Micrometeorology

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Edited for English by Carmen J. Nappo

Springer

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Cover illustration: Measuring system consisting on a sonic anemometer (CSAT3, Campbell Sci. Inc.) and an IR gas analyzer (LI-7500, LI-COR Inc.) for estimating the fluxes of sensible and latent heat and carbon dioxide using the eddy-covariance method as explained in Chapter 4.1 (Photograph: Foken)

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Preface

After the successful issue of two editions of the German book *Applied Meteorology – Micrometeorological basic* I am happy that the Springer publishing house has agreed to publish an English edition for a probably much larger community of readers. The present edition is the translation of the second German edition of 2006 with only small corrections and changes. It is named only *Micrometeorology* because this title is more appropriate to the context of the book. I am extremely happy that I found with Carmen Nappo a scientist, who has edited my first translation into the English language in such a way that keeps alive the style of a German or European book and also makes it easily readable.

It was not my aim to transfer the book into a style where the German and Russian backgrounds of my teachers cannot be seen. On the other hand, I hope that the reader will find some references of interest. These are mainly references to German standards or historical sources. The book is addressed to graduate students, scientists, practical workers, and those who need knowledge of micrometeorology for applied or ecological studies. The main parts are written as a textbook, but also included are references to historical sources and recent research even though the final solutions are still under discussion. Throughout the book, the reader will find practical hints, especially in the chapters on experimental techniques where several such hints are given. The appendix should give the reader an overview of many important parameters and equations, which are not easily found in other books.

Now I hope that the number of small printing errors converges to zero, but I would be very happy if the reader would inform me about such problems or necessary clarifications as well as parts that should be added or completed in a hopefully further edition.

I am extremely thankful for the wonderful cooperation with Carmen Nappo in the translation of the book and to Ute who gave me the opportunity and encouragement to do this time consuming work.

Bayreuth and Knoxville, Spring 2008

Thomas Foken

Preface of the 1st German Edition

Even though the beginning of modern micrometeorology was started 60–80 years ago in the German speaking countries, the division of meteorological phenomena according their scales in time and space is generally not used in Germany. Perhaps because the classic book by R. Geiger (1927) *The climate near the ground* focused on a phenomenological description of the processes at the ground surface, the word *micro* became associated with very small-scale processes. The development of micrometeorology combined with progress in turbulence theory started in the 1940s in the former Soviet Union, and continued e.g. in Australia and the USA. In these countries, *micrometeorology* is a well-established part of meteorology of processes near the ground surface occurring on scales some decameters in height and some kilometers in horizontal extension. In the Russian-speaking countries, *experimental meteorology* is more common than micrometeorology, but not connected to meteorological scales, and instead is used for all experiments. Because the area of investigation of micrometeorology is nearly identical with the area of human activity, it is obvious that applied meteorology and micrometeorology are connected; however, the latter is more theoretical and orientated toward basic research. That both fields are connected can be seen in the papers in the *Journal of Applied Meteorology*. In Germany, applied meteorology is well established in the environment-related conferences METTOOLS of the German Meteorological Society, but the necessary basics are found only with difficulty mostly in the English literature. While Flemming (1991) gave a generally intelligible introduction to parts of meteorology which are relevant for applied meteorology, the present book gives the basics of micrometeorology. It is therefore understandable that a book in German will provide not only quick and efficient access to information, but also encourage the use of the German scientific language. Furthermore, this book seeks to give the practical user directly applicable calculating and measuring methods and also provides the basics for further research.

This book has a long history. Over nearly 30 years spent mainly in experimental research in micrometeorology, it was always fascinating to the author, how measuring methods and the applications of measuring devices are directly dependent on the state of the atmospheric turbulence and many influencing phenomena. This connection was first discussed in the book by Dobson et al. (1980). The present book is a modest attempt along these lines. It is nearly a didactically impossible task to combine always divided areas of science and yet show their interactions. Contrary to the classical micrometeorological approach of looking only at uniform ground surfaces covered with low vegetation, this book applies these concepts to heterogeneous terrain covered with tall vegetation. References are given to very recent research, but these results may change with future research. The progressive application of micrometeorological basics in ecology (Campbell and Norman 1998) makes this step necessary.

The sources of this book were lectures given in *Experimental Meteorology* at the Humboldt-University in Berlin, in *Micrometeorology* at the University of

Potsdam, and since 1997 similar courses at the University of Bayreuth. The book would not be possible to write without my German and Russian teachers, my colleagues and co-workers, and master and PhD students who supported me in many cases. Many publishing houses and companies very kindly supported the book with pictures or allowed their reproduction. Mr. Engelbrecht has drawn some new pictures. Special thanks are given to Prof. Dr. H. P. Schmid for his critical review of the German manuscript, and to Ute for her understanding support of the work and for finding weaknesses in the language of the manuscript.

Bayreuth, October 2002

Thomas Foken

Contents

Symbols

Symbols that are used only in single equations are not included in this list, but are explained in the text.

a	albedo	
a	absolute humidity	kg m^{-3}
a	scalar (general)	*
a_G	molecular heat conductance coefficient in soil	W m^{-1} K^{-1}
a_T	molecular heat conductance coefficient in air	W m^{-1} K^{-1}
A	rain fall	mm
A	Austausch coefficient	*
b	accuracy (bias)	*
b	constant used for REA measurements	
b_{st}	species-dependent constant according to Jarvis	W m^{-2}
B	sublayer Stanton number	
Bo	Bowen ratio	
C_D	drag coefficient	
C_E	Dalton number	
C_G	volumetric heat capacity	W s m^{-3} K^{-1}
C_H	Stanton number	
C_n^2	refraction structure-function parameter	m$^{-2/3}$
C_T^2	temperature structure-function parameter	K m$^{-2/3}$
$C_{x,y}$, Co	cospectrum (general)	*
c	sound speed	m s^{-1}
c	concentration (general)	*
c	comparability	*
c_p	specific heat at constant pressure	J kg^{-1} K^{-1}
c_v	specific heat at constant volume	J kg^{-1} K^{-1}
c_x	structure constant (general)	
d	displacement height	m
d	measuring path	m
D	molecular diffusion constant (general)	*
D	structure function (general)	*
Da_k	Kolmogorov-Damköhler number	
Da_t	turbulent Damköhler number	
DOY	day of the year: Jan. 1 = 1	
e	basis of the natural logarithm	
e	water vapor pressure	hPa
e'	fluctuation of the water vapor pressure	hPa
E	water vapor pressure at saturation	hPa
E	power spectra (general)	*
E_a	ventilation term	hPa m s^{-1}
EQT	equation of time	h

Eu	Euler number	
f	function (general)	
f	frequency	s^{-1}
f	Coriolis parameter	s^{-1}
f	footprint function	*
f_g	cut frequency	s^{-1}
f_N	Nyquist frequency	s^{-1}
F	flux (general)	*
F	power spectra (general)	*
Fi	inverse Froude number	
Fi_o	inverse external Froude number	
F_w	ventilation flow	$kg\ m^{-1}\ s^{-1}$
g	acceleration due to gravity	$m\ s^{-2}$
h	height of a volume element	m
h	wave height	m
H	water depth	m
I	long-wave radiation	$W\ m^{-2}$
$I\downarrow$	down-welling long-wave radiation	$W\ m^{-2}$
$I\uparrow$	up-welling long-wave radiation	$W\ m^{-2}$
I^*	long-wave net radiation	$W\ m^{-2}$
k	wave number	m^{-1}
k	absorption coefficient	m^{-1}
k	reaction rate	*
K	turbulent diffusion coefficient (general)	$m^{-2}\ s^{-1}$
K_E	turbulent diffusion coefficient of latent heat	$m^{-2}\ s^{-1}$
K_H	turbulent diffusion coefficient of sensible heat	$m^{-2}\ s^{-1}$
K_m	turbulent diffusion coefficient of momentum	$m^{-2}\ s^{-1}$
$K\downarrow$	down-welling short-wave radiation (at surface) global radiation	$W\ m^{-2}$
$K\downarrow_{extr}$	extra terrestrial radiation	$W\ m^{-2}$
$K\uparrow$	reflected short-wave radiation (at the ground surface)	$W\ m^{-2}$
l	mixing length	m
L	Obukhov length	m
L	characteristic length	m
L	distance constant	m
L_h	horizontal characteristic length	m
L_s	shearing parameter	m
L_z	vertical characteristic length	m
LAI	leaf area index	$m^2\ m^{-2}$
m	mixing ratio	$kg\ kg^{-1}$
n	dimensionless frequency	
N	precipitation	mm
N	Brunt-Väisälä frequency	Hz

N	cloud cover	
N	dissipation rate (general)	*
Nu	Nusselt number	
Og	ogive function	*
p	air pressure	hPa
p_0	air pressure at sea level	hPa
p'	pressure fluctuation	hPa
PAR	photosynthetically active radiation	μmol m^{-2} s^{-1}
Pr	Prandtl number	
Pr_t	turbulent Prandtl number	
q	specific humidity	kg kg^{-1}
q_c	specific concentration	*
q_a	specific humidity near the ground	kg kg^{-1}
q_e	conversion factor from specific humidity into water vapor pressure	kg kg^{-1} hPa^{-1}
q_s, q_{sat}	specific humidity by saturation	kg kg^{-1}
q_*	scale of the mixing ratio	kg kg^{-1}
Q	source density (general)	*
Q_c	dry deposition	kg m^{-2} s^{-1}
Q_E	latent heat flux	W m^{-2}
Q_E	latent heat flux expressed as a water column	mm
Q_G	ground heat flux	W m^{-2}
Q_H	sensible heat flux	W m^{-2}
Q_{HB}	buoyancy flux	W m^{-2}
Q^*_s	net radiation	W m^{-2}
Q_η	source density of the η parameter	*
r	correlation coefficient	
r_a, r_t	turbulent atmospheric resistance	s m^{-1}
r_c	canopy resistance	s m^{-1}
r_g	total resistance	s m^{-1}
r_{mt}	molecular-turbulent resistance	s m^{-1}
r_{st}	stomatal resistance	s m^{-1}
r_{si}	stomatal resistance of a single leaf	s m^{-1}
R	resistance	Ω
R	relative humidity	%
R_G	relative humidity near the surface	%
R_L	gas constant of dry air	J kg^{-1} K^{-1}
R_s	relative humidity near the surface	%
R_W	gas constant of water vapor	J kg^{-1} K^{-1}
R	universal gas constant	mol kg^{-1}K^{-1}
Re	Reynolds number	
Re_s	roughness Reynolds number	
Rf	flux Richardson number	
Ri	Richardson number, gradient Richardson number	

Ri_B	bulk Richardson number	
Ri_c	critical Richardson number	
Ro	Rossby number	
s	precision	*
s_c	temperature dependence of specific humidity at saturation	$kg\ kg^{-1}\ K^{-1}$
S	power spectra (general)	*
S	solar constant	$W\ m^{-2}$
Sc	Schmidt number	
Sc_t	turbulent Schmidt number	
Sd	duration of sunshine	h
Sd_0	astronomical maximal possible sunshine duration	h
Sf	radiation error	K
t	time	s
t	temperature	°C
t'	wet-bulb temperature	°C
T	transfer function	
T	temperature, temperature difference	K
T'	fluctuation of the temperature	K
T_*	temperature scale	K
T^+	dimensionless temperature	
T_K	transmission coefficient	
T_0	surface temperature	K
T_p	wavelet coefficient	*
T_s	sonic temperature	K
T_v	virtual temperature	K
u	wind speed	$m\ s^{-1}$
u	longitudinal component of the wind velocity	$m\ s^{-1}$
u_g	horizontal component of the geostrophic wind velocity	$m\ s^{-1}$
u_{10}	wind velocity at 10 m height	$m\ s^{-1}$
u'	fluctuation of the longitudinal component of the wind velocity	$m\ s^{-1}$
u_*	friction velocity	$m\ s^{-1}$
v	lateral component of the wind velocity	$m\ s^{-1}$
v_g	lateral component of the geostrophic wind velocity	$m\ s^{-1}$
v'	fluctuation of the lateral component of the wind velocity	$m\ s^{-1}$
v_D	deposition velocity	$m\ s^{-1}$
V	characteristic velocity	$m\ s^{-1}$
w	vertical component of the wind velocity	$m\ s^{-1}$

w'	fluctuation of the vertical component of the wind velocity	$m\ s^{-1}$
w_*	Deardorff (convective) velocity	$m\ s^{-1}$
w_0	deadband for REA method	$m\ s^{-1}$
x	fetch	m
x	horizontal direction (length)	m
x, X	measuring variable (general)	*
y	horizontal direction (length, perpendicular to x)	m
y, Y	measuring variable (general)	*
Z	geopotential height	m
z	height (general, geometric)	m
z_i	mixed-layer height	m
z_m	measuring height	m
z_R	reference height	m
z_0	roughness parameter, roughness height	m
z_{0eff}	effective roughness height	m
z_{0E}	roughness height for water vapor pressure	m
z_{0T}	roughness height for temperature	m
z'	height (aerodynamic)	m
z^+	dimensionless height	
z_*	height of the roughness sublayer	m
α	angle of inflow	°
α_{pt}	Priestley-Taylor coefficient	
α_0	ratio of the exchange coefficients of sensible heat to momentum	
α_{0E}	ratio of the exchange coefficients of latent heat to momentum	
β	Kolmogorov constant (general)	
γ	psychrometeric constant	$hPa\ K^{-1}$
γ	factor in O'KEYPS-Formel	
Γ	profile coefficient	$m\ s^{-1}$
Γ_d	dry adiabatic temperature gradient	$K\ m^{-1}$
δ	depth of the internal boundary layer	m
δ	depth of the molecular-turbulent (viscous) sublayer	m
δ_{ij}	Kronecker symbol	
δ_w	thickness of the mixing layer	m
δ_T	thickness of the thermal internal boundary layer	m
δ_T	thickness of the molecular temperature boundary layer	m
δ_T^+	dimensionless thickness of the molecular temperature boundary layer	m
Δc	concentration difference	*
Δe	water vapor pressure difference	hPa

ΔP	pressure difference	hPa
ΔT	temperature difference	K
Δu	wind velocity difference	m s^{-1}
Δz	height difference	m
ΔQ_S	energy source or sink	W m^{-2}
ΔS_W	water source or sink	mm
Δ_z	characteristic vertical gradient	*
ε	energy dissipation	m^2 s^{-3}
ε_{IR}	infrared emissivity	
ε_{ijk}	Levi-Civita epsilon tensor	
ζ	dimensionless height z/L	
η	measurement variable	*
θ	potential temperature	K
θ_v	virtual potential temperature	K
κ	von-Kármán constant	
λ	heat of evaporation for water	J kg^{-1}
Λ	local Obukhov length	m
Λ_u	Eulerian turbulent length scale for the horizontal wind	m
Λ_x	ramp structure-parameter	m
μ	dynamic viscosity	kg m^{-1} s^{-1}
ν	kinematic viscosity	m^2 s^{-1}
ν_T	thermal diffusion coefficient	m^2 s^{-1}
ξ	scalar (general)	*
ξ	time delay	s
ρ	air density	kg m^{-3}
ρ'	air density fluctuation	kg m^{-3}
ρ_c	partial density	kg^2 kg^{-1} m^{-3}
σ_{cH}	cloud cover for high cloud	
σ_{cL}	cloud cover for low clouds	
σ_{cM}	cloud cover for middle high clouds	
σ_c	standard deviation of the concentration	*
σ_{SB}	Stefan-Boltzmann constant	W m^{-2} K^{-4}
σ_u	standard deviation of the longitudinal wind component	m s^{-1}
σ_v	standard deviation of the lateral wind component	m s^{-1}
σ_w	standard deviation of the vertical wind component	m s^{-1}
σ_T	standard deviation of the temperature	K
σ_θ	standard deviation of the potential temperature	K
σ_φ	standard deviation of the wind direction	°
τ	dew point temperature	K

τ	shear stress	kg m^{-1} s^{-2}
τ	time constant	s
Φ	geopotential	m^2 s^2
φ	geographical latitude	°
φ_m	universal function for momentum exchange	
φ_H	universal function for sensible heat flux	
φ_E	universal function for latent heat flux	
φ_T	universal function for temperature structure function parameter	
φ_ε	universal function for energy dissipation	
φ_*	correction function for the roughness sublayer	
χ	scalar (general)	*
ψ	integral of the universal function	
Ψ	inclination of the sun	°
ω	circular frequency	
Ω	angular velocity of the rotation of the Earth	s^{-1}

Indices:

a	air
w	water

Remark:

* dimension according to the use of the parameter