Physical Principles of Meteorology and Environmental Physics

Global, Synoptic and Micro Scales

David Blake
The University of Queensland, Australia

Robert Robson
James Cook University, Townsville and
The Australian National University, Canberra, Australia

World Scientific
NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI
For Josephine and Robert John Robson
About the Authors

David Blake (PhD, University of Queensland) is a physics researcher at the University of Queensland, and managing director of Solar Sells Pty. Ltd., a renewable energy consultancy. Robert Robson (PhD, ANU; Fellow, Royal Meteorological Society; Fellow, American Physical Society) is a physics and meteorology researcher and lecturer at the Australian National University and James Cook University, and a former forecaster with the Australian Bureau of Meteorology.
Preface

Meteorology is generally regarded as a discipline in its own right and is normally taught at universities (if at all) separately from mainstream physics. In general the research literature is divided along similar lines, with some outstanding exceptions to this rule, e.g., Lorenz’s 1963 paper in the Journal of the Atmospheric Sciences, which has provided a springboard for the burgeoning field of chaos and nonlinear dynamics. One of the goals of our book is to bring the two fields a little closer, for there has never been a better time to do so.

At the time of writing, the public debate over the global climate has reached a frenzied pitch with the release of the 4th Report of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch/). Moreover, a widespread perception is that water, rather than oil or even terrorism, will be the other main global political issue of the century. Never has it been more important for the scientific community to provide the decision makers with objective and accurate information. Unfortunately the global climate models upon which the IPCC, economists, politicians and others rely to make their decisions, are by their very nature complex and opaque to all but the specialist few. This provides fertile ground for the global warming skeptics, and there is by no means general acceptance of anthropogenic warming, even among meteorologists and climatologists.

This book provides both theoretical and practical grounding in meteorology, with an emphasis on phenomena in the boundary layer, and aims at furnishing either a stand alone course or a firm platform for the reader to proceed with further study in one of the specialist areas, including global climate modeling. The theory component derives from a course of about 40 lectures given at the senior undergraduate and graduate level, and is of a
standard comparable with the Australian Bureau of Meteorology’s graduate training course for weather forecasters.

The main practical component concerns a research project measuring CO2 exchange between the atmosphere and (a) native tropical rainforest and (b) introduced sugar cane in tropical north-eastern Australia. The aim here is to introduce the reader to experimental techniques and procedures, but there is a particularly important lesson to be learned from the results: during the peak growth phase, it is observed that sugar cane sequestrates more than three times as much carbon dioxide as does rainforest on an average daily basis! This result seems to contradict the widespread belief that clearing rainforest and replacing it with crops is self-evidently a bad thing, but of course one has to take many other factors into account. Whatever its implications for climate modeling might be, it only serves to reinforce our belief that unsubstantiated assumption is never a substitute for hard physics. That, in a nutshell spells out what this book is all about.

David Blake
The University of Queensland, Australia

Robert Robson
James Cook University, Townsville and
The Australian National University, Canberra, Australia

January, 2008
Acknowledgments

The authors would like to thank Professor Steve Turton and Dr Michael Liddell of James Cook University who provided the equipment used in the experimental component of this work. The authors are also very grateful to Dr. Hank de Wit, of the Australian Bureau of Meteorology, for help with the aerological diagram which accompanies this book. The support of the Queensland Sugar Research and Development Corporation is gratefully acknowledged.
Contents

About the Authors vii
Preface ix
Acknowledgments xi
List of Figures xix
List of Tables xxv

Theoretical Foundations 1

1. The Big Picture 3
   1.1 Introduction 3
   1.2 The Atmospheric Environment 5
      1.2.1 Composition of the Atmosphere 5
      1.2.2 Vertical Structure of the Atmosphere 7
      1.2.3 The Horizontal Picture 9
      1.2.4 Water in the Atmosphere 9
   1.3 Solar Radiation 11
      1.3.1 Solar Constant 11
      1.3.2 Radiative Equilibrium, Atmospheric Solar Energy Budget 12
   1.4 Estimation of Average Terrestrial Temperatures 12
   1.5 Enhanced Greenhouse Effect 15
   1.6 Problems for Chapter 1 16
Problems for Chapter 1 16
2. Atmospheric Thermodynamics and Stability
   2.1 Equation of State of the Atmosphere .......... 21
   2.2 Atmospheric Thermodynamics ................. 23
   2.3 Hydrostatic Equilibrium, Height Computations .. 28
   2.4 Thermodynamic Diagrams ..................... 31
   2.5 Examples on the Use of the F160 Diagram ....... 33
   2.6 Lapse Rate and Stability, Adiabatic Lapse Rate ... 36
   2.7 Saturated Adiabatic Lapse Rate ............... 39
   2.8 Stable Atmosphere, Brunt-Vaisala Frequency .... 41
   2.9 Model Atmospheres ................................ 41
      2.9.1 Homogeneous Atmosphere ..................... 41
      2.9.2 Isothermal Atmosphere ..................... 42
      2.9.3 Constant Lapse Rate Atmosphere ............ 42
   Problems for Chapter 2 ............................... 43

3. Air Flow on a Rotating Earth
   3.1 Introduction, Equation of Motion ................. 47
   3.2 Decoupling of Vertical and Horizontal Motion ..... 51
   3.3 Geostrophic Approximation ...................... 52
   3.4 Balanced Curved Flow: Natural Coordinates ....... 53
      3.4.1 Acceleration in Natural Coordinates ........ 53
      3.4.2 Equation of Motion in Natural Coordinates ... 55
   3.5 Inertial, Cyclostrophic and Gradient Flow ....... 56
      3.5.1 Inertial Flow ................................ 56
      3.5.2 Cyclostrophic Flow .......................... 57
      3.5.3 Geostrophic Flow ............................. 58
      3.5.4 Gradient Flow ................................. 58
      3.5.5 Trajectories and Streamlines ................. 60
   3.6 Frictional Effects ................................ 60
   3.7 Vertical Variation of the Geostrophic Wind ....... 62
      3.7.1 Isobaric Coordinates ........................ 62
      3.7.2 Wind Shear and Thermal Wind Equation ........ 64
      3.7.3 Implications of the Equations ............... 65
   Problems for Chapter 3 ............................... 69

4. Divergence, Vorticity and Circulation
   4.1 Equation of Continuity ............................ 73
   4.2 Mechanism of Pressure Change .................... 75
## Contents

4.3 Vorticity and Circulation Theorems .......................... 77
4.4 The Vorticity Equation and its Implications ............... 79
4.5 Potential Vorticity ......................................... 83
4.6 Further Comments on Vorticity .............................. 84
4.7 Rossby Waves .................................................. 85
Problems for Chapter 4 ............................................. 87

5. Boundary Layer Meteorology .................................... 91
5.1 Introduction ..................................................... 91
5.2 Turbulence in the Atmosphere ................................. 91
5.3 Turbulent Balance Equation ................................. 94
  5.3.1 Momentum Balance (Equation of Motion) .............. 96
  5.3.2 Energy Balance ........................................... 96
  5.3.3 Moisture Balance Equation ............................. 96
5.4 Calculation of Vertical Flux; Flux-Gradient Relationships ............................................. 97
5.5 Turbulent Transport Equations ............................... 98
5.6 Surface Boundary Layer ....................................... 98
5.7 Momentum Flux, Vertical Wind Profile ...................... 99
5.8 Energy Fluxes at the Earth’s Surface ...................... 103
5.9 Planetary Boundary Layer ................................. 107
  5.9.1 Heat Transfer in the Planetary Boundary Layer ..... 108
  5.9.2 Wind in the Planetary Boundary Layer ...................... 111
  5.9.3 Dispersion of Pollutants from an Elevated Source 113
5.10 Richardson Number, Obukhov Length .......................... 116
Problems for Chapter 5 ............................................. 118

6. Biometeorology, Environmental Biophysics .................. 123
6.1 Introduction ..................................................... 123
6.2 Metabolism, Maintenance of Body Temperature .......... 124
6.3 Molecular Versus Turbulent Transport ....................... 125
6.4 Modes of Heat Transfer ....................................... 128
  6.4.1 Radiation .................................................. 128
  6.4.2 Convective Heat Transfer .................................. 130
  6.4.3 Evaporation, Latent Heat Exchange ..................... 130
  6.4.4 Heat Conduction ........................................... 131
6.5 Summary of Formulae and Expression for Total Heat Loss 133
6.6 The Importance of Latent Heat: Some Examples ........... 133
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6.1</td>
<td>Energy Expended in Respiration</td>
<td>134</td>
</tr>
<tr>
<td>6.6.2</td>
<td>Heat Loss from a New-Born Infant</td>
<td>136</td>
</tr>
<tr>
<td>6.7</td>
<td>Inside the Organism: When Heat Conduction is Important</td>
<td>137</td>
</tr>
<tr>
<td>6.7.1</td>
<td>Temperature Rise in a Working Muscle</td>
<td>137</td>
</tr>
<tr>
<td>6.7.2</td>
<td>Conduction and Convection</td>
<td>139</td>
</tr>
<tr>
<td>6.8</td>
<td>Transpiration in Plants</td>
<td>141</td>
</tr>
<tr>
<td>6.8.1</td>
<td>Resistance to Diffusion</td>
<td>141</td>
</tr>
<tr>
<td>6.8.2</td>
<td>Leaf Structure</td>
<td>142</td>
</tr>
<tr>
<td>6.8.3</td>
<td>Diffusion from a Circular Orifice, Perforated Screen</td>
<td>142</td>
</tr>
<tr>
<td>6.8.4</td>
<td>Transpiration from Leaves</td>
<td>145</td>
</tr>
<tr>
<td>6.9</td>
<td>Flux Versus Temperature, Fact Versus Fiction</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>Problems for Chapter 6</td>
<td>148</td>
</tr>
</tbody>
</table>

**Experiments in the Tropical Boundary Layer**  

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Introduction to the Experiments</td>
<td>157</td>
</tr>
<tr>
<td>7.1</td>
<td>Measurements</td>
<td>157</td>
</tr>
<tr>
<td>7.2</td>
<td>A Brief Survey of Eddy Correlation Measurements</td>
<td>161</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Instrumentation</td>
<td>162</td>
</tr>
<tr>
<td>7.2.2</td>
<td>Topography, Vegetation and Geophysical Variability</td>
<td>164</td>
</tr>
<tr>
<td>7.3</td>
<td>Practical Considerations</td>
<td>167</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Approaches to Measurement of Net Ecosystem Exchange</td>
<td>169</td>
</tr>
<tr>
<td>8.1</td>
<td>Introduction</td>
<td>169</td>
</tr>
<tr>
<td>8.2</td>
<td>Comparison of Flux Measurement Techniques</td>
<td>170</td>
</tr>
<tr>
<td>8.2.1</td>
<td>Flux Gradient Methods</td>
<td>170</td>
</tr>
<tr>
<td>8.2.2</td>
<td>Eddy Correlation Methods</td>
<td>170</td>
</tr>
<tr>
<td>8.3</td>
<td>Approaches to NEE Measurement</td>
<td>171</td>
</tr>
<tr>
<td>8.3.1</td>
<td>The Balance Equation</td>
<td>171</td>
</tr>
<tr>
<td>8.3.2</td>
<td>The Reynolds Approach</td>
<td>172</td>
</tr>
<tr>
<td>8.3.3</td>
<td>The WPL Approach</td>
<td>173</td>
</tr>
<tr>
<td>8.3.4</td>
<td>The Lee Approach</td>
<td>176</td>
</tr>
<tr>
<td>8.3.5</td>
<td>Reconciling the WPL and Lee Approaches</td>
<td>178</td>
</tr>
<tr>
<td>8.4</td>
<td>Summary</td>
<td>180</td>
</tr>
</tbody>
</table>
9. Application of the WPL Method ................................................................. 183
   9.1 Introduction .................................................................................... 183
   9.2 Coordinate Frames ......................................................................... 183
      9.2.1 General .................................................................................. 183
      9.2.2 Coordinate Rotations ............................................................. 184
   9.3 Fourier Analysis .............................................................................. 186
   9.4 Averaging Periods .......................................................................... 188
   9.5 Sampling Rates ............................................................................... 190
   9.6 Sensor Placement ............................................................................ 192
      9.6.1 Sensor Height ......................................................................... 192
      9.6.2 Sensor Separation, Flow Distortion and Path Length Averaging .... 192
   9.7 Summary ......................................................................................... 193

10. Experimental Methods ................................................................. 195
   10.1 Introduction .................................................................................. 195
   10.2 Instrumentation ........................................................................... 196
      10.2.1 Sonic Anemometer ................................................................. 196
      10.2.2 Infrared Gas Analyser (IRGA) ............................................ 197
      10.2.3 Datalogger ............................................................................ 197
      10.2.4 Flux Measurement System .................................................. 197
   10.3 Calibration .................................................................................... 198
      10.3.1 Sonic Anemometer ................................................................. 198
      10.3.2 Infrared Gas Analyser .......................................................... 199
   10.4 Processing Software ..................................................................... 201
      10.4.1 Fourier Analysis ................................................................. 201
      10.4.2 Logger Program ................................................................... 203
      10.4.3 Analysis Program ................................................................. 203
   10.5 Error Analysis .............................................................................. 206
   10.6 Experimental Sites ...................................................................... 208
   10.7 Summary ....................................................................................... 209

11. Results and Analysis ..................................................................... 211
   11.1 Introduction .................................................................................. 211
   11.2 Time Series Analysis .................................................................... 212
      11.2.1 Rainforest ........................................................................... 212
      11.2.2 Sugar Cane ......................................................................... 219
      11.2.3 Summary ............................................................................. 223
11.3 Effects of Averaging Period and Sampling Rate
Variations on Flux Measurements .......................... 228
11.3.1 Averaging Periods .................................. 228
11.3.2 Sampling Rates ..................................... 229
11.4 Fluxes ..................................................... 231
11.5 Error Analysis .............................................. 239
11.6 Summary of Experimental Issues ......................... 239
11.7 Main Results ............................................... 241
11.8 Recommendations for Further Study ....................... 242
11.8.1 Allowance for Convergence in the Horizontal Wind 242
11.8.2 Energy Balance Closure ............................... 242
11.8.3 Transfer Functions .................................... 242
11.8.4 Equipment Mounting ................................. 243
11.8.5 Detrending ............................................. 243
11.8.6 Software ............................................... 243

Appendix A Some Useful Numerical Values 245
Appendix B Saturated Vapour Density and Pressure of H₂O 247
Appendix C Vector Identities 249

Bibliography 251
References 255
Index 257
## List of Figures

1.1 Schematic representation of the vertical temperature structure in the lowest 100 km of the atmosphere .......... 8
1.2 Schematic representation of radiative equilibrium in the Earth-atmosphere system .......................... 12
1.3 Average solar radiation budget in the Earth-atmosphere system .................................................. 13
1.4 Simplified model of radiative transfer processes in the atmosphere ............................................. 13
1.5 Schematic representation of the three possible radiative equilibrium points for a model absorption coefficient a(T) .. 19

2.1 Schematic representation of adiabats and isotherms on a $p - \alpha$ diagram .............................. 26
2.2 Cartesian coordinate systems used in meteorology ................................................................. 28
2.3 Vertical column of air, showing forces acting on a slab ......................................................... 28
2.4 Graphical method of determination of mean temperature of a layer from observed radiosonde temperature trace .......................... 30
2.5 Adiabats, isotherms and isobaric surface on an emagram ..................................................... 32
2.6 Method of calculation of thermodynamic parameters .......................................................... 34
2.7 Method of calculation of lifting condensation level (LCL) and cloud heights for data shown in Table 2.1 .................. 35
2.8 Schematic illustration of stability in a simple mechanical system ............................................. 36
2.9 Illustration of a rising air parcel and environmental lapse rate referred to in the text ....................... 37
2.10 Four types of plume behaviour under various conditions of stability and instability. At left: broken lines, dry adiabatic lapse rate; full lines, existing lapse rates

2.11 Schematic representation of a turbulent eddy in the boundary layer

3.1 Schematic illustration of Buys-Ballots law

3.2 Model of the Earth showing latitude measured positive in the northern hemisphere, and negative in the southern hemisphere

3.3 Horizontal forces (x-direction only shown) acting on an air parcel

3.4 The coordinate system describing curved flow

3.5 Calculation of $\delta \theta$

3.6 Inertial flow in both hemispheres

3.7 (i) $R_t > 0$, $\frac{\partial \theta}{\partial h} < 0$ (ii) $R_t < 0$

3.8 Force balance in the four types of gradient flow: (a) regular low, (b) regular high, (c) anomalous low, (d) anomalous high

3.9 Balanced flow in the presence of friction

3.10 Schematic representation of two isobaric surfaces in the vertical plane

3.11 Schematic representation of geostrophic flow in relation to height contours on an isobaric surface

3.12 Vertical section of the atmosphere showing a layer of air bounded by two isobaric surfaces

3.13 Global mean zonal temperature distribution and vertical wind shear in the southern hemisphere

3.14 Horizontal cold air advection and backing of wind with height

3.15 Diagrams for Worked Example

3.16 Problem 3.1

3.17 Problem 3.4

3.18 Problem 3.6

4.1 A fluid element with horizontal cross section $\delta A$

4.2 Schematic representation of vertical columns of air showing successive zones of surface convergence and divergence

4.3 Frictional convergence in a northern hemisphere cyclone

4.4 Circulation around an arbitrary loop $L$
List of Figures

4.5 Solid body circulation at angular velocity \( \omega \) .......................... 79
4.6 Spin of an element of the Earth's surface of area \( \delta A \) .............. 81
4.7 Anticyclonic circulation resulting from divergence .................. 82
4.8 Vertical cross section showing motion of a fluid element over a north-south mountain range ............................................. 84
4.9 Clockwise rotation of a "paddle wheel" in a shear flow \( \partial u/\partial y > 0 \) ........................................................................ 85

5.1 Schematic representation of average wind flow near the surface ................................................................. 92
5.2 Schematic representation of turbulent eddy motion near the surface ............................................................... 93
5.3 Simple model of an eddy of dimension \( l \) .................................. 93
5.4 Schematic representation of the way in which \( z_0 \) and \( u_* \) are determined from empirical data (+) .................. 101
5.5 Measurement of mean wind versus height for young sugar cane ................................................................. 102
5.6 Partitioning of radiative energy fluxes for day and night .............................................................................. 103
5.7 Surface energy fluxes, day and night, with the energy balance represented by \( R_N = H + LE + G \) .................. 104
5.8 Schematic representation of the (potential) temperature variations in the atmospheric boundary layer over the course of a day .................................................................................. 109
5.9 The Ekman spiral, as given by (5.72), showing winds at three heights .......................................................... 113
5.10 Dispersion of pollutants from an elevated source in the presence of an elevated inversion at height \( l \) .............. 114
5.11 Normalized concentration calculated from (5.76) for a low-level inversion .................................................. 117

6.1 A living "organism" and some forms of energy and matter exchange with its environment .............................. 124
6.2 Schematic diagram showing how the body reacts to overheating in order to maintain body temperature at normal values 126
6.3 Linear temperature profile in slab geometry .................................................. 132
6.4 Simplified physical model of the breathing process .............................................................................. 134
6.5 Cylindrical model of a muscle .................................................................................. 137
6.6 Temperature as a function of radial distance in the cylindrical muscle ........................................................ 139
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>Vertical velocity amplitude spectrum for rainforest, 12pm, day 78, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.3</td>
<td>Horizontal velocity amplitude spectrum for rainforest, 12am, day 78, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.4</td>
<td>Horizontal velocity amplitude spectrum for rainforest, 12pm, day 78, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.5</td>
<td>Vertical power spectrum for rainforest, 11am, day 75, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.6</td>
<td>Horizontal velocity power spectrum for rainforest, 11am, day 75, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.7</td>
<td>Vertical velocity weighted energy density spectrum for rainforest, 11am, day 75, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.8</td>
<td>Horizontal velocity weighted energy density spectrum for rainforest, 11am, day 75, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.9</td>
<td>Mean temperature and mean variance of wT time series (five minute means), rainforest, day 78</td>
</tr>
<tr>
<td>11.10</td>
<td>Mean temperature and mean variance of wρe time series (five minute means), rainforest, day 78</td>
</tr>
<tr>
<td>11.11</td>
<td>Mean temperature and mean variance of wρe time series (five minute means), rainforest, day 78</td>
</tr>
<tr>
<td>11.12</td>
<td>Mean variance of vertical wind and mean variance of wT time series (five minute means), rainforest, day 78</td>
</tr>
<tr>
<td>11.13</td>
<td>Vertical velocity amplitude spectrum for sugar cane, 12am, day 23, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.14</td>
<td>Vertical velocity amplitude spectrum for sugar cane, 12pm, day 23, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.15</td>
<td>Horizontal velocity amplitude spectrum for sugar cane, 12am, day 23, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.16</td>
<td>Horizontal velocity amplitude spectrum for sugar cane, 12pm, day 23, 1hr @ 20Hz</td>
</tr>
<tr>
<td>11.17</td>
<td>Vertical velocity power spectrum for sugar cane, 7am, day 21, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.18</td>
<td>Horizontal velocity power spectrum for sugar cane, 7am, day 21, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.19</td>
<td>Weighted vertical velocity energy density spectrum for sugar cane, 11am, day 21, 3.8 days @ 0.2Hz</td>
</tr>
<tr>
<td>11.20</td>
<td>Weighted horizontal velocity energy density spectrum for sugar cane, 11am, day 21, 3.8 days @ 0.2Hz</td>
</tr>
</tbody>
</table>
11.21 Mean temperature and mean variance of $wT$ time series (five minute means), sugar cane, day 23 .............. 226
11.22 Mean temperature and mean variance of $w\rho_v$ time series (five minute means), sugar cane, day 23 .............. 226
11.23 Mean temperature and mean variance of $w\rho_v$ time series (five minute means), sugar cane, day 23 .............. 227
11.24 Mean variance of vertical wind and mean variance of $wT$ time series (five minute means), sugar cane, day 23 .............. 227
11.25 $CO_2$ Flux for various averaging periods (as marked) ......... 228
11.26 $CO_2$ Flux for various averaging periods (as marked) ......... 230
11.27 $CO_2$ Flux for various sampling rates (as marked) .......... 230
11.28 Eight day mean sensible heat flux – rainforest ............. 232
11.29 Eight day mean uncorrected latent heat flux – rainforest ... 232
11.30 Eight day mean corrected latent heat flux – rainforest ....... 233
11.31 Eight day mean uncorrected $CO_2$ flux – rainforest .......... 233
11.32 Eight day mean corrected $CO_2$ flux – rainforest .......... 234
11.33 Eight day mean WPL correction to the $CO_2$ flux – rainforest 234
11.34 Eight day mean sensible heat flux – sugar cane ............. 235
11.35 Eight day mean uncorrected latent heat flux – sugar cane ... 235
11.36 Eight day mean corrected latent heat flux – sugar cane ....... 236
11.37 Eight day mean uncorrected $CO_2$ flux – sugar cane .......... 236
11.38 Eight day mean corrected $CO_2$ flux – sugar cane .......... 237
11.39 Eight day mean WPL correction to the $CO_2$ flux – sugar cane 237

B.1 Saturated vapour density ($\rho_v$) and saturated vapour pressure
  ($\epsilon_s$) for water ........................................... 247
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Various length scales encountered in physical systems</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Mass and energy in the Earth-atmosphere system</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Composition of dry air below ~80 km</td>
<td>6</td>
</tr>
<tr>
<td>2.1</td>
<td>Radiosonde data at Townsville on 26.4.74 at 0900</td>
<td>34</td>
</tr>
<tr>
<td>2.2</td>
<td>Stability criteria for saturated and unsaturated air</td>
<td>39</td>
</tr>
<tr>
<td>3.1</td>
<td>The various allowed solutions of (3.34) for the northern hemisphere f &gt; 0</td>
<td>59</td>
</tr>
<tr>
<td>5.1</td>
<td>Typical values of roughness length and friction velocity</td>
<td>101</td>
</tr>
<tr>
<td>6.1</td>
<td>Representative values for emissivity</td>
<td>129</td>
</tr>
<tr>
<td>11.1</td>
<td>Peak CO₂ flux value for varying averaging periods (polynomial fit to data, day 23)</td>
<td>229</td>
</tr>
<tr>
<td>11.2</td>
<td>Summary of results of eight-day mean flux measurements over rainforest and sugar cane</td>
<td>231</td>
</tr>
<tr>
<td>D.1</td>
<td>Saturated vapour density (ρₚ) and saturated vapour pressure (eₛ) for water</td>
<td>247</td>
</tr>
</tbody>
</table>