

# Principles of Environmental Physics

Plants, Animals, and the Atmosphere

Fourth Edition



John L. Monteith • Mike H. Unsworth



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*John L. Monteith<sup>†</sup> and Mike H. Unsworth*



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Fourth Edition

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# Preface to the Fourth Edition

Sadly, John Monteith, my colleague, mentor and friend, died in July 2012 before this edition was complete. For more than 50 years he pioneered the application of physics to the study and analysis of biological processes. He began his career in the Physics Department of Rothamsted Experimental Station, where his collaboration with Howard Penman led to the Penman-Monteith equation that has been so influential in ecophysiology and hydrology for estimating evaporation and transpiration. At Rothamsted he also collaborated with Geza Szeicz and others in designing and building some of the first instruments for Environmental Physics, including early versions of tube solarimeters and porometers that became much-used tools for investigating canopy and leaf environments. He was also among the first to use infrared gas analyzers for micrometeorological measurements of the carbon dioxide exchange of crop canopies.

In 1967 he moved to the University of Nottingham School of Agriculture where he built up the first academic department with a focus on Environmental Physics. The first edition of this book in 1973 was derived from the course that he developed there for senior undergraduates, which was unique in covering both plant and animal interactions with the environment. The text quickly became essential reading for researchers in the expanding field of Environmental Physics worldwide and was translated into several languages. When I joined John as co-author for the second edition (1990), we updated the book, expanded several chapters, and added new sections on non-steady-state heat balances and on particle and pollutant gas transfer in recognition of the emerging discipline that would eventually be termed biogeochemistry.

By the time of the third edition (2008), Environmental Physics had expanded rapidly, driven by concerns over increasing global carbon dioxide concentrations and changing climate. In particular, research on the carbon and water budgets of forests and natural vegetation had greatly increased. Availability of new fast-response instrumentation for trace gas measurement allowed the previously esoteric micrometeorological method of eddy covariance measurement to be widely applied. Consequently we added more material about eddy covariance and included more examples of applications in forest science. We also responded to requests to include more worked examples and problem sets for student use. The Preface to the Third Edition, which is reproduced below, captures many of John's insights into the development of Environmental Physics, and reveals some of the thinking behind how this book is structured and the conventions we have chosen to adopt.

This fourth edition provides an opportunity to improve on the presentation of material, update the core chapters, and summarize some of the highlights of the huge expansion in published work in Environmental Physics over the past decade. In keeping with the title, we have chosen to focus on *principles*; readers seeking more advanced treat-

ments of topics are encouraged to explore some of the texts mentioned in the Bibliography. In choosing examples from published research we have continued our practice of focusing on work that presents new insights and applies principles from the text; this becomes increasingly challenging as Environmental Physics grows, so we have included many new references aimed to help readers follow up on emerging topics.

It has always been our aim to keep the mathematics in this book at a level accessible to readers competent in algebra but not necessarily familiar with calculus. We have responded to suggestions from our students and others by expanding many of the algebraic derivations to show intermediate steps, and we have placed some of the more complex mathematics in text boxes which could be omitted by the general reader. More has been included about the Penman-Monteith equation and its applications, and about coupling of vegetation to the atmosphere. And we have increased the material on eddy covariance and modified the presentation of gradient methods in micrometeorology so that much of the discussion of non-neutral stability could be bypassed.

We are grateful to our many students and colleagues who have given us feedback on their use of this book and have provided many of the research examples that are mentioned in the text. Comments (both positive and negative!) on this edition will be most welcome and can be addressed to [pepcomments@gmail.com](mailto:pepcomments@gmail.com).

**Mike Unsworth, 2013.**

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# Preface to the Third Edition

In the time since the first edition of *Principles of Environmental Physics* was published in 1973 the subject has developed substantially; indeed, many users of the first and second editions have contributed to the body of research that makes this third edition larger than the first. From the start, this text has been aimed at two audiences: first, undergraduate and graduate students seeking to learn how the principles of physics can be applied to study the interactions between plants and animals and their environments; and second, the research community, particularly those involved in multidisciplinary environmental research. In many ways, environmental physics has become more thoroughly embedded in environmental research over the decades. For example, in ecology and hydrology, concepts of atmospheric exchange of gases and energy between organisms and the atmosphere, and the resistances (or conductances) controlling them are commonly applied. And in atmospheric science, soil-vegetation-atmosphere transfer schemes (SVATS) are an integral part of general circulation, mesoscale, and climate models. This “union of ideas” across the disciplines has made it challenging to define the scope of this third edition and to keep the size manageable. In doing so we have been guided by the word “Principles” in the title, so have focused, as in previous editions, on describing the critical principles of energy, mass, and momentum transfer, and illustrating them with a number of examples of their applications, taken from a range of classic and more recent publications.

Several themes have waxed and waned over the editions. At the time of the first edition, agricultural crop micrometeorology was a dominant application of environmental physics, beginning with the desire to quantify the water use and irrigation requirements of crops, and extending, as new instrumentation became available, to the analysis of carbon dioxide exchange in efforts to identify the environmental controls of crop productivity. There has been much less new work on agricultural crop micrometeorology in the last decade or two, but applications of environmental physics to the study of managed and natural forests and other ecosystems gathered pace through the 1970s and 1980s, and probably currently account for a larger fraction of the annual reviewed publications in environmental physics than agricultural applications. Also in the 1970s and 1980s, concerns over human influences on air quality (particularly acid rain and ozone) grew, leading to the application of environmental physics to study fluxes of pollutant gases, acidic particles, and mist to crops and forests. Additionally, the technology for remote sensing from satellites developed considerably.

The second edition of *Principles of Environmental Physics*, published in 1990, reflected these developments by adding a new chapter on particle transfer, new material on radiative transfer, and expanding the sections on micrometeorological methods. It also expanded treatment of the environmental physics of animals and their

environments, influenced by the work of a number of researchers studying the heat balance of livestock and wild animals, who began to use the terminology of environmental physics, thus establishing parallels with the integration of environmental physics into plant science. The identification of the ozone hole above Antarctica in 1985, and its influence on ultraviolet radiation at the surface received a short mention in the second edition, but emerging research on deposition of nitrogen-containing gases to vegetation was not covered; both topics receive more attention in this edition.

Through the 1980s, extending to the present time, concern over rising concentrations of carbon dioxide and other greenhouse gases in the atmosphere and consequent likely effects on climate has been a dominant topic, leading to an explosion of measurement and modeling research programs that make use of principles described in this book. Two developments have been particularly important: improved instrumentation allowing the eddy covariance technique in micrometeorology to be applied for studies of land-atmosphere exchange of carbon dioxide, water vapor, and some other trace gases over seasonal and multi-annual periods; and theoretical advances to enable models of plant-atmosphere exchange to be scaled up from the leaf scale to landscape, regional and even global scales, creating links between the principles described in this book at organism and canopy levels with the type of regional and global modeling necessary to address climate-change concerns. This edition contains two substantially revised chapters on micrometeorology with expanded treatment of the eddy covariance method, and which contain several new case studies to illustrate the application of micrometeorological methods over forests and natural landscapes. We have also expanded the material on solar and terrestrial radiation with new discussion of the roles of radiatively active greenhouse gases and aerosols.

Although eddy covariance has become the method of choice for micrometeorology in many situations, we have retained the material describing profile (similarity) techniques for deducing fluxes, because an understanding of similarity methods is essential for large-scale models and because profile methods have advantages in terms of simplicity of instrumentation when designing student projects or working with limited resources.

A number of other changes in this edition have resulted from our own experience and feedback from others using this book as a teaching text: several sections that were particularly condensed in earlier editions have been expanded to aid clarity, and some sections have been rearranged to improve the flow; more worked examples have been included in the text; some specialized material (for example, details of the physics of radiative emission and of radiation interaction with aerosols) has been added in text boxes that can be omitted by readers seeking a briefer treatment of the subject; and numerical problems have been added at the end of each chapter. Many of the numerical problems are more extensive than typically found in textbooks. This reflects requests we have had over the years from teachers who would like to explore realistic applications of the subject; many of the problems have been used in our own undergraduate and graduate teaching at Nottingham and Oregon State Universities, and we thank many students for their feedback and suggestions for improvements to the problems.

In planning this third edition we debated whether to change nomenclature in flux equations from resistances to conductances, and whether to express quantities in “mole” units rather than “m·kg<sup>-1</sup>·s<sup>-1</sup>” units. Biologists increasingly use conductances and moles



in their analyses, and there are some good theoretical and didactic arguments for this. But, on balance, we preferred to retain the “resistance” terms and “ $\text{s m}^{-1}$ ” units used in earlier editions: the analogy with Ohm’s Law emphasizes the underlying physics of many analyses used in this book, and units of  $\text{s m}^{-1}$  for resistances are more intuitive for heat and mass transfer calculations in energy balance and hydrological applications. Nevertheless, we recognize that many readers will be familiar with conductance and mol units, so we have discussed conversions of units at several appropriate points in the text. There are many advantages in environmental physicists trying to become comfortable in working with both systems of units to facilitate communication across the disciplines.

We intend this text to be useful for teaching undergraduates and graduate students specializing in physics, biology, and the environmental sciences. The mathematical treatment is deliberately kept relatively simple, with little use of calculus; the biology is also strictly limited, consisting principally of material essential for understanding the physical applications. There is a bibliography directing readers to more detailed texts if necessary. For our other category of readers, research scientists, we have continued the approach of previous editions by including a large number of references to the peer-reviewed literature, identifying a mix of papers that we consider classics and ground-breaking research applications; more than 30 of the references in this edition have been published since 1990.

In the preface to the second edition we expressed the hope that our book would encourage more university physics departments to expose their students to environmental physics. Our impression is that progress has been slow. This surely cannot be because of a lack of career opportunities—current environmental concerns open many possibilities for environmental physicists in the atmospheric sciences, hydrology, ecology, and biology, particularly if they enjoy the challenges of multidisciplinary work. Nor does it seem to be because physics students lack interest in environmental subjects. Perhaps it is inevitable that the crowded physics curriculum leaves little room for options such as environmental physics, but it would be satisfying if, by the time the fourth edition of this book appears, environmental physics was as common as astronomy or meteorology as an optional course in physics departments.

**John Monteith and Mike Unsworth, 2006.**

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# Symbols

The main symbols used in this book are arranged here in a table containing brief definitions of each quantity. A few of the symbols are universally accepted (e.g.  $R$ ,  $g$ ), some have been chosen because they appear very frequently in the literature of environmental physics (e.g.  $r_s$ ,  $z_0$ ,  $K_M$ ), and some have been devised for the sake of consistency. In particular, the symbols **S** and **L** are used for flux densities of short- and long-wave radiation with subscripts to identify the geometrical character of the flux, e.g.  $S_d$  for the flux density of diffuse short-wave radiation from the sky.

Flux densities of momentum, heat, and mass are printed in bold case throughout the book (e.g.  $\tau$ , **C**, **E**) and so is the latent heat of vaporization of water  $\lambda$ , partly to distinguish it from wavelength  $\lambda$  and partly because it is often associated with **E**. Uppercase subscripts are used to refer to momentum, heat, vapor, carbon dioxide, etc., e.g.  $r_V$ ,  $K_M$ ; most other subscripts are lowercase, e.g.  $c_p$  for the specific heat of air at constant pressure.

The complete set of symbols represents the best compromise that could be found between consistency, clarity, and familiarity.

## Roman Alphabet

$A$	area; azimuth angle with respect to south
$A_b$	area of solid object projected on a horizontal plane
$A_p$	area of solid object projected on plane perpendicular to solar beam
$A(z)$	amplitude of soil temperature wave at depth $z$
<b>B</b>	total energy emitted by unit area of full radiator or black body
$B$	wet-bulb depression
<b>B</b> ( $\lambda$ )	energy per unit wavelength in spectrum of full radiator or black body
$c$	volume fraction at $\text{CO}_2$ (e.g. vpm); fraction of sky covered by cloud; velocity of light; mean velocity of gas molecules
$c_d$	drag coefficient for form drag and skin friction combined
$c_f$	drag coefficient for form drag
$c_p$	specific heat of air at constant pressure; efficiency of impaction of particles
$c_s$	specific heat of solid fraction of a soil (similarly, suffixes l and g refer to liquid and gaseous fractions)
$c_v$	specific heat at constant volume
$c'$	bulk specific heat of soil
<b>C</b>	flux of heat per unit area (flux density) by convection in air

<i>E</i>	heat capacity of an organism per unit surface area
<i>d</i>	zero plane displacement
<i>D</i>	saturation vapor pressure deficit; diffusion coefficient for a gas in air (subscripts V for water vapor; C for CO <sub>2</sub> ); damping depth ( $= (2\kappa'/\omega)^{1/2}$ )
<i>e</i>	partial pressure of water vapor in air
$e_s(T)$	saturation vapor pressure of water vapor at temperature <i>T</i>
$\delta e$	saturation deficit, i.e. $e_s(T) - e$
$E_q$	energy of a single quantum
<b>E</b>	flux of water vapor per unit area; evaporation rate
<b>E<sub>r</sub></b>	respiratory evaporation rate of an animal
<b>E<sub>s</sub></b>	rate of evaporation from skin
<b>E<sub>t</sub></b>	rate of evaporation from vegetation
<i>F</i>	generalized stability factor $(\phi_v \phi_m)^{-1}$
<i>F</i>	drag force on a particle; retention factor
<b>F</b>	mass flux of a gas per unit area; flux of radiant energy
<i>g</i>	acceleration by gravity ( $9.81 \text{ m s}^{-2}$ )
<b>G</b>	flux of heat per unit area by conduction
<i>h</i>	Planck's constant ( $6.63 \times 10^{-34} \text{ J s}$ ); relative humidity of air; height of cylinder, crop, etc.
<b>H</b>	total flux per unit area of sensible and latent heat
<i>i</i>	intensity of turbulence, i.e. root mean square velocity/mean velocity
<b>I</b>	intensity of radiation (flux per unit solid angle)
<b>J</b>	rate of change of stored heat per unit area
<i>k</i>	von Karman's constant (0.41); thermal conductivity of air; attenuation coefficient; Boltzmann constant ( $1.38 \times 10^{-23} \text{ J K}^{-1}$ )
<i>k'</i>	attenuation coefficient; thermal conductivity of a solid
<i>K</i>	diffusion coefficient for turbulent transfer in air (subscripts H for heat, M for momentum, V for water vapor, C for CO <sub>2</sub> , S for general scalar entity)
<b>K</b>	canopy attenuation coefficient
<i>l</i>	mixing length, stopping distance; length of plate in direction of airstream
<i>L</i>	leaf area index; Monin-Obukhov length
<b>L</b>	flux of long-wave radiation per unit area (subscript u for upwards; d for downwards; e from environment; b from body)
<i>m</i>	mass of a molecule or particle; air mass number
<b>M</b>	rate of heat production by metabolism per unit area of body surface
<i>M</i>	gram-molecular mass (subscripts a for dry air, v for water vapor)
<i>n</i>	represents a number or dimensionless empirical constant in several equations
<i>N</i>	Avogadro constant ( $6.02 \times 10^{23}$ ); number of hours of daylight
<b>N</b>	radiance (radiant flux per unit area per unit solid angle)
<b>P</b>	latent heat equivalent of sweat rate per unit body area
<i>p</i>	total air pressure; interception probability in hair coats
<i>q</i>	specific humidity of air (mass of water vapor per unit mass of moist air)
<b>Q</b>	rate of mass transfer

$r$	radius; resistance to transfer (subscripts M momentum, H heat, V water vapor, C for CO <sub>2</sub> ), usually applied to boundary layer transfer; atmospheric mixing ratio (mass of substance per unit mass of dry air)
$r_a$	resistance to transfer in the atmosphere (subscripts M, H, V, C as above)
$r_b$	additional boundary layer resistance in a canopy for mass transfer
$r_c$	canopy resistance
$r_d$	thermal resistance of human body
$r_f$	thermal resistance of hair, clothing; resistance for forced ventilation in open-top chambers
$r_h$	resistance of hole (one side) for mass transfer
$r_i$	incursion resistance for open-top chambers
$r_p$	resistance of pore for mass transfer
$r_s$	resistance of a set of stomata
$r_t$	total resistance of single stoma
$r_H$	resistance for heat transfer by convection, i.e. sensible heat
$r_R$	resistance for radiative heat transfer ( $\rho c_p/4\sigma T^3$ )
$r_{HR}$	resistance for simultaneous sensible and radiative heat exchange, i.e. $r_H$ and $r_R$ in parallel
$r_V$	resistance for water vapor transfer
$R$	Gas Constant (8.31 J mol <sup>-1</sup> K <sup>-1</sup> )
$R_n$	net radiation flux density
$R_{ni}$	isothermal net radiation, i.e. net radiation absorbed by a surface at the temperature of the ambient air
$s$	amount of entity per unit mass of air
$S$	gas concentration
$S_d$	diffuse solar irradiance on horizontal surface
$S_e$	solar radiation received by a body, per unit area, as a result of reflection from the environment
$S_p$	direct solar irradiance on surface perpendicular to solar beam
$S_b$	direct solar irradiance on horizontal surface
$S_t$	total solar irradiance (usually) on horizontal surface
$t$	diffusion pathlength
$T$	temperature
$T_a$	air temperature
$T_b$	body temperature
$T_c$	cloud-base temperature
$T_d$	dew-point temperature
$T_e$	equivalent temperature of air ( $T + (e/\gamma)$ )
$T_e^*$	apparent equivalent temperature of air ( $T + (e/\gamma^*)$ )
$T_f$	effective temperature of ambient air
$T_s, T_o$	temperature of surface losing heat to environment
$T_v$	virtual temperature
$T'$	thermodynamic wet bulb temperature
$T^*$	standard temperature for vapor pressure specification
$u$	optical pathlength of water vapor in the atmosphere

$u(z)$	horizontal velocity of air at height $z$ above earth's surface
$u_*$	friction velocity
$v$	molecular velocity
$v_d$	deposition velocity
$v_s$	sedimentation velocity
$V_m$	molar volume at STP (22.4 L)
$V$	volume
$\dot{V}$	minute volume
$w$	vertical velocity of air; depth of precipitable water
$W$	body weight of animal
$x$	volume fraction (subscripts s for soil; l for liquid; g for gas); ratio of cylinder height to radius
$z$	distance; height above earth's surface
$z_0$	roughness length
$Z$	height of equilibrium boundary layer

## Greek Alphabet

$\alpha$	absorption coefficient (subscripts p for photosynthetically active; T for total radiation; r for red; i for infrared)
$\alpha(\lambda)$	absorptivity at wavelength $\lambda$
$\beta$	solar elevation; ratio of observed Nusselt number to that for a smooth plate
$\gamma$	psychrometer constant ( $= c_p p / \lambda \varepsilon$ )
$\gamma^*$	apparent value of psychrometer constant ( $= \gamma r_v / r_H$ )
$\Gamma$	dry adiabatic lapse rate, DALR ( $9.8 \times 10^{-3} \text{ K m}^{-1}$ )
$\delta$	depth of a boundary layer
$\Delta$	rate of change of saturation vapor pressure with temperature, i.e. $\partial e_s(T) / \partial T$
$\varepsilon$	ratio of molecular weights of water vapor and air (0.622)
$\varepsilon_a$	apparent emissivity of the atmosphere
$\varepsilon(\lambda)$	emissivity at wavelength $\lambda$
$\theta$	angle with respect to solar beam; potential temperature
$\kappa$	thermal diffusivity of still air
$\kappa'$	thermal diffusivity of a solid, e.g. soil
$\lambda$	wavelength of electromagnetic radiation
$\lambda$	latent heat of vaporization of water
$\mu$	coefficient of dynamic viscosity of air
$\nu$	coefficient of kinematic viscosity of air; frequency of electromagnetic radiation
$\rho$	reflection coefficient, albedo (subscripts p for photosynthetically active; c for canopy; s for soil; r for red; i for infrared; T for total radiation); density of a gas, e.g. air including water vapor component
$\rho_a$	density of dry air
$\rho_c$	density of $\text{CO}_2$
$\rho_l$	density of a liquid

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