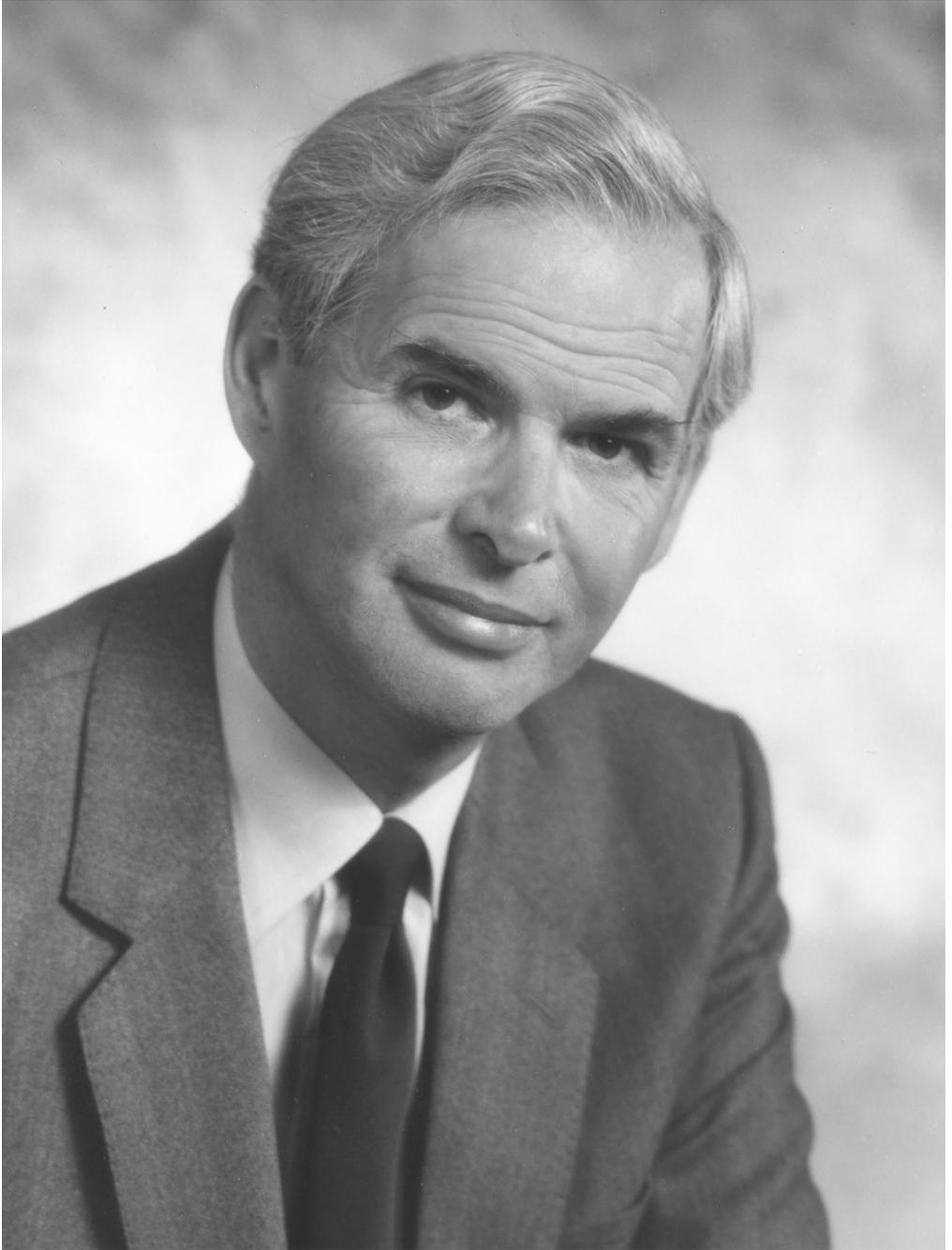


JOHN LENNOX MONTEITH  
3 September 1929 — 20 July 2012



*J. L. Monteath*



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Elected FRS 1971

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John Monteith fundamentally changed the way in which physical and biological scientists explore the interactions between living organisms and their environments. Trained in physics and meteorology, he pioneered innovative ways of measuring and analysing exchanges of heat, water vapour and carbon dioxide between leaves, crops, animals and the atmosphere. Building on the work of Howard Penman, with whom he worked for almost two decades, he developed the Penman–Monteith equation that is widely used in planning irrigation and water resource development. Subsequently, as the first Professor of Environmental Physics at the University of Nottingham, he brought together multidisciplinary groups to study the growth of temperate and tropical crops and the heat balance of animals. His Environmental Physics group trained graduates and postdoctoral scientists who have joined research establishments and universities worldwide. The final phase of his long career was spent at the International Crops Research Institute for the Semi-Arid Tropics, where he directed teams applying his experimental methods and analyses to benefit crop production in developing countries—a topic that epitomized his desire to have his science make an impact for the good of mankind. In addition to his exceptional ability in research and teaching, John Monteith was an outstanding communicator and leader who made substantial contributions to many national and international organizations.

## EARLY LIFE AND EDUCATION

John Lennox Monteith was born in 1929 in St Margaret's Manse, Fairlie, a small village on the Firth of Clyde in Ayrshire, Scotland. He was the only son of the Reverend John and Margaret Lennox Monteith. His father was a minister of the Church of Scotland; his mother had been an English teacher before her marriage. When he was three years old, the family moved to

Bridge of Weir, Renfrewshire. John began school at the age of six years in the primary section of Paisley Grammar School; his mother had home-schooled him during the previous year.

His interest in science was first stimulated when his primary class visited the upper school science laboratory to see a teacher make a mercury-in-glass thermometer. It may be coincidental that one of his first scientific publications (1954) was concerned with errors in temperature measurement! He had hours of fun with electricity and chemistry sets during his school days and with homemade instruments. These included an induction coil, with which he could ‘electrocute five or six of his friends simultaneously’—practical joking was part of John’s nature, as was his interest in building instruments.

When John was 11 years old, his father developed multiple sclerosis and the family moved to Edinburgh, where his father died shortly afterwards. John was enrolled at George Heriot’s School, where his mother had taught in the 1920s. Heriot’s, one of Edinburgh’s merchant schools founded in the seventeenth century, is one of the most distinguished in Scotland. He proved to be an academic all-rounder, winning prizes in mathematics, applied science, English literature and public speaking, and was active in drama, debating and music. He was ‘Dux’ of the school in 1946–47, but no sportsman—he reported holding a place in the lowest rugby team only on the basis of his height. In his final years John specialized in mathematics, physics, chemistry, English and Latin, having abandoned biology after one year because of his ineptitude in drawing specimens. Fortunately he discovered later in life that there were more exciting aspects of biology. English and Latin left him with a love of language and composition, so that later his publications, and those of colleagues for whom he reviewed drafts (with heavy use of his red pen), were exemplary in clarity and style.

#### UNIVERSITY STUDENT YEARS

In 1947 he began as an undergraduate in the Physics Department at the University of Edinburgh. He greatly enjoyed project work in the laboratory, where he could tinker with instruments. James Paton’s lectures on heat and thermodynamics and on meteorology (Paton was the sole meteorologist in the University at that time) particularly stimulated him, and he decided that specializing in meteorology as a postgraduate student would lead him to a career in which physics could be applied outside the laboratory. An uncle, David Cuthbertson, who was Director of the Rowett Research Institute in Aberdeen, further focused John’s interest by suggesting that agricultural meteorology might be a satisfying career; the idea of applying physics to improve food production appealed strongly to the young man.

After graduating from Edinburgh with first-class honours in 1951, he was awarded a two-year scholarship of £250 a year by the Department of Scientific and Industrial Research (DSIR) and began a postgraduate course for the Diploma in Meteorology at Imperial College, London, intending to continue on to a PhD. At that time the Department of Meteorology at Imperial College, led by Sir David Brunt FRS, was extraordinarily strong and included P. A. Sheppard (FRS 1964) and B. J. (now Sir John) Mason (FRS 1965) among its seven faculty members. The others, R. Scorer, E. T. Edie, F. Ludlam and R. Goody, were also highly respected meteorologists, so the class of about 11 students received outstanding tuition and research advice. A taught postgraduate-level course was very unusual in the UK at that time, and the Meteorology Diploma attracted students from throughout the Commonwealth, several of whom became John’s lifelong friends. The sound grounding that

he received in meteorology served him well, particularly during his term as President of the Royal Meteorological Society.

Early in his first year, John visited Rothamsted Experimental Station in Harpenden to seek advice from Howard Penman (FRS 1962) in the Physics Department about suitable PhD problems in agricultural meteorology. Penman suggested the physics of dew deposition, because the influence of leaf wetness on the development of plant disease was an important interest at Rothamsted, particularly with the microbiologist P. H. Gregory (FRS 1986) and his team. This proved an ideal topic for John, because it combined the opportunities of designing and building sensitive equipment to measure dew deposition and its associated microclimatic factors, with the analytical challenge of elucidating the heat balance of vegetation at night. Between lectures he frequented the Meteorology Department workshops, where he became a competent user of lathes, milling machines and other equipment. The training in workshop techniques that he received there from E. G. (Ted) Jennings provided him with the skills necessary to build equipment for micrometeorology at a time long before specialized manufacturers existed. When he later became Professor of Environmental Physics at the University of Nottingham all research students in his group were expected to construct some of their own equipment.

His PhD project proceeded rapidly, and by the spring of his second year, with the help of Jennings, he had built an ingenious recording dew balance that provided a sensitive record of the rate of dewfall (1)\*. A concurrent theoretical analysis of errors and accuracy associated with the use of thermocouples for measuring atmospheric temperature profiles during dewfall yielded a second publication (2). He did not realize at the time that having two publications in prestigious journals so early in a PhD programme was highly unusual.

Throughout the summers of 1953 and 1954 he collected data from his instruments, which were installed on the Imperial College playing fields at Harlington ‘a bit off the edge of the cricket pitch’. On nights when dew was likely he would ride to the site on his bike and attempt to stay awake all night to tend the instruments. A careful look at the published data, in a paper ‘Dew’ (3) that must vie for the shortest title on record, reveals occasional gaps when his resolve failed.

When John’s DSIR grant ran out at the end of his second year at Imperial College, Penman made the unusual arrangement of appointing him to the staff of the Rothamsted Physics Department but permitted him to remain in London to complete his PhD research.

### FIRST POST AND MATRIMONY

With his thesis complete, John finally moved to Rothamsted Experiment Station late in the summer of 1954, taking his dew balance and other paraphernalia with him. But first priority was marriage. In his second year as an undergraduate in Edinburgh he had met Elsa Wotherspoon at a youth fellowship in Greenbank church; the romance was cemented by weekly letters while he was in London and she was completing her teaching certificate at Moray House in Edinburgh. They became engaged in 1953 and married in July 1955, beginning a long and happy partnership that they shared for the next 57 years. In Harpenden they settled initially into a rented flat with no running hot water; over the next 12 years they had five children and moved house twice to accommodate the growing clan.

\* Numbers in this form refer to the bibliography at the end of the text.



Figure 1. Morning coffee in the Physics Department, Rothamsted Experimental Station, in about 1955. Penman is in the right foreground; Monteith is sipping coffee. (Photograph supplied by Elsa Monteith.) (Online version in colour.)

Soil physics had been the focus of research in the Physics Department up to the 1950s, an emphasis dating back to the first department head, Bernard Keen FRS. Monteith received little guidance in choosing his research topics—the philosophy ‘decide what you think you’d be interested in and get on with it’ had long been embedded in the department. John was initially disappointed that he did not receive much guidance from his senior colleagues, but, as he later typically understated it, ‘Fortunately I managed to find one or two things that led me into very interesting areas of agricultural meteorology.’

The Physics Department was small (figure 1) and remained so throughout the 1950s and 1960s, probably because Penman focused on the quality of staff and had no interest in ‘empire building’. There was a shortage of space, so John was initially allocated a desk in Penman’s large office, relative luxury for the new junior Scientific Officer. A few months later, Penman was promoted to Head of the Physics Department when R. K. Schofield moved to become Head of the larger Chemistry Department; as Penman would now occupy the Department Head’s office, Monteith successfully made a case for staying put and converting the room into a combined workshop and office. This workshop space was certainly needed, because John had thrown himself enthusiastically into new research projects. At first he continued his interest in practical microclimatology, which required building his own instruments to measure the components of the energy balance. His familiarity from his student days with the many stores around Tottenham Court Road in London specializing in military surplus electrical equipment enabled him to find cheap motors, relays and other components for his instruments. Twenty years later it was still possible to rummage in cupboards of his office at Sutton Bonington and find a treasure trove of components and prototype instruments that he had hoarded ‘just in case they should turn out useful’. This was a far cry from the present day in which several specialist companies make highly sophisticated microclimatological instruments.

It soon became clear that John needed an assistant to help him with the instrumentation and field measurements. Penman advertised and almost immediately received an application from a Hungarian, Geza Szeicz, who had worked in the meteorological section of the Hungarian



Figure 2. At the Rothamsted weather station, in about 1955. (Photograph supplied by Elsa Monteith.)

Air Force and had left the country after the 1956 uprising was crushed. Unable to find other employment, Geza was working as a waiter at London's Savoy Hotel. After a brief meeting, he was appointed on faith because he had no documentation proving his qualifications. John reminisced, 'that ... turned out to be exactly the right thing to do because he was excellent both at making equipment and getting it running in the field.' With a like-minded assistant in place, John's relative isolation in the department was relieved, and the pair thrived both intellectually and socially. Their studies of the radiative components of the heat balance of soils and crops led to six publications on short-wave and long-wave radiation between 1959 and 1962, for which Monteith was awarded the Buchan Prize of the Royal Meteorological Society in 1962.

Inevitably John's interest in crop heat balance led him to thinking about evaporation, a topic he had tended to avoid because it was Penman's forte. In seeking ways of extending Penman's formula to explicitly separate the physical and physiological controls of evaporation from vegetation, he developed the idea of using a one-dimensional electrical analogue to describe the aerodynamic and canopy transfer of heat and water vapour, with resistances dependent on atmospheric turbulence and canopy properties (figure 2). His treatment of the canopy as a 'big leaf', with a canopy resistance analogous to the resistance imposed by stomata on transpiration by individual leaves, was both novel and controversial. In 1962, when he was invited by Lloyd Evans to present these ideas at a symposium in Australia (6), he found that several respected micrometeorologists, including R. J. Taylor, W. C. Swinbank, C. B. Tanner and J. R. Philip (FRS 1974) were highly critical of his one-dimensional model. The principal concern, voiced by Swinbank among others, was that assumptions in the 'big leaf' model ignored the complexity of turbulent transfer in canopies. These exchanges were the start of a long-running feud between practitioners and theoreticians, of which Philip was the most prominent. In a characteristically forthright review, 'Plant water relations: some physical aspects' (Philip 1966), he made several attacks on one-dimensional models and the 'big leaf' analogy, criticizing 'work which is superficially mathematical-physical, but which contains loose thinking, non-rigorous calculations, uncoordinated physical measurements in

the field, and overinflated claims, [that] may temporarily impress our colleagues less familiar with mathematical-physical concepts.' Philip opined that Monteith's canopy resistance 'is an artifact of a somewhat unrealistic analysis, and its physiological significance is questionable.' The criticism of canopy resistance clearly stung, but in print Monteith allowed himself only the relatively mild riposte in his first edition of *Principles of environmental physics* (16): 'No more appropriate index (of the physiological control of water loss) has yet been devised despite attacks which are based on armchair speculators divorced from experience in the field.' Although Philip never completed the theoretical paper that he hoped (Philip 1966) would demonstrate the unreliability of canopy resistance, over the years experimental and theoretical advances by Philip's colleagues Denmead & Bradley (1985) and Raupach & Finnigan (1988), among others, have better defined the conditions when canopy resistance can be used appropriately, and elucidated other situations in which the concept fails.

By 1964, Monteith had developed his resistance analysis considerably further, applied it to data from several crops, and addressed some of the earlier criticisms. The time had come to publish the results. Rather than split the material into several papers, he took advantage of an invitation to speak at a meeting of the Society for Experimental Biology in Swansea, and submitted the entire work as a paper in the published proceedings (8). With some trepidation he had asked Penman to review the draft paper; unusually, it had come back with none of Penman's often severe editing, only a note at the end—'Bit of a Mahler symphony isn't it John?' (Penman, who was an accomplished member of the BBC Choral Society, would have been well aware of the large scale and complexity of Mahler's symphonic scores.)

The Swansea meeting was also significant for John's career path in another way. Fred Milthorpe, Professor of Agricultural Botany at the University of Nottingham's School of Agriculture (located near the small village of Sutton Bonington, and generally referred to as SB) mentioned at a chance meeting over coffee that Nottingham hoped to appoint a Professor of Environmental Physics in about three years. He encouraged John to consider a move when the opportunity arose. The distant prospect hardly registered with Monteith at the time.

The next three years passed quickly with the dual demands of a growing family at home and a multi-pronged research operation at work. John was also increasingly involved in international committee work. In particular, he was appointed to the Photosynthesis Subcommittee of the International Biological Program, and to the World Meteorological Organization (WMO) Working Group on Micrometeorology, organizations through which he made many lasting friendships around the world.

In the spring of 1967 the University of Nottingham contacted him. The Environmental Physics position mentioned by Milthorpe had materialized and, rather than advertising in what would have been a very sparse field, the university invited John to interview for the chair. He and Elsa struggled over what to do: their growing family was settled in Harpenden; they had just moved into a comfortable Edwardian house of which they were very fond; John's research at Rothamsted was productive and highly respected; and the prospect of taking over as Head of the Physics Department when Penman retired was implicit. On the other hand, a university position would open prospects of expanding his research group (opportunities for hiring at Rothamsted were very limited) and for developing new research lines such as animal heat balance. There was also a base on which to build: Milthorpe and John Hudson, Professor of Horticulture, had already established an MSc course on water relations, and the School of Agriculture had several staff interested in crop-atmosphere interactions: Jerry Clark, a physicist, recently hired to replace Ian Cowan, who had departed for Australia; Mike McGowan, a

soil scientist with research interests in crop water use; and Keith Scott, an agronomist studying crop growth and the weather. Unfortunately, Fred Milthorpe left in 1968 to take the Chair in Biological Sciences at Macquarie University in Australia.

John and Elsa concluded that after 18 years at Rothamsted it might be a good time to explore fresh fields, so John went to the interview, was offered the chair and accepted it on the spot. John recollected that telling Penman of his decision to leave Rothamsted was the most awkward situation he had ever encountered. Penman sat shocked and silent, gazing out of the window for what seemed an interminable time; he had clearly not foreseen this loss of his most productive staff member and his likely successor. But over the next few weeks he came to terms with the departure and gave the Monteiths a rousing and convivial send-off; he and John maintained their friendship and professional interactions, but Penman still wrote a scathing letter to Nottingham accusing them of baby-snatching!

Just before John moved to SB he made an overseas trip that turned out to have a major influence on his future career path, although it took more than a decade to develop to fruition. Hugh Bunting, Professor of Agricultural Botany at the University of Reading, arranged for him to visit Ahmadu Bello University in Nigeria, where Bunting had established a strong collaboration studying semi-arid cropping systems. Jeremy Elston, on the staff at Reading (and later Professor of Agriculture at the University of Leeds), was working there; he became one of John's closest lifelong friends. Their respective individual strengths in biology and physics led to several insightful joint reviews over the years (13, 32). On this visit John became aware of some of the unique challenges of unravelling crop–environment interactions in semi-arid agriculture, in contrast to the moist temperate cropping systems that he had so successfully studied at Rothamsted.

## ENVIRONMENTAL PHYSICS AT THE UNIVERSITY OF NOTTINGHAM

The Monteiths moved to SB in the summer of 1967 and the family settled into a comfortable university-owned house, St Michaels, in the village. A few years later they purchased the family house, Hillcroft, at the edge of campus. John quickly wrote successful grant proposals to support three lines of research. The Nuffield Foundation supported a large programme on the microclimate and carbon balance of barley crops, using the micrometeorological methods he had developed at Rothamsted but adding physiological, agronomic and hydrological studies through collaboration with Keith Scott and Mike McGowan. Two postdoctoral scientists, Paul Biscoe and Keith Gregson, were employed to develop physiological research and data acquisition, respectively, and several PhD students also contributed. The Natural Environment Research Council supported a project to study the water balance of the local catchment (watershed); Mike McGowan took responsibility for the hydrology, and Monteith supervised the microclimatological measurements, again with several PhD students involved. And John began a completely new line of research on animal heat balance through a grant from the Science Research Council, employing a Polish postdoctoral research assistant, Kris Cena. Each topic required major investment in new equipment and the construction of other instrumentation that was not commercially available, using a new workshop staffed by several technicians.

Shortly after arriving at SB, John received permission to hire an additional Assistant Lecturer in Environmental Physics. He advertised the position, indicating that an interest in

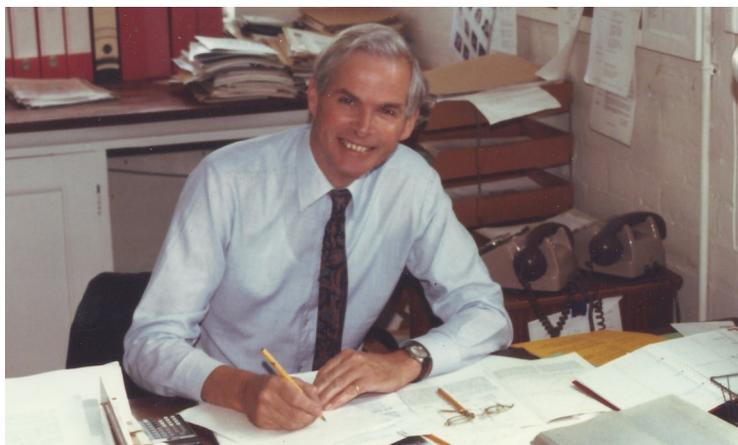


Figure 3. Monteith at his desk in the Environmental Physics Section, University of Nottingham School of Agriculture, Sutton Bonington, in 1980. (Photograph supplied by Elsa Monteith.) (Online version in colour.)

radiation measurement would be advantageous. (He hoped to encourage work that would continue his interest in the radiation budget at the surface.) He always joked that I was the only applicant for the job, and that I had probably misunderstood the wording, as I had just completed a PhD on the measurement of therapeutic X-radiation. However, the appointment turned out to be a wonderful opportunity for me; John helped me adapt to studying radiation of longer wavelengths than I had been used to, and we began a close working relationship and a friendship that continued until his death.

The formation of an Environmental Physics Section as part of the Department of Physiology and Environmental Studies (later the Department of Physiology and Environmental Science) at SB also required that the subject be taught to undergraduates. The three-year course leading to the honours BSc in agricultural science was structured so that students devoted the final term of their second year and all of their third year to the study of only three topics that formed a cohesive set (the ‘triad’); an honours research project was undertaken in one of the subjects. John set to work developing an environmental physics option to be offered as a triad subject; he was determined that it would include a substantial amount of practical work, much of it outdoors, to reinforce the lecture material. As there was no appropriate textbook, John compiled extensive notes (figure 3). He proved to be a superb teacher. The first environmental physics class (1968) consisted of four undergraduates and several postgraduates, postdoctoral workers and members of staff. Shortly afterwards the publisher Edward Arnold approached John, and the class notes formed the basis of *Principles of environmental physics*, published in 1973 (16). The book was immediately successful (although the first undergraduate class to use it at SB delighted in finding several minor mathematical errors!); the International Biological Program (IBP) had created a worldwide group of young scientists applying physics to biology, and the book’s approach was unique. It quickly became a much-used text on researchers’ bookshelves and was adopted at several universities for undergraduate teaching. Translations into German, Japanese, Polish and Portuguese followed. John invited me to join him in co-authoring the second edition (1990); a third (2008) and fourth (2013) ensued.

With his main research areas at SB thriving and producing an increasing stream of publications as the research teams grew, Monteith was able to undertake more foreign travel in

addition to serving terms as Department Head (1970–73 and 1979–82) and Dean of the School of Agriculture (1985–86). An IBP/UNESCO meeting in Kampala (1970), at which he spoke on ‘Solar radiation and productivity in tropical ecosystems’ (14), allowed him to visit Malawi, Kenya and Nigeria, further strengthening his enthusiasm for applying environmental physics to tropical agriculture. The prospect of making a significant impact on food production in developing countries had a great appeal for John.

A visit to the Cocoa Research Station in Brazil raised questions of how microclimate influenced fungal infection on cocoa pods. The solution that Monteith and David Butler (one of the first environmental physics graduates from Nottingham) found (24) lay in a rather subtle mechanism for condensation, harking back to John’s PhD research. But in the Section we suspected that John’s notorious sweet tooth was what particularly attracted him to this work—there was always much amusement when ‘the men from Mars’ visited (the Mars chocolate company funded the work).

The Brazilian project was the forerunner of other tropical research for which John was awarded grants from the Overseas Development Agency (ODA). In each case a postdoctoral scientist undertook the work, spending time at SB before and after undertaking research in the field. Geoff Squire studied the microclimatology and environmental physiology of tea in Malawi, including designing a controlled environment glasshouse for aspects of the research (foreshadowing later developments at SB); Rob Sunderland investigated the gas exchange of plantation forest in Malaysia; and John Littleton used a field-based controlled-environment chamber in West Africa to study the environmental physiology of cowpeas.

In 1974 John made his first visits to the recently established International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad, India, and the International Rice Research Institute (IRRI) in the Philippines. Both institutes had been funded by the Rockefeller and Ford Foundations and the World Bank to exploit advances from the ‘Green Revolution’ and develop methods of increasing crop production in developing countries. Monteith had already demonstrated that the methods and analyses that his group at SB had developed could be applied with similar benefits to study crop–environment interactions in the tropics, and he now saw the potential for further collaboration. On his return to the UK he began discussions with R. K. Cunningham, Head of the Natural Resources Division of the ODA, about establishing a unit at Nottingham for research on tropical crop microclimatology.

In 1976 the ODA decided to fund Monteith’s proposal, which called initially for the hiring of four postdoctoral scientists and two technicians, and the construction of major facilities for growing tropical crops in field-like conditions at SB. The grant also covered 50% of Monteith’s salary, allowing him to spend the mornings in his professorial duties on campus and the afternoons at the ODA Unit, which was accommodated by reconfiguring St Michaels House. John and his ODA team set about planning the tropical growth facilities and settling on the crops to be studied. The main research facility for the Unit was a suite of five glasshouses with temperature and humidity controls in which realistic stands of tropical crops could be grown to maturity. A key concept was that the SB facilities would be used to investigate how the crops responded to radiation, temperature and humidity in a controlled and intensively monitored environment, and then the team members would conduct field experiments with staff at ICRISAT to compare responses in real tropical conditions.

The plan worked extremely well: over the next 11 years the ODA Unit produced almost 100 papers and trained a large number of postgraduate students and institute researchers at Nottingham and ICRISAT. Postdoctoral research scientists employed in the Unit included

Peter Gregory, Nick Gallagher, Geoff Squire, Bruce Marshall, Dave Harris, Robin Matthews, Chin Ong, Sayed Azam-Ali and Lester Simmonds.

Although most of John's plant environment research was now focused on tropical crops, studies of the physics of the animal environment progressed well in the University Section. Alastair McArthur, another physics graduate from Scotland, had joined the Section in 1972 to study the heat balance of sheep outdoors. After the award of his PhD he was hired as the fourth environmental physics lecturer. The appointment of Lawrence Mount from the Institute of Animal Physiology, Babraham, as a visiting Special Professor brought expertise that supported teaching and research in animal heat balance and the microclimatology of animal housing. He was succeeded on his retirement by his colleague Doug Ingram.

Encouraged by another visiting Special Professor, Arthur Chamberlain, from the UK Atomic Energy Research Establishment, Harwell, I began to develop work on micrometeorological and physiological aspects of air pollution, and this topic quickly expanded to support its own group of PhD students and postdoctoral researchers.

The Environmental Physics Section was now large enough to support three main thrusts of research: Monteith on microclimate and crop productivity (temperate and tropical), Clark and McArthur on the microclimatology of animals (housed and in the field) and Unsworth (followed in 1983 by Jeremy Colls) on air pollution.

In 1984 the Monteiths decided that, with their family all 'out of the nest', it was time to take a long-postponed sabbatical year. They spent the first five months at ICRISAT, where John relished the freedom from administration that allowed him to ruminate on how he might apply his knowledge of temperate and tropical crop microclimatology to crop models. He had often complained that most crop-climate models were far too complex and could not be tested in the conventional sense; now he taught himself to program and began to develop parsimonious models that built on his well-known penchant for linear relationships and the principle of Occam's Razor.

After their stay at ICRISAT the Monteiths moved on to spend five months at NASA's Goddard Space Flight Center, outside Washington DC—a startling cultural contrast. Here John worked with Robert Gurney and Bhaskar Choudhury, again on models, but this time extending a canopy heat balance model (36) appropriate for remote sensing applications.

## ICRISAT, HYDERABAD

A year after returning from sabbatical, Monteith was contacted by the Director General of ICRISAT, advising him that there was a vacancy for Director of the Resource Management Division, and encouraging him to apply. Mirroring their quandary 20 years previously, John and Elsa struggled to balance the attractions of this position and its potential to influence crop production in the developing world with the satisfaction of heading an established research group and being part of village life at SB. The lure of the tropics won, and in the summer of 1987 Monteith resigned from the university and he and Elsa moved to Hyderabad (figure 4).

The Resource Management Division at ICRISAT had about 80 staff, distributed between atmospheric and soil science, crops and cropping systems, and the economics of human resources; thus Monteith's management responsibility was a lot more than he had been used to. Perhaps the institute was not quite as convinced as John that he was up to the challenge, as they promptly sent him for three weeks of management training in The Netherlands. There he suffered a barrage of personality tests, discovering, as all of us who worked with him knew



Figure 4. John and Elsa Monteith at a street market near Hyderabad, India, in about 1988. (Photograph by Ed Potter.) (Online version in colour.)

already, that he was exceptionally intuitive in problem solving (for example finding elegant solutions but often with mathematical errors), and was a finisher rather than a procrastinator (as seen by his extensive publication list).

During his tenure at ICRISAT he designed experiments to study the interaction between irrigation and nitrogen in determining sorghum yield, using the unique advantage of having many willing field workers to undertake weekly growth analyses including detailed measurements of root growth and development. Such work put into practice many of the techniques and interpretations that his ODA Unit had perfected on a smaller scale in more controlled conditions. The outcome was a satisfying understanding of how maximum yields could be secured when water and fertilizer were in short supply. Although most of his responsibility was at ICRISAT, he also supervised teams at outstations elsewhere in the semi-arid tropics, for example Niger in the sub-Sahel. The Monteiths quickly became immersed in the community; they rented a comfortable house to the west of Hyderabad and adjusted to the vagaries of life in a developing country: frequent losses of electrical power, dubious drains and an unreliable water supply that they circumvented by stocking the refrigerator with large numbers of water-filled gin bottles. The Monteith house became known as a place where local school children were always welcome to bring their unanswered questions about many aspects of science, literature, history and life, explaining that at school they were ‘not allowed to have doubts’ (in other words, question the teachers). John and Elsa became members of a nearby English-speaking church congregation where John occasionally substituted for the regular organist, the delightfully named Isiah Comfort.

However, after five enjoyable years John began to feel that he was losing touch with the wider field of science, and both he and Elsa missed being close to their children and grandchildren. So in 1991 they left ICRISAT and returned to their Scottish roots, settling in Edinburgh

close to the university. He accepted the offer of an office at the Institute of Terrestrial Ecology (Natural Environment Research Council), where a former environmental physics student, David Fowler (FRS 2002), was head of the biogeochemistry group. John imagined that he would ease into retirement, but colleagues thought differently. At that time the Natural Environment Research Council had launched a large research programme named TIGER (Terrestrial Initiative in Global Environmental Research). Several groups included John as a consultant on their TIGER research proposals to develop and test soil–vegetation–atmosphere transfer (SVAT) models. When the grants were announced he found that he had eight months of salary funded, working with Robert Gurney (Reading University, ex-NASA), Paul Jarvis (University of Edinburgh) and Melvin Cannell (Institute of Terrestrial Ecology, Edinburgh). During almost 10 years as a Senior Visiting Fellow at the Institute of Terrestrial Ecology he made progress on several aspects of the Penman–Monteith equation applied at regional scales, and took part in several international meetings. He also tackled some of the mountain of unpublished work that he had accumulated, publishing on the topics that he saw as most valuable. When spotted in the car park disposing of remaining papers in the waste bins, his response was that the only really important products of ‘our research’ are in peer-reviewed journals, and he was content that his most important findings ‘are out there’.

#### NATIONAL AND INTERNATIONAL WORK

Monteith served on committees, councils and as an officer of several scientific societies. He was Vice-President of the Royal Meteorological Society from 1977 to 1978, and its President from 1979 to 1980. He was also Vice-President of the British Ecological Society (1977–78), probably the only time a person was simultaneously a Vice-President of these two societies. During his tenure as President of the Royal Meteorological Society he led the negotiations with the publisher John Wiley to establish the *International Journal of Climatology* under the Society’s aegis.

He served on the Meteorology Sub-Committee and the Hydrology Sub-Committee of the Natural Environment Research Council, chaired its Applied Climatology Research Group, and was a member of its Council (1980–84). He was a governor of both the Grassland Research Institute (1975–83) and Silsoe Research Institute (1993–97), and was a member of the Lawes Agricultural Trust Committee (1983–86), overseeing developments at Rothamsted Experimental Station. He was an external advisor to the Physics Department at the University of the South Pacific, Fiji, an Honorary Professor at the University of Edinburgh and an Adjunct Professor at the University of Florida.

Possibly his international committee work with the most enduring outcome was his participation in 1990 in the Working Group of the UN Food and Agriculture Organization (FAO), which revised the FAO recommendations on ‘Estimation of irrigation need’ (figure 5). These discussions led to the adoption of the Penman–Monteith equation with specified crop resistances to provide estimates of water use by so-called ‘reference crops’ in relation to local weather parameters. The document known as FAO56 has been widely accepted worldwide for irrigation planning (Allen *et al.* 1998). (For details of the Penman–Monteith formula and crop resistance see below.)

Monteith was also a regular and active participant in national and international conferences. Contributions of particular significance were made at the 1962 Canberra conference ‘Environmental Control of Plant Growth’ mentioned above, in which canopy resistance



Figure 5. Participants in the FAO Expert meeting that led to the adoption of the Penman–Monteith ‘reference crop evapotranspiration’ method, Rome, Italy, in 1990. Front row, left to right: J. L. Monteith (UK), W. O. Pruitt (USA), R. Francaviglia (Italy), J. Doorenbos (FAO); second step, right: M. Smith (FAO); next row: M. Jensen (USA), H. Gunston (UK), L. Cavazza (Italy); second row from top: R. Feddes (The Netherlands), E. Romani (Italy), A. Perrier (France), P. Fleming (Australia), R. Gommès (FAO), L. Pereira (Portugal); top row: A. Segeren (FAO), R. Allen (USA), D. Rijks (WMO, The Netherlands). (Photograph supplied by R. Gommès.) (Online version in colour.)

models were introduced (6); the 1963 Symposium of the Society of Experimental Biology (the Penman–Monteith formula (8)); the 1967 UNESCO Symposium ‘Functioning of Terrestrial Ecosystems’ (micrometeorological analysis of carbon dioxide exchange of crops (10)); the 1969 Symposium of the American Society of Agronomy and the Crop Science Society of America, ‘Physiological Aspects of Crop Yield’ (radiation absorption in crop canopies (11)); the 1973 University of Nottingham Easter School ‘Heat Loss from Animals and Man’ (physical analysis of animal heat balance (17)); and the 1986 Royal Society Discussion Meeting ‘The Scientific Basis for Irrigation’ (integrating atmospheric and soil controls of crop water use (32)).

John’s presence at a meeting, usually in the front row, could be rather daunting to new presenters, but even his most searching questions were asked in a polite and encouraging style. A distinguished American professor once described him as ‘the classic British gentleman—smooth as goose grease’. His penchant for humour often lightened discussion sessions. One tongue-in-cheek interjection occurred at a British Ecological Society conference in Cambridge in 1974 on ‘Light as an Ecological Factor’. Monteith was asked during the discussion to

comment on the origin of the term 'albedo', used to describe the reflection coefficient of surfaces. He launched straight-faced into a spurious story about an American astronomer Al Bedo who had studied the reflectivity of stars; the rapporteur dutifully recorded the information, and it is preserved for posterity in the conference proceedings (Evans *et al.* 1976).

## HONOURS AND AWARDS

Monteith's contributions to meteorology and agricultural science were recognized in numerous medals, prizes and awards. The Royal Meteorological Society awarded him the Buchan Prize (1962), the Symons Memorial Medal (1995) and the James Paton Prize for Photography (1988). This last particularly pleased him because it was named after his mentor while he was an undergraduate at Edinburgh University, and recognized his perceptive photographs and interpretations of meteorological phenomena, a lifetime interest.

For his contributions to agriculture he received the Solco Tromp Award for Biometeorology (1983), the Rank Prize for Nutrition and Crop Husbandry (1989) and an honorary doctorate from the Agricultural University of Athens (1993).

He was elected a Fellow of the Royal Society in 1971, a Fellow of the Royal Society of Edinburgh (1972), an Honorary Member of the British Ecological Society (1991), an Honorary Member of the European Geophysical Society (1992) and an Honorary Fellow of the Royal Meteorological Society (1997). In 1989 his alma mater, the University of Edinburgh, awarded him an honorary DSc.

## RECREATION

Music played a large role in John's life. It was a catalyst in bringing John and Elsa together and was always an important feature of their home. John was an accomplished pianist and organist, and played the organ at the Methodist church in SB and at churches in Hyderabad and Edinburgh. He also loved to sing; each Christmas he would assemble a choir of students at SB and put on a concert for the village and university communities. True to their heritage, the Monteiths organized occasional Burns Night celebrations with other Scottish exiles at their home in SB, complete with traditional songs and dramatic poetry readings.

He was an accomplished photographer who always kept a camera close by to capture interesting observations. Several of his photographs illustrating environmental topics (including coalesced fog drops on my beard) appear in *Principles of environmental physics*, and others, particularly of clouds, were published in the journal *Weather*.

Walking, particularly in the Scottish mountains, was John's favourite form of exercise (figure 6). Their annual family summer holiday was always taken in Scotland and usually involved the ascent of a Munro or two (Munros are all the Scottish mountains with elevations exceeding 3000 feet (914 m)). Science was not always entirely put aside on these trips: several of John's excellent cloud photos were taken then, and one memorable family ascent of Scotland's highest mountain Ben Nevis (1344 m) involved multiple stops to make measurements. At the time, John and I were studying the influence of atmospheric aerosol on the intensity of solar radiation. A rare cloudless day in the Highlands was too much to miss, so the family carried a Linke-Feussner radiometer, microvoltmeter and sling psychrometer up



Figure 6. A relaxed moment in the Scottish Highlands, in about 1970. (Photograph supplied by J.L.M.)

the mountain, taking radiation and humidity measurements every 200–300 m. The effort in carrying the 20 kg or so package of instruments may not have been popular with the family, but the results were a valuable addition to the subsequent publication (15).

## RESEARCH AND WRITING

With a publication record extending over 50 years, including almost 200 papers, it is not easy to give the reader an adequate flavour of Monteith's research and its impacts on science. In his publication list, John classified his publications into six broad headings (plus 'reviews' and 'miscellaneous'), and the following adopts that classification.

### *Instrumentation*

Three examples of John's work on instrumentation are discussed here because each contains aspects that arise again in later work.

Much of his early research required measurements for which there were either no commercial instruments made or for which the principles of instruments were poorly understood. As a postgraduate student he and his mentor Ted Jennings built a recording dew balance on which the change of weight of a block of turf and soil was detected by the photographic record when light from a spot galvanometer struck photographic paper on the rotating drum of a cannibalized barograph (1). With this device, and concurrent measurements of wind speed and surface energy balance, Monteith discovered that both distillation (water evaporating from the soil and depositing on leaf surfaces) and dewfall (the turbulent transfer of water vapour from the atmosphere and its condensation on leaves) could be significant sources of 'dew' on clear nights (3). The relative importance of the two processes depended on the surface heat budget, which Monteith studied by measuring air temperature, humidity and wind speed profiles and net radiation.

In designing fine wire wet-and-dry-junction thermocouple systems (psychrometers) for the temperature and humidity profiles, Monteith needed to assess errors associated with such thermocouple psychrometry. This led to his earliest theoretical paper (2) in which he considered how the classical theory of psychrometry needed to be modified in practice because of the boundary layer existing around finite thermocouple sensors. He presented a new derivation of the psychrometer equation by using an approach to heat transfer that employed non-dimensional numbers (Reynolds, Nusselt and Prandtl), a style that he often used in later work. This choice may well have been influenced by his academic supervisor, B. J. Mason, who was studying heat transfer from water drops and ice crystals. Monteith also considered the exchange of radiation between thermocouple psychrometers and their surroundings, and he adopted a linearized radiative transfer equation that also appeared in several of his later publications. The resulting linear equations took a form similar to Ohm's law and although Monteith did not at this time take the step of explicitly using an Ohm's law analogue, this analysis may have sown the seeds for the development of resistance models later.

A second area in which instrumentation was needed arose shortly after Monteith began work at Rothamsted. He needed to understand how solar radiation was absorbed and transmitted through tall crop canopies. This knowledge was also needed for investigating how canopy light distribution influenced photosynthesis. However, there were no suitable instruments. He seized on a technique first used by Wilson & Epps (1919) to construct thermopiles by electroplating copper onto constantan wire wound around a former. In this way Monteith and Szeicz built 'tube solarimeters', consisting of a thermopile up to 1 m long enclosed in a glass tube (7). The linear sensor allowed the instrument to average the irradiance in sunflecks and shade, and arrays of tube solarimeters at various heights in a canopy allowed Monteith and Szeicz to investigate radiation absorption in relation to leaf distribution and spectral properties. Tube solarimeters were also built with gelatin filters inside to separate photosynthetically active (visible) and near-infrared radiation (Szeicz 1974).

Knowledge gained from tube solarimeters allowed Monteith to develop and test mathematical models of radiation absorption by plant canopies (9), and ultimately supported the adoption of a simple model of crop and forest productivity based on measurements of radiation interception that can be made from aircraft and satellites (36) (Landsberg & Waring 1997; Choudhury 2001).

A third example of Monteith's influence in employing new instruments in environmental physics is his contribution to diffusion porometry to study evaporation from leaves. Plant physiologists use porometers to investigate the stomatal control of transpiration. Calibration of early instruments that measured the relationship between air pressure and the viscous flow of air through part of a leaf clamped in the porometer cup was a problem until Penman, collaborating successively over a period of 25 years with F. G. Gregory FRS, O. V. S. Heath FRS and F. L. Milthorpe, derived and eventually improved a theoretical relation between the resistance to flow and stomatal aperture (Milthorpe & Penman 1967). However, making absolute measurements in the field remained a problem. In the mid 1960s small humidity sensors became available, allowing the development of a new generation of dynamic diffusion and steady-state porometers. After a visit by C. H. M. van Bavel to Rothamsted, at which he discussed new approaches to porometry, W. Stiles and T. A. Bull built a prototype diffusion porometer, and Monteith authored a paper with Bull on the theory, calibration and performance of the instrument (12). When Monteith moved to Nottingham he continued his interest in

porometer design; P. V. Biscoe and other postgraduate students brewed foul-smelling potions in the laboratory to make miniaturized sulphonated polystyrene humidity sensors, and then used the porometers in their field studies of sugar beet and barley. These measurements helped to confirm the validity of Monteith's canopy resistance parameter as a measure of stomatal control. By 1972 a prototype automatic porometer had been built in the Section and was field tested by Geoff Squire in Malawi. He recalls that its slow-response sensor needed considerable nursing to obtain reliable measurements in humid conditions.

The availability of porometers also allowed Biscoe and Unsworth, supervising an undergraduate student project, to begin investigations of the influence of the air pollutant sulphur dioxide on stomatal behaviour (Unsworth *et al.* 1973). The research field of air pollution transfer and effects blossomed into one of the main themes of work in the Section over the next three decades. Much later, Monteith's understanding of the theory of porometry allowed him (with his PhD student Anne Wheldon) to improve the interpretation of measurements made with a 'skin evaporimeter', used to assess water loss from premature babies as discussed below (28).

In 1973 Monteith wrote to E. A. (Ed) Potter, who had recently set up a small instrument manufacturing business, Delta-T, near Cambridge, asking whether his company would be interested in making commercial versions of tube radiometers and porometers. The venture was highly successful, and since then Delta-T has sold large numbers of both instruments around the world. The first commercial Delta-T porometer (1975) was fully automated and much easier to use than the version that Geoff Squire had used. The design continued to be improved in sensor design and electronics with advice and encouragement from Monteith; in 1988, Monteith, Campbell and Potter published an extension of the theory behind the instrument, taking into account the sensor time response and adsorption of water on the cup materials (35).

Monteith also helped found Campbell Scientific Ltd, the European subsidiary of the environmental instrumentation company Campbell Scientific Inc. The impetus for the venture was a sabbatical year spent by Gaylon Campbell in the Environmental Physics Section in 1977–78. Gaylon was an extraordinarily stimulating and productive visitor. He introduced new ideas from soil science, animal science and electronics in a string of eight publications co-authored with Monteith and other members of the Section, and he taught short courses on special topics in instrumentation such as sonic anemometry and thermocouple psychrometry. After Gaylon returned for a second sabbatical at SB in 1984, Campbell Scientific Ltd was established; Dick Saffell from the ODA Unit was recruited as its first chief executive officer. The fledgling company initially set up offices on the School of Agriculture campus.

### *Radiation climatology*

In an extension of the research that Monteith and Szeicz undertook on the radiation budget of crops, Monteith took a wider interest in radiation climatology, recognizing that better understanding of the causes of spatial variation in components of the radiation budget would improve the accuracy of estimations of potential evaporation. In the 1950s there were no robust net radiometers, and few weather stations made routine solar radiation measurements. Penman had circumvented this problem in his classic paper (Penman 1948) by using an empirical expression correlating daily solar radiation receipt at Rothamsted with sunshine hours (which were also widely measured elsewhere) and estimating the long-wave radiation balance of the surface from records of temperature, humidity and cloud cover.

From 1960 onwards Monteith published several papers in the *Quarterly Journal of the Royal Meteorological Society* on estimating long-wave radiation exchanges and on the climatology of solar radiation in the British Isles. His resulting estimates of the surface heat budget, compared with hydrological data that Penman had analysed, revealed a puzzle (4). It appeared that Penman's estimates of potential evaporation in Scotland were about 25% too low. The answer lay in an analysis that Monteith made of observations from the five locations in the UK and Ireland where solar radiation was measured directly. The remote western coastal stations of Valentia in Ireland and Aberporth in Wales recorded more solar radiation per hour of sunshine than elsewhere (5). Monteith suspected that smoke and other aerosol pollutants in the atmosphere at Rothamsted and elsewhere in central England reduced the amount of solar energy reaching the ground, and consequently Penman's Rothamsted-derived correlation between radiation and sunshine hours underestimated radiation receipt in cleaner parts of the UK. With the correction that Monteith proposed, potential evaporation estimates for Scotland increased and the discrepancy disappeared.

The aerosol explanation was not accepted by some meteorologists who argued that cloud distribution and/or density might differ between coastal and inland sites. So, when I joined the Environmental Physics Section in 1968, John suggested that we take a closer look at the influence of aerosols on radiation to see if it explained what Penman liked to call 'the excesses at Aberporth'. For several years we used a Linke–Feussner pyrheliometer to measure solar beam irradiance and the angular distribution of long-wave radiation whenever there were cloudless skies. To avoid missing those rare cloudless days, the instrument accompanied John and me on several family holidays (for example the Monteiths on Ben Nevis; see above) and on business trips. On one occasion in Nigeria, when John stopped by a busy road near an airport to take measurements, he was quickly surrounded by armed soldiers who suspected him of setting up a mortar.

When the data were analysed in terms of an aerosol turbidity coefficient (15) it emerged that aerosol associated with different air mass origins (maritime or continental) accounted for large variations in diffuse and direct solar radiation and in downward long-wave radiation at the surface (Dalrymple & Unsworth 1978). Coastal sites where clean arctic maritime air masses were common received much more radiant energy per hour of sunshine than sites in heavily populated parts of the country. More recent spectral measurements at the surface and from satellites are consistent with those early observations.

#### *Evaporation and condensation*

If there is one piece of work with which Monteith's name is most closely identified, it is the Penman–Monteith equation that is firmly embedded in agriculture, ecology, hydrology, and meteorology. His PhD research on dew had given him a firm grasp of the physics of evaporation and condensation processes and their role in the surface energy balance. Now, as he worked on the radiation budget of cereal crops at Rothamsted, it became clear that the next step was to understand how the absorbed net radiation was partitioned between evaporation and transpiration, sensible heating of the atmosphere, and heat storage in the soil. He needed to solve the heat balance of plant canopies, and thus he sought to extend the physical analysis that Penman had so successfully pioneered.

Penman had combined the surface energy balance and aerodynamic equations to develop a formula for estimating evaporation from a surface where water was freely available (Penman 1948). A valuable feature of his 'combination method' was that it eliminated the need to know

the temperature of the evaporating surface (a difficult measurement with the instruments then available). The amount of the available energy  $H$  at the surface that was used in evaporation  $E$  depended on a function of wind speed  $f(u)$ , the saturation deficit of the air ( $e_s - e_d$ ), and two thermodynamic constants, the rate of change of saturation vapour pressure with temperature  $\Delta$ , and the psychrometer constant  $\gamma$ . Thus

$$E = \frac{\Delta H + \gamma f(u)(e_s - e_d)}{\Delta + \gamma}.$$

Penman showed that estimates of evaporation using his formula agreed well with measured evaporation from wet surfaces, but evaporation was overestimated from drying soil and vegetation where air at the surface was not saturated with water vapour.

Around 1962 John began to extend the Penman formula for application to vegetation. Somewhat surprisingly, he chose to publish his main report of the work in the proceedings of the 1964 annual meeting of the Society for Experimental Biology (8). Despite its relatively obscure location, the work has become a Citation Classic, with almost 4000 citations.

He began by rewriting the Penman formulation in a form applicable to single leaves, emphasizing the fundamental thermodynamic principles. He then extended the concept so that diffusion from saturated surfaces *within* leaves became part of the transfer pathway to the atmosphere. Thus, with an additional parameter describing the restriction to diffusion imposed principally by stomata, the modified Penman formula could be applied to estimate rates of transpiration from individual leaves.

In the thermodynamic analysis Monteith replaced Penman's aerodynamic transfer function by a parameter  $r_a$ , representing the time in which a unit volume of air exchanged heat with a unit area of the surface. Values of  $r_a$  for single leaves could be estimated as a function of wind speed and leaf size by using empirical equations from fluid dynamics (drawing on his earliest paper). If the (unsaturated) vapour pressure at a leaf surface is  $e_0$  and in the free atmosphere is  $e_d$ , then the transpiration rate is proportional to  $(e_0 - e_d)/r_a$ ; by analogy with Ohm's law, Monteith called  $r_a$  an external diffusion resistance, because it controlled the flux of water vapour (current) that was driven by the potential difference ( $e_0 - e_d$ ). The principle of continuity also requires that the flux of water vapour from saturated surfaces inside the leaf is proportional to  $(e_s(T_0) - e_0)/r_1$ , where  $e_s(T_0)$  is the saturation vapour pressure at leaf temperature  $T_0$ , and  $r_1$  is the internal resistance of the leaf. With these modifications and some algebraic manipulation to eliminate  $T_0$ , Penman's formula became

$$E = \frac{\Delta H + \rho c_p (e_s - e_d)/r_a}{\Delta + \gamma(1 + r_1/r_a)},$$

where  $\rho c_p$  is the volumetric heat capacity of air. This has become known as the Penman–Monteith (PM) equation. For a single leaf adequately supplied with water, the value of  $r_1$  closely approximates the resistance imposed by the stomata, which is governed by the size and number of pores per unit leaf area. This simple equation demonstrates the dependence of transpiration rates on meteorological variables: available energy (net radiation), wind speed, air temperature and atmospheric saturation deficit ( $e_s - e_d$ ), and on the physiological variable stomatal resistance.

The next stage of Monteith's analysis was more controversial. He assumed that a uniform crop canopy fully covering the ground could be treated as a 'big leaf', with an external (aerodynamic) resistance  $r_a$  associated with the canopy roughness and wind speed, and an internal

resistance  $r_c$  associated with the stomatal resistances of all the leaves in the canopy. When he first presented this idea at a conference in Canberra in 1962 he was severely criticized, as discussed above. There were two main objections: first, the aerodynamic resistances for water vapour and heat transfer are different from that for momentum because there is no mechanism for heat and mass transfer that is equivalent to drag caused by pressure gradients in momentum transfer. This results in values of  $r_c$  that are not independent of  $r_a$ . Second, the analysis does not yield a unique value of internal resistance  $r_c$  unless the spatial distributions of heat and water vapour sources in the canopy are identical.

Monteith addressed the first issue by introducing an additional aerodynamic resistance  $r_b$  in series with  $r_a$  to parameterize the separation of the heat, mass and momentum sinks (16, 25). The work of his PhD student Alastair Thom (Thom 1975) underpinned much of the analysis. Monteith argued that the second issue was unlikely to invalidate the analysis when the canopy was sufficiently dense for all incident radiant energy to be absorbed by foliage, but he accepted that values of  $r_c$  deduced from measurements above more open canopies would be influenced by physical restrictions on evaporation from the soil as well as by the physiologically controlled resistances of stomata. His 1965 paper, and many publications since, presented compelling evidence from field observations that, for many agricultural crops and forest stands with closed canopies,  $r_c$  varies diurnally and seasonally in the same way as stomatal resistance.

The PM equation incorporating Monteith's concept of canopy—or, more generally, surface—resistance has been widely used. As mentioned earlier, the UN FAO recommends the equation to estimate crop water requirements (Allen *et al.* 1998, 2006); canopy and surface resistances of different vegetation classes and land cover types have been tabulated (Wilson & Henderson-Sellers 1985; Kelliher *et al.* 1995) and may be used to estimate the hydrological consequences of a change in land use (such as deforestation); the PM equation has been manipulated and applied in many different ecosystems to demonstrate how vegetation is 'coupled' to the atmosphere (Jarvis & McNaughton 1986); and several models of general circulation and climate change use surface resistance in parameterizing surface heat balance (Cox 1999; Cox *et al.* 2001).

Monteith recognized the implicit circularity of the PM equation: evaporation rate calculated from the equation depends on air temperature and humidity, but at sufficiently large scales temperature and humidity in the atmospheric convective boundary layer (CBL) are influenced by the heat balance at the surface, creating a feedback mechanism. Priestley & Taylor (1972) theorized that the feedbacks were such that, over extensive uniform surfaces, the evaporation rate should attain an equilibrium value  $E_{eq} = \Delta H / (\Delta + \gamma)$ . In practice they found that actual evaporation in such situations was  $\alpha E_{eq}$ , where  $\alpha$  was an empirical factor. In some of his final research publications Monteith addressed these feedbacks: he reanalysed published reports of stomatal responses to humidity to assert that transpiration rate rather than atmospheric humidity itself controlled the responses (38), and he elegantly combined the PM equation with a simple CBL model to show that there is a nearly linear correlation between the surface resistance and  $\alpha^{-1}$  (39, 40), which must have been satisfying because he so often sought linear relationships in his analyses.

#### *Microclimate and crop growth*

The prospect of using agricultural meteorology to benefit crop production drove much of Monteith's research. At SB and ICRISAT he assembled teams of physicists, biologists and soil

scientists to tackle such problems; one of his great strengths was his ability to build bridges and communicate across these disciplines.

He had begun linking physics and biology at Rothamsted in the early 1960s as he tried to explore crop productivity by drawing together measurements of leaf photosynthesis in the laboratory and field measurements of the light distribution in crops. He used his binomial model of light interception in crops ((9), another Citation Classic) to explore how light distribution in the canopy, influenced by leaf angle and spectral properties, could be related to crop carbon assimilation. But what was needed was an experimental method to measure the CO<sub>2</sub> exchange of field crops.

At that time Lemon at Cornell and Inoue in Tokyo had shown that new, sensitive CO<sub>2</sub> analysers could be used to make micrometeorological measurements of crop CO<sub>2</sub> exchange. With support from the Rockefeller Foundation, Monteith and Szeicz persuaded a British company, Grubb-Parsons, to construct a prototype CO<sub>2</sub> analyser that was sufficiently sensitive. Although it required a replacement sensor every two weeks and considerable nursing in the field, John and Geza succeeded in making the first CO<sub>2</sub> flux measurements in Europe over a crop (10) and related their results to canopy light interception. However, there were unanswered questions about how the assimilation of individual leaves was related to crop growth, and addressing these needed a larger research team than Rothamsted could muster.

Arriving at SB in 1967, Monteith assembled a multidisciplinary team of staff and postgraduate students to study the carbon budget of barley crops with the use of micrometeorological, physiological and agronomic techniques to explore carbon sinks and sources on timescales from minutes to weeks. This was the first time that a crop had been studied continuously in this way over whole growing seasons. The measurements were challenging: infrared gas analysers for carbon dioxide and water vapour were the size and weight of large microwave ovens and required frequent calibration; one analyser was mounted on a rail track so it could be moved through the crop to study leaf photosynthesis; another was kept in a trailer alongside an early minicomputer that stored records of gas concentrations and microclimate data on punched tape, taken each day to the university's only mainframe computer for analysis. A neutron probe was used to measure changes in the soil water profile over the season.

The project revealed how the growth of the crop was related to the weather over a timescale fine enough for mechanisms of assimilation, transpiration and resource allocation to be identified. For example, relationships between solar irradiance and net CO<sub>2</sub> fixation of the canopy (light response curves) were developed throughout the life of the canopy and compared with the responses of single leaves, and excellent agreement was achieved between estimates of crop dry matter production based on integrated CO<sub>2</sub> flux measurements and those based on harvested plants (18).

In addition to demonstrating the power of combining micrometeorological and physiological measurements in relating crop growth to microclimate, this work also led Monteith towards a series of groundbreaking analyses concerning weather, climate and the efficiency of crop production (22, 23, 29–31).

He pioneered a way of thinking about the environment and crop growth. Historically, agronomists and crop physiologists had used factors such as net assimilation rate and relative growth rate to seek correlations with weather elements, with little general success. Now Monteith endeavoured to build simple models that related crop yield to factors that were, as far as possible, independent of each other. To begin, his measurements and his theoretical models of radiation transfer in canopies confirmed that the rate at which crops produced dry

matter for much of the growing season was proportional to the rate at which radiant energy was intercepted by the canopy. Crop yields were also linearly related to the total intercepted radiation over a growing season (30). This relationship led to a valuable practical application: intercepted radiation measurements from satellites or aircraft can be used to deduce growth and yield (37) (Waring *et al.* 2010).

The concept that intercepted radiation is a major discriminant of crop growth therefore provides a framework for analysing crop yields and for identifying how breeders and growers can increase yields in a given environment. In essence, the amount of intercepted radiation and the efficiency with which it contributes to yield must be maximized by the following: lengthening the growing season; decreasing time lost at the beginning and end of the season when interception is reduced by sparse leaf cover or by senescing foliage; breeding and managing for optimal leaf light response, both to increase maximum growth rate in bright light and to maintain photosynthetic efficiency in low light; and breeding and managing to optimize the proportion of assimilated dry matter that the plant allocates between light-capturing leaves and harvestable yield.

Between 1976 and 1987 the UK Overseas Development Agency supported Monteith in a major project to gain a better understanding of how the weather affects the yield of tropical crops. As described above, he set up a Unit for research on the microclimatology of tropical crops, involving research in tropicalized glasshouses at SB and in the field at ICRISAT. The design criteria for the glasshouse system were novel: crops would be grown in stands mimicking an extensive crop canopy; the crop area would be large enough to allow sequential harvests without significant effects on plant population density; the system would control mean temperature and saturation deficit over ranges experienced in the tropics but would allow the range of these factors to vary throughout each day as they do in nature; and experiments would consist of a set of treatments covering a range of a single factor, with other environmental factors kept constant.

The Unit decided to focus on investigating how solar radiation, temperature and humidity affected the growth and yield of a cereal crop (millet) and a legume (groundnut). Stages in growth and yield were studied in 'developmental periods', focusing on rates of change in the numbers, size and weight of crop structures (such as leaves and grains). Three processes were followed in this way: expansion of the canopy and root system, the production of dry matter, and the partitioning of dry matter between crop elements (such as leaves, roots and fruiting structures).

Over the 11 years that the Unit operated, close to 100 papers were published in refereed journals. Their findings from glasshouse and field experiments can be summarized in terms of two distinct situations: when the soil was moist, yield depended on the amount of solar energy intercepted by the canopy (as in moist temperate climates); when the soil was drying over the season, yield depended on the amount of water that a crop stand could extract from the soil and on the amount of dry matter produced per unit of water transpired. Common to both situations were an expansion process that generated both a canopy and a root system to capture the limiting resource (light or water), and a conversion process generating dry matter, of which the yield is a part.

Monteith's team adopted several concepts that allowed them to simplify the analysis of environmental influences on growth and yield. They made extensive use of the concept of 'thermal time', the integral of time and temperature (degree-days) above a threshold temperature at which a process begins, and showed that the concept greatly simplified their analysis of rates and

durations. In particular they emphasized the importance of thermal time in determining the rate of expansion and the duration of crop canopies and quantified the restriction imposed by low humidity on these processes (34) (Squire 1990). Coupled with the relationship relating yield to intercepted radiation, a simple model of crop growth when water supply was not limiting could be developed. When water *was* limiting, Monteith's principal contribution was in demonstrating how the rate at which the root system descends into the soil and proliferates governs the rate at which the stand transpires (33). The time available for growth thus depends on atmospheric and soil factors. Later, during his time at ICRISAT, he directed even more intensive studies of environmental controls of root system dynamics, including interactions with nutrition.

When Monteith began his tropical microclimatology work in the mid 1970s, many of the concepts mentioned above relating crop growth to microclimate were relatively new. The progress he made in experimental science and in communicating his results to the wider community has resulted in agronomists, crop physiologists, soil scientists and microclimatologists having a common framework to describe the responses of crops to the environment. The simple models resulting from his analyses have enabled breeders and crop managers to target their efforts more effectively to increase yields.

#### *Microclimate and animal heat balance*

When Monteith was appointed to the Chair of Environmental Physics at Nottingham in 1967 he began research into the physics of animal heat balance. At the time, the main centres for livestock/environment research were the Rowett Research Institute, Aberdeen (K. L. (later Sir Kenneth) Blaxter FRS), the Institute of Animal Physiology, Babraham (L. E. Mount), and the Hannah Dairy Research Institute, Ayr (J. A. McLean). Their main focus was on calorimetry in a controlled environment to study the metabolic rates of sheep, cattle and pigs. Animal heat losses were partitioned into the sensible and evaporative components, and there were some attempts to quantify insulation. Monteith and Blaxter had corresponded in the mid 1960s on solar radiation interception by sheep, and John was probably struck by the similarity between the physics of radiation interception in animal coats and in crop canopies.

John saw that a better understanding of the thermal insulating properties of animal coats would allow knowledge gained in calorimeters to be applied to heat balances in the more complex outdoor environment. He appointed a Polish physicist, Kristof Cena, to begin measurements of transfer processes in animal coats; the results for radiative transfer, heat conduction and convection, and water vapour transfer were reported in three groundbreaking papers in *Proceedings of the Royal Society* (19–21) in which an elegant physics-based approach to the heat transfer analyses was adopted. This work provided a theoretical basis for specifying the physical properties of animal coats and for determining how the state of the underlying skin surface was related to the thermal environment. The next stage was to apply the principles to whole animals indoors and outdoors, and this topic became the focus of research by Jerry Clark and Alastair McArthur.

Alastair recalls Monteith getting him started on his PhD research with the Rothamstedesque advice 'Go and sort out the physics of heat loss for sheep.' Fortunately McArthur turned out to be very effective and he, Monteith and Jerry Clark built a strong research group in the Section, with several postgraduate students studying the heat balance of sheep, cattle, goats, poultry, newborn foals and infants. McArthur's full-sized model sheep, a fleece-covered cylinder, was displayed at an exhibition reviewed by the Queen to mark the centenary of the Royal Meteorological Society; her remark 'But it hasn't got a head!' fortunately did not impact the

scientific value of the work that McArthur and Monteith published in *Proceedings of the Royal Society* (26, 27).

Monteith became a regular attendee at meetings of the UK Climatic Physiology Group. As one of the few physicists in the group he encouraged a more rigorous analysis of environmental aspects of animal heat balance. Traditionally, animal scientists quantified insulation in units that obscured the similarity of heat and mass transfer, and there was often confusion between the insulation of the coat and that of the boundary layer surrounding it. Monteith advocated using resistance analogues to distinguish between tissue, coat and boundary-layer controls of heat transfer, as had become accepted in flux analysis in plant science and ecology. It proved a struggle to encourage some entrenched experimentalists to accept the elegance and utility of resistance analogues, and there is still a much greater mix of units used in animal heat balance studies than there is in the plant sciences.

In 1973 Monteith and L. E. Mount (Special Professor in Environmental Physics) organized an influential Easter School at Nottingham entitled 'Heat loss from animals and man'. In a complementary pair of papers in the proceedings, Monteith expounded his physics-based approach to the specification of the environment in thermal physiology (17), and Mount, with input from conference participants, reviewed the concepts of thermoneutrality and demonstrated how its physical and physiological aspects could be brought together (Mount 1974); these remain classic references for those entering the field.

Although most of Monteith's research on animal–environment interactions focused on agriculture, a chance meeting at a university committee with David Hull, Professor of Child Health, led to a valuable input of environmental physics into human health. It had proved extremely difficult to keep premature babies warm in normal incubators, with the result that survival rates were compromised. Monteith, Hull and his colleague N. Rutter received funding from the Medical Research Council to study the heat balance of babies, and an environmental physics postgraduate student, Ann Wheldon, was recruited for the work. Rutter had observed that the water loss through skin of premature babies was much larger than for full-term babies, and the group recognized that this evaporative loss equated to a large heat loss. To quantify this term, Wheldon and Monteith took the theoretical principles that Monteith had developed for leaf porometers and applied them to a commercial skin evaporimeter. Using resistance analogues they showed that the calibration supplied by the manufacturer severely underestimated skin permeability in premature babies (28). Applying their new calibration, the large evaporative heat loss from the premature babies was confirmed; improvements to incubator design have followed, and there is now much greater attention paid to the heat balance of babies in incubators and the maintenance of thermoneutral environments.

## PERSONAL QUALITIES

John Monteith is particularly remembered by his colleagues and students for his personal qualities of patience and approachability and his belief in doing science that benefited society. Known to many as 'JLM', he was a great listener and a great communicator. On dropping by his office, staff and students marvelled at his ability to switch instantaneously from a mundane administrative task to a thoughtful discussion of a challenging problem in their research. His intuition could be humbling—he would see a solution to a problem that his visitor had struggled with for days, although his enthusiasm often ran ahead of mathematical thoroughness so

that one left the office with a few scribbled equations on a scrap of paper that took the rest of the week to prove. In some of his theoretical publications these intuitive leaps between equations could be challenging to follow, and readers of the first edition of *Principles of environmental physics* with non-mathematical backgrounds also confessed that they found some sections hard going. His lectures were delight to those fortunate enough to attend. For many years he delivered the introductory science lecture to all first-year undergraduates at SB. Relatively few of the students were strong in physics, but on one occasion he was so taken aback by the speed and accuracy with which a student answered a challenging question that he felt compelled to part company with his much-loved Royal Society booklet *Quantities, Units, and Symbols* as a prize!

His writing is memorable for its clarity, brevity and style, the title of a short course on scientific writing that he regularly gave to postgraduate students. He was generous in supporting the preparation of publications, always willing to review drafts and offer suggestions. Manuscripts that he returned were always dismayingly heavily annotated in red ink in his almost indecipherable script, but this was a result of his enthusiasm and insight, not an attempt to impose a standard style. Those of us who continued as teachers inherited his ‘tough love’ style of editing for our own students’ work.

As Head of the Environmental Physics Section at Nottingham he set an example with his well-mannered non-confrontational style and his professional planning. Everyone got a chance to speak at department meetings; dissenting views were listened to and consensus was always sought. These same skills served him well when he chaired much more exalted committees at learned societies and research councils. He applied the same style at conferences and seminars—he might disagree strongly with a presentation or interpretation and could demolish an argument with one or two rapier-like comments, but these were usually made in such an elegant style that the victim sometimes did not realize he was being skewered.

However, his reputation was not always recognized; he was left bemused on one occasion when he returned home to Hillcroft to find his 12-year-old daughter setting up a rain gauge immediately adjacent to the house for a school project. When he gently pointed out that this sheltered location was inappropriate, she reportedly retorted ‘Oh go away, Dad, what do you know about it?’

He was a modest man, always ready to give credit to his colleagues, students and others where it was due. Although his name is firmly associated with the Penman–Monteith equation, he regularly pointed out that the resistance model had been proposed by several others, including Penman, who had developed an equation similar to the PM equation in a little-known publication but with different interpretation of the terms (Penman 1952); and Rijtema in the Netherlands had independently formulated a resistance model in his PhD thesis (Rijtema 1965). John claimed that his contribution was only in clarifying the meaning of the crop resistance term.

He was also very inclusive. The Environmental Physics Section received a large number of visitors, obviously wanting particularly to meet him, but he always made sure that visitors spent time with all his colleagues and research students. Similarly, when junior colleagues attended meetings with John he made a point of introducing them to his eminent contemporaries.

John was a very social animal. Environmental Physics parties that he hosted were memorable for the initiations of new members of the Section—a balding student planning a thesis on solar radiation might have his head decorated with a radiometer design, and a faculty member might be teased for some embarrassing event in their research (Monteith himself was a victim

one year when he contaminated the gold-lined tubes of a gas analyser with mercury during an overenthusiastic attempt at calibration). The Christmas party at John and Elsa's home was always a highlight, with John's holly-shaped bow tie making its annual appearance. During their time in Hyderabad the Monteith home became a popular place for social gatherings that integrated newcomers into the community.

John's Christian beliefs were very important to him and underlay his career decisions and his treatment of others. Elsa and John were active members of their churches in SB and Hyderabad. In 1994 he visited me at Oregon State University, and over two days we taped his personal record of his life (available as electronic supplementary material at <http://dx.doi.org/10.1098/rsbm.2014.0005>). In the final minutes he reminisced about some of the happiest memories of his professional life: the guidance he believed God had given him to follow the career path described in this memoir; his pleasure at his election to the Royal Society at the age of 41 years, the award of his Rank Prize for 'contributions to crop husbandry and nutrition' while at ICRISAT, and the award of an honorary DSc by his alma mater, the University of Edinburgh, 38 years after his graduation in physics. But most particularly he valued the satisfaction of teaching and encouraging the careers of his students and colleagues to develop; many went on to hold senior positions in universities and research institutes in the UK and overseas.

One of his final comments was: 'The work is never finished but I managed to get a reasonable number of things done.'

In his last few years John was cruelly affected by an Alzheimer's-like decline. He died in Edinburgh on 20 July 2012 at the age of 82 years.

#### ACKNOWLEDGEMENTS

I am most grateful to the many people who have helped in providing material and memories for this review. Elsa Monteith and the family provided many personal details about John and his life. The taped record of his life that John made with me in 1994 is the source of many of the anecdotes and personal memories that are included in this memoir. Conversations with Jeremy Elston, Paul Jarvis FRS and Jim McCulloch gave insight into their interactions with John and his contributions to agriculture, forestry and hydrology. Fraser Sim, the archivist at George Heriot's School, Edinburgh, sent me details of John's school career. Many of John's former colleagues and friends provided reminiscences and anecdotes, and helped give perspective on the wide-ranging impact of his work: Gaylon Campbell, Jerry Clark, Tom Denmead, David Fowler FRS, Keith Gregson, Alastair McArthur, Geoff Squire, David Spittlehouse, Christopher Wathes and others. In particular Alastair McArthur, David Fowler and Geoff Squire read drafts of this manuscript, provided valuable suggestions for improvements, and corrected several examples of stylistic and grammatical errors at which John would have cringed.

The frontispiece photograph was taken in 1980 by Godfrey Argent and is reproduced with permission.

#### REFERENCES TO OTHER AUTHORS

- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop evapotranspiration (guidelines for computing crop water requirements)* (FAO Irrigation and Drainage Paper no. 56). Rome: UN Food and Agriculture Organization.
- Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., Yrisarry, J. B., Smith, M., Pereira, L. S., Raes, D., Perrier, A., Alves, I., Walter, I. & Elliott, R. 2006 A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. *Agric. Water Mgmt* **81**, 1–22.

- Choudhury, B. J. 2001 Estimating gross photosynthesis using satellite and ancillary data: Approach and preliminary results. *Remote Sens. Environ.* **75**, 1–21.
- Cox, P. 2001 *Description of the TRIFFID Dynamic Global Vegetation Model* (Hadley Centre Technical Note no. 24). Bracknell: UK Met Office.
- Cox, P., Betts, R., Bunton, C., Essery, R., Rowntree, P. & Smith, J. 1999 The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dyn.* **15**, 183–203.
- Dalrymple, G. J. & Unsworth, M. H. 1978 Longwave radiation at the ground. IV. Comparison of measurement and calculation of radiation from cloudless skies. *Q. J. R. Met. Soc.* **104**, 989–997.
- Denmead, O. T. & Bradley, E. F. 1985 Flux-gradient relationships in a forest canopy. In *The forest–atmosphere interaction* (ed. B. A. Hutchinson & B. B. Hicks), pp. 421–442. New York: D. Reidel.
- Evans, G. C., Bainbridge, R. & Rackham, O. (eds) 1976 *Light as an ecological factor: II*. Oxford, UK: Blackwell Scientific.
- Jarvis, P. G. & McNaughton, K. G. 1986 Stomatal control of transpiration: scaling up from leaf to region. *Adv. Ecol. Res.* **15**, 1–49.
- Kelliher, F. M., Leuning, R., Raupach, M. R. & Schulze, E. D. 1995 Maximum conductances for evaporation from global vegetation types. *Agric. Forest Meteorol.* **73**, 1–16.
- Landsberg, J. J. & Waring, R. H. 1997 A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecol. Mgmt* **95**, 209–228.
- Milthorpe, F. L. & Penman, H. L. 1967 The diffusive conductivity of the stomata of wheat leaves. *J. Exp. Bot.* **18**, 422–457.
- Mount, L. E. 1974 The concept of thermal neutrality. In *Heat loss from animals and man: assessment and control. Proceedings of the Twentieth Easter School in Agricultural Science, 1974 University of Nottingham School of Agriculture* (ed. J. L. Monteith & L. E. Mount), pp. 425–439. London: Butterworths.
- Penman, H. L. 1948 Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond. A* **194**, 120–145.
- Penman, H.L. 1952 The physical bases of irrigation control. In *Proceedings of the 13th International Horticultural Congress*, pp. 913–924. London.
- Philip, J. 1966 Plant water relations: some physical aspects. *Annu. Rev. Plant Physiol.* **17**, 245–268.
- Priestley, C. H. B. & Taylor, R. J. 1972 On the assessment of surface heat flux and evaporation using large scale parameters. *Mon. Weather Rev.* **100**, 81–92.
- Raupach, M. R. & Finnigan, J. 1988 ‘Single-layer models of evaporation from plant canopies are incorrect but useful, whereas multilayer models are correct but useless’: discuss. *Aust. J. Plant Physiol.* **15**, 705–716.
- Ritjema, P. 1965 *An analysis of actual evapotranspiration*. PhD thesis, Agricultural University, Wageningen.
- Squire, G. R. 1990 *The physiology of tropical crop production*. Wallingford: CAB International.
- Szeicz, G. 1974 Solar radiation for plant growth. *J. Appl. Ecol.* **11**, 617–636.
- Thom, A. S. 1975 Momentum, mass and heat exchange of plant communities. In *Vegetation and the atmosphere* (ed. J. L. Monteith), pp. 57–109. London: Academic Press.
- Unsworth, M. H., Biscoe, P. V. & Pinckney, H. R. 1973 Stomatal responses to sulphur dioxide. *Nature* **239**, 458–459.
- Waring, R. H., Coops, N. C. & Landsberg, J. J. 2010 Improving predictions of forest growth using the 3-PGS model with observations made by remote sensing. *Forest Ecol. Mgmt* **259**, 1722–1729.
- Wilson, M. & Henderson-Sellers, A. 1985 A global archive of land cover and soils data for use in general circulation climate models. *J. Climatol.* **5**, 119–143.
- Wilson, W. H. & Epps, T. D. 1919 The construction of thermocouples by electro-deposition. *Proc. Phys. Soc. Lond.* **32**, 326.

## BIBLIOGRAPHY

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material at <http://dx.doi.org/10.1098/rsbm.2014.0005> or via <http://rsbm.royalsocietypublishing.org>.

- (1) 1954 (With E. G. Jennings) A sensitive recording dew-balance. *Q. J. R. Met. Soc.* **80**, 222–226.
- (2) Error and accuracy in thermocouple psychrometry. *Proc. Phys. Soc. B* **67**, 217.
- (3) 1957 Dew. *Q. J. R. Met. Soc.* **83**, 322–341.
- (4) 1961 An empirical method for estimating long-wave radiation exchanges in the British Isles. *Q. J. R. Met. Soc.* **87**, 171–179.
- (5) 1962 Attenuation of solar radiation: a climatological study. *Q. J. R. Met. Soc.* **88**, 508–521.
- (6) 1963 Gas exchange in plant communities. In *Environmental Control of Plant Growth* (ed. L. T. Evans), pp. 95–112. New York: Academic Press.
- (7) 1964 (With G. Szeicz & J. Dos Santos) Tube solarimeter to measure radiation among plants. *J. Appl. Ecol.* **1**, 169–174.
- (8) 1965 Evaporation and environment. *Symp. Soc. Exp. Biol.* **19**, 205–234.
- (9) Light distribution and photosynthesis in field crops. *Ann. Bot.* **29**, 17–37.
- (10) 1968 Analysis of the photosynthesis and respiration of field crops from vertical profiles of carbon dioxide. In *UNESCO Symposium on Functioning of Terrestrial Ecosystems at the Primary Production Level, Copenhagen, July 1965* (ed. F. E. Eckhardt), pp. 349–358. UNESCO.
- (11) 1969 Light interception and radiative exchange in crop stands. In *Physiological aspects of crop yield* (ed. J. D. Eastin, F. A. Haskins, C. Y. Sullivan & C. H. M. van Bavel), pp. 89–115. New York: Academic Press.
- (12) 1970 (With T. A. Bull) A diffusive resistance porometer for field use. II. Theory, calibration and performance. *J. Appl. Ecol.* **7**, 623–638.
- (13) 1971 (With J. F. Elston) Microclimatology and crop production. In *Potential crop production* (ed. P. F. Waring & J. P. Cooper), pp. 129–139. London: Heinemann.
- (14) 1972 Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecol.* **9**, 747–766.
- (15) (With M. H. Unsworth) Aerosol and solar radiation in Britain. *Q. J. R. Met. Soc.* **98**, 778–797.
- (16) 1973 *Principles of environmental physics*, 1st edn (241 pages). London: Edward Arnold.
- (17) 1974 Specification of the environment for thermal physiology. In *Heat loss from animals and man: assessment and control. Proceedings of the Twentieth Easter School in Agricultural Science, 1974 University of Nottingham School of Agriculture* (ed. J. L. Monteith & L. E. Mount), pp. 1–17. London: Butterworths.
- (18) 1975 (With P. V. Biscoe & R. K. Scott) Barley and its environment. III. Carbon budget of the stand. *J. Appl. Ecol.* **12**, 269–293.
- (19) (With K. Cena) Transfer processes in animal coats. I. Radiative transfer. *Proc. R. Soc. Lond. B* **188**, 377–393.
- (20) (With K. Cena) Transfer processes in animal coats. II. Conduction and convection. *Proc. R. Soc. Lond. B* **188**, 395–411.
- (21) (With K. Cena) Transfer processes in animal coats. III. Water vapour diffusion. *Proc. R. Soc. Lond. B* **188**, 413–423.
- (22) 1977 Climate and the efficiency of crop production in Britain. *Phil. Trans. R. Soc. Lond. B* **281**, 277–294.
- (23) 1978 Reassessment of maximum growth rates for C<sub>3</sub> and C<sub>4</sub> crops. *Exp. Agric.* **14**, 1–5.
- (24) 1979 (With D. Butler) Dew and thermal lag: a model for cocoa pods. *Q. J. R. Met. Soc.* **105**, 207–215.
- (25) 1981 Evaporation and surface temperature. *Q. J. R. Met. Soc.* **107**, 1–27.
- (26) 1980 (With A. J. McArthur) Air movement and heat loss from sheep. I. Boundary layer insulation of a model sheep, with and without fleece. *Proc. R. Soc. Lond. B* **209**, 187–208.
- (27) (With A. J. McArthur) Air movement and heat loss from sheep. II. Thermal insulation of fleece in wind. *Proc. R. Soc. Lond. B* **209**, 209–217.
- (28) (With A. E. Wheldon) Performance of a skin evaporimeter. *Med. Biol. Engng Comput.* **18**, 201–205.
- (29) 1981 Climatic variation and the growth of crops. *Q. J. R. Met. Soc.* **107**, 749–774.
- (30) Does light limit crop production? In *Physiological processes limiting plant productivity. Proceedings, Easter School in Agricultural Science, University of Nottingham* (ed. C. B. Johnson), pp. 23–38. London, Elsevier.
- (31) 1982 (With R. K. Scott) Weather and yield variation of crops. In *Food, nutrition and climate* (ed. K. L. Blaxter & L. Fowden), pp. 127–149. Barking: Applied Science Publishers.

- (32) 1983 (With J. F. Elston) Performance and productivity of foliage in the field. In *The growth and functioning of leaves* (ed. J. E. Dale & F. L. Milthorpe), pp. 499–518. Cambridge University Press.
- (33) 1986 How do crops manipulate water supply and demand? *Phil. Trans. R. Soc. Lond. A* **316**, 245–259.
- (34) 1987 (With G. R. Squire & C. K. Ong) Crop growth in semi-arid environments. In *International Pearl Millet Workshop, Patancheru, India, 7–11 April 1986*, pp. 219–231. ICRISAT Open Access Repository. (See [http://oar.icrisat.org/4435/1/CP\\_375.pdf](http://oar.icrisat.org/4435/1/CP_375.pdf).)
- (35) 1988 (With G. S. Campbell & E. A. Potter) Theory and performance of a dynamic diffusion porometer. *Agric. Forest Meteorol.* **44**, 27–38.
- (36) (With B. J. Choudhury) A four-layer model for the heat budget of homogeneous land surfaces. *Q. J. R. Met. Soc.* **114**, 373–398.
- (37) 1989 (With G. Russell & P. G. Jarvis) Absorption of radiation by canopies and stand growth. In *Plant canopies: their growth, form and function* (ed. G. Russell, B. Marshall & P. G. Jarvis), pp. 21–39. Cambridge University Press.
- (38) 1995 A reinterpretation of stomatal responses to humidity. *Plant Cell Environ.* **18**, 357–364.
- (39) Accommodation between transpiring vegetation and the convective boundary layer. *J. Hydrol.* **166**, 251–263.
- (40) 1998 (With C. Huntingford) The behaviour of a mixed-layer model of the convective boundary layer coupled to a big leaf model of surface energy partitioning. *Boundary-Layer Meteorol.* **88**, 87–101.