HANDBOOK OF
WIND RESOURCE ASSESSMENT

SIMON WATSON

WILEY

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Preface

When Wiley first approached me to write this book, I naively thought it would be a process that would take about a year or so. Fast-forward five years and, owing to the pressures of work and a change of job (and country), progress had been painfully slow. Then came the infamous global pandemic. Finally, the constraints of lockdown focused my mind and gave me the required impetus to (electronically) put pen to paper and deliver the completed manuscript to a very patient publisher. I say ‘complete’, though I still consider it a work in progress in many ways. Nonetheless, I hope it now contains sufficient useful information to practitioners in the field of wind resource assessment.

Wind energy has come a long way since I started working in the field back in 1990. It promises to make a major contribution to the energy transition as the world attempts to move away from the climate-damaging effects of burning fossil fuels. Where to site wind turbines and, just as importantly, where not to site them is a very practical and economic consideration. An accurate prediction of the expected wind resource at a potential wind farm site is, therefore, vital. Several books have been written about wind resource assessment, but I wanted something that was a practical guide with enough underlying theory for students and researchers to understand the measurement techniques that are used and the physical and statistical processes that are being modelled in trying to predict the behaviour of the wind. I also wanted to give some impression of the limitations of the measurements and models and their accuracy. In so doing, I have drawn on my experience of over 30 years of research in the field of wind energy and wind resource and the material that I have taught my students. I have also tried to draw on a wide range of literature to cover the different aspects of wind resource assessment in the many environments where wind turbines and wind farms are sited. I have deliberately stayed away from translating wind resource into energy yield (apart from a couple of very brief forays) as to cover the topic of wind farm yield, including wakes, would warrant a book on its own. Maybe this will be my next book when I have had enough time to recover from this venture.

I hope you will find this book a useful reference in understanding the science and engineering of wind resource assessment. Comments and feedback are welcome as I work on the next edition of what is an evolving field of research.

Simon Watson
The Hague

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About the Author

Simon Watson is Professor of Wind Energy Systems at Delft University of Technology. He has worked in the field of wind energy for over 30 years having graduated with a degree in physics from Imperial College London and a PhD from Edinburgh University. He began his career at the Energy Research Unit of the Rutherford Appleton Laboratory, near Oxford, UK before moving to a small start-up company which later became the green electricity supply company Good Energy. In 2001, he moved to the Centre for Renewable Energy Systems Technology at Loughborough University, Leicestershire, UK, becoming a full professor in 2010. In 2017, he moved to the Netherlands to take up his present position. Professor Watson has published widely in a range of wind energy topics, including resource assessment, wind turbine condition monitoring, and wind energy integration.

1

Introduction

1.1 Early Wind Measurements

Wind power has come a long way since the earliest windmills were built to grind corn for flour or wind pumps installed to drain the marshes for growing crops. The siting of these early machines was driven more by the practical necessity to be close to the local populace than for maximum economic benefit. Estimates of the local wind climate could mostly be obtained from local informed opinion or visual clues such as the angle of growth of trees, or indeed the complete absence of trees at extremely windy sites. Measurement of wind direction, as opposed to wind speed, has been made for far longer. One of the earliest-known examples of this is a weathervane in the shape of the god Triton which stood atop the Tower of the Winds in Athens when it was first built around 50 BCE or possibly earlier (see Figure 1.1). Weathervanes on buildings such as churches in the Western world have also been a common sight for centuries. Although giving an indication of the local wind direction at the time of observation, such early devices were not generally used in the recording of historical wind direction distribution. Before the development of instruments to measure the magnitude of the wind speed, human perception or slightly more objective visual indicators were used to provide a wind speed scale. For example, the famous English writer Daniel Defoe, following the Great Storm of 1703 which caused significant destruction in southern England, proposed an 11-point scale based on common phrases, as detailed in Table 1.1 (The Weather Window, n.d.). Scale point 6, describing ‘a top sail gale’, gives a clue to the importance of such information for the maritime community, and several such empirical wind speed scales devised by sailors were known to exist in the seventeenth century and probably much earlier. Possibly the most famous such scale was developed in 1805 by the

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Figure 1.1 The Tower of Winds in Athens. *Source:* Joanbanjo / Wikipedia Commons / CC BY-SA 3.0.

Irish hydrographer Francis Beaufort, a Royal Navy officer who later became a rear admiral and trained Robert FitzRoy who, in turn, founded what later became the UK Meteorological Office. The so-called Beaufort scale was designed as a 13-point scale based on the impact the wind speed had on the sails of a ship. These initial visual descriptors would be later converted into

Table 1.1 Daniel Defoe’s proposed verbal wind speed scale from around 1704.

Scale point	Description
0	Stark calm
1	Calm weather
2	Little wind
3	A fine breeze
4	A small gale
5	A fresh gale
6	A top sail gale
7	Blows fresh
8	A hard gale of wind
9	A fret of wind
10	A storm
11	A tempest

an actual measurement scale, which is still in use today for some applications (e.g. shipping broadcasts) and is detailed in Table 1.2.

Table 1.2 describes three units of measurement including the knot (often abbreviated to ‘kt’, or ‘kts’ if plural) which may be less familiar. This is a unit of speed derived from the days of sailing ships when sailors would use a long length of rope to which pieces of wood would be tied using knots at regular intervals which would be paid out from the stern (rear) of a ship as it travelled for a defined period of time determined using an hourglass. The number of knotted pieces of wood paid out in this time period would be used to calculate the speed of the ship. The modern knot is defined as one nautical mile (1.852 km) per hour which is equivalent to $0.514\,\mathrm{ms}^{-1}$. This unit is still used to describe the speed of ships or aircraft and is sometimes used by meteorological agencies to measure wind speed, though the unit of ms^{-1} is more widely used nowadays.

These early wind measurements were primarily of interest for mariners where the wind was an important source of motive power. Today, it is generally only leisure shipping which still uses the wind to provide propulsion. However, now our attention has turned to use of the wind for generating electrical power and the quest to decarbonise the energy system. In this book, we look at the science of wind resource assessment from the point of view of measurement and modelling.

Table 1.2 The Beaufort scale with modern equivalent units of wind speed.

Wind force	Description	Wind speed			Specifications *(italics refer to conditions at sea)*	Wave height		Sea state
		km/h	mph	knots		Probable (m)	Max. (m)	
0	Calm	<1	<1	<1	Smoke rises vertically *Sea like a mirror*	—	—	0
1	Light air	1–5	1–3	1–3	Direction shown by smoke drift but not by wind vanes *Sea rippled*	0.1	0.1	1
2	Light breeze	6–11	4–7	4–6	Wind felt on face; leaves rustle; wind vane moved by wind *Small wavelets on sea*	0.2	0.3	2
3	Gentle breeze	12–19	8–12	7–10	Leaves and small twigs in constant motion; light flags extended *Large wavelets on sea*	0.6	1.0	3
4	Moderate breeze	20–28	13–18	11–16	Raises dust and loose paper; small branches moved *Small waves, fairly frequent white horses*	1.0	1.5	3–4
5	Fresh breeze	29–38	19–24	17–21	Small trees in leaf begin to sway; crested wavelets form on inland waters *Moderate waves, many white horses*	2.0	2.5	4

6	Strong breeze	38–49	25–31	22–27	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty *Large waves, extensive foam crests*	3.0	4.0	5
7	Near gale	50–61	32–38	28–33	Whole trees in motion; inconvenience felt when walking against the wind *Foam blown in streaks across the sea*	4.0	5.5	5–6
8	Gale	62–74	39–46	34–40	Twigs break off trees; generally impedes progress *Wave crests begin to break into spindrift*	5.5	7.5	6–7
9	Strong gale	75–88	47–54	41–47	Slight structural damage (chimney pots and slates removed) *Wave crests topple over, spray affects visibility*	7.0	10.0	7
10	Storm	89–102	55–63	48–55	Seldom experienced inland; trees uprooted; considerable structural damage *Sea surface largely white*	9.0	12.5	8
11	Violent storm	103–117	64–72	56–63	Very rarely experienced; accompanied by widespread damage *Medium-sized ships lost to view behind waves; sea covered in white foam; visibility seriously affected*	11.5	16.0	8
12	Hurricane	≥118	≥73	≥64	Devastation *Air filled with foam and spray; very poor visibility*	≥14	—	9

Source: taken from The Royal Meteorological Society (n.d.).

1.2 The Need for Wind Resource Assessment

The need for accurate assessment of the wind conditions at a site has been driven by the rapid expansion of wind power worldwide. By the end of 2020, a total capacity of 743 GW had been installed around the globe (Lee and Zhao, 2021). The global weighted-average installed cost for onshore wind energy in 2020 was \$1355 kW^{-1} (IRENA, 2020). For a 100 MW wind farm this equates to a total investment of \$140 million. The equivalent cost offshore is somewhat higher at around \$3185 kW^{-1} (though costs have fallen significantly) and a 'typical' offshore wind farm may have a combined capacity approaching 1000 MW. This equates to an investment cost of just over \$3 billion. In terms of the levelised cost of energy, the most recent figures are stated to be \$0.041 kW^{-1} onshore and \$0.084 kW^{-1} offshore (IRENA, 2020). A well-used measure of the operational efficiency of a wind farm is that of the capacity factor which is the ratio of the long-term power output of a farm to its total rated power capacity. A typical onshore wind farm may have a capacity factor of 25–35%, and an offshore wind farm may exceed 50%. Figure 1.2 shows the dependence of capacity factor on average wind speed (Watson et al., 2015) based on a Rayleigh distribution of wind speeds (wind speed distributions are discussed in Chapter 4). Assuming an onshore average hub height wind speed of 7 ms^{-1}, and a value of 10 ms^{-1} offshore, a 5% uncertainty in the long-term wind speed estimate represents an uncertainty of 9% in the capacity factor for the onshore farm and 5% for the offshore site in this example.

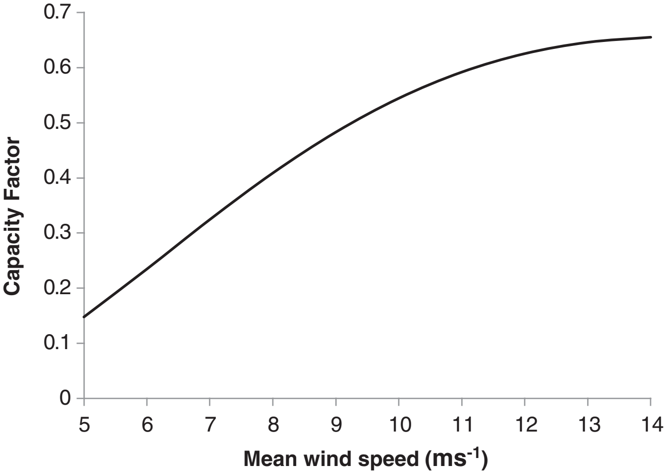

Figure 1.2 Capacity factor of a Vestas V80 2MW wind turbine as a function of wind speed. *Source:* adapted from Watson et al. (2015).

This uncertainty equates to $24 million for a 100 MW onshore wind farm and $460 million for a 1000 MW offshore wind farm. It is clear from these numbers that a modest investment to reduce the uncertainty in a long-term mean wind speed estimate for a site can have a large impact in terms of the viability of a wind farm, where frequently the lowest projected energy yield given the expected uncertainties is used in a financial investment decision.

1.3 A Brief Overview of the Wind Resource Assessment Process

To assess the long-term energy yield of a wind farm is a multistep process and is shown schematically in Figure 1.3. Initially, a wind atlas may be used to assess the approximate wind resource over a wide area to identify a candidate wind farm site. This site will then be the subject of a more comprehensive measurement campaign based on measurements made onsite at one or more masts covering the area of potential interest. A measurement campaign, for practical reasons, may last only 1–2 years, which is insufficient to capture the climatological variability that would be expected over the lifetime of a typical wind farm (20–25 years). To account for this, some form of long-term correction is required. This, in turn, will only give detailed information about the long-term resource at

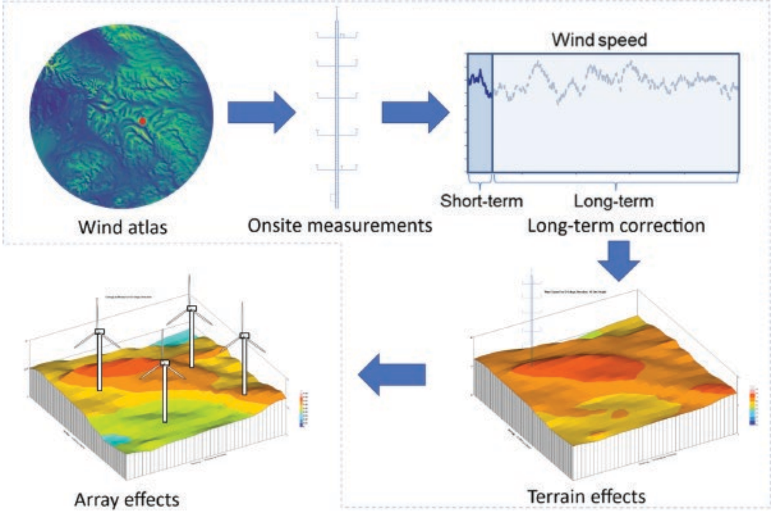

Figure 1.3 The wind resource assessment process. The scope of this book is shown within the dashed box. *Source:* the 3D surface plots were reproduced from ReSoft WindFarm software (resoft.co.uk) / with permission of Alan Harris.

the mast (or masts). The next step is to extrapolate the wind speed conditions from the mast (or masts) over the wider area within which a wind farm is expected to be built. This area will depend on several factors, including the area available; the expected total capacity of the wind farm, which will be driven by factors that may be economically related or linked to the capacity of the nearby grid; and the size of the turbines. The spatial extrapolation of the wind speed, both horizontally and vertically, to take account of different potential turbine sizes, is generally carried out using a physical or statistical model which can be of various levels of sophistication depending on the complexity of the terrain and the size of the wind farm, and thus the size of the investment. The final step is to determine the optimum siting of the turbines considering the spatial variation in the wind speed and the aerodynamic interactions between the turbines (i.e. array effects, including wakes). This last step may require an iterative process, so it may be that a simpler, faster numerical, or physically based empirical model is used first that may be slightly less accurate than a more sophisticated model but is accurate enough to determine an optimum layout. A final stage of fine-tuning the layout and determining the expected long-term energy yield may then be carried out using a more sophisticated but computationally intensive numerical model. It should be noted that the emphasis of this book is on assessing the long-term *wind speed* rather than the energy yield and so only the steps within the dashed box in Figure 1.3 are covered in the remaining chapters. Array effects are relatively complex and warrant a detailed book in themselves. It is for this reason that they are considered outside the scope of this book.

1.4 Layout of this Book

The remainder of this book describes the important elements in the wind resource assessment process. Chapter 2 introduces the basic atmospheric properties of the wind and the structure of the atmospheric boundary layer. Chapter 3 looks at the measurement of the key variables in the process of assessing wind resource, including a description of the most commonly used instruments. Chapter 4 considers the temporal variability in wind speed over different scales, ranging from years to less than a second, and their importance in resource assessment and reviews the most popular mathematical distributions which are used to characterise the statistical properties of the wind for the long and short term. Chapter 5 describes how the spatial variation of the wind is modelled, starting with the governing equations for fluid flow and the models which are based on these.

Chapter 6 looks at empirical and semi-empirical modelling approaches which can be used to predict spatial variation in the wind in specific cases. Chapter 7 reviews some of the well-known orographic test cases which have been used to validate and test different wind resource model predictions. Chapter 8 considers statistical approaches which are used to extrapolate short-term wind speed measurements to the long-term and techniques to interpolate spatial data that do not require complex physical models. Chapter 9 describes the technique of reanalysis to reconstruct long-term wind speed time series. It also looks at some of the more popular reanalysis datasets, and their use in wind resource assessment, including the production of wind atlases. Chapter 10 reviews mesoscale phenomena and how they might potentially affect the variability of the local wind resource. Chapter 11 reviews the evidence for potential future trends in global wind speed patterns and how this may affect wind resource assessment.

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2

The Atmospheric Boundary Layer

In wind resource assessment, the spatial and temporal characteristics of wind are most relevant close to the ground, though with the advent of airborne wind energy (AWE) the resource higher up is of some relevance. Nonetheless, the conditions within the atmospheric boundary layer (ABL) are of most importance for modern wind energy generation systems. In this chapter, the structure of the ABL and how it may be parameterised for the purposes of wind resource assessment are described.

2.1 The Structure of the Atmospheric Boundary Layer

The ABL defines that region close to the earth's surface where the influence of the surface has an impact on the wind profile, above which is the free atmosphere where the wind is assumed to be geostrophic, which is described in Section 2.3. Typically, the height of the ABL, h_{ABL}, is around 1–2 km during daytime when the air is well mixed but can be much lower during calm night-time periods. The ABL is divided into two main layers: the Ekman layer and the surface layer as shown in Figure 2.1.

In the Ekman layer, the behaviour of the wind is little influenced by the surface but is strongly influenced by the Coriolis force and there is a significant turning of the wind direction with height. The surface layer extends to around 100–200 m above the ground, and this is the layer of most significance for wind energy. In this layer, Coriolis effects are somewhat less important, but the wind profile is strongly influenced by the characteristics of the underlying surface. This layer consists of an upper inertial sublayer where the wind profile shows a strong shear with height which depends on the orography and the aerodynamic surface roughness length z_0. Below z_0, in the roughness sublayer, the wind flow is stagnant and molecular

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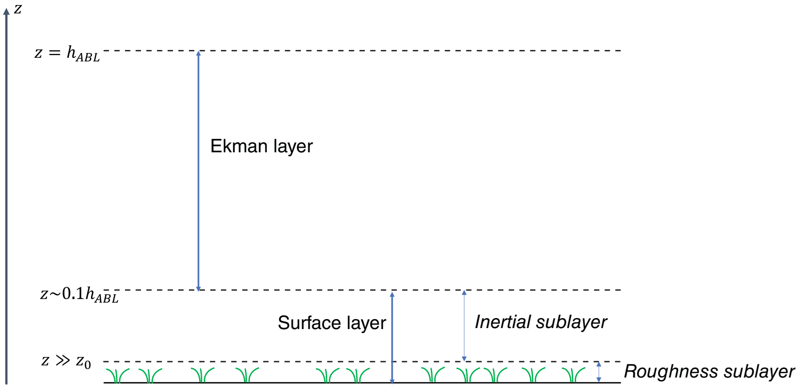

Figure 2.1 The structure of the atmospheric boundary layer (ABL): h_{ABL} is the height of the ABL, z is height above the surface, and z_0 is the aerodynamic roughness length due to roughness elements on the surface. *Source:* adapted from Garratt (1994).

diffusion processes are important. From observations, a classification scheme has been developed relating terrain type to roughness length. This was originally developed by Davenport and was later updated by Wieringa (Davenport, 1960; Wieringa, 1992). Table 2.1 describes this scheme and also lists the approximate equivalent shear exponent factor for flat terrain explained in Section 2.2.

Over water surfaces, the roughness length is not constant and depends on the wind speed above the surface. A commonly used expression to calculate the roughness length over a water surface which is applicable for open sea is the *Charnock relationship* (Charnock, 1955)

$$z_0 = \alpha_c \frac{u_*^2}{g} \tag{2.1}$$

where α_c is a constant determined from empirical observations and has a value of ≈ 0.014 (although it has been seen to have a higher value for coastal sites), $g = 9.81\ \mathrm{ms}^{-2}$ is the acceleration due to gravity, and u_* is the friction velocity, which, as we will see in Section 2.2, is related to shear stress at the surface. Other more sophisticated relationships have been formulated to take account of sea fetch and wave age, but this equation remains the most used in wind resource assessment.

Table 2.1 Wieringa's updated version of Davenport's original roughness classification scheme (Wieringa, 1992). Approximately equivalent flat terrain shear exponent factors (α) are also shown (see Section 2.2).

z_0 (m)	α	Terrain description
0.0002 (Sea)	0.09	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac, and concrete, with a free *fetch* (length of sea over which the wind blows) of several kilometres
0.005 (Smooth)	0.12	Featureless land surface without any noticeable obstacles and with negligible vegetation (e.g. beaches, pack ice without large ridges, morass, and snow-covered or fallow open country)
0.03 (Open)	0.16	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights (e.g. grazing land without windbreaks, heather, moor, and tundra, runway area of airports)
0.10 (Roughly open)	0.20	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g. low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights
0.25 (Rough)	0.24	Recently developed 'young' landscape with high crops or crops of varying height, and scattered obstacles (e.g. dense shelterbelts, vineyards) at relative distances of about 15 obstacle heights
0.5 (Very rough)	0.29	'Old' cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights Also, low large vegetation with small interspaces, such as bushland, orchards, young densely planted forest
1.0 (Closed)	0.37	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights (e.g. mature regular forests, homogeneous cities or villages)
2.0 (Chaotic)	≥ 0.49	Centres of large towns with mixture of low-rise and high-rise buildings Also, irregular large forests with many clearings

2.2 The Surface Layer Wind Speed Profile

When estimating the mean wind speed at the hub height of a wind turbine, it is important to have an accurate model of the variation of wind speed with height in the surface layer. An engineering approximation to calculate the wind speed u_2 at a height z_2 based on the wind speed u_1 at a height z_1 is the *power law*

$$u_2 = u_1 \left(\frac{z_2}{z_1} \right)^{\alpha} \tag{2.2}$$

where α is the shear exponent factor, which depends on the terrain orography, surface coverage, and surface layer stability. Table 2.1 gives approximate values of α for different terrain types, assuming flat terrain and a neutral surface layer.

The most widely used parameterisation of the vertical variation in wind speed which has a more physically based justification is the *logarithmic profile*, the stability dependent (*diabatic*) form of which is given by the integration of the surface layer relationship

$$\frac{\partial u}{\partial z} = \frac{u_*}{\kappa z} \phi_m \left(\frac{z}{L} \right) \tag{2.3}$$

to give

$$u(z) = \frac{u_*}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) - \psi_m \left(\frac{z}{L} \right) \right] \tag{2.4}$$

where κ is the von Kármán constant (≈ 0.4), ϕ_m is a stability function which depends on height z, and *Monin–Obukhov length* L and ψ_m is given by

$$\psi_m = \int_0^{z/L} \frac{(1 - \phi_m)}{z'} dz' \tag{2.5}$$

Strictly, the logarithmic profile is only applicable in flat homogeneous terrain. The friction velocity u_* relates to the shear stress τ_x at the ground and the air density ρ

$$u_* = \sqrt{\frac{\tau_x}{\rho}} \tag{2.6}$$

The shear stress for a Newtonian fluid is given by the expression

$$\tau_x = \mu \frac{\partial u}{\partial z} \tag{2.7}$$

where μ is the dynamic viscosity. This equation is normally applied on the microscopic scale, but by analogy it can be applied at the macroscopic scale for wind flow where the microscopic viscosity is replaced by an eddy viscosity K_M.

An alternative expression for τ_x relates the stress to the rate at which the horizontal momentum of the air is transferred vertically to the surface by turbulence

$$\tau_x = -\rho \overline{u'w'} \tag{2.8}$$

where u' and w' are turbulent fluctuations in the streamwise and vertical wind speeds, respectively. Combining Eqs. (2.6) and (2.8) gives

$$u_*^2 = -\overline{u'w'} \tag{2.9}$$

So u_* is a measure of the momentum flux close to the ground and is assumed to be constant in the surface layer. This means that Eq. (2.4) can be used to extrapolate a measured wind speed from one height to another in a similar way to the power law.

At this point, it is useful to introduce several variables:

- T : the absolute temperature
- T_v : the virtual absolute temperature
- θ : the potential temperature
- θ_v : the virtual potential temperature.

The virtual absolute temperature T_v of a moist parcel of air is the equivalent absolute temperature T at which a dry parcel of air would have a total pressure and density the same as the moist parcel of air and is given by

$$T_v = T\,(1 + 0.61q) \tag{2.10}$$

where q is the specific humidity which defines the mass of water vapour per unit mass of moist air.

The potential temperature θ is the absolute temperature that would result if a parcel of dry air were brought adiabatically[1] to a reference pressure ($p_{ref} = 1000\,\text{hPa}$)

$$\theta = T\left(\frac{p}{p_{ref}}\right)^{-R_d/C_p} \tag{2.11}$$

where R_d is the specific gas constant of dry air ($= 287.05\,\text{J}\,\text{kg}^{-1} \cdot \text{K}^{-1}$) and C_p is the specific heat capacity at constant pressure ($= 1005.7\,\text{J}\,\text{kg}^{-1} \cdot \text{K}^{-1}$ at 273 K for dry air).

The virtual potential temperature θ_v is the equivalent of θ for a moist parcel of air based on the virtual absolute temperature T_v, i.e.

$$\theta_v = T_v\left(\frac{p}{p_{ref}}\right)^{-R_d/C_p} \tag{2.12}$$

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[1] Without any heat transfer to or from the parcel of air.