7.1 **50 YEARS OF THE MONIN-OBUKHOV SIMILARITY THEORY**

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1. INTRODUCTION

After Obukhov found in 1946 a universal length scale for exchange processes in the surface layer, a logical consequence was the development of the similarity theory by Monin and Obukhov in 1954. This theory was the starting point for the development of new devices and for several experiments, as well as for the formulation of the presently used universal functions.

In this paper, a short historical survey is presented, followed by a description of the present status of the theory, covering topics such as the accuracy of the universal functions, the influence of moisture, and the turbulent Prandtl number.

My personal and professional contact with A. M. Obukhov and A. S. Monin developed during common expeditions. In 1975 and 1976 I was a member of the KASPEX-75 and KASPEX-76 expeditions (Foken et al., 1978) of the Institute of Oceanology, Moscow (Director: A. S. Monin) and in 1981 I participated in the International Turbulence Comparison Experiment (ITCE-81) in Tsimlyansk, Russia (Tsvang et al., 1985) of the Institute of Physics of the Atmosphere (Director: A. M. Obukhov). From 1980 to 1990, I was scientific secretary of the KAPG-Project (cooperation of the East European Academies of Science in geoscience) "Atmospheric Boundary Layers" initiated by A. M. Obukhov (Bernhardt and Foken, 1994).

2. HISTORICAL OVERVIEW

On the occasion of the 100 years anniversary of Reynolds' decomposition (Reynolds, 1894), J. A. Businger gave an overview of the history of boundary layer meteorology (micrometeorology) during the Tenth Conference on Turbulence and Boundary Layers (Portland, 1992). Following this presentation, a short historical survey will be presented to show the place of the Monin-Obukhov similarity theory (Monin and Obukhov, 1954) in historical context.

At the beginning of the last century, much progress was made in hydrodynamics connected with the fundamental papers by Taylor (1915), Richardson (1920), and Prandtl (1925). Before the second world war, experimental studies were mainly done in German speaking countries. In Vienna Schmidt (1925) formulated the 'Austausch coefficient'; in Munich Geiger (1927) summarized microclimatological works in his famous and even now available book 'The climate near the ground' (Geiger et al., 1995); and in Potsdam, after many experimental studies (Kleinschmidt, 1935), Albrecht wrote the first paper about the energy balance of the earth (Albrecht, 1940).

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After fundamental studies were published about the turbulence spectra (Kármán and Howarth, 1938; Taylor, 1938), investigations were continued by Russian scientist during the second world war, mainly by Kolmogorov (1941a; 1941b). In 1946, three years before Lettau, Obukhov (1946) found the scaling length for the surface layer. This was the basis of the Monin-Obukhov similarity theory (1954). At the beginning of the 1950s many famous experiments took place, mainly connected with names like Lettau, Swinbank, Dyer, and Tsvang. In addition, the idea of a direct measuring method for turbulent fluxes, now known as the eddy covariance method, was developed (Montgomery, 1948; Obukhov, 1951; Swinbank, 1951). This method only emerged later, after the development of the sonic anemometer by Bovscheverov and Voronov (1960) and later on by Kaimal and Businger (1963) and Mitsuta (1966). These phase shift anemometers have now been replaced by running time anemometers with time measurements (Hanafusa et al., 1982).

This was the basis for famous experiments, including so-called comparison experiments for turbulence sensors (Dyer and Bradley, 1982; Miyake et al., 1971; Tsvang et al., 1973; Tsvang et al., 1985) with some basic investigations, and experiments for studying the turbulent exchange processes, mainly the KANSAS 1968 experiment (Izumi, 1971) which was the basis for the presently and predominantly used universal function by Businger et al. (1971). An important summary about the status of the knowledge of turbulent exchange processes between the atmosphere and the surface was given in 1973 at the Workshop on Micrometeorology (Haugen, 1973).

After some criticism of the experimental design of the KANSAS experiment by Wieringa (1980) and the reply by Wyngaard et al. (1982), which focussed in the decision to repeat the experiment, nearly no new experimental efforts were initiated on this topic. The corrected universal functions by Högström (1988) comprise our most current knowledge.

3. THE OBUKHOV LENGTH

Obukhov (1946) assumed according to Buckingham's Π-theorem that the parameters g/T_0 (g: gravity acceleration, T_0: surface temperature), v_* (friction velocity), and $q/(c_p \cdot \rho)$, with q: kinematical heat flux, c_p: specific heat, and ρ: air density, describe the atmospheric turbulence above the canopy. All symbols are used according to the original papers. Only one parameter with the dimension of length is possible to describe these processes – the Obukhov Length –

$$L = -\frac{v_*^3}{\kappa \cdot \frac{g}{T_0} \cdot \frac{q}{c_p \cdot \rho}} \quad (1)$$

with κ: von-Kármán-constant. In the surface layer (Prandtl-layer, constant flux layer), the vertical fluxes were assumed to be constant with the height:

$$\overline{w'T'} = \frac{q}{c_p \cdot \rho} = const, \quad (2)$$

$$-\rho\,\overline{u'w'} = \tau = const \qquad v_* = \sqrt{\frac{\tau}{\rho}} \quad (3)$$

with T': fluctuations of the temperature, w': fluctuations of the vertical wind velocity, and τ : shear stress. Because L was established about 8 years before the publication of the Monin-Obukhov similarity theory (Monin and Obukhov, 1954), this length scale is called 'only' Obukhov-length. The same scale was found three years later by Lettau.

Obukhov (1946) proposed that the absolute measurement of the shear stress with the eddy-covariance method

$$\tau = -\rho\ \overline{u'w'} \quad (4)$$

is of fundamental importance for the investigation of the surface layer and for the control of indirect methods. Therefore, in 1949 Konstantinonov (Obukhov, 1951) developed a wind vane with two hot wire anemometers (90° angle) for the measurement of the friction velocity (Fig. 1). This work was contemporaneous with similar investigations by Montgomery (1948) and Swinbank (1951).

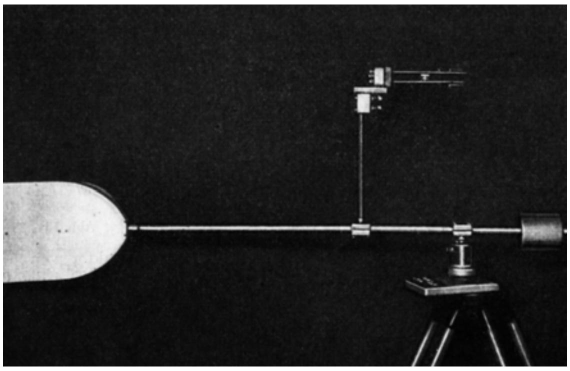

Fig. 1: Wind vane with two hot wire anemometers (90° angle) for the measurement of the friction velocity on the basis of Konstantinonov's work in 1949 (Obukhov, 1951).

4. THE MONIN-OBUKHOV SIMILARITY THEORY

A. S. Monin (* 02.07.1921) and A.M. Obukhov (05.05.1918 – 03.12.1989), seen in Fig. 2, developed their famous similarity theory (Monin and Obukhov, 1954) on the basis of the following finding:

- Fundamental experimental works of the Geophysical Main Observatory Leningrad mainly connected with scientists like Lajchtman, Budyko, etc.,
- Logarithmic wind profile (Prandtl, 1925),
- Zero-plane displacement (Paeschke, 1937),
- Obukhov length (Obukhov, 1946).

Fig. 2: A.S. Monin (left) and A.M. Obukhov (right)

Also, according to Buckingham's Π-theorem, for the dimensionless wind- and temperature profile Monin and Obukhov assumed

$$\frac{\kappa \cdot z}{v_*} \cdot \frac{\partial \overline{v}}{\partial z}, \quad (5)$$

$$\frac{z}{T_*} \cdot \frac{\partial \overline{T}}{\partial z} \quad (6)$$

with v: wind velocity and T_*: dynamical temperature, and both only a function of the parameters g/T_0, v_*, $q/(c_p \cdot \rho)$, and the height z. There exists only one dimensionless coefficient z/L.

It should be noted that the dimensionless profiles are written without the von-Kármán-constant κ and with a turbulent Prandtl number Pr_t =1. They knew Priestley's and Swinbank's (1947)assumption for the exchange coefficients of heat and momentum $K_H > K_m$ for unstable stratification,

$$\frac{1}{\mathrm{Pr}_t} = \frac{K_H}{K_m} > 1, \quad (7)$$

but instead used $K_H = K_m$ because of experimental deficits. They also documented a modification of their theory.

In accordance with the dimensionless parameter z/L, the wind and temperature profiles can be written with universal functions:

$$\frac{\kappa \cdot z}{v_*} \cdot \frac{\partial \overline{v}}{\partial z} = \varphi_1\left(z/L\right), \quad (8)$$

$$\frac{z}{T_*} \cdot \frac{\partial \overline{T}}{\partial z} = \varphi_2\left(z/L\right) \tag{9}$$

The universal function can be developed as a power series in the case of |z/L| < 1 with β = 0.6:

$$\varphi\left(z/L\right) = 1 + \beta \frac{z}{L}, \tag{10}$$

For strong unstable stratification, z/L « -1, the assumed power law is:

$$f\left(z/L\right) \approx C\left(z/L\right)^{-1/3} + const \tag{11}$$

For strong stable stratification, z/L » 1, because:

$$K = \kappa \cdot v_* \cdot L \cdot Ri \tag{12}$$

where $Ri \approx R = const$.

20-30 years ago, the Monin-Obukhov similarity theory was like a dogma and it was nearly impossible to publish in reviewed journals and papers any results which were not in agreement with the similarity theory (especially in Russia), e.g. the first studies about counter gradients were published in grey literature:

- above the ocean (Foken and Kuznecov, 1978),
- in the forest (Denmead and Bradley, 1985).

Obukhov also published other similarity functions which are absolutely independent of the Monin-Obukhov similarity theory, e.g. the similarity functions for the temperature structure parameter

$$C_T^2 \approx \overline{w'T'}^{4/3} \cdot \left(\frac{g}{T_0}\right)^{-2/3} \cdot z^{-4/3} \tag{13}$$

was found by Obukhov (1960).

5. UNIVERSAL FUNCTIONS

After the development of the similarity theory for the surface layer, a lot of experimental efforts were done to determine universal functions. First functions were published by Swinbank (1964; 1968), Tschalikov (1968), and Zilitinkevich and Tschalikov (1968); for an overview, see Foken (2003). The presently used universal functions by Businger et al. (1971) are based on the data of the 1968 KANSAS experiment (Izumi, 1971) and are different for momentum and heat exchange:

$$\varphi_m\left(z/L\right) = \begin{Bmatrix} \left(1 - 15\, z/L\right)^{-1/4} & -2 < z/L < 0 \\ 1 + 4.7\, z/L & 0 < z/L < 1 \end{Bmatrix}, \tag{14}$$

$$\varphi_H\left(z/L\right) = \begin{Bmatrix} 0.74 \cdot \left(1 - 9\, z/L\right)^{-1/2} & -2 < z/L < 0 \\ 0.74 + 4.7\, z/L & 0 < z/L < 1 \end{Bmatrix}. \tag{15}$$

Note that the functions are based on κ = 0.35 and $Pr_t^{-1} = 1.35$.

During the Workshop on Micrometeorology (Haugen, 1973), the fundament relationships were also discussed, so the O'KEYPS-equation (Obukhov, Kaimal, Elliot, Yamamoto, Panofsky, Sellers)

$$\left[\varphi_m\left(z/L\right)\right]^4 - \gamma \cdot z/L \left[\varphi_m\left(z/L\right)\right]^3 = 1 \tag{16}$$

which can be solved using the universal function of the Dyer-Businger type (Businger, 1988):

$$\varphi_m\left(z/L\right) = \left(1 + \gamma \cdot z/L\right)^{-1/4} = 1 \tag{17}$$

The relationship of the universal function of heat to the universal function of momentum is provided by the Dyer-Businger equation:

$$\varphi_H = \begin{Bmatrix} \varphi_m^2 & z/L < 0 \\ \varphi_m & z/L \geq 0 \end{Bmatrix}. \tag{18}$$

An important issue is the normalization of the Obukhov length (Yaglom, 1977):

$$L = -\frac{u_*^3}{\kappa \cdot \frac{1}{Pr_t} \cdot \frac{g}{T_0} \cdot \frac{\overline{w'T'}}{c_p \cdot \rho}}, \tag{19}$$

(u_*: friction velocity) which can be normalized also with the turbulent Prandtl number or used without the von-Kármán-constants, the latter like in the papers by S.S.Zilitinkevich. Also, the turbulent Prandtl number can be used either in the profile equation

$$\frac{\kappa}{Pr_t} \cdot \frac{z}{T_*} \cdot \frac{\partial \overline{T}}{\partial z} = \varphi_H\left(z/L\right), \tag{20}$$

or in the universal function

$$\varphi_H\left(z/L\right) = Pr_t\left(1 + \gamma \cdot z/L\right)^{-1/2} \quad z/L < 0, \tag{21}$$

as done by Högström (1988).

The Obukhov length was defined for dry air. The use of the virtual (or sonic) temperature T_v is physically more adequate for moist air, but all universal functions were determined for dry conditions:

$$L = -\frac{u_*^3}{\kappa \cdot \frac{g}{T_{v0}} \cdot \frac{\overline{w'T_v'}}{c_p \cdot \rho}} \tag{22}$$

6. PRESENT STATUS OF THE MONIN-OBUKHOV SIMILARITY THEORY

The criticism of the KANSAS experiment by Wieringa (1980) was connected with flow distortion problems of the tower, overspeeding of the cup anemometers, uncertainties of the phase shift sonic anemometers, and an unrealistic von-Kármán-constant. According to these findings, Högström (1988) re-formulated the universal functions. The function by Businger et al. (1971) is presently used in the form:

$$\varphi_m\left(z/L\right)=\begin{cases}\left(1-19.3\,z/L\right)^{-1/4} & -2<z/L<0\\ 1+6\,z/L & 0<z/L<1\end{cases}, \qquad (24)$$

$$\varphi_H\left(z/L\right)=\begin{cases}0.95\cdot\left(1-11.6\,z/L\right)^{-1/2} & -2<z/L<0\\ 0.95+7.8\,z/L & 0<z/L<1\end{cases} \qquad (25)$$

Note that the functions based on $\kappa = 0.40$ and $Pr_t^{-1} = 1.05$ is used in the universal function.

A summary of recent studies of the Monin-Obukhov similarity theory was published by Högström (1996). A value of 0.40 for the von-Kármán-constant is widely accepted. Even today the accuracy of the turbulent Prandtl number is only 5-10 % (see Table 1).

Table 1: Values for the reciprocal turbulent Prandtl-number (Foken, 2003)

Author	$1/Pr_t$
Businger et al. (1971)	1.35
– Correction according to Wieringa (1980)	1.00
– Correction according to Högström (1996)	1.05
Kader and Yaglom (1972)	1.15 – 1.39
Foken (1990)	1.25
Högström (1996)	1.09 ± 0.04

Högström (1996) gave the following values for the accuracy of the presently used universal functions:

- $|z/L| \le 0.5$: $|\delta\varphi_H| \le 10$ %
- $|z/L| \le 0.5$: $|\delta\varphi_m| \le 20$ %
- $z/L > 0.5$: φ_H, φ_m = const ? E.g. Handorf et al. (1999) found $\varphi_m = 4$ for $z/L > 0.6$
- φ_H, $\varphi_m = f(z_i)$? According recent findings by Johannson et al. (2001), the universal functions depend on the mixed layer height z_i.

It should be noted that the limitations on the accuracy of the turbulent Prandtl and Schmidt numbers as well as the universal functions are limitations in all weather and climate models! A further problem is the so-called residuum in the energy balance closure (Culf et al., 2004; Foken, 1998). An additional influence on the accuracy of the universal functions occurs when the 'unclosed' energy balance is caused by deficits in the turbulent fluxes determined with the eddy covariance method.

7. CONCLUSIONS

At the present time, use of the Monin-Obukhov similarity theory is limited by the validity only in the surface layer (constant flux layer) above the roughness sublayer (probably not valid above tall vegetation), the range of validity of |z/L| ≤ 1…2, and the limitation to homogeneous surfaces.

A better understanding of the limitations and non-ideal conditions depends upon an exact knowledge of all parameters of the similarity theory. Therefore, we should agree with Wyngaard et al. (1982) in that the problems with KANSAS 1968 can only be solved with a new experiment. At the present time, we have a good basis for this, because the eddy covariance method was highly updated in the last 5-10 years (new sensors, updated corrections, data quality checks).

Modellers must understand that only better physics and not 'screws' are the key to better models, and that surface layer fluxes are an important part of each model.

8. ACKNOWLEDGMENT

The 50 years of the Monin-Obukhov similarity theory also represent 50 years of modern micrometeorology. Most of our teachers have written this story. We are grateful to them.

I want especially to thank my Russian colleagues, who gave me the opportunity to study the Monin-Obukhov similarity theory in the places where the theory was developed.

9. REFERENCES

Albrecht, F., 1940. Untersuchungen über den Wärmehaushalt der Erdoberfläche in verschiedenen Klimagebieten. Reichsamt für Wetterdienst, Wissenschaftliche Abhandlungen, Bd. **VIII**, Nr. 2: 1-82.

Bernhardt, K. and Foken, T., 1994. Atmospheric Boundary Layer Research in Central and East European Countries with KAPG, 1981-1990. Geophysical Report, **01**: 1-58.

Bovscheverov, V.M. and Voronov, V.P., 1960. Akustitscheskii fljuger. Izvestia AN SSSR, seria Geofizika, **6**: 882-885.

Businger, J.A., 1988. A note on the Businger-Dyer profiles. Boundary-Layer Meteorology, **42**: 145-151.

Businger, J.A., Wyngaard, J.C., Izumi, Y. and Bradley, E.F., 1971. Flux-profile relationships in the atmospheric surface layer. Journal Atmospheric Science, **28**: 181-189.

Culf, A.D., Foken, T. and Gash, J.H.C., 2004. The energy balance closure problem. In: P. Kabat et al. (Editors), Vegetation, water, humans and the climate. A new perspective on an interactive system. Springer, Berlin, Heidelberg, pp. 159-166.

Denmead, D.T. and Bradley, E.F., 1985. Flux-gradient relationships in a forest canopy. In: B.A. Hutchison and B.B. Hicks (Editors), The forest-atmosphere interaction. D. Reidel Publ. Comp., Dordrecht, Boston, London, pp. 421-442.

Dyer, A.J. and Bradley, E.F., 1982. An alternative analysis of flux-gradient relationships at the 1976 ITCE. Boundary-Layer Meteorology, **22**: 3-19.

Foken, T., 1990. Turbulenter Energieaustausch zwischen Atmosphäre und Unterlage - Methoden, meßtechnische Realisierung sowie ihre Grenzen und Anwendungsmöglichkeiten. Berichte des Deutschen Wetterdienstes, **180**: 287 pp.

Foken, T., 1998. Die scheinbar ungeschlossene Energiebilanz am Erdboden - eine Herausforderung an die Experimentelle Meteorologie. Sitzungsberichte der Leibniz-Sozietät, **24**: 131-150.

Foken, T., 2003. Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Heidelberg, 289 pp.

Foken, T., Kitajgorodskij, S.A. and Kuznecov, O.A., 1978. On the dynamics of the molecular temperature boundary layer above the sea. Boundary-Layer Meteorology, **15**: 289-300.

Foken, T. and Kuznecov, O.A., 1978. Die wichtigsten Ergebnisse der gemeinsamen Expedition "KASPEX-76" des Institutes für Ozeanologie Moskau und der Karl-Marx-Universität Leipzig. Beitr. Meeresforsch., **41**: 41-47.

Geiger, R., 1927. Das Klima der bodennahen Luftschicht. Friedr. Vieweg & Sohn, Braunschweig, 246 pp.

Geiger, R., Aron, R.H. and Todhunter, P., 1995. The climate near the ground. Friedr. Vieweg & Sohn Verlagsges. mbH, Braunschweig, Wiesbaden, 528 pp.

Hanafusa, T., Fujitana, T., Kobori, Y. and Mitsuta, Y., 1982. A new type sonic anemometer-thermometer for field operation. Papers in Meteorology and Geophysics, **33**: 1-19.

Handorf, D., Foken, T. and Kottmeier, C., 1999. The stable atmospheric boundary layer over an Antarctic ice sheet. Boundary-Layer Meteorology, **91**: 165-186.

Haugen, D.H. (Editor), 1973. Workshop on micrometeorology. Am. Meteorol. Soc., Boston, 392 pp.

Högström, U., 1988. Non-dimensional wind and temperature profiles in the atmospheric surface layer: A reevaluation. Boundary-Layer Meteorology, **42**: 55-78.

Högström, U., 1996. Review of some basic characteristics of the atmospheric surface layer. Boundary-Layer Meteorology, **78**: 215-246.

Izumi, Y., 1971. Kansas 1968 field progarm data report. Air Force Cambridge Research Papers, No. 379, Air Force Cambridge Research Laboratory, Bedford, MA.

Johansson, C., Smedman, A., Högström, U., Brasseur, J.G. and Khanna, S., 2001. Critical test of Monin-Obukhov similarity during convective conditions. Journal Atmospheric Science, **58**: 1549-1566.

Kader, B.A. and Yaglom, A.M., 1972. Heat and mass transfer laws for fully turbulent wall flows. International Journal of Heat and Mass Transfer, **15**: 2329-2350.

Kaimal, J.C. and Businger, J.A., 1963. A continuous wave sonic anemometer-thermometer. Journal of Climate and Applied Meteorology, **2**: 156-164.

Kármán, T.v. and Howarth, L., 1938. On the statistical theory of isotropic turbulence. Proceedings Royal Society London, **A 164**: 192-215.

Kleinschmidt, E. (Editor), 1935. Handbuch der meteorologischen Instrumente und ihrer Auswertung. Springer, Berlin, 733 pp.

Kolmogorov, A.N., 1941a. Lokalnaja struktura turbulentnosti v neschtschimaemoi schidkosti pri otschen bolschich tschislach Reynoldsa. Doklady AN SSSR, **30**: 299-303.

Kolmogorov, A.N., 1941b. Rassejanie energii pri lokolnoisotropoi turbulentnosti. Doklady AN SSSR, **32**: 22-24.

Mitsuta, Y., 1966. Sonic anemometer-thermometer for general use. Journal of the Meteorological Society of Japan, Ser. II, **44**: 12-24.

Miyake, M. et al., 1971. Comparison of acoustic instruments in an atmospheric flow over water. Boundary-Layer Meteorology, **2**: 228-245.

Monin, A.S. and Obukhov, A.M., 1954. Osnovnye zakonomernosti turbulentnogo peremesivanija v prizemnom sloe atmosfery. Trudy geofiz. inst. AN SSSR, **24** (151): 163-187.

Montgomery, R.B., 1948. Vertical eddy flux of heat in the atmosphere. Journal Meteorology, **5**: 265-274.

Obukhov, A.M., 1946. Turbulentnost' v temperaturnoj - neodnorodnoj atmosfere. Trudy Inst. Theor. Geofiz. AN SSSR, **1**.

Obukhov, A.M., 1951. Investigation of the micro-structure of the wind in the near-surface layer of the atmosphere (in Russian). Izvestia AN SSSR, seria Geofizika, **3**: 49ff.

Obukhov, A.M., 1960. O strukture temperaturnogo polja i polja skorostej v uslovijach konvekcii. Izvestia AN SSSR, seria Geofizika: 1392-1396.

Paeschke, W., 1937. Experimentelle Untersuchungen zum Rauhigkeitsproblem in der bodennahen Luftschicht. Zeitschrift für Geophysik, **13**: 14-21.

Prandtl, L., 1925. Bericht über Untersuchungen zur ausgebildeten Turbulenz. Zeitschrift für angewandte Mathematik und Mechanik, **5**: 136-139.

Priestly, C.H.B. and Swinbank, W.C., 1947. Vertical transport of heat by turbulence in the atmosphere. Proceedings Royal Society London: 543-561.

Reynolds, O., 1894. On the dynamical theory of turbulent incompressible viscous fluids and the determination of the criterion. Phil. Trans. R. Soc. London, A **186**: 123-161.

Richardson, L.F., 1920. The supply of energy from and to atmospheric eddies. Proceedings Royal Society, A **97**: 354-373.

Schmidt, W., 1925. Der Massenaustausch in freier Luft und verwandte Erscheinungen. Henri Grand Verlag, Hamburg, 118 pp.

Swinbank, W.C., 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal Meteorology, **8**: 135-145.

Swinbank, W.C., 1964. The exponential wind profile. Quarterly Journal of The Royal Meteorological Society, **90**: 119-135.

Swinbank, W.C., 1968. A comparison between prediction of the dimensional analysis for the constant-flux layer and observations in unstable conditions. Quarterly Journal of The Royal Meteorological Society, **94**: 460-467.

Taylor, G.I., 1915. Eddy motion in the atmosphere. Phil. Trans. R. Soc. London, **A 215**: 1-26.

Taylor, G.I., 1938. The spectrum of turbulence. Proceedings Royal Society London, **A 164**: 476-490.

Tschalikov, D.V., 1968. O profilja vetra i temperatury v prizemnom sloe atmosfery pri ustojtschivoj stratifikacii. Trudy Glavny Geofiziceskij observatorii, **207**: 170-173.

Tsvang, L.R. et al., 1973. Comparison of turbulence measurements by different instuments; Tsimlyansk field experiment 1970. Boundary-Layer Meteorology, **3**: 499-521.

Tsvang, L.R. et al., 1985. International turbulence comparison experiment (ITCE-81). Boundary-Layer Meteorology, **31**: 325-348.

Wieringa, J., 1980. A revaluation of the Kansas mast influence on measurements of stress and cup anemometer overspeeding. Boundary-Layer Meteorology, **18**: 411-430.

Wyngaard, J.C., Businger, J.A., Kaimal, J.C. and Larsen, S.E., 1982. Comments on 'A revaluation of the Kansas mast influence on measurements of stress and cup anemometer overspeeding'. Boundary-Layer Meteorology, **22**: 245-250.

Yaglom, A.M., 1977. Comments on wind and temperature flux-profile relationships. Boundary-Layer Meteorology, **11**: 89-102.

Zilitinkevich, S.S. and Tschalikov, D.V., 1968. Opredelenie universalnych profilej skorosti vetra i temperatury v prizemnom sloe atmosfery. Izvestia AN SSSR , Fizika Atmosfery i Oceana, **4**: 294-302.