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JOOST BUSINGER– HIS CAREER IN BOUNDARY-LAYER METEOROLOGY IN A NUTSHELL

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To celebrate the career of Joost A. Businger a symposium was held at the joint assembly of the American Geophysical Union (AGU) and European Geophysical Society (EGS) at Nice, 6–11 April 2003. During that symposium Joost Businger received the EGS Vilhelm Bjerknes Medal. To follow up on this memorable event we present here this special issue of *Boundary-Layer Meteorology*, which contains a number of papers based on talks given at this EGS-AGU symposium. The main goal of this issue is to celebrate the 80th birthday of Joost Businger on the 29th March 2004. In this introduction to the special issue we take the opportunity to briefly describe the career of Joost Businger and highlight some of the notable events in his scientific life.

Joost Businger was one of the first, who recognized that the atmospheric boundary layer (ABL) has a great practical and scientific importance, practical in the sense that most of men's activities take place within it and scientific in the sense that the boundary layer forms the interaction region between the free atmosphere and the earth's surface and therefore is a major factor in our weather and climate. Furthermore, Joost Businger was one of the first who recognized that boundary-layer flows are usually turbulent which implies that, for the time being, ABL processes can be described only in terms of simplified models or parameterizations. One of the parameterization schemes, to which Joost Businger contributed early in his career, has been the similarity approach. He realized that such an approach requires a combination of theoretical and experimental work. He kept this attitude for his whole career.

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† Frans Nieuwstadt, a recently retired member of the BLM Editorial Board and a well-known member of the boundary-layer/turbulence community, died unexpectedly on 18 May 2005. An obituary will appear in a later issue of BLM.

As a graduate student Joost Businger was exposed to the program Technical Physics at the University of Utrecht, which focused on turbulent transfer of heat, mass and momentum in the atmospheric surface layer (ASL) and which made extensive use of similarity approach. In this context Joost Businger applied these techniques to the interactions between the earth's surface and the atmosphere. He developed a similarity concept, in which he defined a length scale that is nowadays known as the *Obukhov length*. This work was done simultaneously with, but independently of, the research done by Monin and Obukhov (1954) in the Soviet Union (in those days exchange of scientific ideas across the '*Iron Curtain*' was virtually impossible). Based on this work Joost Businger received his PhD degree (Businger, 1954, 1955a) in the same year that the theory of Monin and Obukhov (1954) appeared in the Russian literature. The two similarity approaches have in common that they both use the *Obukhov* length scale, but the difference is that Joost Businger considered the roughness length as the *relevant* length scale instead of the height above the surface as proposed by Monin and Obukhov (MO). Joost Businger soon accepted that the MO theory is more adequate than his own 1954 approach, although it is interesting to note that in various ABL studies the roughness length is considered a relevant length scale for boundary-layer flows. An example is the Rossby-number similarity approach for the entire ABL (see Garratt, 1994, pp. 43–47). Moreover, over sea and flexible vegetation the roughness length appears to be related to wind speed (see e.g. Brutsaert, 1982, pp. 113–121). Joost Businger's thesis also contained some pioneering studies in air-mass modification in the boundary layer.

In the next phase of his scientific life, Joost Businger spent some time at the Institute for Horticultural Engineering, Wageningen, The Netherlands. There he was involved in studying the microclimate in greenhouses (e.g., Businger, 1955b, 1963), evapotranspiration (Businger, 1955c) and frost protection of crops by sprinkling (Businger, 1965a). He tested the latter technique experimentally. Nowadays the sprinkling method is applied operationally in agricultural practice.

After he moved to the U.S.A. in 1956 to work with V.E. Suomi at the University of Wisconsin, Joost Businger continued his experimental ASL studies. He was one of the first who worked on (the development of) the *sonic anemometer*, which nowadays is the standard instrument of choice in ABL research (see e.g., Businger and Suomi, 1958; Suomi and Businger, 1959; Kaimal and Businger, 1963a, b; Kaimal et al., 1964 and later: Larsen et al., 1979; Zhang et al., 1986). Its prime application as already envisaged by Joost Businger lies in the so-called eddy-correlation method (see e.g. the pioneering paper by Swinbank, 1951) to measure turbulent fluxes (Businger et al., 1967; Businger and Deardorff, 1968; Businger and Miyake, 1968; Businger 1982a). It should be also noted here that computer-based data loggers and data processing procedures did not exist in those times and consequently the

Joost Businger at Pt Barrow.

processing of sonic anemometer data was a huge and time consuming task. Furthermore, Joost Businger contributed to methods for measuring the net radiative flux and its divergence (e.g. Businger and Kuhn, 1960; Tanner et al., 1960). He worked also on the mixing length concept (Businger, 1959) and the relation between the spectrum of turbulence and the wind profile (Businger, 1960).

The pinnacle in Joost Businger's work on MO similarity theory is without any doubt the Businger et al. (1971) paper. The number of citations of this paper is still increasing and approaches 1500. It should, however, be emphasized that this milestone paper was a logical consequence of the research described in his thesis and later papers (see also Monin and Yaglom, 1971, pp. 453–454). In spite of the high number of citations of this 1971 paper, Joost Businger considered his own contribution to the MO flux–profile relationships as modest. This follows, for instance, from his effort (with A.M. Yaglom) to produce an English translation of the Obukhov (1946) paper, in which the *Obukhov length* is introduced (Businger and Yaglom, 1971), and from his note on the Businger–Dyer relations pointing out the contribution by A.J. Dyer (Businger, 1988a). Furthermore, Joost Businger recognized that the ASL is affected by the entire boundary layer. For this reason he stressed the importance of measuring boundary-layer quantities also in ASL field experiments (see e.g. Businger, 1975a).

In 1975, Joost Businger spent a sabbatical year at KNMI where at that time we (HDB and FN) both were employed in the Department of Physical Meteorology. In this period Joost Businger wrote one of his first manuscripts on air–sea interaction, Businger (1975a, b). This work includes issues relating to the marine ABL, molecular sub-layers, remote sensing techniques to measure ocean surface stress and cloud formation over the sea (see Liu and Businger, 1975; Katsaros et al., 1977; Liu et al., 1979; Stage and Businger, 1980a, b; Businger and Charnock, 1983; Businger and Shaw, 1984; Businger, 1985; Rogers and Businger, 1988; Charnock and Businger, 1991; Large and Businger, 1988; Koracin et al., 2001). Moreover, this work also resulted in a text book (Kraus and Businger, 1994).

Joost Businger's research interests broadened from the ASL towards boundary-layer meteorology in general in the 1980s. This resulted in studies on neutral, convective and cloud-topped (marine) boundary layers and on remote sensing techniques to measure ABL parameters. In relation to this work we mention here his insight that coherent structures must play a role in boundary-layer dynamics. In particular his work together with J.C. Kaimal and others (see later) on temperature ramps in the convective boundary layer should be mentioned, which since then have been rediscovered in the engineering literature on scalar mixing. Also the work with J. Wilczak on convective plumes deserves a special mentioning (Wilczak and Businger, 1983).

After he moved to the University of Washington and later to the National Center for Atmospheric Research (NCAR) Joost Businger continued to work on methods of observation. For instance, he paid attention to remote sensing techniques (e.g., Guymer et al., 1981) and, last but not least, he contributed to methods to measure fluxes of gas species (Businger, 1975d, 1986; Businger and Delany, 1990). The conditional sampling method (or relaxed eddy accumulation approach) has been patented (Businger and Oncley, 1990).

To enable other researchers to carry out experimental ASL or ABL research he contributed to the NCAR ASTER facility (Businger et al., 1990).

That Joost Businger recognized the importance of collecting experimental data sets under a wide range of environmental conditions follows from his participation in various important field experiments, for instance at Pt Barrow, Alaska (1960, 1962, 1971); at the Blue Glacier, Washington, U.S.A. (1964); at Hay, Australia (1966); at Hanford, Washington, U.S.A. (1967); at Tsimliansk, Soviet Union (1970) and the field experiments known through their acronym (see annex): the AFCRL experiment in Kansas (1968); GATE (1974); JASIN (1978) and FASINEX (1986). Futhermore, Joost Businger participated in some smaller field experiments in Washington and Wyoming.

His papers on the MO flux–profile relationships have received much attention, but Joost Businger felt that the other issues he worked on were at least as important from a scientific point of view. An example is the work he carried out with J.C. Kaimal and others on dust devils and convective plumes (Kaimal and Businger, 1970, 1971; Businger and Frisch, 1972; Frisch and Businger, 1973; Businger and Khalsa, 1978; see also Wilczak and Businger, 1983). The Kaimal–Businger 1970 paper is still one of the few in which raw eddy-correlation data of these structures in the convective ABL are analyzed. Recently, scientific interest in dust devils has reappeared in their role as very vigorous weather phenomena on Mars where they appear to play an essential role in the Martian climate. As a result novel dust devil research has been initiated. Joost Businger worked also on free convection conditions in general (see e.g. Businger, 1971, 1973a; Katsaros et al., 1977).

Joost Businger has always encouraged research on simple methods of observation such as the variance approach (Businger, 1973b). Furthermore, other approaches, such as the dissipation method received his attention (Khalsa and Businger, 1977). His broad interest in environmental sciences becomes clear from his work on issues such as *'thermal contact coefficient'* (Businger and Buettner, 1961), *'blowing snow'* (Businger, 1965b), *'unidentified sounds'* (Businger, 1968), *'clear-air turbulence'* (1969a), *'ice on Venus'* (Businger and Holton, 1968), *'aerodynamics of vegetated surfaces'* (Businger, 1974), *'radiative cooling at cloud tops'* (Nieuwstadt and Businger, 1984, 1986), *'air modification'* (Vugts and Businger, 1977), *'meso-scale variability'* (Glendenning et al., 1986) *'meso-scale and terrain effects on ABL'* (Businger, 1988b), *'internal boundary layers over irrigated areas in desert environment'* (Businger, 1994), *'dissipation of turbulence kinetic energy in storms'* (Businger and Businger, 2001), and *'stratus fog'* (Koracin et al., 2001).

From his own perspective, Joost Businger felt that he failed to solve the problem of the very stable ABL, in particular, with respect to the meaning and magnitude of the critical Richardson number Ri_{fcr}. Here we cite some fragments of Businger (1973b): *"The... Ri_{fcr} is reached ... at some height above, but relatively close to the surface. As soon as this happens the turbulence will be dampened and a laminar layer will tend to form. This layer is an effective barrier for all the fluxes. The transfer of momentum and heat from higher layers will be blocked... The result is that the wind diminishes and a period of calm sets in... The temperature near the surface drops dramatically... In the meantime, above the laminar layer momentum is still transferred downward... Consequently, the momentum increases in the upper part of the laminar layer... A strong wind shear builds up... Ri must decrease, eventually reaching a value below Ri_{cr}. Eventually the turbulence reaches the ground associated with a burst of momentum and heat. After this the entire sequence of events may repeat itself".* Here Joost Businger proposes as one of the first a mechanism by which the flow in the very stable ABL can become intermittently turbulent. The problem of how to 'catch' this complex phenomenon in parameterization schemes for the ABL in numerical weather and climate models is still an unsolved issue.

Joost Businger's skills as a teacher and supervisor of MSc and PhD students are generally acknowledged. He gained much satisfaction from teaching a course on radiation, explaining that for life on earth to exist the expansion of the universe is as important as the closeness of the sun. In this context, Joost Businger's contributions to textbooks are worthwhile to mention also. Examples are the chapters on the ABL in Fleagle and Businger (1963, 1980), the chapter he wrote in the book published on the Workshop of Micrometeorology held in 1973 at Boulder (Businger, 1973b) and his contribution to Nieuwstadt and en Van Dop (1982), see Businger (1982b). The citation index of these publications is high; for instance that for Businger (1973b) approaches 400. This emphasizes that the text book contributions by Joost Businger are still used to teach micrometeorology all over the world.

As mentioned earlier Joost Businger considered his own contributions to science as of modest interest. This might be due to his Dutch genes, because in the Netherlands people are expected to behave "gewoon" (which means 'normal', 'common' or 'as everybody else'). Fortunately, others have recognized the significance of Businger's work, which resulted, among others, in the 1978 AMS Half Century Award and the 2003 EGS Vilhelm Bjerknes Medal, with which we have started this brief biography.

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Annex 1. Acronyms used in paper

ABL	Atmospheric Boundary Layer
AFCRL	Air Force Cambridge Research Laboratory
AGU	American Geophysical Union
AMS	American Meteorological Society
ASL	Atmospheric Surface Layer
ASTER	Atmosphere/Surface Turbulent Exchange Research
EGS	European Geophysical Society
FASTEX	Fronts and Atlantic Storm-Track EXperiment
GATE	GARP Atlantic Tropical Experiment
GARP	Global Atmospheric Research Experiment
JASIN	Joint Air-Sea Interaction Experiment
KNMI	Royal Netherlands Meteorological Institute
NCAR	National Center for Atmospheric Research

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