and has operated continuously since the 1986/87 seasonally. Italian scientific expeditions to the Ross Sea region are organised under the auspices of the Italian Antarctic Research Program (PNRA) and the government agency implementing it (ENEA). An area of approximately 92,000 m² is occupied by the station, which comprises seven main buildings (some double storied) and several smaller buildings. The station can accommodate up to 90 people. Facilities include administration and accommodation buildings as well as laboratories, aquaria, workshops, power and water supply buildings, a sewage treatment plant, bulk fuel storage tanks, equipment and storage areas, and aircraft and vehicle facilities. Italy operates three helicopter pads over the summer period and a sea ice runway for fixed-wing aircraft in the early part of the season, and has facilities for launching small boats as well as offloading cargo from the annual resupply ship.

Annual exchanges of information under the Antarctic Treaty by countries active in the Ross Sea region indicate that approximately 70,000 people have been involved in scientific research and its associated logistic support in the region over the last 50 year. The research stations, ships, aircraft, vehicles and field camps in the Ross Sea region all depend on petroleum products for their operation. The primary fuel used for power generation, heating and most vehicle and aircraft operation in the Ross Sea region is known as AN-8 (Chiang et al. 1997). This fuel is

A light petroleum distillate aviation turbine fuel, which contains an antifreeze additive and antioxidant, antistatic, corrosion inhibitor and metal deactivator compounds (less than 100 ppm of each). AN-8 is a derivative of JP-8, which has been the main fuel used in the past, along with other diesel and jet fuel variants such as JP-4, JP-5, DFA (Diesel Fuel Arctic) and DFM (Diesel Fuel Marine). The precise fuel type used has varied by application across programmes and over time.

The other main types of fuel in use are mogas (a military grade of gasoline or petrol) and small amounts of kerosene. In addition, various petroleum products such as glycol and oils are used for antifreeze, hydraulics and as lubricants.

Currently Terra Nova Bay Station is consuming 145000 litres Kerosene-Type Jet Fuel annually. In order to calculate the electrical power consumed at this station according Jet
Fuel consumption: The energy content of diesel is approximately 0.030 Gigajoules per litre. One gigajoule equals 277.8 kilowatt-hours, so 0.030 Gigajoules equals 8.33kWh. Keeping the efficiency of diesel generator 35% into consideration, the total electrical power consumed annually at this station is: 145000*8.33*0.35 = 422748 kWh. According price of Kerosene-Type Jet Fuel at 2007 September is about 422.1 nominal $ Cents per Gallon (http://www.economagic.com/em-cgi/dsata.exe/doeme/jktcuus). 145000 litres Jet Fuel equal to 126k Euro, and plus the long distance transportation and storage costs estimated at 100% of annual aero fuel consumption which is still keeping on rising, the annual energy consuming cost at Terra Nova Bay Station is about 252k Euro. So from the power consumption and diesel generator operation cost we can get the energy price at Terra Nova Bay Station is about 252k Euro/ 422748 kWh = 0.6 Euro/ kWh.

Wind-based alternative energy systems and solar based alternative energy systems are not in use at Mario Zucchelli (TNB).

2.2 Dome C-Concordia Station

The Antarctic plateau provides unique opportunities for research. The French and Italian Antarctic programmes have agreed to cooperate in developing a research programme that includes the construction and operation of a scientific base located at Dome C. A cooperation agreement was signed in March 1993.

Dome C Concordia is situated on the East Antarctic Plateau, inland from Banzare Coast at 75°06'06"S, 123°23'43"E, and 3,220 m above sea level. The surface is a snow covered ice cap surface.

The station is 950 km far from the Antarctic coastline and the Vostok Station (Russia) (560 km) is the nearest station, and the Hobart, Tasmania (3,770 km) is the nearest port. Dumont d’Urville (France) and Casey (Australia) are about 1,100 km away to the North over the ice cap while Terra Nova Bay (Italy) is about 1,200 km away to the East behind the Transantarctic mountain range.

Dome C-Concordia consists of a core group of three ‘winter’ buildings coupled by a summer camp. Access is by traverse tractor trains for heavy equipment and by light ski-equipped planes for personnel and selected light cargo. Jointly operated by France and Italy, Concordia is open for research to the worldwide scientific community. Officially open for routine summer operation in December 1997, Concordia should be open year round from 2003 upon completion of the core winter buildings. Facilities are designed for
a winter population of 16 researchers, nine persons conducting scientific experiments and seven support staff.

Meteorological conditions are characterised by low wind speeds, low precipitation and low temperatures. 14 years of Automatic Weather Station (AWS) records by the University of Wisconsin show an average wind speed of 2.8 m/s (5.4 knots) and an average temperature of –50.7°C (-59.3°F) with a minimum of –84.6°C (-120.3°F). Typical summer monthly average is around –30°C (-22°F) and typical winter monthly average around –60°C (-76°F).

The station opened in December 1997 (summer-only operation); and in February 2005 (year-round operation).

Accommodation will be provided for a typical population of 15 over winter and 30 over summer. The typical winter group will be composed of 4 technicians for the station infrastructure, 9 technicians supporting the science programmes, 1 chef and 1 medical doctor.

The station infrastructure consists of:
- 500,000 m^2 total station area
- 12 buildings
- 3,000 m^2 combined floor area
- 500 m^2 used as accommodation

The Energy Requirement is:
- 400V 50Hz power supply
- 540 kW power generation capacity
- 3 generators
- Generators fuelled with Special Antarctic Blend (SAB) Diesel Fuel
- 45,000 litres of fuel used annually

Electricity will be produced by three generator sets of 140 kVA each capable of providing the entire station's electrical load. During normal operation, one set is running, one is on standby and one is providing back-up.

Space heating will be provided by a network of hot water radiators using heat recovered from the cooling circuit of the generator sets and supplemented by boilers.
Fresh water for drinking and cooking will be produced, at a rate of 300 litres per day, by melting snow. All other water needs will be met with recycled water, produced from waste water at a rate of 3,000 litres per day. Engine heat is recovered with boilers satisfying additional heating requirements. Annual fuel consumption is expected to be around 250m³ or 200 tonnes of Diesel fuel to meet average electrical and heating load around 100 and 75 kW respectively.

Downloading data form the 21 AWS, positioned from the coast of the Ross Sea, to the Italian-French station Concordia at Dome C (figure 2.2), time series from wind speed and wind direction have been analyzed.

2.3 Data Aspects

Automatic weather Stations are instruments used to measure near surfaces continuous values, such as, temperature, pressure, wind speed, and wind direction. The stations are positioned in remote areas during summer and usually they are not visited until the next summer field season. 80% or more of the observation are needed to available for a station, to avoid being classified as having missing data for any month. There were data not being available because of transmission problems, malfunctions of particular sensors, which can severely limit the monitoring of particular parameters. Infact, because the instruments are recording data in an extreme environment, such as the one present in Antarctica, low temperatures and rime formations can affect the recording of the parameters. In 1989, for example, a serious breakdown associated with the anemometer positioned at AWS 09 was noticed. There was a presence of some extended calm periods in August and September, due to rime build on the anemometer. Until this point not much attention has been paid to icing of the wind gauges, even tough anemometers and vanes are very sensitive to icing.

Small amounts of ice, in fact, reduce measured wind speed significantly, and large ice accretion can stop the anemometer completely.

The physical mechanisms associated with ice accretion are numerous and complex and can be roughly divided into three categories:

1) Meteorological processes,
2) Mechanical processes associated with the motion of super-cooled water droplets that strike and produce icing on the accretion surface; these processes can be described by the equations from fluid and particle mechanics which determine the trajectory pattern of the droplets within the air flow.

3) Thermodynamic mechanisms involved directly or indirectly in the energy balance (such as latent heat release, forced convection, evaporative heat transfer, exchange of thermal energy, etc.)

Rime formation is related to icing phenomena. Icing phenomena is due to low temperatures under 0°C (even less than -20°C) for considerable periods of the year, due to clouding, high relative humidity, rain and snow, sea spray.

In-clouding icing occurs if the height of cloud base is less than the site elevation and temperatures at the site are below zero. Frost occurs when the surface temperature drops below the frost point temperature due to radiation heat transfer. There are a large number of parameters affecting the icing of a structure, but only a few can be dealt within a practical experiment

An understanding of the icing mechanism is essential for estimating the intensity of the process and developing adequate means to reducing the hazards and inconveniences.

The freezing process can be divided in two stages:
1. part of the supercooled water in the droplet freezes rapidly
2. The remaining part of water turns into ice, through convection, evaporation, conduction. The speed at which this second process occurs determines a typical time, which characterizes the kind of ice being formed.

If $\Delta \tau$ denotes the time interval between droplet striking the same spot on the surface, then the type of ice formed may be defined as follows:
1. $\tau << \Delta \tau$ soft rime (dry growth)
2. $\tau < \Delta \tau$ hard rime
3. $\tau < \Delta \tau$ glaze (freezing rain)
4. $\tau > \Delta \tau$ glaze (wet growth)
5. $\tau = \Delta \tau$ condition which suggests that the presence of an uniform film of water over the surface, and the presence of runoff water.

When super-cooled water droplets fall or move with wind, hit a structure and freeze.
The freezing process and its results is affected by the characteristics of:

1. The air flow
2. The impinging water drops
3. The colliding structure

Rime is usually associated with freezing fog with droplet size 0 - 10 mm when the air temperature is well below 0°C (less than -5°C), supercooled droplets freeze quasi-instantly on impaction. We can divide in:

- hard rime: granular, white or translucent, density 600-900 kg/m³
- soft rime: white or opaque, density: 100-600 kg/m³

Figure 3: Rime forms in dry-growth conditions with a surface below 0°C

The formation of rime is due mainly to the following factors: as the drops can no longer flow together the accretion grows against the airflow around edges in the form of humps.

From the accreted snow crystals a rough surface develops appearing brittle and milky, also containing air bubbles. In dry growth all the impinging water droplets freeze completely and rime is formed. Consequently the icing intensity $I$ (g·m⁻²/s) of rime formations on a vertical surface can be formulated as:

$$I = LWC \cdot v \cdot E$$

where

- $LWC=$ liquid water content
- $V=$ relative velocity of the droplet (usually the terminal velocity is negligible in small droplets causing rime, thus relative velocity can be adopted)
- $E=$ collection efficiency (that is the ratio of the mass flow of water droplet striking the surface to the mass flow that would strike the surface if the droplet had not been deflected in the air stream.

“Assessing wind energy potential In Antarctica”-Marianna Imbimbo, student number:s061762
Danish Technical University, 2006-2008
The ice formation is a statistical concept and probability analysis of icing conditions can provide data from which a designer can choose a wide range of simultaneous combinations of meteorological variables each have the same probability of being exceeded.

Figure 2.4: equi-probability surface.

By use of this equi-probability surface, the most critical combinations of meteorological variables can be established for the thermal system. A prerequisite for icing is supercooled water droplets. Their number depends beside other factors on air temperature.

- Between 0°C and –12°C the water particles are in the majority;
- In the range between –13°C to –20°C the number of ice and water particles is approximately equal;
- In the range between –21°C to –40°C the ice particles prevails;
- Below –40°C only ice particles exist.

Because the ice particles in the air create no icing, the greatest ice probability lies between –4°C and –8°C.
When anomalous low speeds were found in recording data, a correction procedure has been carried out. This consists in making a comparison between the wind speed records at the station where the problem is found, and those at surrounding sites, both before and after the abrupt change indicated in the recording multiplying the wind speeds by a correction factor.

**Figure 2.5** Relative frequency (in %) of observed cases with icing in relation to air temperature

**Figure 2.6** Temperature time series recorded at Eneide station Terra Nova Bay

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Danish Technical University, 2006-2008
In figure 2.7 the wind speed vs. wind direction plot it is shown, recorded at Eneide station (Terra Nova bay). The figure shows that the wind speeds stronger than 15m/s are almost confined to the sectors of 230°-310° (Reeves Glacier direction). To make this plot have been used 20 years of preliminary raw data without correction.

The raw data are available from the AWS website. The Automatic weather station data can be viewed by year. They are in the form of twenty years time series. Data are three-hourly till 1991, and hourly from 1992.

![Wind speed vs. wind direction plot - Eneide station, Terra Nova Bay](image)

Figure 2.7: Wind speed versus wind direction plot - Eneide station, Terra Nova Bay

From figure 2.7 can be seen a second directional clustering is centred around 170°. These events are concentrated in the warmer months (November-February) when katabatic winds are weaker and occur in conjunction with relative warm and moist conditions. In fact at Terra Nova bay the surface winds are channelled towards the bay primarily though the Reeves Glacier.

In figure 2.8 is shown the location of the anemometer.

This sensor is a 3-cup opto-chopper anemometer (VAISALA WAA 15A model). The pulse frequency is directly proportional to wind speed.

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Danish Technical University, 2006-2008
The sensor accuracy is about ±2% with 0.4 m/s wind speed, it does not need to be calibrated, but the ball bearings must be replaced every year. The height of measurements above the surface is not constant, since snow accumulates throughout the year. No corrections are made for the height, which normally varies between 1.5m and 3.0m. This especially affects the wind speed.

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<tr>
<td>Power supply</td>
<td>N°4 solar panels 40 W and batteries</td>
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Table 2.1: Anemometer characteristics at Eneide station, Terra Nova bay
Eneide station is positioned on the eastern side of the Northern foothills (Terra Nova bay), and the resultant wind speed shows frequent airflow down the locally high terrain.

The anemometer has been installed in the summer 1987-88, in a complex terrain, as it can be seen from the picture, at an elevation of 90m a.s.l, at a distance from 500m from the shoreline. Throughout the campaign, the terrain was almost completely deglaciated, while the sea as initially covered by pack-ice for a width of about 3 km.

Figure21 shows a minimum wind speed for the directions around 90° and a maximum in the 240°-310° directions.

The reason for the minimum of occurrence is due to the orography which at Terra Nova bay runs north to South and constitutes a well known barrier to the penetration of Easterly winds.

The occurrence of large wind speed values appears related to the direction of arrival with a tendency approximately to veer from 270° to 210°. The range of directions indicates that the source is Reeves Glacier. Katabatic airflow from Reeves Glacier, can reach the station despite the large topographic obstacles, between the glacier and the site. The stability and the momentum conditions of the katabatic winds are such as to allow them to surmount the obstructing obstacles.
The katabatic winds occur not only in coastal areas, like Terra Nova Bay, but also influence most of the inland stations, which are normally located on a slope terrain (see appendix C). The slope angle must be small, and not visible to naked eye. The only AWS which is not influenced by katabatic flow is the top of Dome C (Dome Charlie), a flat topped dome with an elevation of 3280m, at a site originally chosen for a drilling experiment.

Dome C is very cold, an absolute value of -84.5°C was recorded and the average winter temperature is -60°C. The time series of the Temperature recorded at Dome C is shown in figure 2.10.
Dome C lies in the dry snow zone. It is located 950 Km from the Antarctic Coastline where melting snow never occurs.

Figure below shows the sensor used for recording the wind speed and wind direction at Dome C Concordia.
Figure 2.12 show the plot of the wind speed vs., wind direction recorded at Dome C Concordia. The plot shows that the wind speeds are not stronger than 15m/s. for this plot of 2 years (2005-2007) preliminary raw data without correction have been used.

The speed vs. wind direction plot shows that Dome C, where gravitational flow cannot take place, is not influenced by the katabatic flow. In fact the plot shows no strongly constancy in wind direction, which is defined as the ratio of the mean vector to the scalar mean wind speed.

Moreover the wind speed at Dome C is very light A comparison with other inland stations( see appendix A) show that Dome c experiences the lowest wind speed of any inland station in Antarctica. For what concerning the wind direction, the strong directional constancy for the slope stations, indicates that the downslope gravitational flow, is the major determining factor for the inland stations. At Dome C, where gravitational flow cannot take place, a large variation in wind speed is observed.

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<tr>
<td>Power supply</td>
<td>Net from Concordia (220 V)</td>
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Table 2.2: anemometer characteristics at Dome C Concordia
Figure 2.12: Wind speed vs. wind direction plot calculated for Dome C Concordia
Chapter 3: Methodology of Data Analysis with the WAsP9 (Wind data Analysis and Application Program) and WAsP Engineer Application

In this chapter it is reported the methodology of the analysis of the data taken from the Italian meteorological stations in Antarctica (AWS), using two software, WAsP9 and WAsP engineering2.

The software is based on the wind atlas methodology, which was developed in the 80’s and used initially for creation of the European Wind Atlas. The wind resource assessment started the work to develop the micro scale flow model, WAsP, conceived and developed at Risø National Laboratory. WAsP generates what it is called an observational wind atlas as described below.

The observed wind climates are thus representative for specific locations and heights above ground level, so in order to be able to predict the wind climate at a given wind turbine or wind farm site the observed wind climates must be transformed into generalised regional wind climates. The observed wind climates contain the wind speed and direction distributions derived from long-term time-series of wind speed and direction measurements at the meteorological stations.

Wind resource assessment is applied for determination of wind conditions and energy production estimation for many purposes, including physical planning (national, regional or local), wind farm siting, project development, and wind farm layout design, micros ting and wind farm performance verification.

The various purposes require coverage and modelling of different size geographical domains and different levels of accuracy. However, the extended wind atlas method employing both the numerical wind atlas method and the observational wind atlas method verified against measurements offer opportunities to serve all purposes.

The observed wind climate method can be divided in two blocks (see figure 3.1):

1. Analysis Procedure ↑( WAsP)
2. Application procedure↓(WAsP)

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

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

![Figure 3.1: Generalized regional wind climatology](image)

### 3.1 What is WAsP9 and WAsP engineering?

WAsP9 is a PC-program for the vertical and horizontal extrapolation of wind climate statistics. It contains several models to describe the wind flow over different terrains and close to sheltering obstacles. WAsP9 consists of five main calculation blocks:

- Analysis of raw data. This option enables an analysis of any time-series of wind measurements to provide a statistical summary of the observed, site-
specific wind climate. This part is implemented in separate software tools: the Observed Wind Climate (OWC) Wizard and the WAsP Climate Analyst.

- Generation of wind atlas data. Analyzed wind data can be converted into a regional wind climate or wind atlas data set. In a wind atlas data set the wind observations have been 'cleaned' with respect to site-specific conditions. The wind atlas data sets are site-independent and the wind distributions have been reduced to some standard conditions.

- Wind climate estimation. Using a wind atlas data set calculated by WAsP or one obtained from another source – e.g. the European Wind Atlas – the program can estimate the wind climate at any specific point by performing the inverse calculation as is used to generate a wind atlas. By introducing descriptions of the terrain around the predicted site, the models can predict the actual, expected wind climate at this site.

- Estimation of wind power potential. The total energy content of the mean wind is calculated by WAsP. Furthermore, an estimate of the actual, annual mean energy production of a wind turbine can be obtained by providing WAsP with the power curve of the wind turbine in question.

- Calculation of wind farm production. Given the thrust coefficient curve of the wind turbine and the wind farm layout, WAsP estimates the wake losses for each turbine in a farm and thereby the net annual energy production of each wind turbine and of the entire farm, i.e. the gross production minus the wake losses.

WAsP9 is a program characterized by the following features:

- hills treated as first order perturbation
- first order closure
- varying surface roughness
- shelter effects of obstacles

Measurements are associated with uncertainties. In addition to errors and inaccuracies in the measured data, the transformation involves models, the specification of climatologies parameters, and of parameters such as roughness to each measuring station, and as consequence uncertainties will accumulate.

How representative a transformed data is depends on the complexity of topography and obstacles surrounding the meteorological stations. The transformation of data is a
procedure for the calculation of wind statistics away from the point of measurements. The representative is reduced with increasing complexity of the surrounding topography. Data climatologies based on data measured in sites with obstacles and high and variable roughness, for example, are affected by large uncertainties and errors. In fact the model for roughness change and assignment of surface roughness introduce uncertainties which are largest at the higher end of the roughness scale.

WAsP engineering2 is a program created for the estimation of loads on wind turbines and other civil engineering structures situated in complex terrain. The wind properties that are treated are:

- Extreme wind speeds, e.g. the 50-year wind. If a wind turbine is well situated on a hill the mean wind speed and thereby the energy production can be increased significantly compared to that over flat terrain. Unfortunately, the 50-year wind will increase correspondingly, maybe calling for increased strength of the blades, tower or other parts of the turbine.

- Wind shears and wind profiles. Strong mean wind shears (large differences of the mean wind speed over the rotor) give large fluctuating loads and consequently fatigue on wind turbine blades, because the blades move through areas of varying wind speed.

- Turbulence. Turbulence (gusts of all sizes and shapes) causes dynamic loads on various civil engineering structures, including wind turbines. The strength of the turbulence varies from place to place. Over land the turbulence is more intense than over the sea. Also the hills affect the structure of turbulence. We model various terrain dependent properties of turbulence.

The 50 year wind is the wind speed which on average is exceeded once in 50 years, by ten minutes average wind speed. The 50 year is called Return Period, while the 10 minutes is called Average time.

The uncertainties of the estimation of the 50 years wind are:

- statistical uncertainties( time series too short)
- the assumption of a Gumbel distribution does not hold
- the wind data are poor of quality
- Averaging time and data stride

Assuming that the wind velocity is known at a particular location and the elevation near a structure, where it is unaffected by any obstructions and is therefore indicative of
the ambient wind environment. The wind pressure at a point on the building surface, or the wind force on a member, is a function of that wind speed and can be determined from results of wind tunnel or full-scale tests.

In the Wind Climate Analyst (a tool available in WAsP Eng2) and in WAsP Engineering2, extreme wind plots are needed, which display how the extreme wind increases with the specified return time. This is (normally) represented by a Gumbel distribution.

Gumbel statistics imply that the ranked sequence of maximum wind speeds (from a certain basic period) is normally well represented by the following equation:

\[ U_{i}^{\text{max}} = \beta_0 + \alpha \left[ -\ln \left( -\ln \left( \frac{i-1/2}{N} \right) \right) \right] \]

\[ \text{eq 11} \]

Here \( \alpha \) and \( \beta_0 \) can be found by simple expressions involving the sequence of maximum wind speeds, and \( N \) is the number of values in the sequence, and \( T_0 \) is the basic period.

With the same parameters, \( \alpha \) and \( \beta_0 \), the expected extreme wind dependency of return time is like:

\[ U_{\text{max}}(T) = \beta_0 + \alpha \ln \left( \frac{T}{T_0} \right) \]

\[ \text{eq 12} \]

Especially in the Wind Climate Analyst there is also a need to display how well the Gumbel distribution fits the ranked sequence of maximum wind speeds (e.g. one value for each of 20 consecutive years), from which the Gumbel distribution was derived. This will give an immediate impression of the uncertainty of the extreme wind estimation.

Fortunately it is possible to serve both purposes if one interprets the X-axis in two ways:

- As representing the return-time for which the extreme wind is wanted; or
- As representing the rank-index in the sequence of maximum wind speeds.

There are many steps in the process of estimating extreme winds at a particular site. First winds measured for a long period at other sites should be analyzed for extremes. Then regional extreme wind climate should be derived through flow calculations, and this...
should be applied to a wind turbine site at a particular height. Each of these steps introduces uncertainties. The relatively short time series give statistical uncertainties of the order of 7% while the measurements themselves may have uncertainties of at least a couple of percent. The flow calculation may introduce 5–10% while the terrain description may add to more uncertainty to this.

For what concerning the models behind WAsP engineering2 they can be listed as follows:

- LINCOM, linearized flow model
- Fetch and wind dependent water roughness
- Modification of turbulence due to orography and roughness changes
- Extreme wind estimations

LINCOM, LINearized COMputation, is a simple model for neutrally stable flow over hilly terrain; it is different from the flow model in WAsP 9(Mortensen et al, 1993) in several aspects. WAsP uses a Fourier-Bessel expansion on a polar zooming grid and calculates the wind speed at the central point only. The zooming grid resolves the landscape better the closer to the centre, which is obviously appropriate.

LINCOM, used in WAsP engineering2, calculates the wind vector by Fourier techniques in every mesh point of a rectangular grid.

LINCOM splits the wind field into a uniform main field in balance with a flat terrain with uniform surface roughness and a perturbation field accounting four differences between the real field and this main field. It models the influence of varying surface roughness, based on the assumption that close to the ground the flow is in equilibrium with the local surface roughness, and on a complicated model for the vertical extent of this equilibrium zone.

The idea at the base of the Linearization is to treat the elevation $h(x,y)$ as a small perturbation, according to the following steps:

1. flatten the orography by a coordinate transformation
2. write Navier-Stokes equation in new coordinates
3. Apply first order closure to averaged NS equation
4. linearize with respect to $h$, for ex. Drop $h^2$
5. solve the equations
6. Change back to original coordinates.

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Danish Technical University, 2006-2008
For complex terrain LINCOM apply the following procedure:

1. finding the friction velocity $u_*$ for site1 ($u_* = \frac{k U_1}{\log(z/z_1)}$)

2. use the geostrophic drag law to find $G = \frac{u_*}{k} \sqrt{\left[ \log \left( \frac{u_*}{f z_01} \right) - A \right] + B^2}$

3. use the geostrophic drag law in reverse to find $u_*$ at site2

$G = \frac{u_*}{k} \sqrt{\left[ \log \left( \frac{u_*}{f z_02} \right) - A \right] + B^2}$

4. find the wind speed from the log-law at site2 ($U = \frac{u_*}{k} \log(z/z_02)$)

Another requirement for the site assessment, which can be calculated with WAsP Engineering, is the turbulence estimations. Turbulence can be described in a mathematical form according to the Reynolds decomposition: it stated that, the total wind vector $W$, could be thought as consisting of two parts, a constant mean velocity, $\bar{W}$, and a fluctuating or turbulent part, $W'$, so that the real wind is given by the following formula:

$W = \bar{W} + W'$

eq 13

or in component form.

The fluctuations in the wind speed are of the same order of magnitude as the mean speed.

The turbulence can be described also with the following properties:
1. standard deviation
2. Spectra
3. length scale
4. probability density function

The standard deviation is given by equation 14, while the turbulence intensity is given by equation 15:

$\sigma^2 = \langle (u - \langle u \rangle)^2 \rangle$  

eq 14

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\[ I_a = \frac{\sigma_v}{U} \quad \text{eq 15} \]

It can be said that turbulence is affected by orography. In fact compression or stretching of the flow over hills, will distort the turbulence, or gradual changes in turbulence levels are due to changing in surface roughness; or recirculation zones in very complex terrain.

### 3.2 Limitations

Measurements are associated with uncertainties. In addition to errors and inaccuracies in the measured data, the transformation involves models, the specification of climatologies parameters, and of parameters such as roughness to each measuring station, and as consequence uncertainties will accumulate.

How representative a transformed data is depends on the complexity of topography and obstacles surrounding the meteorological stations. The transformation of data is a procedure for the calculation of wind statistics away from the point of measurements. The representativeness is reduced with increasing complexity of the surrounding topography. Data climatologies based on data measured in sites with obstacles and high and variable roughness, for example, are affected by large uncertainties and errors. In fact the model for roughness change and assignment of surface roughness introduce uncertainties which are largest at the higher end of the roughness scale.

The largest expected errors in the model are related to the calculation of flow in complex orography, and the model works well for the prediction of flow perturbations over not too steep hills and ridges.

1. **WAsP9 limitations:**
   - Measurements are associated with uncertainties
   - The transformation involves models
   - As consequences uncertainties will accumulate
   - The prediction errors are large when maps are based on grids with large grid cell sizes (>75m); the height contour map has a resolution of about 500m.
• The height of measurements above surface is not constant since snow accumulates throughout the year. This affects the wind speeds.

2. WEng2 limitations:
   • Flow modelling (no recirculation)
   • Only neutral conditions
   • Turbulence (only neutral conditions)
   • Extreme winds (Gumble distribution)
   • Obstacle cleaning from OWEC to REWC not included
   • Turbulence model (length of scale grow linearly with height)

3.3 Wind measurements and analysis of wind data

In order to calculate the site assessment, for both Weng2 and WAsP9, the following inputs are required:
   • Map with orography and roughness
   • Wind farm and site
   • Obstacles
   • Extreme wind atlas (REWC)
   • Wind Atlas file

For a selected site, it can be obtained as input:
   • U50=(Vref)
   • Turbulence(σ_u, σ_v, σ_w)
   • Wind shear(du/dz)
   • Wind speed probability function
   • Terrain inclinations
   • Flow angle

The digital maps have been created with a WAsP tool, called WAsP map editor, from downloading SRTM elevation data. SRTM data are not projected (latitude, longitude). Horizontal reference system is WGS84 and the vertical reference system is EGM96 geoid.

The SRTM elevation data have been input in Surfer8, software which transformed the data in a contour map file, which could be read from the WAsP map editor, according to the following procedure:
   • Download the data
• Unzip the zip file
• Rename the HGT file to DEM
• Convert the DEM file to a contour map using surfer8
• Adjust contour level
• Export the map as DFX map file extension in WAsP map editor

Figure 3.2: Map of Terranova bay created by WAsP map editor

Figure 3.3 shows the roughness map designed for Terra Nova Bay. The contour lines in the figure represent the different values of roughness assigned to the site, according to the characteristics of the terrain.

For example, for Terra Nova Bay there were assigned three levels of roughness height:

1. 0.0000 m which is the roughness on the sea water
2. 0.05m which is the roughness height of the ice covering the area
3. 0.1 m which is the roughness corresponding farmland with closed appearance

(source: European Wind Atlas).
Figure 3.4 represents the WAsP digital map created for the Dome C area. The map was created without using STRM data from available on internet. This is because the area of Dome C is a completely flat area, and for this reason the WAsP digital map was built designing a square of a height contour equal to 0m. For what concerning the roughness of the area, because no sonic data of friction velocity, and z/L values were available for the roughness analysis, the roughness assigned was the 0.001m, the one reported in the European Wind Atlas.
The data utilized for the calculations to define the wind atlas analysis have been “cleaned” from out-of-range values, which indicates an error condition in the reading apparatus or is used as a flag for missing observations. This can be done directly in WASP 9 opening the OWC-Wizard-Define Wind Data Limits. Also the unit of the raw wind speed data are in knots and for this reason was necessary to convert that unit in m/s, in order to input the raw data in WASP9. This could be done using the correction speed multiplier in WASP9. The correction is made according to the usual form $y = ax + b$, where the offset value is $b$ and the multiplier value is $a$. For converting knots in m/s the multiplier value is 0.5144.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Units</th>
<th>Value for missing datum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind direction</td>
<td>degree</td>
<td>-10</td>
</tr>
<tr>
<td>Wind speed</td>
<td>kts</td>
<td>-10</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>99.9</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>%</td>
<td>-10</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>hPa</td>
<td>-10</td>
</tr>
</tbody>
</table>

Table3: AWS raw data characteristics

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Because, as it has been specified in the first chapter, Antarctica is considered as the remotest, coldest, driest, windiest, and highest continent on the Earth, characterized by 24 hour sunlight in the height of summer and by almost complete darkness in winter. The lowest temperature ever recorded on earth being $-89.2 \, ^\circ C (\sim -128.6 \, ^\circ F)$ at Vostok Station. The average yearly precipitation is of only 166 mm, on most parts of the continent the snow never melts and is eventually compressed to become the glacial ice that makes up the ice sheet. Because of the features described above, before using the WAsP program for the wind resources calculation, it was needed to change the values of the heat fluxes and of the rms value of the heat fluxes, which are related to the atmospheric stability, and then insert these new values in WAsP9 (Antarctica is a polar site, and WAsP9 is a program built for the calculation concerning neutral conditions, like Danish sites).

The values can be changed opening the Configuration Editor, and then clicking on WAsP Wind Modelling. The default value for the heat flux over land is $-40 \, \text{Wm}^{-2}$, and the value has been substituted with $-44 \, \text{Wm}^{-2}$; the rms heat flux over land value has been substituted with the value of 48:

- Offset heat flux over land: $-44.00$ (default is $-40.00$)
- Rms heat flux over land: $48.00$ (default is $100.00$)

The turbine is an Enercon E30 WT, special class (class S), Polar Model. The figure below shows the power curve of the turbine. The power curve of the turbine depends on:

- The air density
- Control system

There is no simple scaling between power curve and air density, it depends for example if it is stall or pitch regulated. Site specific power curve has been supplied by the manufacture Enercon.

The thrust coefficient for a wind turbine is given by the following formula

$$C_t = \frac{2F_t}{\rho \pi R^2 U^2}$$  \hspace{1cm} \text{eq 16}
While the yearly power output of a single wind turbine, for a wind distribution $f(v)$, can be calculated as

$$E_1 = 8760 \cdot \int_{v=v_{ci}}^{v=v_{co}} P(v) \cdot f(v) dv$$ \hspace{1cm} \text{eq 17}$$

Where $v_{ci}$ is the cut in wind speed, and $v_{co}$ is the cut-off wind speed.

WAsP9 Turbine Editor needs both the power and the CT curve (which is the thrust curve) as inputs for the calculations. For the Enercon E30 Polar mode, the Ct curve was missed inside the power curve file. For this reason, the Enercon E-30 E2 300-30 Ct values have been used. The use of these values could probably generate uncertainties in the calculations, because they are not specific of the Enercon E30s wind turbine.

Figure 31 shows the Enercon E-30 Polar model prototype already installed in the Australian Antarctic division.

The converters of the turbine must withstand extreme stresses, being exposed to temperatures as low as -40°C and wind speeds of up to 80m/s. These conditions called for specially modified towers, strong enough to withstand the special loads presented by air density and wind, and manufactured of special steel suitable for the very low temperatures. The nacelle itself is mostly fitted with standard components. Only the cast parts have been manufactured. With some small modifications that adapt them to the low temperatures. A thermal supply was required for the electrical parts. The electrical boxes, for instance, were fitted with heaters. The rotor blades conform to ENERCON standards. Blade heaters are not necessary because of the extremely low air humidity.
The wind farm, installed at Mawson, together with the power-house control and storage system, provides 95% of the station load for long periods of time. Common features of the wind hydro systems designs utilized at Mawson st. in the Australian Antarctic Division:

- wind turbines were installed (except when 2 or 4 turbines are assessed),
- 200 kW peak electrical loads and a total annual heating load of 2020 MWh,
- Use of the practical load profile for the computer simulations,
- The electrolyser component switched into idle mode when not producing hydrogen, with an idle demand load (EIL) of 40% of rated power,
- The FC components switched into idling mode when not operating to meet user demand for electricity, with an idling power electricity output and corresponding hydrogen consumption of 5% of rated power,
- The AC-DC converters on the FC and electrolyser had conversion efficiencies of approximately 87%,
- The HEGS component switched off when not needed for electricity production, and was only used when the electricity provided by the FC and wind was insufficient to meet the electrical load of the station.
- Waste heat available from the FC and HEGS was captured at 30% efficiency, based upon the performance of the existing diesel-based CHP system
Figure 3.5: Enercon E-30 installed in Antarctica

Data of the gearless E-30/3.30/E2 are shown in table 3.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>300 kW</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>30 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>33 m</td>
</tr>
<tr>
<td>Nacelle weight</td>
<td>2.6 t</td>
</tr>
<tr>
<td>Hub and blade weight</td>
<td>5.63 t</td>
</tr>
<tr>
<td>Generator weight</td>
<td>9.76 t</td>
</tr>
<tr>
<td>Total tower weight (3 sections)</td>
<td>38.2 t</td>
</tr>
</tbody>
</table>

The characteristics of the rotor are listed in table 3.2:

<table>
<thead>
<tr>
<th>Type</th>
<th>upwind rotor with active pitch control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of rotation</td>
<td>clockwise</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Swept area</td>
<td>707 square m</td>
</tr>
<tr>
<td>Blade material</td>
<td>fibreglass (reinforced epoxy)</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>variable, 18-46 rpm</td>
</tr>
<tr>
<td>Tip speed</td>
<td>28-72 m/s (54.4 knots; 100 kmh - 140 knots; 260 kmh)</td>
</tr>
<tr>
<td>Pitch control</td>
<td>three synchronised blade pitch systems with emergency supply</td>
</tr>
</tbody>
</table>


In table 3.3 are shown the characteristics of the generator of the Enercon E-30 wind turbine.

<table>
<thead>
<tr>
<th>Hub</th>
<th>rigid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main bearing</td>
<td>tapered roller bearings</td>
</tr>
<tr>
<td>Generator</td>
<td>direct-driven ENERCON multi-pole ring generator</td>
</tr>
<tr>
<td>Generator output</td>
<td>690 v, 16.5Hz</td>
</tr>
<tr>
<td>Grid feeding</td>
<td>ENERCON inverter</td>
</tr>
<tr>
<td>Braking system</td>
<td>• 3 independent pitch control systems with emergency supply</td>
</tr>
<tr>
<td></td>
<td>• rotor brake</td>
</tr>
<tr>
<td></td>
<td>• rotor lock for service and maintenance</td>
</tr>
<tr>
<td>Yaw control</td>
<td>active through adjustment gears load-dependent damping</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>2.5 m/s (4.9 knots; 9 kmh)</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>12.0 m/s (23.3 knots; 43.2 kmh)</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>28-34 m/s (54.4 knots; 100 kmh - 66 knots; 122 kmh)</td>
</tr>
</tbody>
</table>

Table 3.3: generator with drive train. Source http://www.aad.gov.au/
Figure 3.6 shows a schematic representation of the Enercon E-30 wind turbine. It is a variable-speed, 300kW machines without gearboxes, mounted on steel towers. Matching an appropriate turbine design to the local climatic conditions has to be coupled with innovative solutions to the logistics and installation issues.

A computerised power-house management system is vital to the efficient operation of such a wind farm. This will optimise the instantaneous wind resource and diesel generator outputs to the station load.

When the wind resource exceeds around 40% of the station load, short-term energy storage systems such as fly-wheels, batteries or hydrogen powered fuel cells are required to hold the station load while different combinations of wind and diesel are switched onto the grid.
In figure 3.6 it is shown 'ring' generator, blade attachment and yaw mechanism within the nacelle.

Figure 3.7 shows the power curve and the thrust curve of the Enercon E-30 Polar Model used in the WAsP analysis.

Figure 3. 7: Power curve and the Thrust curve for the Enercon E-30 Polar model
3.4 Results

In figure 3.8 it is shown the WAsP digital map of Terra Nova bay, including the wind speed calculation. The different colours show the different wind speed affecting the area. The wind speed ranges from a minimum of 9.04 m/s, represented by the blue colour on the map, to a maximum value of 27.43 m/s represents by the red colour. The mean wind speed is 16.94 m/s, according to the WASP9 Wind Atlas Calculations.

Figure 3.8: Wind mean speed for Terra Nova bay
Figure 3.9: Power density production for Terra Nova bay calculated with WasP9

Figure 3.9 represents the WAsP digital map of Terra Nova bay, including the calculation of the power density. According to the WAsP9 Wind Atlas calculations, the mean value for the power density production is 13899 W/m².

Comparing figures 3.8 and figure 3.9 it can be seen that there is a correlation between wind speed and the power output, because the areas affected by strong winds are also the ones characterized by the greatest power production. The correlation is given by the following formula according to the cube law:

\[ P = \nu^3 \]

This means that the wind speed is extremely important for the amount of energy a wind turbine can convert to electricity: The energy content of the wind varies with the cube (the third power) of the average wind.
Figure 3.10: AEP calculated for Terra Nova bay with WAsP9

Figure 3.10 shows the annual energy production calculated from WAsP9 for Terra Nova bay. The values can be summarized in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Value</td>
<td>868.812 MWh</td>
<td>(72640.0, 48162.0)</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>623.896 MWh</td>
<td>(59140.0, 41862.0)</td>
</tr>
<tr>
<td>Mean Value</td>
<td>756.067 MWh</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Annual Energy Production for Terra Nova Bay.
Figure 3.11: Alternative positions of the two wind turbines, here positioned along the coastline

Figure 3.13 and 3.14 show the wind rose and the emergent and fitted Weibull distribution.

The wind rose gives the relative winds coming from each of twelve sectors. The probability distribution of wind speed data is studied using a two-parameter Weibull distribution $A(m/s)$ and $k$ the shape parameter.

In WASP 9, the wind turbine productions are based on the so-called emergent distribution and this distribution is the standard total or all-sector distribution referred to.

Site description: 'Terra Nova bay'; Position: -75.40°N 164.24°E; Anemometer height: 10.00 m a.g.l.
Figure 3.12 and Table 3.5 show the WAsP9 Wind Atlas Results for Terra Nova Bay. The Wind Atlas is the meteorological basis for estimating the wind climate and wind energy resources of any particular site. For the analysis there were taken in considerations both the height contours of the site and different roughness heights which characterise the territory of Terra Nova Bay.

The figure shows that the values of the wind speed and power production for Terra Nova bay are higher than the ones calculated from the Observed Wind Climate (table 3.6), which requires only raw meteorological data from the analysis.

In case of The WAsP9 Wind Atlas Analysis, table 3.5 shows the mean wind speed and means power density of the wind for the different roughness lengths and standard heights. The graph in figure 3.12 shows the frequency distribution of wind speeds, and the Weibull-A and Weibull-k parameters for the sector. All these calculations have been made considering the snow roughness length of 0.05m.

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Figure 3.12: Wind Atlas Analysis of WAsP 9

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Danish Technical University, 2006-2008
Table 3.5: WAsP 9Wind Atlas Results for Terra Nova Bay

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured Values</th>
<th>Weibull Fit</th>
<th>Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed [m/s]</td>
<td>unknown</td>
<td>6.32</td>
<td>unknown</td>
</tr>
<tr>
<td>Mean power density [W/m²]</td>
<td>unknown</td>
<td>965</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Table 3.6: Mean wind speed and Power density calculated from the Observed Wind Climate of WAsP9 for Terra Nova bay

Figure 3.13: Wind Rose calculated from the WAsP Observed Wind Climate for Terra Nova Bay

As it can be seen from figure 3.13, the wind rose, calculated from the Observed Wind Climate (WASP9), shows predominant directions of the wind. These directions are defined...
in the second (300°), the third (270°) and the fourth (240°) sectors of the rose, the wind field, in fact, falls almost in one dominating directional sector.

The constant direction of the wind, in this case, is due to the presence of katabatic winds which reaches the meteorological station at Terra Nova Bay

![Weibull distribution calculated from WasP9 for Terra Nova bay](image)

**Figure 3.14**: Weibull distribution calculated from WasP9 for Terra Nova bay

The Weibull distribution, represented in figure 3.14, shows an exponential behaviour. The k-factor value is very low; in fact it is around 0.93. This is reasonable, because the seasonal and latitude variations affect these parameters, and in this case we are considering a cold climate region.

The all-sector histogram is represented by a single, fitted Weibull distribution. Concerning the Weibull distribution, the emergent distribution (solid curve) – which is the weighted sum of the sectorial Weibull-distributions, gives a proper representation of the fit.

<table>
<thead>
<tr>
<th>Sector</th>
<th>A</th>
<th>k</th>
<th>U</th>
<th>E</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.4</td>
<td>1.36</td>
<td>2.18</td>
<td>20</td>
<td>5.9</td>
</tr>
<tr>
<td>30</td>
<td>2.3</td>
<td>1.51</td>
<td>2.07</td>
<td>15</td>
<td>4.1</td>
</tr>
<tr>
<td>60</td>
<td>2.2</td>
<td>1.61</td>
<td>1.99</td>
<td>12</td>
<td>4.1</td>
</tr>
<tr>
<td>90</td>
<td>2.4</td>
<td>1.55</td>
<td>2.13</td>
<td>15</td>
<td>4.4</td>
</tr>
<tr>
<td>120</td>
<td>2.7</td>
<td>1.54</td>
<td>2.40</td>
<td>22</td>
<td>4.4</td>
</tr>
<tr>
<td>150</td>
<td>3.2</td>
<td>1.43</td>
<td>2.87</td>
<td>42</td>
<td>4.1</td>
</tr>
<tr>
<td>180</td>
<td>2.9</td>
<td>1.10</td>
<td>2.78</td>
<td>63</td>
<td>5.0</td>
</tr>
<tr>
<td>210</td>
<td>3.5</td>
<td>0.95</td>
<td>3.57</td>
<td>189</td>
<td>5.2</td>
</tr>
<tr>
<td>240</td>
<td>5.2</td>
<td>0.83</td>
<td>5.72</td>
<td>1177</td>
<td>8.2</td>
</tr>
<tr>
<td>270</td>
<td>12.1</td>
<td>1.55</td>
<td>10.9</td>
<td>2143</td>
<td>14.7</td>
</tr>
<tr>
<td>300</td>
<td>12.4</td>
<td>1.54</td>
<td>11.0</td>
<td>1785</td>
<td>18.3</td>
</tr>
<tr>
<td>330</td>
<td>2.2</td>
<td>1.43</td>
<td>2.50</td>
<td>110</td>
<td>20.7</td>
</tr>
<tr>
<td>All</td>
<td>5.8</td>
<td>0.93</td>
<td>6.32</td>
<td>965</td>
<td>5.3</td>
</tr>
</tbody>
</table>

**Table 3.7**: Weibull parameters, mean wind speed, frequency and Power calculated for all the sectors

A and U are given in m/s, E in W/m² and the frequencies of occurrence in per mille and per cent.
Figure 3.15: Mean wind speed calculated with WAsP9 for Terra Nova Bay with roughness value 0.002m for the ice covering the area.
In figure 3.15 it is shown the WAsP digital map of Terra Nova bay, including the wind speed calculations. In this case the map has been build assigning to the snow roughness a lower value than the than calculated in Chapter 1, the roughness height in this case is 0.002m. The different colours show the different wind speed affecting the area. The wind speed ranges from a minimum of 5.37 m/s, represented by the blue colour on the map, to a maximum value of 13.28, represents by the red colour. The mean wind speed calculated is 7.73 m/s.

Figure 3.16 WasP9 wind data analysis (Weibull fit), for Terra Nova bay roughness length 0.002m

Figure 3.16 shows the WAsP9 Wind Atlas analysis for Terra nova bay, considering the roughness length of 0.002m. Considering low roughness value for the snow, as for instance the one reported in the European wind Atlas, which is of the order of $10^3$, the mean wind speed result is lower compared to the one calculated with higher roughness, in fact in this case the mean wind speed value is 7.73 m/s. Consequently, the power density value decreases to a mean value of 1954W/m$^2$. 
Table 3.8: WASP9 Wind Atlas analysis for Terra Nova Bay, roughness length 0.002 m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
<th>Weibull fit</th>
<th>Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed [m/s]</td>
<td>unknown</td>
<td>5.93</td>
<td>unknown</td>
</tr>
<tr>
<td>Mean power density [W/m²]</td>
<td>unknown</td>
<td>959</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Table 3.9: Mean wind speed and power production values calculated with WASP 9 Observed wind climate, assigning to the snow roughness the value of 0.002

Figure 3.18 shows the wind rose calculated from WASP9 for Terra Nova Bay, with the value of the snow roughness equal to 0.002 m. In this case the wind direction is the same calculated with the higher values of roughness. This means that the wind field, in fact, falls almost in one dominating directional sector.

Figure 3.17: Wind rose calculated from WASP9 with the roughness value of 0.002 m.
Figure 3.19 shows the Weibull distribution calculated from WAsP9, with the snow roughness value of 0.002m. In this case the Weibull fit shows an exponential behaviour as well, but the Weibull parameters A, and k, show lower values compared to the previous case.

![Figure 3.18: Weibull distribution calculated from WAsP9 for Terra Nova bay, with the snow roughness value of 0.002m.](image)

<table>
<thead>
<tr>
<th>Sector: All</th>
<th>A: 5.7 m/s</th>
<th>k: 0.92</th>
<th>U: 5.93 m/s</th>
<th>P: 959 W/m²</th>
<th>Fitted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.10: Weibull parameters, mean wind speed, frequency and Power calculated for all the sectors, with snow roughness value of 0.002m.
If we compare the results obtained from the WAsP9 Observed Wind Climate, between the previous case, when the roughness height was 5 cm and the case when the roughness value of the snow is 0.002, we can see that increasing the roughness, there is also an increase in the wind speed. The results are summarized in the table 3.11:

<table>
<thead>
<tr>
<th>Snow roughness 0.05m</th>
<th>Snow Roughness 0.002m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed</td>
<td>6.32 m/s</td>
</tr>
<tr>
<td>Power Density</td>
<td>965 W/m²</td>
</tr>
</tbody>
</table>

Table 3.11: comparison of the results calculated for site 1 and site 2

The increasing in the wind speed, due to an increase in the roughness value of the snow, for Terra Nova Bay, can be explained through the correlation between the roughness ($z_0$) and the Geostrophic wind.

The Geostrophic wind is the wind high above the ground where the orography has no influence. It is uniform over large areas and it results from the balance between the pressure gradient and the Coriolis force:

$$G = \frac{u_s}{k} \ln \left( \frac{u_s}{\beta z_0} \right) - A^2 + B^2$$  \hspace{1cm} eq 19

Table 3.12 shows the mean wind speed and the power density calculated from WAsP9 for Dome C.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
<th>Weibull fit</th>
<th>Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed [m/s]</td>
<td>unknown</td>
<td>2.40</td>
<td>unknown</td>
</tr>
<tr>
<td>Mean power density [W/m²]</td>
<td>unknown</td>
<td>43</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Table 3.12: Site Dome C ; Position: 75.06°N -123.24°E; Anemometer height: 3.00 m a.g.l.

“Assessing wind energy potential In Antarctica”-Marianna Imbimbo, student number:s061762
Danish Technical University, 2006-2008
Comparing the results with the ones obtained for Terra Nova bay, it can be seen that the mean wind speed for dome C are very low.

Indeed the mean wind speed is 2.40 m/s, which is lower that the cut-in wind speed of a wind turbine.

![Wind Rose calculated for Dome C with WasP9](image1)

**Figure 3.19:** Wind Rose calculated for Dome C with WasP9

![Weibull fit calculated for Dome C with WasP9](image2)

**Figure 3.20:** Weibull fit calculated for Dome C with WasP9

The wind rose, figure 3.20, doesn’t show any predominant wind direction, while the Weibull fit, figure 3.21, still presents an exponential behaviour.

<table>
<thead>
<tr>
<th>A</th>
<th>0.9</th>
<th>0.9</th>
<th>1.1</th>
<th>1.7</th>
<th>2.6</th>
<th>2.7</th>
<th>3.7</th>
<th>3.3</th>
<th>2.4</th>
<th>2.5</th>
<th>2.5</th>
<th>2.2</th>
<th>1.1</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0.75</td>
<td>0.67</td>
<td>0.71</td>
<td>0.76</td>
<td>0.97</td>
<td>1.03</td>
<td>1.42</td>
<td>1.46</td>
<td>1.31</td>
<td>1.35</td>
<td>1.04</td>
<td>0.81</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>1.03</td>
<td>1.25</td>
<td>1.32</td>
<td>2.02</td>
<td>2.60</td>
<td>2.71</td>
<td>3.37</td>
<td>2.98</td>
<td>2.17</td>
<td>2.31</td>
<td>2.13</td>
<td>1.22</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>10</td>
<td>26</td>
<td>24</td>
<td>69</td>
<td>70</td>
<td>68</td>
<td>69</td>
<td>46</td>
<td>21</td>
<td>24</td>
<td>32</td>
<td>12</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>5.5</td>
<td>5.2</td>
<td>5.4</td>
<td>6.1</td>
<td>8.1</td>
<td>9.6</td>
<td>14.8</td>
<td>12.1</td>
<td>9.6</td>
<td>10.2</td>
<td>7.6</td>
<td>5.8</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.13:** A, U(m/s), k, f, and E calculated by WAsP 2Eng for Dome C Concordia

"Assessing wind energy potential In Antarctica"-Marianna Imbimbo, student number:s061762
Danish Technical University, 2006-2008
A and U are given in m/s, E in W/m² and the frequencies of occurrence in per mille and per cent (f).

After having importing the WAsP digital map of Terra Nova bay in WAsP engineering2, it is possible, through the building of a transect, for example, to calculate the 50 year winds, turbulence, and other parameters which allow us to identify the class of the wind turbine needed for the site considered.

Figure 3.22 shows a transect build on Inexpressive Island at Terra Nova Bay. The digital map utilised is the same imported for the calculations in WAsP9. A transect is a line in the terrain defined by two end points. The transect is extending 1km long from the Inexpressive Island top site, in the SW and NE directions.

Figure 3.21: transect view build on the digital map with Weng2
Using the transect it is possible with WEng2 to calculate the following parameters:

- Elevation [m]
- Roughness [m]
- Friction velocity [m/s]
- Terrain inclination [°]
- Velocity tilt [°]
- $\frac{dU}{dx}$ [/s]
- Alpha

Figure 3.22: Graphics calculated with WEng2, using the transect on Inexpressive Island
Figure 3.24 shows the terrain elevation calculated from WEng2. It also possible to see the transect, and the position of the turbine sites around Eneide station.

The turbine sites are positioned at different elevation, one wind turbine has been positioned along the coastline, while the others two are positioned at 400 m agl.
Figure 3.25 shows the terrain inclination, measured in° with WEng2. The range of the slope varies from -21.5° to 21.86° from the figure it can be seen that the maximum value corresponds to the top of Inexpressive Island, and at 500m a.s.l.

Figure 3.26 shows the value of the friction velocity, calculated with WEng2 for Terra Nova bay.
The friction velocity is very low at the sea, in fact the value corresponds to the minimum value 0.143 m/s, while the maximum is reached in areas which correspond to high roughness value of the terrain in this case $z_0=0.1$ m for Terra nova bay.
Figure 3.26: tilt angle 300° calculated with WEng2 for terra Nova bay.
Figure 3.27 shows the tilt angle calculated for the wind direction of 300°, which corresponds to the main direction of the katabatic wind, when it reaches Terra Nova bay. The range of the tilt angle varies from a minimum of -17.99° to a maximum of 19.15°. It can be seen from the figure that most of the terrain reaches a maximum value of tilt angle.

Figure 3.28 shows the two different sites chosen for the installation of the wind turbines generator in Antarctica, around Terra Nova Bay.

Figure 3.27: Turbine sites represented on WAsP digital map
Figure 3.29 shows the plot of the vertical wind profile, calculated from WEng2, for the top of Inexpressive Island, at different heights. On the x-axes there is represented the mean wind velocity, while on the y-axes there are represented the different heights at which the mean wind velocity has been calculated.

Figure 3.28: Vertical wind profile calculated for the top of Inexpressive Island
Figure 3.30 shows the vertical wind profile calculated for the wind turbine located at 400 m agl (1802.3 in WGS84) above the ground level. The plot seems to follow the logarithmic wind profile law.

Figure 3.29: Vertical wind profile for turbine site1 at Terra Nova bay
Figure 3.31 shows the vertical mean wind profile calculated for the wind turbine positioned at site2, along the coastline. The plot shows a behaviour which tends to differ slightly from the logarithmic wind profile law. The shape of the log wind profile shown in figure 56, seems to be close to the shape of the log wind profile for stable conditions, like the case of katabatic winds in Antarctica, but as height increases, the wind velocities increase, instead of decreasing.

This behaviour can be explained because when slopes are larger than 20-30 degrees, the WEng2 model fails.

Escarpment or big obstacles create turbulence by detached eddies and give raise to high loads. Combinations of steep slopes nearby and just in front of the turbine locations create extra turbulence.
Figure 3.32 shows the WEng2 window to generate a “rose” of turbulence intensity, in this case for turbine site 2. On the top of the window there is a text explaining which site and which height have been used. The rose graphic gives a preview of the rose structure.

Each rose sector will contain the turbulence intensity value calculated for a wind with direction equal to the centre angle of the sector. For the turbulence intensity calculations it should be used a high speed like 25m/s, because WEng2 does not provide good predictions of turbulence at low speeds.

For the turbine site 2, the calculations show that the main turbulence intensity is represented in sector of 30° direction.

Table 3.14 shows the turbulence intensity, the velocity tilt and the horizontal speed calculate for 300°, for the turbine site 2, which is the direction dominating sector of the katabatic wind flow, reaching Terra Nova bay.

<table>
<thead>
<tr>
<th>Direction [°]</th>
<th>Horizontal speed [m/s]</th>
<th>Velocity tilt [°]</th>
<th>$(u^2+I^2)^{1/2}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300° at 6.32 m/s</td>
<td>291.4</td>
<td>8.48</td>
<td>-3.39</td>
</tr>
</tbody>
</table>

Table 3.14: Turbulence intensity, horizontal speed and velocity tilt calculated for turbine site 2.
Figure 3.33 shows the turbulence intensity rose calculated for turbine site 1, using WEng2. The turbulence intensity for this site reaches the main intensity in the 0° direction, 180°, and 30°.

Table 3.15 shows the turbulence intensity, the velocity tilt and the horizontal speed calculate for 300° for the turbine site 1, which is the direction dominating sector of the katabatic wind flow, reaching Terra Nova bay

<table>
<thead>
<tr>
<th>Direction [°]</th>
<th>Horizontal speed [m/s]</th>
<th>Velocity tilt [°]</th>
<th>((u^2 + v^2)^{1/2} [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>300° at 6.32 m/s</td>
<td>285.4</td>
<td>13.21</td>
<td>-1.42</td>
</tr>
</tbody>
</table>

Table 3.15: Turbulence intensity, direction, horizontal wind speed and velocity tilt calculated for turbine site 1.
Figure 3.33: turbulence intensity rose calculated for Inexpressive Island

Figure 3.34 shows the turbulence intensity rose calculated for the top hill point of Inexpressive Island. From the rose it can be seen that the most turbulence intensity sectors are the 0° degrees sector, 150° and 120°.

Table 3.16 shows the turbulence intensity, the velocity tilt and the horizontal speed calculated for 300°, which is the direction dominating sector of the katabatic wind flow, reaching Terra Nova bay.

<table>
<thead>
<tr>
<th>Direction [°]</th>
<th>Horizontal speed [m/s]</th>
<th>Velocity tilt [°]</th>
<th>$(u^2 + v^2)^{1/2}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300° at 74.34 m/s</td>
<td>292.8</td>
<td>126.49</td>
<td>4.74</td>
</tr>
</tbody>
</table>

Table 3.16: Turbulence intensity, direction, horizontal wind speed and velocity tilt calculated for the top of Inexpressive Island.
Figure 3.34: 50 year wind calculated with WEng2

Figure 3.35 shows the Extreme wind climate calculated for Terra Nova Bay with WEng2. The extreme wind climate displays how the extreme wind increases with the specified return time. This is (normally) represented by a Gumble distribution.

The 50 year wind speed calculated from WEng2 is estimated 187 m/s, which can be considered a reasonable value if we take into account that the maximum wind speed recorded in Antarctica is 192 m/s, near Vostok Station (see chapter 1).

The extreme wind atlas is given in terms of sector-wise Gumbel distribution for the friction velocity pressure, which is what is used in WAsP Engineering 2, and it is possible, in principle, from the description make a EWC from long meteorological time series. This analysis is made by a crude estimation of the EWC based on the information available in the WAsP9 lib file.

The figure is divided in four windows. In the first window: up on the left, there is shown the wind rose, calculated by WAsP9 through the analysis of the meteorological data.
The window up to the right, in fact, shows the Weibull distribution calculated for Terra Nova bay with the relatives Weibull parameters. The WAsP9 wind atlas (lib file) contains a wind rose, giving the probabilities of wind in typically 12 sectors, and Weibull A and k parameters for each sector. This is given for various heights above the flat, homogeneous terrain (z) and for various roughness lengths (z0). An extreme wind atlas contains sector-wise information on strong winds pertaining to z=10 m and z0 = 0.05 m. The extreme wind rose is shown in the window down to the left of figure 60.

To the left, at the bottom there is shown the curve for the estimation of extreme winds with other return period. In the plot the solid line represents the return time dependency of the extreme wind, when referring to the lower x-axis. The rank indices are marked on the upper axis. They can be compared with the solid curve, when this is interpreted as the theoretical distribution of extreme speeds, referring to the upper rank-index x-axis.

In connection with the ranked speed-sequence, the x-axis may also be understood as a measure of the cumulative probability for a certain maximum speed in the sequence:

\[ X = -\ln(1 - F(U^{\max})) \]  \hspace{1cm} \text{eq 20} \\

with

\[ U^{\max} = \beta_0 + \alpha X \]  \hspace{1cm} \text{eq 21} \\

Equation 21 represents the Gumble distribution.

“Cumulative probability” means the probability that some wind speed observations exceed the specific wind.
Table 3.17 and table 3.18 show the values of the site assessment reports calculated by WEng2 for turbine site 1 and turbine site 2.

<table>
<thead>
<tr>
<th>Direction</th>
<th>alpha</th>
<th>TI</th>
<th>Sigma-U</th>
<th>Flow angle</th>
<th>Terrain inclination</th>
<th>V-ref (50 yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[°]</td>
<td>[%]</td>
<td>[m/s]</td>
<td>[°]</td>
<td>[°]</td>
<td>[m/s]</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.155</td>
<td>12.2</td>
<td>1.8</td>
<td>0.9</td>
<td>1.3</td>
<td>14.73</td>
</tr>
<tr>
<td>30</td>
<td>0.145</td>
<td>11.7</td>
<td>1.93</td>
<td>3.2</td>
<td>3.3</td>
<td>16.51</td>
</tr>
<tr>
<td>60</td>
<td>0.128</td>
<td>9</td>
<td>1.56</td>
<td>4.3</td>
<td>4.4</td>
<td>17.29</td>
</tr>
<tr>
<td>90</td>
<td>0.115</td>
<td>7.6</td>
<td>1.43</td>
<td>4</td>
<td>4.4</td>
<td>18.9</td>
</tr>
<tr>
<td>120</td>
<td>0.141</td>
<td>9.6</td>
<td>1.78</td>
<td>3</td>
<td>3.1</td>
<td>18.47</td>
</tr>
<tr>
<td>150</td>
<td>0.131</td>
<td>11.3</td>
<td>2.08</td>
<td>1.4</td>
<td>1.1</td>
<td>18.35</td>
</tr>
<tr>
<td>180</td>
<td>0.14</td>
<td>12</td>
<td>2.21</td>
<td>-1</td>
<td>-1.3</td>
<td>18.32</td>
</tr>
<tr>
<td>210</td>
<td>0.143</td>
<td>12.2</td>
<td>4.16</td>
<td>-3.4</td>
<td>-3.3</td>
<td>34.04</td>
</tr>
<tr>
<td>240</td>
<td>0.122</td>
<td>11</td>
<td>10.32</td>
<td>-4.3</td>
<td>-4.4</td>
<td>94.25</td>
</tr>
<tr>
<td>270</td>
<td>0.106</td>
<td>9.9</td>
<td>14.37</td>
<td>-4</td>
<td>-4.4</td>
<td>145.55</td>
</tr>
<tr>
<td>300</td>
<td>0.112</td>
<td>9.5</td>
<td>11.71</td>
<td>-3.1</td>
<td>-3.1</td>
<td>122.76</td>
</tr>
<tr>
<td>330</td>
<td>0.142</td>
<td>11.1</td>
<td>1.44</td>
<td>-1.6</td>
<td>-1.1</td>
<td>12.98</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>145.6</td>
</tr>
</tbody>
</table>

Table 3.17: Site assessment for turbine site 1
### Site assessment report for site 'turbine site2' in project: 'TNB'

Using regional extreme wind climate 'TNB'

<table>
<thead>
<tr>
<th>Direction</th>
<th>alpha</th>
<th>TI</th>
<th>Sigma-U</th>
<th>Flow angle</th>
<th>Terrain inclination</th>
<th>V-ref (50 yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[°]</td>
<td>[°]</td>
<td>[%]</td>
<td>[m/s]</td>
<td>[°]</td>
<td>[°]</td>
<td>[m/s]</td>
</tr>
<tr>
<td>0</td>
<td>0.18</td>
<td>17.1</td>
<td>2.13</td>
<td>-1</td>
<td>-0.6</td>
<td>12.45</td>
</tr>
<tr>
<td>30</td>
<td>0.169</td>
<td>18.8</td>
<td>2.5</td>
<td>0.9</td>
<td>1.2</td>
<td>13.26</td>
</tr>
<tr>
<td>60</td>
<td>0.163</td>
<td>16.9</td>
<td>1.99</td>
<td>2.6</td>
<td>2.7</td>
<td>11.77</td>
</tr>
<tr>
<td>90</td>
<td>0.088</td>
<td>12.6</td>
<td>1.62</td>
<td>3.4</td>
<td>3.5</td>
<td>12.86</td>
</tr>
<tr>
<td>120</td>
<td>0.081</td>
<td>7.8</td>
<td>1.1</td>
<td>3.2</td>
<td>3.3</td>
<td>14.17</td>
</tr>
<tr>
<td>150</td>
<td>0.076</td>
<td>7.1</td>
<td>1.26</td>
<td>2.3</td>
<td>2.3</td>
<td>17.6</td>
</tr>
<tr>
<td>180</td>
<td>0.121</td>
<td>12.9</td>
<td>2.17</td>
<td>0.7</td>
<td>0.6</td>
<td>16.85</td>
</tr>
<tr>
<td>210</td>
<td>0.177</td>
<td>16.9</td>
<td>4.42</td>
<td>-1.1</td>
<td>-1.2</td>
<td>26.15</td>
</tr>
<tr>
<td>240</td>
<td>0.212</td>
<td>18.2</td>
<td>11.57</td>
<td>-2.8</td>
<td>-2.7</td>
<td>63.6</td>
</tr>
<tr>
<td>270</td>
<td>0.212</td>
<td>19.2</td>
<td>17.87</td>
<td>-3.5</td>
<td>-3.5</td>
<td>92.96</td>
</tr>
<tr>
<td>300</td>
<td>0.211</td>
<td>16.9</td>
<td>13.89</td>
<td>-3.3</td>
<td>-3.3</td>
<td>81.96</td>
</tr>
<tr>
<td>330</td>
<td>0.199</td>
<td>17.4</td>
<td>1.73</td>
<td>-2.3</td>
<td>-2.3</td>
<td>9.96</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>93</td>
</tr>
</tbody>
</table>

Table 3.18: site assessment for turbine site 2. Calculated with Weng2
Based on the project set-up which includes a regional extreme wind climate, the following parameters are calculated:

- Sector wise extreme winds
- Turbulence
- Flow angle
- Terrain inclinations
- Shear parameters for each site with the selected height
According to the IEC 61400-1 standard, in order to identify the design and class of the wind turbine, for a specific site, the following parameters are required:

- $V_{\text{ref}}$, extreme wind expected with fifty years recurrence
- $I_{\text{ref}}$, turbulence intensity
- Shear of vertical wind profile $0<\alpha<0.2$
- Flow inclination angle $[-8^\circ….+8^\circ]$

IEC international standard 61400 series specifies essential design requirements to ensure the engineering integrity of wind turbines. It provides an appropriate level of protection against damage from all hazards during the planned lifetime.

Antarctic sites fall into the special Class S, in which loads causes have to be agreed between the customer and manufacturer.

IEC international standard 61400-1, recommends taking ice loads into account but a special load cause is not given and no minimum ice requirements are given for standard wind turbine.

During the tests of wind turbines at Artic and Antarctic sites (Polar sites) it is important to have the right results from wind speed measurements. It is important also to analyse the properties of the wind speed instruments, i.e. response, distance constants, calibration curves.

IEC international standards 61400-12 provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines. The standard will benefit those parties involved in the manufacture, installation planning and permitting, operation,

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Danish Technical University, 2006-2008
utilization, and regulation of wind turbines. The technically accurate measurement and analysis techniques recommended in this standard should be applied by all parties to ensure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to environmental concerns. This standard presents measurement and reporting procedures expected to provide accurate results that can be replicated by others.

Meanwhile, a user of the standard should be aware of differences that arise from large variations in wind shear and turbulence, and from the chosen criteria for data selection. Therefore, a user should consider the influence of these differences and the data selection criteria in relation to the purpose of the test before contracting the power performance measurements.

A key element of power performance testing is the measurement of wind speed. This standard prescribes the use of cup anemometers to measure the wind speed. This instrument is robust and has long been regarded as suitable for this kind of test. Even though suitable wind tunnel calibration procedures are adhered to, the field flow conditions associated with the fluctuating wind vector, both in magnitude and direction will cause different instruments to potentially perform differently.

Special care should therefore be taken in the selection of the instruments chosen to measure the wind speed.

<table>
<thead>
<tr>
<th>Wind turbine classes</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{ref}}$</td>
<td>(m/s)</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>A</td>
<td>I_{ref} (-)</td>
<td></td>
<td></td>
<td>0.16</td>
</tr>
<tr>
<td>B</td>
<td>I_{ref} (-)</td>
<td></td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>C</td>
<td>I_{ref} (-)</td>
<td></td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Design life time ≥ 20 YR</td>
</tr>
</tbody>
</table>

**Figure 3.36: Basic parameters for wind turbine classes according to the IEC standard**

The site assessment calculations made by WEng2, for the two turbine sites, are shown in table 3.19. The results reported in table 3.19, together with the turbulence intensity calculations, show that the parameters calculated for the two wind turbine site don’t fall in any of the three classes, class I-II-III. This means that the turbines, fall in the so called

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class S or Special Class, it means that they have to be designed and projected by the
designer and the manufacturer.

<table>
<thead>
<tr>
<th>Turbine Site1</th>
<th>Flow angle max</th>
<th>Alpha min value</th>
<th>Alpha max value</th>
<th>I ref %</th>
<th>V ref(m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.3</td>
<td>0.145</td>
<td>0.106</td>
<td>12.6</td>
<td>145.6</td>
</tr>
<tr>
<td>Turbine Site2</td>
<td>3.4</td>
<td>0.212</td>
<td>0.076</td>
<td>23.3</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 3. 19: site assessment values for the turbine site1 and turbine site2
Chapter 4: Environmental Impact Assessment

Overview and identification of critical issues:

This chapter will brief the site environment and point out the critical issues, which are to be addressed in following sections. After analysis, the critical issues were identified out as birds and oil pollution.

Antarctica is probably one of the last pure pristine places on earth. So ensuring the minimal level environmental impact to surroundings is extremely important.

Table 4.1 shows a synthesis of the principles of the Madrid Protocol, or Protocol on Environmental Protection to the Antarctic Treaty.

The Protocol was adopted in 1991 in response to proposals that the wide range of provisions relating to protection of the Antarctic environment should be harmonised in a comprehensive and legally binding form. It draws on and updates the Agreed Measures as well as subsequent Treaty meeting recommendations relating to protection of the environment.

<table>
<thead>
<tr>
<th>Environmental principles of the Madrid Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Protocol provides that protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica must be fundamental considerations in the planning and conduct of all human activities in Antarctica. With this aim, all such activities are to be planned and conducted so as to [11]:</td>
</tr>
<tr>
<td>1. limit adverse impacts on the Antarctic environment; and</td>
</tr>
<tr>
<td>2. avoid</td>
</tr>
<tr>
<td>a. adverse effects on climate or weather patterns;</td>
</tr>
<tr>
<td>b. significant adverse effects on air or water quality;</td>
</tr>
<tr>
<td>c. significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environments;</td>
</tr>
<tr>
<td>d. detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora;</td>
</tr>
<tr>
<td>e. further jeopardy to endangered or threatened species; or</td>
</tr>
<tr>
<td>f. degradation of or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance; and</td>
</tr>
<tr>
<td>g. accord priority to preserving the value of Antarctica for scientific research.</td>
</tr>
</tbody>
</table>

The environmental principles in the Protocol also include requirements for:

1. prior assessment of the environmental impacts of all activities; and
2. regular and effective monitoring to assess predicted impacts and to detect unforeseen impacts.

Table 4.1: Environmental principles of the Madrid Protocol.

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Terra Nova Bay is proposed as an Antarctica Specially Protected Area (ASPA) by Italy, on the ground that it is an important littoral area for well-established and long term scientific investigations.

The ASPA entry restrictions will be installed at Terra Nova Bay Station. The coast is 2.3 km south of Terra Nova Bay Station, so the wind turbines’ position shall be southern of station, keeping significant distance from ASPA.

Neighbours are far away; the nearest station is far away from Terra Nova Bay Station – the proposed WTG site.

- Analysis of critical EIA issues
- Impacts on Birds

Wind turbines’ possible impact on birds is estimated at a low level because of their location.

To minimize WTG’s disturbance to birds, wind turbines will be installed in the inland direction to station, at least 2.3 km away from coast, at the same time concentrations of birds are most often found in coastal areas.

The studies in Danish offshore wind farm Tunø Knob show the wind turbine will not give significant effect on water birds. Furthermore, according the bird life study by radar at Tjaereborg wind farm site, birds are able to change their flight route to avoid collision to the wind turbines either in daytime or night.

However, there are almost no trees, overhead lines, masts, poles existing in Antarctica, presenting in high air as obstacles, so it might take longer time for some kind of birds to get accustomed to wind turbines which is new to Antarctica land.

Before any conclusion was made, the authors suggest initializing the below two investigation activities in order to evaluate the wind turbine’s short-term and long-term impact on bird life and habit:

a) Monitoring bird’s activities and any bird collision in the existing Antarctica Enercon wind turbine site.
b) Monitoring bird’s activities at Terra Nova Bay Station site, for example, the fly frequency, track, and time.

4.1 Oil Pollution

By using none-gearbox wind turbine, during the wind turbine operation, the possibility of oil pollution is minimized to a very limited level, during the construction phase, careful consideration must be put to avoid oil spill.

Some examples could be:

- Use double walls oil tank for construction vehicles
- to install oil spillage detecting and collection system in WTG

4.2 Noise

Neighbours are far away; the nearest station is hundreds km away from the proposed WTG site, also the turbine will be installed 400 meters agl away from Terra Nova Bay Station which is on the coastline, so noise is not an issue in this case.

4.3 EMI (electro magnetic interferences)

With the distance from WTG to station, there shall be no electromagnetic effect which will significantly compromise communication systems.

According the results of the electromagnetic undertaken at the North Hoyle wind farm, no problems with basic GPS reception or positional accuracy were reported. The wind farm structures had no noticeable effects on any voice communications systems.
4.4 Shadow Casting

The main concern is the impact of shadow casting on creatures along the coast instead of the human being. As the sun is always low in the high altitude polar area, if the rotor blades chop the sunlight, shadow casting can travel to a very long distance, which might be annoying for coastal animals habits, especially in native birds breeding season between September and May.

Most of potential shadow casting will happen in the summer season, as in the winter season there is no sunshine at all.

Simulation of shadow casting needs to be developed in WindPro showing the rotor shadow approaching area, if necessary, the wind turbine can be stopped at certain time of the day to avoid shadow flicker.

4.5 Mitigation of impact

During the construction period, below measures might be considered to minimize the environmental impact:

• Time of Construction: Most native bird species at coastal locations in Antarctica between September and May, so the construction shall be out of the main breeding periods, to minimize disturbance.

• Complete and detailed transportation plan and risk evaluation.

During the operating period, below measures might be considered to minimize the environmental impact:

• Special type of aviation light might be considered to avoid light pollution to ground.

• To minimize birds’ strikes, consideration on avoiding wind turbine operation after dark between September and May, when prions and petrels are active.1

4.6 Discussion of positive impact

The Antarctic continent has no indigenous inhabitants, and the human presence is only due to research interest and the connected logistics. However, human impact is likely to increase, due to tourist reasons. For these reasons good and environmental friendly energy services are necessary for the operation of Terra Nova bay base, to support the science.
programs but also to keep the scientists warm and productive in the freezing polar conditions.

Energy services for these stations, providing electricity, heat, water production, waste disposal and transportation, are met with liquid fossil fuels (a diesel derivative). This requires the import of millions of litres of fossil fuels each year to the stations. These fuel supplies are taken by ship from Australia, transported across the rough Southern Ocean, and stored and consumed in the pristine and sensitive polar environment. A range of factors, including the growing purchase price of fossil fuels, the high embodied cost of delivering the fuels to Antarctica, and the local and global environmental impacts of using fossil fuels, are prompting the consideration and development of more sustainable energy systems within Antarctic communities.

The high energy costs of Antarctic operations and the pristine nature of the operating environment provide strong motivations for the introduction of energy supply technologies that offer independence from fossil fuels and less environmental impact. These factors could motivate Antarctic operators to purchase new energy technologies (renewable energies).
Conclusions

The unique natural resources of Antarctica, including the crucial planetary-wide atmospheric and oceanic effects they help generate, are of great importance to all world nations and their citizens.

The economic activities of Antarctic science, fishing, and tourism give rise to a number of specific problems that demonstrate the need for policy attention if the Antarctic natural resource “engines” for the global atmospheric and oceanic commons, along with other Antarctic commons features, are to be preserved for future generations.

The central feature of these economic-efficiency problems derives from the difficulty markets encounter in pricing the benefits and costs of:

(a) Public goods, such as science in Antarctica,
(b) The Antarctic natural resource commons,
(c) The significant externalities that accompany the allocation of the Antarctic private goods, fishing and tourism.

Since Antarctica does not possess a sovereign, decision-making government, policies dealing with these issues must be formulated within an adapted governmental setting. In the absence of a politically sovereign governance body, the economic resources of the so-called seventh continent are under the direction of a non-sovereign international treaty regime, the Antarctic Treaty System. The Antarctic Treaty System—a non-sovereign, international governance body that grew out of the Antarctic Treaty of 1959—directs an important policy role in the face of such obstacles. The primary goal of a successful policy is the long-term sustainability of the globally strategic Antarctic commons and natural resources.

The need to develop and implement measures to alleviate and combat the pollution of Antarctic waters and atmosphere has been the subject of several Recommendations adopted at Antarctic Treaty Consultative Meetings (ATCMS) in recent years. At the 1989 ATCM, Recommendation XV-4 specifically called on the Governments of Treaty Parties to establish contingency plans for marine pollution response in Antarctica, including plans for vessels carrying oil.

1. The need to develop contingency plans for response to marine pollution incidents is also a Requirement of Annex IV of the “Protocol to the Antarctic Treaty on Environmental Protection”.

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2. Defining a recommended format and specifying specifies the information to be included in oil spill contingency plans which are to be prepared by national Antarctic operators for facilities or larger geographic areas in Antarctica.

Atmospheric emissions from fossil fuel burning (power and heat generation, aircraft, vehicles, etc.), emissions from incineration and other general activities can alter local environments. These activities can result in the introduction of particles as well as specific contaminants to the atmosphere (e.g., polycyclic hydrocarbons probably from exhaust). On a larger scale, they may affect the scientific value of Antarctica for monitoring low-level global changes in atmospheric aerosols.

When alternative energy systems, in this case Wind Energy, are introduced in Antarctica the following mitigations are expected:

- large scale reductions in the emission of greenhouse gases
- reduced risks of oil spills and damage to the environment
- significant reduction in the direct cost of power generation
- Increased efficiency of station operations due to the ability to automate more processes, which will result in a reduction of staffing levels.

The present work concerned the evaluation of a possibility to use wind energy as energy supply for the scientific stations in Antarctica, more in detail, the Italian scientific bases located at Terra Nova bay and Dome C Concordia.

From the analysis of the meteorological data, acquired in situ(Chapter1), downloaded online from the automatic weather stations (AWS)( Chapter 2), and with the use of WAsP9, Wind Data Analysis and Application Program, and WAsP Engineering2, it was possible to identify, with a certain range of uncertainty, the sites in which it is possible to introduce wind turbines in order to supply electricity, through the use of renewable energies, in this case wind energy, to the scientific stations located in Antarctica.

As specified before, in the present work, the analysis has been made for two specific sites in the Antarctic continent, Dome C 75°06′S 123°24′E) and Terra Nova bay (74°41′45.33313″S 164°05′31.83782″E).

For what concerning the analysis for Dome C, the WAsP9 results, show that the wind speed on the plateau is so low (mean wind speed at Dome C is only 2.32m.s⁻¹) that wind power is all but impractical. In fact the mean wind speed is below the cut-in velocity, which is the starting velocity limit of a wind turbine.
The analysis of the wind energy resources made for Terra Nova bay show that it is possible to introduce wind energy for supplying electricity to the scientific station located in the area. The mean wind speed velocity, in fact, is higher than the cut-in velocity limit of a wind turbine, in fact the results discussed in Chapter 3 show that the value is 6.32 m.s\(^{-1}\). The analysis of wind energy resources for Terra Nova Bay has been made for two locations, one along the coastline (site 2), and one at 400m a.s.l. (site 1). After having considered the wind characteristics and the turbulence intensity values, it is more convenient to install wind turbines generators at site 1. This is because the analysis shows greater values of wind speed and power density, for that site, and lower value of turbulence intensity, which affect the life time of the wind turbines.

Table 4.1 presents the wind turbines already installed in the Antarctica, which are currently supplying the scientific stations located in different parts of the continent.

<table>
<thead>
<tr>
<th>National Program</th>
<th>Station Base</th>
<th>Turbine Type</th>
<th>No.</th>
<th>Manufacturer</th>
<th>Annual Output (Kwh/year)</th>
<th>% Of Station Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>Belgrano II</td>
<td>none</td>
<td></td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argentina</td>
<td>Esperanza</td>
<td>none</td>
<td></td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argentina</td>
<td>Dumont</td>
<td>none</td>
<td></td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argentina</td>
<td>San Martin</td>
<td>none</td>
<td></td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>Casey</td>
<td>Horizontal</td>
<td>1</td>
<td>Vergnet</td>
<td>10,760</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>Mawson</td>
<td>Horizontal</td>
<td>2</td>
<td>Enercon</td>
<td>12,000</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Neumayer</td>
<td>Vertical</td>
<td></td>
<td>Heidelberg Motor, Germany</td>
<td>40,000</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>Maitri</td>
<td>Horizontal</td>
<td></td>
<td>Matic, UK</td>
<td>3 x 30 W + 1 x 300 W</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Syowa</td>
<td>Horizontal</td>
<td></td>
<td>Kawasaki Co. Ltd</td>
<td>2240kW/hr</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>Juan Carlos I</td>
<td>Horizontal</td>
<td>3</td>
<td>Solaris Bonny</td>
<td>3521 KWh</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>McMurdo</td>
<td>Horizontal</td>
<td></td>
<td>Northern Power, USA</td>
<td>9000 kW</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Installed wind turbine in Antarctica. Source: COMNAP

Australia is the first country to obtain a significant electricity supply for its Antarctic stations. Two 300 kW wind turbines were installed at Mawson in 2003 and now make a significant contribution to the station's power requirements. The Mawson wind turbine system ranks among the world's most innovative, and is capable of providing 600 kW of renewable power.

Due to the implementation of energy saving initiatives such as the installation of wind turbines and utilising a cogeneration system, considerable savings have been made in the

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amount of diesel fuel consumed on Australian Antarctic Stations. This benefits the environment due to reduced green house gas emissions while directly saving money.

Mawson station is able to produce environmentally friendly power via the wind turbines to supply both electricity and heat.

Figure 1: Mawson station in Antarctica. Source: http://www.aad.gov.au
From the Australian Antarctic division experience it can be said that the fierce Antarctic climatic conditions, with strong, gusty winds and freezing temperatures, place enormous stresses on wind turbine rotors and cause frequent mechanical failures. The logistics of installing efficient turbines pose significant challenges. For what concerning the installation issues, transportation needed special cranes and transport equipment is required to move the components from the re-supply vessel to the site. Alternative erection systems such as tilt-up or self-erecting climbing cranes will need to be considered for remote installations such as those in Antarctica. Also to be considered is the small period of opportunity over summer to undertake an installation.

For what concerning the icing problem, icing of blades, furling mechanisms and monitoring equipment would normally only be a problem at sites where onshore wind-blown wet snow or rain occurs. At most Antarctic stations, cold dry snow from the continental interior prevail and icing would not be an issue. Most large turbines are now available with blade heating systems, which prevent the formation of ice on the blade.

Using wind turbines will mark a major change in the Italian Antarctic stations, which now are still relying on diesel generators causing pollution in the ecologically fragile area. Diesel sets were deployed because wind turbines were thought not to be sturdy enough for the harsh environment.

Terra Nova bay station and Dome C don’t present any energy management programs, but energy planning studies with regards to Antarctic activities are in phase of planning. The main target of the study is to point out the best technology of energy saving and renewable energy utilize.
Appendix A: WAsP Eng2 turbulence reports for all sites

WAsP Engineering turbulence report for one site (‘Inexpressive Island Top’) and one wind (‘300° at 6.32 m/s’). Height = 50.0 m

Inexpressive Island Top

Project parameters
Project name: TNB giugno
Vector map source name: C:\Documents and Settings\MariannaImbimbo\Documents\DTU\Thesis\terranovabay_map\Tnb_new_rou1.map
Latitude of area: 52°
Calculation domain:
   East-West extension: 42579 m to 94329 m
   South-North extension: 22496 m to 76546 m
   Resolution: 575 m
   Number of points in East-West direction: 90
   Number of points in South-North direction: 94

Site description
Position and terrain elevation: (59200, 40545, 342.9) m
Dynamic Roughness: 0.10000 m
Height: 50.0 m

Mean flow and turbulence (Simui and Scanlan(1996)) for all winds

<table>
<thead>
<tr>
<th>Direction °</th>
<th>Horizontal speed [m/s]</th>
<th>Velocity tilt °</th>
<th>(u² + v²)¹/₂ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300° at 6.32 m/s</td>
<td>285.2</td>
<td>12.97</td>
<td>1.35</td>
</tr>
</tbody>
</table>

WAsP Engineering turbulence report for all sites and one wind (‘300° at 6.32 m/s’).
Height = 50.0 m

Project parameters
Project name: TNB giugno
Vector map source name: C:\Documents and Settings\MariannaImbimbo\Documents\DTU\Thesis\terranovabay_map\Tnb_new_rou1.map
Latitude of area: 52°
Calculation domain:
   East-West extension: 42579 m to 94329 m
   South-North extension: 22496 m to 76546 m
   Resolution: 575 m
   Number of points in East-West direction: 90
   Number of points in South-North direction: 94

Site list

<table>
<thead>
<tr>
<th>Site</th>
<th>x/m</th>
<th>y/m</th>
<th>Terrain elev./m</th>
<th>roughness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59200</td>
<td>40545</td>
<td>352.1</td>
<td>0.10000</td>
</tr>
<tr>
<td>2</td>
<td>59907</td>
<td>41252</td>
<td>176.8</td>
<td>0.10000</td>
</tr>
<tr>
<td>3</td>
<td>59731</td>
<td>41076</td>
<td>285.7</td>
<td>0.10000</td>
</tr>
<tr>
<td>4</td>
<td>59555</td>
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</tr>
<tr>
<td>5</td>
<td>59379</td>
<td>40724</td>
<td>334.5</td>
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</tr>
</tbody>
</table>

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<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>59204</td>
<td>40549</td>
<td>352.1</td>
<td>0.1000</td>
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<tr>
<td>7</td>
<td>59028</td>
<td>40373</td>
<td>352.1</td>
<td>0.1000</td>
</tr>
<tr>
<td>8</td>
<td>58852</td>
<td>40197</td>
<td>330.7</td>
<td>0.1000</td>
</tr>
<tr>
<td>9</td>
<td>58676</td>
<td>40021</td>
<td>216.3</td>
<td>0.1000</td>
</tr>
<tr>
<td>10</td>
<td>58500</td>
<td>39845</td>
<td>216.3</td>
<td>0.1000</td>
</tr>
<tr>
<td>11</td>
<td>70289</td>
<td>64062</td>
<td>473.3</td>
<td>0.1000</td>
</tr>
<tr>
<td>12</td>
<td>72807</td>
<td>66293</td>
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<td>0.0000</td>
</tr>
<tr>
<td>13</td>
<td>67459</td>
<td>31014</td>
<td>0.0</td>
<td>0.0000</td>
</tr>
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<td>14</td>
<td>66760</td>
<td>31898</td>
<td>0.0</td>
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</tr>
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<td>15</td>
<td>66060</td>
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<td>0.0000</td>
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<td>16</td>
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<td>0.0</td>
<td>0.0000</td>
</tr>
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<td>0.0000</td>
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<td>63962</td>
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<td>0.0000</td>
</tr>
<tr>
<td>19</td>
<td>63262</td>
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<td>0.1000</td>
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<td>62563</td>
<td>37207</td>
<td>109.4</td>
<td>0.1000</td>
</tr>
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<td>38091</td>
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<td>0.1000</td>
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<td>61164</td>
<td>38976</td>
<td>164.7</td>
<td>0.1000</td>
</tr>
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<td>23</td>
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Appendix B: Radio sounding plots for Terra Nova Bay and DOMEC

Figure 0-1: Dew point Temperature at Terra Nova bay

AWS Eneide (7353) Terra Nova Bay
Relative Humidity (%)
From 01/08/1997 at 00:00 UTC to 11/12/2007 at 03:00 UTC
http://www.dimantartide.it

Figure 0-2: Relative Humidity Terra nova bay

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Figure 0-3: atmospheric temperature Terra Nova Bay

Figure 0-4: Mixing ratio Terra Nova Bay

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Figure 0-5: Relative humidity at Terra Nova bay

Figure 0-6: Relative humidity at Dome C

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tnumber:s061762
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Figure 0-7: Skew and Temperature Radiosounding at Dome C
Figure 0-8 Temperature and relative humidity at Dome C

Figure 0-9 Wind speed at Dome C Concordia

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Appendix C: Observed Wind Climate calculated from WAsP9 for the Italian meteorological stations at Terra Nova Bay

'maria st' Observed Wind Climate
Produced on 15/08/2008 at 8.59.35 by licenced user: Marianna Imbimbo using WAsP version: 9.00.0148.

Site description: 'maria st'; Position: -75.06°N 164.24°E; Anemometer height: 10.00 m a.g.l.

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'Iola st' Observed Wind Climate

Produced on 15/08/2008 at 9.02.23 by licenced user: Marianna Imbimbo using WAsP version: 9.00.0148.

Site description: 'Untitled'; Position: 74.30°N 163.40°E; Anemometer height: 10.00 m a.g.l.

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Acknowledgments

This Master thesis project was performed under the supervision of:

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7. Wind Research at Risoe1-2-3(lecture notes 2007) Jakob Mann Wind Energy Department Risø National Laboratory/DTU


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Danish Technical University, 2006-2008
Assessing wind energy potential In Antarctica

Marianna Imbimbo, student number: s061762
Danish Technical University, 2006-2008


18. TURBULENCE CHARACTERISTICS OF THE STABLE BOUNDARYLAYER OVER A MID-LATITUDE GLACIER. PART II: PURE KATABATIC FORCING CONDITIONS
C. J. P. P. SMEETS1, P. G. DUYNKERKE2 and H. F. VUGTS1
1Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands; 2Institute for Marine and Atmospheric Research, University Utrecht, Princetonplein 5, 3584 CC, Utrecht, The Netherlands

19. OBSERVED WIND PROFILES AND TURBULENCE FLUXES OVER AN ICE SURFACE WITH CHANGING SURFACE ROUGHNESS
C. J. P. P. SMEETS
Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands P. G. DUYNKERKE
Institute for Marine and Atmospheric Research, Princetonplein 5, 3584 CC, Utrecht, The Netherlands H. F. VUGTS
Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands


21. A study of surface heat fluxes in the Ross Sea (Antarctica)
GIORGIO BUDILLON*, GIANNETTA FUSCO and GIANCARLO SPEZIE
Istituto di Meteorologia e Oceano Grafia, Istituto Universitario Navale, 6’ia Acton, 38, 801 33 Napoli, Itab *budillon@unina.it

22. Measuring Air-Ice Turbulent Exchange at Terra Nova Bay, Antarctica
Anna Maria Sempreviva1,2 and Alfredo Lavagnini1 1 Istituto di Scienze dell’Atmosfera e del Clima, section of Rome Area di Ricerca CNR di Roma Tor Vergata Via Fosso del Cavaliere 100, 00133 Rome, Italy2 Department of Wind Energy, Risø National Laboratory, PO BOX 49, 4000 Roskilde, Denmark e-mail: am.sempreviva@isac.cnr.it

23. The dynamics of idealized katabatic flow over a moderate slope and ice shelf
By IAN A. RENFREW British Antarctic Survey, Cambridge, UK

Cooperative Institute for Research in Environmental Sciences Department of Atmospheric and Oceanic Sciences
“Assessing wind energy potential In Antarctica”-Marianna Imbimbo, student number: s061762
Danish Technical University, 2006-2008
University of Colorado at Boulder
Boulder, CO 80309

