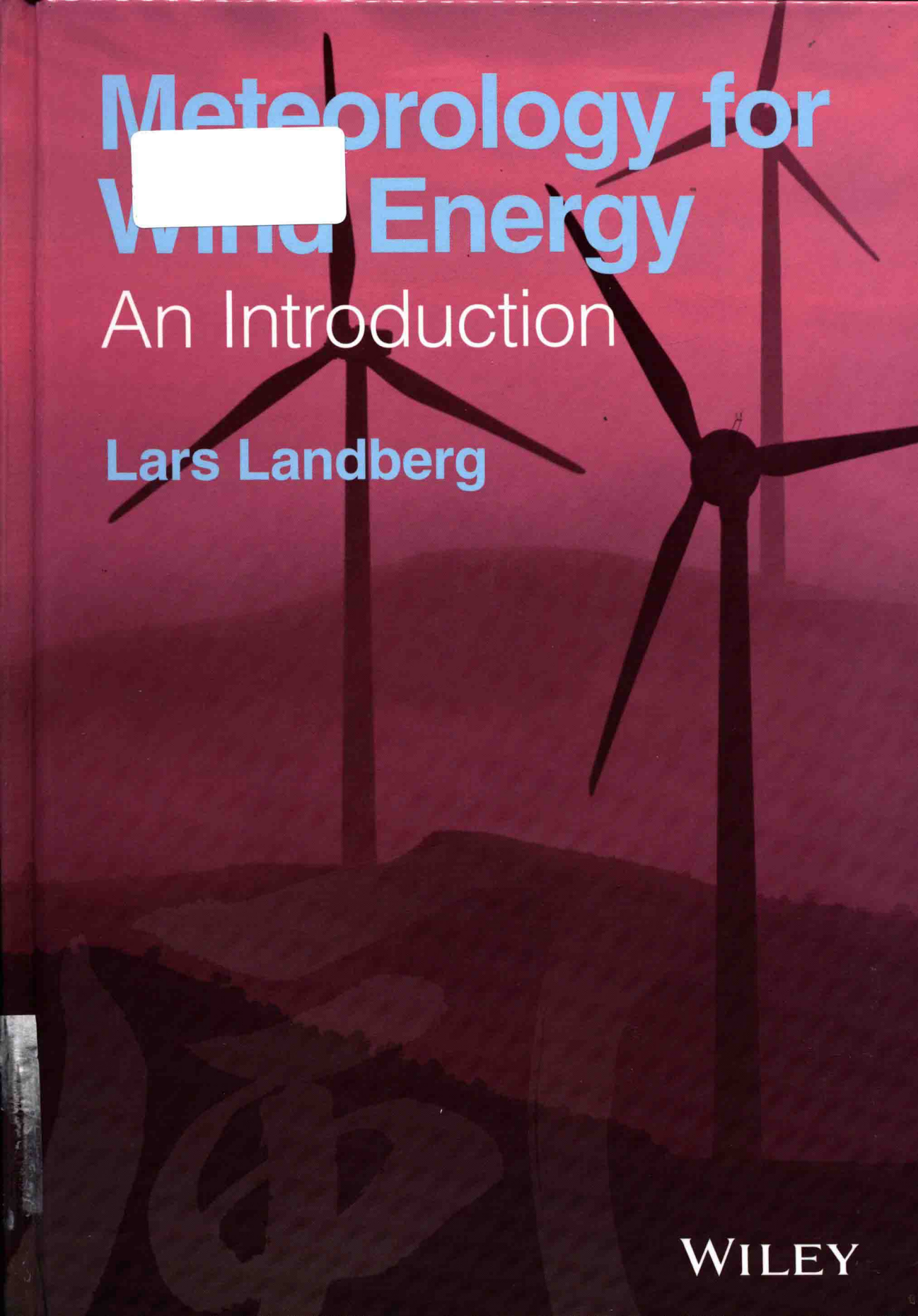
Meteorology for Wind Energy

An Introduction

Lars Landberg



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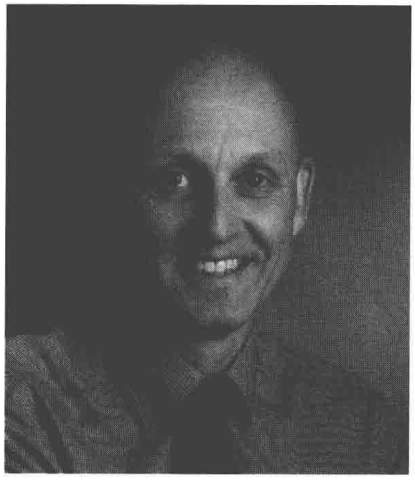
To my family: My wife, Frances, and our two big boys, Marcus and Lucas, thank you so much for your support and understanding.

About the Author



Lars Landberg (born 1964) has been working in the wind energy field since 1989: the first 18 years at Risø National Laboratory (now DTU Wind), a research lab in Denmark, and since then at Garrad Hassan (now DNV GL), a global wind energy consulting company. His main areas of expertise are wind resource estimation and short-term prediction of wind power. Lars has taught meteorology-related courses to the wind energy industry since the first Risø WAsP course in 1991. Lars has a PhD in physics and geophysics from the University of Copenhagen and an MBA from Warwick Business School, United Kingdom.

Foreword

Lars Landberg is right that there are too many of us using the wind without understanding it. Lars' book will help address that problem and it will entertain as well as educate. He has already taught much of the wind industry about meteorology and, through this book his undoubted didactic talents will reach a much wider audience. Part of his job at Garrad Hassan was to encourage free thinking and who better to do that than someone who cut his meteorological teeth on the Martian weather? You can be sure that he will bring a refreshing approach to this difficult subject.

Our generation has witnessed an extraordinary transition in the electricity industry. Wind used to occupy a position on its fringes where we were patronised as eccentric and naïve ideologists – now this fantastic industry is part of the main stream driven by clean and powerful wind. Being able to make a reasonable job of predicting both the behaviour of the wind and the resulting behaviour of the turbines and wind farms has been an essential part of that success.

I have known Lars Landberg for a long time, first as a fellow wind energy enthusiast, then as a colleague and a friend. He was a member of the Garrad Hassan board and it was certainly stimulating to have a board member who had written a book called 'Strategy: No Thanks!'. From that title you can deduce that this book will have unexpected dimensions to it. I came across the Ekman spiral (my first acquaintance with meteorology) while writing my undergraduate thesis in 1973. I am ashamed to say that I did not know that Ekman was a Swede until I opened this book.

The wind is the free, clean fuel that distinguishes our industry from the expensive dirty stuff that others use but it is also the source of the loads that break the turbines. My meeting with Ekman was in the same year that I made my first wind mill alas destroyed by the wind very quickly. The wind therefore commands both our gratitude and our respect. This book will help us all to deliver that respect by initiating a wider understanding of the wind. Well done Lars!

Andrew Garrad
23 March 2015

Preface

Having taught various aspects of meteorology to all kinds of people working in wind energy since 1991, I was very happy to accept the kind offer from Wiley to write a book on the subject. Wind energy, probably like many other 'new' fields, not having a dedicated and established way of teaching the subject (like e.g. medicine), sees people entering the field from a multitude of technical and academic backgrounds, but rarely from meteorology. Often, therefore, the meteorology that people know, is taught to them on a need-to-know basis when they join their companies. This means that I, over the years, have met many people who have lacked the fundamentals of meteorology (general as well as the more specific area of boundary-layer meteorology), and when attending the various courses that I have taught, have expressed great satisfaction in knowing the basics, even though this is 'only' nice to know.

When writing this book, I have had the above-mentioned varied technical and academic background of the reader in mind, so do not expect a PhD-level book, but expect to be able to understand the meteorological basics of what you do every day. As a general principle, I have gone for hand-waving understanding, rather than strict physical explanations, so some corners have inevitably been cut, but I have done my utmost to make sure you are being made aware of this when it happens. In doing so, I might also have made some errors (I hope not of course), and the website (larslandberg.dk/windbook, see QR code in margin) will be updated as soon as I have been made aware of any.

Another important point to stress is that the atmosphere is a **complex, interconnected, three-dimensional physical system**. This means that in order to understand it fully (which nobody does, actually), one needs to solve the entire set of physical laws that govern this system, this is first of all difficult, but secondly it only explains the atmosphere to the level of a black box. So what we will do in this book is that we will zoom in on different aspects, like the low-pressure system, which of course only is a reflection of the laws of motion, temperature and humidity, but dissecting it into fronts helps us understand it much better, in a very useful hand-waving way.

The general idea is that I use simple maths to explain things, so if I can ask you not to be afraid of this, I promise you that I shall guide you through the various lines of reasoning in a safe manner! Also, it is a good idea to fire your favourite spreadsheet up; it is good for looking at numbers and plotting them. In the more difficult or important parts of the text, I have inserted exercises directly in the text, and in many cases I have also done those exercises as part of the text. Despite the fact that you have the answer right after the exercise, please

try to have a go at it first; your understanding of the subject will benefit immensely. If you absolutely hate maths, there is also a path through the book, where you can just read the text and not do any of the exercises, it will not be as fun, of course, but it can be done.

For people interested in digging just one layer deeper, I have inserted boxes in various places along the way. These boxes shall focus on one topic, often quite technical, and explain a bit more about it. If the subject does not interest you, you should be able to skip these boxes without disturbing your overall understanding of the text.

To make the various equations a bit more personal, I have also, in many places, inserted a brief description of the person or persons behind the equation. There are a lot of men in those boxes, despite the fact that I have tried to get both sexes represented.

The structure of the book is that we start with the meteorological basics, where the scene will be set and some fundamentals of general meteorology will be covered. We will then discuss measurements, where some measurement philosophy, theory and basics will be covered. Whether measurements are carried out by means of a mast or a remote-sensing device, the result is a picture of the vertical structure of the atmosphere at the measuring location, we will therefore cover the theory of this vertical structure, often called the *wind profile*. The wind profile is the result of atmospheric flow on many scales and understanding the flows makes us able to infer the profiles (and in many cases vice versa). Two further aspects will then be covered: turbulence and wakes.

Having gone from measurements via flow on all scales to wakes, the circle is complete in some sense; however, in order to understand these topics in more detail, we have introduced a great number of models and it is appropriate to have a chapter on the general aspects of *modelling* (Chapter 8), where no new models will be introduced, but the more philosophical and theoretical aspects of modelling will be discussed.

Lars Landberg
Copenhagen, Denmark

Kaze: The Japanese kanji for 'wind' by Shigemi Nakata

Acknowledgements

The material for this book has been built up in my mind ever since I started working in wind energy, which is 26 years ago. I have met so many people who have taught, inspired and discussed with me, and it is, unfortunately, impossible to list them all here. But I would like to highlight and deeply thank the following people:

At the University of Copenhagen, Aksel Walløe Hansen has been the supervisor on my Masters as well as my PhD thesis: you have always been a great supervisor, and always asked difficult questions that have brought me forward!

At Risø (now DTU Wind), I would like to thank the entire Meteorology Group, but in particular, the members of the WAsP team: Niels Gylling Mortensen, Ole Rathmann, Lisbeth Myllerup and Rikke Nielsen. We have worked together on many of the ideas that you find in this book; thank you for a great time together. Outside the WAsP team my good colleagues Søren E. Larsen, Erik Lundtang Petersen, Leif Kristensen, Jakob Mann and Hans E. Jørgensen also deserve a great thank you, again many of the ideas in my head (and in this book) originated from discussions with you guys.

At Garrad Hassan (now DNV GL), I would in particular like to thank Andrew Garrad. He was the one who saw a business in teaching meteorology to wind energy people and prompted me to develop the course that many of the ideas in this book are based on.

Before starting the book, I would also like to thank the five anonymous reviewers for taking the time to look through the original proposal for the book and making some very useful suggestions, many of which have been included. Wolfgang Schlez, for help in understanding the depths of the Ainslie wake model and also for reading through the wakes chapter and providing very valuable input. Jean-François Corbett, for meticulously reading through the Local Flow and Modelling chapters and also producing very valuable feedback.

I would also like to thank Kurt S. Hansen and winddata.com, for allowing me to use the data for the exercises and examples in the chapter on Measurements.

Thank you also to Søren William Lund, who so readily and without warning lined up a lot of instruments for a 'photo session'.

Shigemi Nakata, for the beautiful kanji that you find on the front cover and on page xvi: domo arigato gozaimasu!

Andrew Garrad has also very kindly written the foreword to this book: thank you very very much, Andrew.

And a general thank you to all the copyright holders who have all – without exception – replied swiftly and positively to my many requests for use of their material.

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List of Abbreviations

ABL	Atmospheric boundary layer
agl	above ground level
CFD	Computational fluid dynamics
DNS	Direct numerical simulation
ENSO	El Ninõ Southern Oscillation
GPS	Global Positioning System
GTS	Global Telecommunication System
IBL	Internal boundary layer
IEC	International Electrotechnical Commission
IPK	International Prototype of the Kilogram
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
ITCZ	Inter Tropical Convergence Zone
LES	Large eddy simulation
MCP	Measure–Correlate–Predict
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PBL	Planetary boundary layer
RANS	Reynolds-averaged Navier–Stokes
SAR	Synthetic Aperture Radar
SOI	Southern Oscillation Index
SST	Sea surface temperature
UN	United Nations
WAsP	Wind Atlas Analysis and Application Programme
WMO	World Meteorological Organisation
WRF	Weather Research and Forecasting