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NOTES AND COMMENTS

Contributions of PA Taylor, L Mahrt, JJ Finnigan, MR Raupach to *Boundary-Layer Meteorology*: 1970–2020

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1 Introduction

The following invited summaries give the reader a good overview of each author's sustained effort over the past 50 years. The reader should also ponder the fact that the authors above have published in a range of journals and, with a few exceptions, their contributions referred to below are specific to *Boundary-Layer Meteorology* alone. We identified four authors: Peter Taylor who first published in *Boundary-Layer Meteorology* in 1970 (total of 55 publications) and joined the Editorial Board in 1971; Larry Mahrt who first published in the inaugural issue in 1970 (total of 47 publications); and the pair John Finnigan and Mike Raupach, who first published in *Boundary-Layer Meteorology* in 1976 and 1979 respectively with a combined total of 51 publications, several of which are joint. One other point should give the young scientist pause for reflection: Larry Mahrt and Peter Taylor in particular, being Board members for much of the 50 years, have each reviewed some hundreds of articles submitted to *Boundary-Layer Meteorology*, an impressive effort in the underpinning of the peer review process.

A little editing has been done to ensure a level of consistency in content (e.g., PhD details, early employment, international activities) and we thank Kathryn Gebauer at the University of Oklahoma for final format editing.

2 Contributions of Peter Taylor, by Joe Fernando (Notre Dame, Indiana) and Jim Wilczak (Boulder, Colorado)

Peter Taylor received his PhD in Applied Mathematics in 1967 at the University of Bristol, UK, and has held a professorial position at York University in Toronto, Canada, for many years. He published an article in the first journal volume (Taylor 1970), was a member of the Editorial Board (1971–95, 2010–20), and was a Co-Editor from 1995 to 2010. His significant

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impact on the journal is well evident from the 55 papers he has published in *Boundary-Layer Meteorology* so far. He was a pivotal organizer of the much celebrated Askervein experiment in the 1980s dealing with flow past a single hill (Taylor and Teunissen 1987). Its benchmark data continue to provide a wellspring of information for boundary-layer meteorologists and wind engineers alike, and was an inspiration for later international projects such as Perdigão (Fernando et al. 2019). Taylor served as Deputy Lead of the Atmospheric Science Theme Group for NASA's Scout program, an initiative for smaller, lower-cost, competed spacecraft. In this role he helped design and evaluate the meteorological instrumentation package on NASA's 2008 Phoenix Mars Lander. In addition to his research, Taylor has been an effective educator and a mentor, and so far has produced a little in excess of 20 PhDs. His former graduate students characterize his mentorship as a thoughtful balance of independence, guidance, and encouragement combined with a warm character and steadfast professionalism.

Taylor's research interests span an impressively wide spectrum of topics:

a. PBL modelling, including model numerics, turbulence parametrizations, model evaluation, and the development of an internal boundary layer due to step-changes in surface roughness or surface heat flux. His theoretical and numerical modelling work demonstrate how sudden changes in roughness and heat flux produce a wide variety of downstream boundary-layer conditions under a range of stability conditions (Taylor 1969, 1970).

b. Ocean-related, primarily model or theoretical investigations of flow over ocean surface waves, but also exploring sediment transport and tidal mixing. In a series of investigations on turbulent airflow over water waves, Gent and Taylor (1976), Taylor and Gent (1978), and Li et al. (2000) delineated useful relationships such as the dependence of drag coefficient on the wave slope and normalized friction velocity, as well as mechanisms of flow separation over wind waves.

c. Model studies of blowing snow—including both dynamical and thermodynamical processes—its parametrization in models, and its impact on visibility. Using numerical and theoretical studies, as well as field experiments using leading-edge radar technologies (Hassan et al. 2017), Taylor made fundamental and practical contributions to the understanding of the characteristics (e.g., particle size distribution, saltation, blowing velocities) and prediction of blowing snow and snow melting (Gordon and Taylor 2009; Gordon et al. 2009).

d. Air quality, including mesoscale meteorological transport of ozone and sulfur processing in clouds. Flagg and Taylor (2011) investigated the characteristics of the urban boundary layer, including their dependence on urban morphology and canopy parameters, and the effects of model grid resolution. Also, his contributions to mesoscale meteorology include studies on surface fronts (Taylor et al. 1993) and convective storm initiation at low-level mesoscale boundaries such as lake breezes (Alexander et al. 2018).

e. Studies on wind energy, including investigations of turbine wake decay and the potential impact of offshore turbines on the mixed layer in lakes. Taylor made key contributions to the understanding of complex terrain flows subjected to varying stability conditions. Particularly noteworthy are his investigations into wind-energy characteristics in complex terrain (Taylor and Teunissen 1987). Salmon and Taylor (2014) carried out in-depth studies on how missing data affect long-term averages, thus helping to quantify uncertainties in wind-farm energy-production estimates.

f. The meteorology of the Martian atmosphere, based on the analysis of the Phoenix Mars Lander observations, with topics including the sublimation of ice, dust distributions, clouds, and dust devils. Based on short-term pressure drops detected by the Lander, Taylor's group (Ellehoj et al. 2010) inferred the probable passage of convective vortices or dust devils on Mars, and investigated how they are related to the weather at the landing site. Their conclusions were compared with existing theories, adding value to the observations. His work also includes the development of instrumentation for planned or future missions to Mars (Gunnlaugsson et al. 2008).

As a final note on his breadth of scientific interests and contributions to the literature, it is remarkable that one of his highest cited articles falls not within meteorology and geophysics at all, but in biology (Taylor and Williams 1975).

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3 Contributions of Larry Mahrt, by Bruce Hicks (Norris, Tennessee)

Larry Mahrt obtained his PhD in Meteorology at the University of Wisconsin, USA, in 1972. After completing a postdoctoral fellowship at the National Center for Atmospheric Research, he became a faculty member in the Atmospheric Sciences Department at Oregon State University. During 2004 he moved to North-West Research Associates and his research started along new paths. His research interests were often taken up as the result of extended visits to institutes in Europe. He published his first *Boundary-Layer Meteorology* article in the journal's first issue (Mahrt and Scherdtfeger 1970). During the early part of his career his research emphasized numerical modelling, but it shifted to observational work in the 1980s. Since 2000, much of his work has concentrated on the stable boundary layer (SBL) in terms of turbulence and non-turbulent small-scale motions. In addition to boundary-layer turbulence, his work has included the transfer of heat and moisture within the soil, sub-canopy transfer, transpiration, and snow processes. He has participated in a number of field programs, in a few as principal investigator, including the Hydrologic Atmospheric Pilot Experiment: Modelisation du Bilan Hydrique (HAPEX MOBILY, France, 1986), Fluxes over Snow Surfaces (FLOSS, Colorado, USA, 2000–2002), and the Shallow Cold Pool Experiment (Colorado, USA, 2012).

His work on the stable boundary layer deserves special mention, particularly regarding turbulence intermittency. There is a long history on nocturnal turbulence intermittency in SBL flow over land. Munn (1966) demonstrated that such sporadic bursts of turbulence were common, but it was Mahrt et al. (1979) who injected some consideration of the applicability or otherwise of Monin–Obukhov similarity theory (MOST). A subsequent series of articles served to return the intermittency issue to a central position in today's science. The new interest arose, in part, when data from the Microfronts project (Howell and Sun 1999) were used by Mahrt et al. (1998) to draw attention to the role of nocturnal turbulence intermittency in the very stable boundary layer. Subsequently, Mahrt (1999) reviewed current understanding, concluding that conventional flux–gradient approaches are confined to unstable and weakly stable stratification, whereas for the very stable case all bets are off. A series of articles followed (e.g., Mahrt et al. 1998, 2013; Mahrt and Vickers 2006) clarifying that, whereas the criteria distinguishing different nocturnal intermittency regimes were originally based on the stability parameter ζ (in line with MOST), later studies departed from MOST. It was the CASES-99 study (Poulos et al. 2002) that bridged the gap between the SBL and the general boundary-layer aspects of the observed phenomenon. The subsequent series of CASES-99 articles (starting with Sun et al. 2002) dominated much of the literature discussion of the following decade, although well supported by data from other locations (e.g., Ohya et al. 2008; Ansorge and Mellado 2014; Cava et al. 2019). In his pursuit of the understanding of the SBL and its turbulence characteristics, Larry has combined the CASES experience with extensive studies of drainage flows (Mahrt et al. 2001; Soler et al. 2002) and locally influenced wind-field variations (Mahrt 2008; 2009). Implications regarding heat exchange, dispersion, and mixing in general (Mahrt and Vickers 2006; Mahrt 2017a, b) have also been explored. In a recent presentation, Mahrt et al. (2020) concentrate on three experiments designed to elucidate specific aspects of the mechanisms of the intermittency. Two studies were of flow within clearly defined valleys. The third was a subset of CASES-99, focused on observations made very close to the surface. It goes without saying that the intermittency phenomenon leads to obvious problems for flux–gradient formulations (Mahrt 2007; 2010; 2011).

Major discussions of the relevant science have been provided within the pages of *Boundary-Layer Meteorology*, and Larry Mahrt has been a major participant (e.g., Mahrt et al. 1979; Mahrt 1999). Elsewhere, he has provided an extensive review of the current understanding of the nocturnal terrestrial atmosphere (Mahrt 2014). It must be hoped that the science will continue to be explored, and that the consequences of atmospheric fluctuations lying outside the universe of spectral uniformity will prove to be describable in a manner permitting adjustment to numerical models of the planetary boundary layer.

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4 Contributions of John Finnigan and Mike Raupach, by John Garratt (Melbourne, Australia)

John Finnigan received his Ph.D. in 1978 at the Australian National University, Canberra, and Mike Raupach in 1976 at Flinders University, Adelaide, joining the CSIRO environmental mechanics group in Canberra in 1972 and 1978, respectively, when John Philip was Chief. Each brought his impressive mathematical and analytical skills, together with physical insights, to a range of boundary-layer problems, focusing initially on turbulent airflow above and within aerodynamically rough surfaces, both in the wind tunnel and in the natural world but later extending to larger scales. All in all, they contributed to 45 publications in *Boundary-Layer Meteorology* – Raupach authored 25 articles, Finnigan 26, most as single authors, and several together. Their earliest articles in *Boundary-Layer Meteorology* are dated 1976 for Finnigan and 1979 for Raupach. Sadly, Raupach died in 2015, whilst Finnigan continues to work and publish to this day.

John Finnigan's main contributions relate to: (i) the description of the mean and turbulent properties of airflow above and within natural plant canopies (a series of seven papers between 1978 and 2000, some with co-authors Y Brunet, PJ Mulhearn, and RH Shaw); (ii) the development of the theory of flow over low hills covered with tall canopies (with SE Belcher and IH Harman); (iii) a unified theory for flow in the canopy layer and in the roughness sublayer (RSL, several papers between 2007 and 2016, with I Harman as senior author); (iv) the clarification of the relationship between the parameters governing the 'big-leaf' description of vegetation-atmosphere exchange, based on the Penman–Monteith or Combination equation, and the physiological parameters that can be measured at leaf level; (v) a two-paper analysis of long-term flux measurement techniques (Finnigan et al. 2003; Finnigan 2004). At larger scales, Finnigan developed theory and observational techniques describing wave–turbulence interaction in the boundary layer (with F Einaudi) and collaborated with Raupach on the development of thermodynamically-based averaging principles for surfaces covered with heterogeneous vegetation or topography.

Mike Raupach's main contributions relate to: (i) scalar dispersion within plant canopies (several papers in the 1980s, with BJ Legg); (ii) turbulent properties of airflow within and above plant canopies; (iii) the RSL (several during the period 1979 to 1992) and drag characteristics of rough surfaces, especially as they affect wind erosion (several between 1992 and 2006). He also steadily moved his attention from the details of turbulent exchange near the surface to larger scales, first answering open questions on the nature of whole-of-PBL feedbacks on surface evaporation by the rigorous application of thermodynamic principles. With these principles firmly established, he became a pioneer in quantifying the global carbon and energy cycles at continental to global scales, eventually leading the Global Carbon Project as its inaugural co-chair.

Two major contributions concerned (i) airflow within and above natural plant canopies, and (ii) the elucidation of the properties of the RSL, leading to analytical expressions for key aerodynamic properties of rough surfaces, such as the roughness length and zero-plane displacement, as functions of surface geometry and of atmospheric stability.

The breakdown of the neutral logarithmic wind law, and in flux–profile relations generally, above tall crops and forests became apparent from 1975 onwards (e.g., Thom et al. 1975; Garratt 1978; Raupach 1979). The term "roughness sublayer" was almost certainly first used by Raupach et al. (1980) as part of a major wind-tunnel study on the breakdown of the log law close to a rough surface. These authors and Raupach (1992) made the first serious attempts at determining analytical expressions for the depth of the RSL and for the profile influence function that described the deviation of the actual RSL profile from the log profile. Some years later this early work was expanded to a unified theory of flow in the canopy layer and in the RSL above, both for wind speed and scalar concentration (Harman and Finnigan 2007, 2008). The key step involved a coupling between the canopy and surface-layer flows using a mixing-layer analogy for the flow at the interface, viz., the canopy top. The approach envisaged the RSL as characterized by coherent eddies, with extra mixing generated by the inviscid instability mechanism acting at the canopy top (Raupach et al. 1996). It follows that the additional relevant length scale that describes the profile influence function is $U/(dU/dz)$ at the inflection point (canopy top). The resulting profile forms, for chosen canopy variables and stability, were compared favourably with observed wind-speed, temperature and humidity profiles within and above several forest canopies, and the resulting theory has now been successfully incorporated in several widely used boundary-layer and climate models.

Finnigan's Ph.D. work in 1979 applied then novel conditional sampling techniques to a canopy of natural wheat and a wind-tunnel model, both of which exhibited the phenomenon of honami or coherent waving. This work, which was soon supported by other researchers—notably RH Shaw—showed that momentum and scalar transport to and from canopies was dominated by eddies of whole canopy scale, which manifest themselves as intermittent 'sweeps' and 'ejections'. This was in contrast to the earlier view that canopy turbulence was dominated by leaf wakes. After Raupach joined the CSIRO group in 1978, the history of the next few years could be summarized as the search for the origin of these large coherent eddies. This was a fruitful period, demonstrating that large eddies can induce counter-gradient diffusion in canopies, an observation that was elegantly explained by Raupach's localized near-field theory and eventually led to a complete description of the nature of canopy eddies when the flow is shear dominated (Finnigan et al. 2009). This understanding in turn indicated the use of the shear instability parameter $U/(dU/dz)$ as the extra length scale in a unified model of canopy and RSL flow noted above.

Finnigan and Raupach played major roles in the overall research activity of the CSIRO group, and each had a major involvement in the atmospheric sciences at the international level.

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