ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2018, Vol. 54, No. 3, pp. 282–292. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © B.M. Koprov, 2018, published in Izvestiya Rossiiskoi Akademii Nauk, Fizika Atmosfery i Okeana, 2018, Vol. 54, No. 3.

From the History of Boundary-Layer Studies at the Institute of Atmospheric Physics

B. M. Koprov
Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow, 119017 Russia
e-mail: bmkoprov@gmail.com
Received October 19, 2017; in final form, January 12, 2018

Abstract—Some results of experimental investigations carried out at the Institute of Atmospheric Physics concerning the role of turbulence in exchange processes in the atmospheric boundary layer are described. From the very beginning, thanks to the works of A.M. Obukhov, the theory of this field strongly surpassed the experiment, and to verify the predictions of the theory and move forward, it was necessary to create new instruments and techniques. As a student of Obukhov, the author personally participated in the creation and practical application of many instruments and techniques. This historical overview presents ten important results that were obtained with the direct involvement of the author and describes the first five results in detail.

Keywords: boundary layer, turbulence, coherent structures, empirical orthogonal functions, acoustic anemometer

DOI: 10.1134/S000143381803009X

INTRODUCTION

It is known that intense experimental research into atmospheric turbulence in Russia began when the Laboratory of Atmospheric Turbulence was organized in the Geophysical Institute of the USSR Academy of Sciences in 1946. It consisted of its first head, A.N. Kolmogorov, and four staff members: A.M. Obukhov, A.M. Yaglom, S.I. Krechmer, and A.V. Perepelkina (Fig. 1). The author was lucky to be a student of A.M. Obukhov and to work under his direct guidance for many years. It is evident that the high position held by the institute in the World's Table of Ranks during the entire time it was headed by Obukhov (over 30 years) is directly related to the scientific and organizational talent of Obukhov himself. The institute's credo, defined by Obukhov, was to equip researchers with the best achievements in physics and mathematics. By the time the Institute of Atmospheric Physics was founded, Obukhov, being a student of Kolmogorov and highly competent in the theory of random processes, had already published remarkable fundamental papers on the turbulence structure, scattering of sound, and dynamic meteorology, which became a theoretical basis for further studies [1]. The works published on turbulence issued from the pen of the staff members of the Institute of Atmospheric Physics number in the hundreds in total. However, the main ones are undoubtedly the monograph Atmospheric Turbulence and Dynamics by Obukhov [1] and the two-volume work Statistical Hydromechanics by A.S. Monin and Yaglom [2, 3].

We note that Obukhov himself participated in developing equipment and measuring turbulence [4, 5]. He believed that a research physicist must by himself find

Fig. 1. First staff members of the Laboratory of Atmospheric Turbulence of the Geophysical Institute of the USSR Academy of Sciences. From left to right: A.M. Obukhov, A.M. Yaglom, A.N. Kolmogorov, S.I. Krechmer, and A.V. Perepelkina.

a solution to a stated problem, create devices, perform in-situ measurements, and compare their results with the theory. The mechanical workshop established at the initiative of Obukhov made it possible to develop the ideas of devices and facilities to the level of working samples. Later on, the devices developed at the institute, including a thermometer of alternate current resistance, acoustic anemometers [9], optical hygrometer [10], and tools for recording and spectral analysis, competed successfully with foreign devices during international expeditions for comparing turbulence measurements by different instruments in Vancouver (1968, [6]), Tsimlyansk (1970, [7]), Australia (1976, [8]), et al.

The experimental groundwork [4, 5] and the theory of locally isotropic turbulence developed by Obukhov [11] and in works by Kolmogorov [12] and J. Batchelor [13], as well as the near-surface layer theory by Monin and Obukhov [14], laid a solid basis for developing studies of the near-surface and boundary layer. A 700 × 700-m portion of the uncultivated steppe found by Obukhov, where acrophysical expeditions were held almost every year, was used as a testing ground for the experimental works. Obukhov participated in almost every expedition, including the summer one based in Rostov for work with Tsimlyansk. Figure 2 shows the location of the expedition at the initial period of the testing ground existence, and Figure 3 demonstrates a working moment of preparing measurements at the Unzha demountable mast.

Below we list ten new geophysical results that have been obtained during the existence of the institute (over 60 years) with the active participation of the author. We note that the authors of these works were also authors of the corresponding devices, which were mostly produced at the workshops of the Institute of Atmospheric Physics.

(1) Development of acoustic anemometers of different purposes for measuring the velocity components by the phase method and the achievement of varied geophysical results on this basis [15–20].

(2) In-flight measurements of the heat turbulent flux profile in the atmospheric boundary layer [16, 21–24].

(3) Development of a technique for the magnetic record of low-frequency signals; creation of a cospectrum analyzer; and measuring Co_{wT}, Co_{uT}, Co_{uw} cospectra and spectral correlation coefficients in the near-surface layer at heights of 2.5, 8, 16, and 37 m under different conditions of stratification [18, 25–27].

(4) Development of an infrared hygrometer and measuring turbulent moisture flows and their spectral composition over dry land in the summer and winter over a freshwater body and ocean in tropical Atlantic [28–36].

(5) Study of the heat balance in the tropical Atlantic during the TROPEKS-72 and ATEP-74 experiments. Based on the results, a hypothesis was stated on the direction of global atmospheric heat transfer near the Intertropical Convergence Zone towards the Intertropical Convergence Zone rather than towards the poles, as was assumed earlier [33, 34], [36–42].

(6) Development of an acoustic meter of velocity circulation and conduct of measurements [43–45].

(7) Construction of a pulsation ozone meter and measuring a vertical turbulent flux of ozone over the steppe [46].

(8) Measuring the spectra of velocity and temperature in the dissipation interval [46–48].

Fig. 2. View of part of the residential segment in the Tsimlyansk testing ground facing the large mast in 1960.

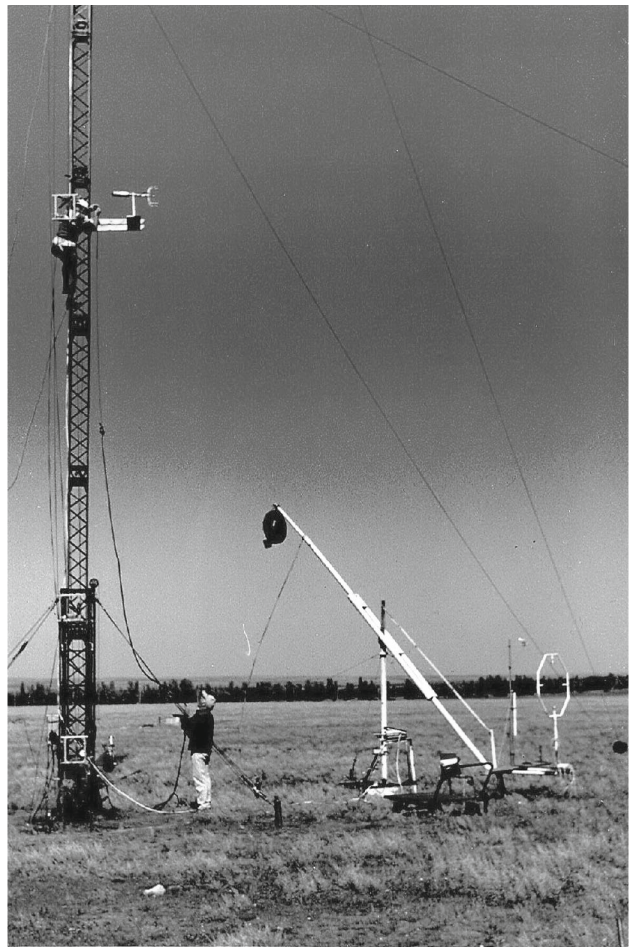

Fig. 3. Mounting of equipment on the Unzha mast; the pantograph mast is on the right.

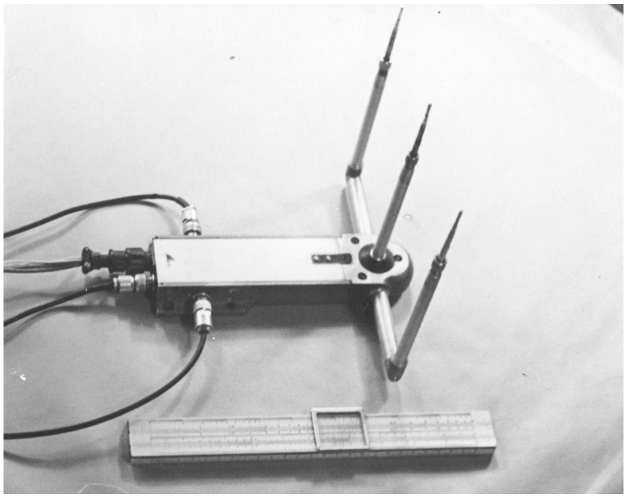

Fig. 4. External part (head) of the acoustic anemometer for aircraft measurements (without wind-protection caps for microphones).

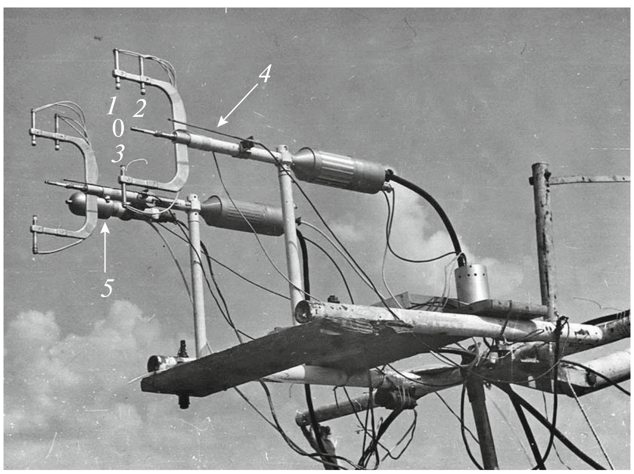

Fig. 5. Acoustic anemometers with X-shaped location of microphones in the experiment on measuring the turbulent flux of ozone. Here, (*0*) radiator, (*1*, *2*, *3*) microphones–receivers of the acoustic anemometer, (*4*) microthermometer sensor, and (*5*) ozone meter sensor.

(9) Measuring and describing instant profiles of a temperature in terms of empirical orthogonal functions in the near-surface atmospheric layer. Study of a spatial–time variation in a temperature [50–52].

(10) Creation of a new method for measuring vorticity by four acoustic anemometers (a tetrahedron method) and measuring helicity density and potential eddy in near-surface turbulence on this basis. Study of spectral compositions of corresponding covariations [53–55].

Next, we describe the studies on the first five items in more detail, but still rather briefly.

1. ACOUSTIC ANEMOMETER

Designed by V.M. Bovsheverov and V.P. Voronov [15], the acoustic anemometer became a prototype for subsequent developments. The device was based on the principle of continuous radiation and measured two horizontal velocity components by the phase method with cylindrical condenser microphones. Figure 4 presents a variant of an aircraft "head" of an anemometer developed by the author for use in experiments on measuring a profile of a turbulent heat flux [16] (item 2 in the above list).

To measure the longitudinal velocity component in the near-surface layer, S.L. Zubkovskii used an anemometer where a transmitter–receiver line was oriented along the wind [17].

Later on (circa 1965), five two-component anemometers were produced with the cruciform configuration of microphones–receivers relative to the radiator intended for the joint measurement of a vertical and longitudinal (along the wind) velocity component. This made it possible to measure $F_{uw}(f), F_{wT}(f)$ cospectra at four levels: 2.5, 8, 16, and 37 m in 1967 (apparently for the first time in the world) [18].

This sensor was improved to the X-shaped sensor; one of its variants is shown in Fig. 5. The sensor is located so that line *1–2* was horizontal and directed along the wind and line *1–3* was vertical. We successfully used anemometers with sensors produced according to this scheme for many years and presented them at the Tsimlyansk International Expedition for Comparison of Instruments in 1970 [11].

Not all the described anemometers with condenser microphones were appropriate for measuring in vapor, clouds, or even at very high relative humidity. The first all-weather three-component anemometer with piezoceramic microphones was developed in cooperation with the Design Bureau of the Institute of Oceanology and was used for the first time in the ATEP 74 expedition. This device, described in [35] (subheading 4 below), was presented at the International Turbulence Comparison Experiment in Australia in 1976 (ITCE-1976) [8].

Another variant of a three-component anemometer of continuous radiation with Bruel & Kjer condenser microphones was proposed in [19] and later on used in Tsimlyansk for many years [20]. The structures of these two three-component anemometers are shown in Fig. 6.

2. MEASURING OF THE PROFILE OF TURBULENT HEAT FLUX FROM AIRCRAFT

Since 1960, the institute has been renting big twin-engine aircraft (Il-14 or Li-2) every year for 100–300 flight hours. Part of this time was used for flights in the Tsimlyansk area.

By this time, the technique for the in-flight measuring of temperature pulsations with a resistance microthermometer had been developed and analog instruments for statistical processing, such as a multi-

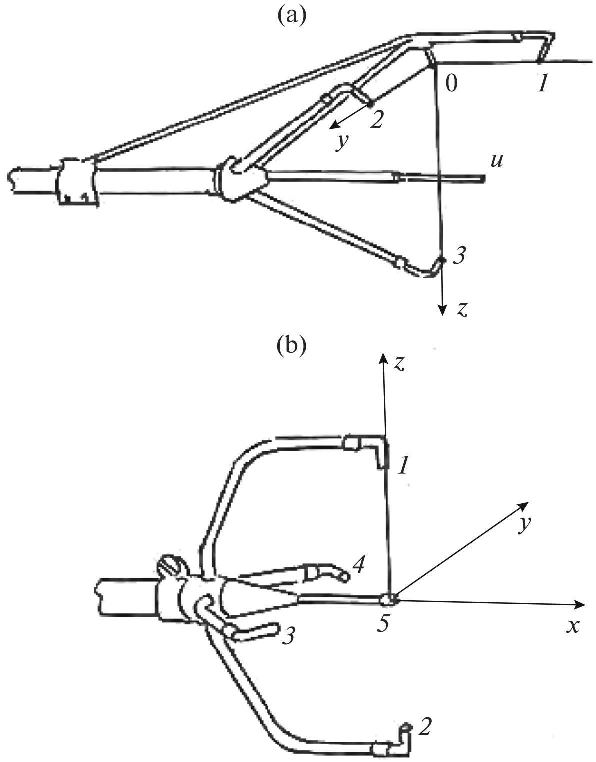

Fig. 6. Heads of three-component anemometers: (a) with face piezo-ceramic microphones [11] and (b) with condenser microphones [18].

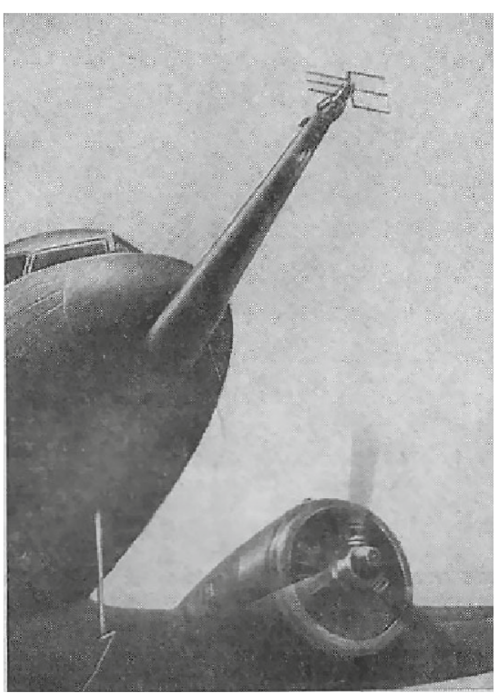

Fig. 7. Acoustic anemometer on the LI-2 aircraft.

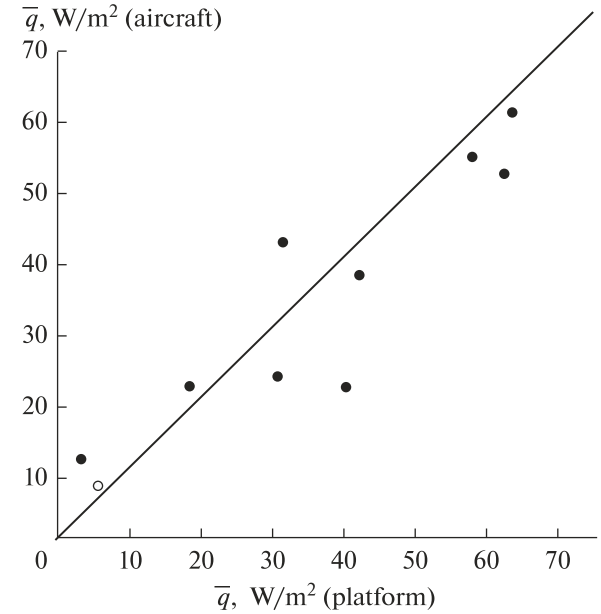

Fig. 8. Comparison of the turbulent heat flux values measured synchronously at a height of 70 m on a platform and from an aircraft.

plier and a frequency analyzer, had been designed, making it possible to obtain covariations, dispersions, and frequency spectra of variations during the measurement procedures [21].

Initially, the task was to calculate the spectra of variations in the vertical velocity component by the measured spectrum of overloads, which was successfully performed. However, of much greater interest was direct in-flight measurements of vertical velocity W with an acoustic anemometer. Figure 7 shows the sensors of the acoustic anemometer (Fig. 4 in subheading 1) and the thermometer mounted on the crossbar in front of the nose cone of the Li-2 aircraft [16].

The influence of the rough flight of the aircraft on the measured value of the vertical velocity was excluded by the introduction of correcting signals. Figure 8 shows a comparison of the vertical heat fluxes that were measured synchronously at a height of 70 m from the platform in Tsimlyansk and from the aircraft.

In July–August 1964, approximately 20 flights were performed; in each flight the turbulent heat fluxes $q = c_p\rho\overline{W'T'}$, as well as the spectra of a temperature and a vertical velocity, were measured at heights of 50, 100, 200, 500, 1000, and 2000 m. Nine of the profiles reported a regular decrease in the flux with height and a change in the flux sign at heights from 200 to 900 m. Figure 9 presents the profile averaged over these nine flights.

At the horizontal homogeneity, the equation of temperature balance may be written in the form

$$\partial\overline{T}/\partial t = -1/c_p\,\rho(\partial q/\partial z\ + \partial q_R/\partial z) + Q_{\mathrm{ph}}/c_p\rho\,.$$

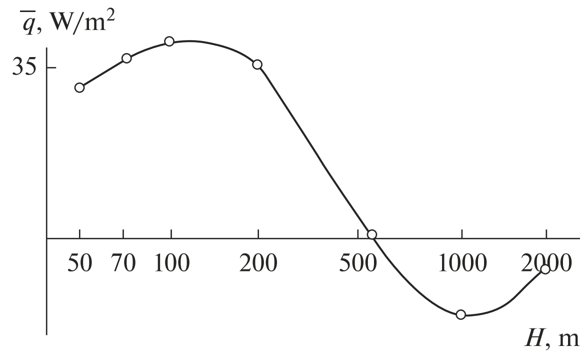

Fig. 9. Averaged summer diurnal profile of the turbulent heat flux in the boundary layer.

Here, $Q_{\rm ph}$ is the heat inflow due to phase transitions and q_R is the radiation flux. In the absence of phase transitions of water, the last term in the right side of this equation may be neglected. We consider the terms to be averaged over time for the interval of about several minutes and take only diurnal variations into account. The calculations show that the temperature change due to divergence of the radiation flux is not large at heights of over 50 m under such conditions. Thus, we suggest that the layer is heated primarily under the impact of turbulent flux divergence. Consequently, the boundary layer above 200 m was nonstationary on a clear day. Later on, we obtained information on the momentum-flux profile in the boundary layer [23].

3. SPECTRA OF TURBULENT HEAT FLUXES AND MOTION QUANTITY IN THE NEAR-SURFACE ATMOSPHERIC LAYER

By the middle of the 1960s, the Institute of Atmospheric Physics had obtained just preliminary data on the spectral composition of the turbulent heat flux at a height of 1 m [24]. Then somewhat more detailed research was carried out in the United States and Canada [24, 25].

In 1966, the 70-m mast of the Tsimlyansk testing ground of the Institute of Atmospheric Physics was equipped with a hoister to measure the longitudinal u' and vertical w' velocity components and temperature in 1967 at four heights: 2.5, 8, 16, and 37 m [18]. By this time, the Institute of Atmospheric Physics had already developed magnetic recording using the method of latitudinal modulation. The spectral analysis of the records was conducted in Moscow with an analog cospectrum analyzer consisting of nine pairs of pairwise identical filters and nine analog multipliers. Increasing the reproducing velocity by a factor of eight when compared to the recording velocity, we performed a spectral analysis with this set of filters in the range of 11.4–0.00525 Hz. The result was the functions $\varphi'_{\alpha\beta}(f)f$, where $\varphi'_{\alpha\beta}(f) = 2\pi\varphi_{\alpha\beta}(\omega)$, $f = \omega/2\pi$, and the pair of subscripts $\alpha\beta$ travels over the values of uw, wT, uu, ww, TT. Atmospheric stratification was characterized by the Richardson number.

Due to measuring of φ_{uu}, φ_{ww}, φ_{TT} autospectra along with the cospectra, we also calculated the spectral coefficients of correlation

$$r_{uw} = \frac{\varphi_{uw}}{[\varphi_{uu}\varphi_{ww}]^{1/2}},\quad r_{wT} = \frac{\varphi_{wT}}{[\varphi_{ww}\varphi_{TT}]^{1/2}}.$$

Instead of wave number $k' = \omega/\overline{U}$, we employed its counterpart $f/\overline{U}$. As the basic spectral characteristics, there were the functions $F(k)$ determined from the relationship $kF(k) = 2\omega\varphi(\omega)$. The results are shown in Fig. 10.

The $kF_{wT}(k)$ spectrum dependence on the stratification conditions is presented in Fig. 11. Figure 12 illustrates the spectral coefficients of correlation r_{wT} (a) and r_{uw} (b) as functions of the dimensionless wave number kz. The fact that, at $kz > 10^0$, r_{wT} decreases as kz grows indicates that in this spectrum interval the cospectrum φ_{wT} decreases with the increase in the frequency ω faster than $\omega^{-5/3}$. This points to the approach to the conditions of local isotropy under which this cospectrum must become zero. We note finally that, at the moment of our measurements, some theorists predicted the same law of –5/3 for the frequency dependence of the cospectra as for the autospectra. The later experimental works provided values from –7/3 to –8/3 for the exponent in the power approximation, i.e., confirmed that we were right.

4. INFRARED HYGROMETER

Water vapor is the main greenhouse gas. This means that the absorption of heat radiation makes a significant contribution to the formation of a temperature profile. The turbulent flux of water vapor determines an important component of heat balance for the underlying surface. In addition to it, the fact of "appearance" during evaporation or "disappearance" when the water vapor condenses onto the soil surface makes a typical assumption on the equality of the vertical velocity on the surface to zero unacceptable.

We also know that, during evaporation from the solutions of NaCl, KCl salts (sea water), the ions of these salts carrying a negative electric charge are transferred to the air [27]. Across the globe, due to this phenomenon, a large number of electric charges is carried to the continent by monsoon, for example, which generates colossal thunderstorm activity.

Therefore, an optical (infrared) hygrometer developed at the optical department of Rozenberg and his postgraduate student L.G. Elagina is an extremely

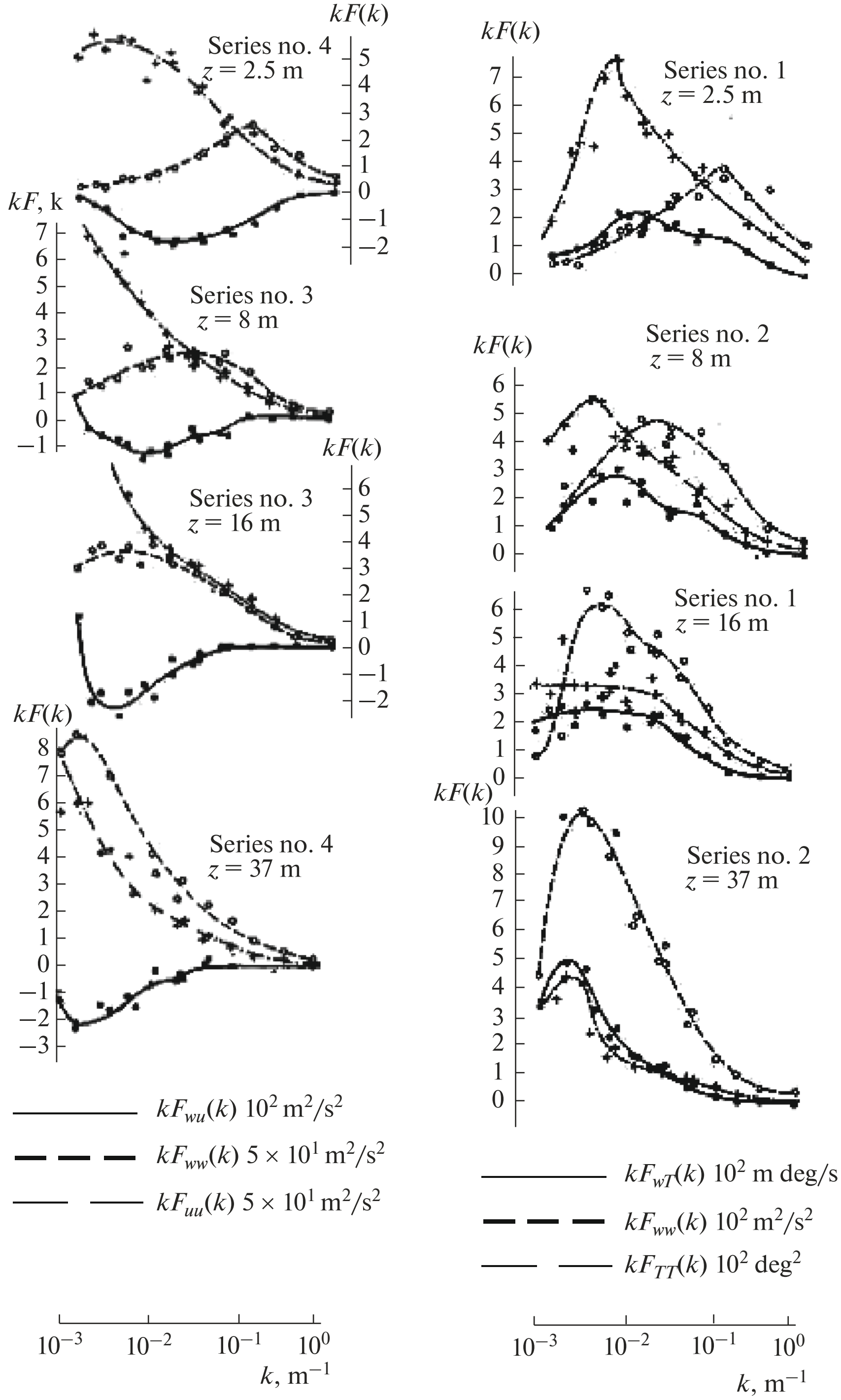

Fig. 10. Autospectra of velocity and temperature components and cospectra of momentum flux and heat flux multiplied by frequency.

important instrument for studying a near-surface atmospheric layer [28]. It was constructed by a two-beam scheme and consisted of a hermetically sealed beam splitter with an optical wedge and a mechanical obturator, as well as an open segment shaped like a multipass cell. They were all located on the solid steel plate, which made the hygrometer rather stable, but awkward at the same time. Nevertheless, the pantograph mast developed by D.Yu. Sokolov at the end of the 1960s allowed using this device together with the anemometer and the thermometer for pulsation measurements at heights of 1–5 m. A spectrum of turbulent variations in humidity was measured in the near-surface layer of the air [29]. A spectrum of a vertical

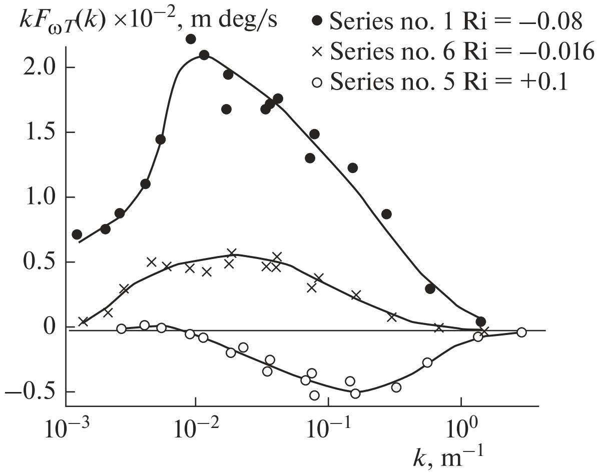

Fig. 11. Stratification dependence of heat flux spectra at a height of 2.5 m.

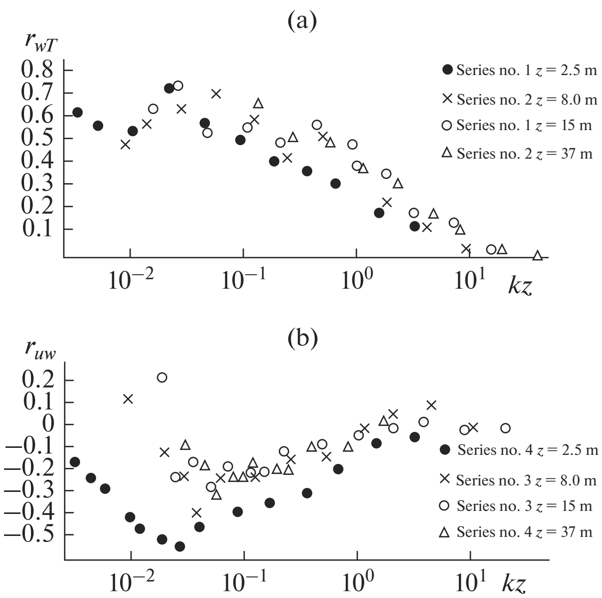

Fig. 12. Spectral coefficients of correlation $r_{wT}(kz)$ and $r_{uw}(kz)$.

turbulent flux of water vapor on the Mozhaisk Sea was measured in 1969 [30]. In the summer of 1971, the turbulent fluxes of water vapor were measured in the steppe in the vicinity of Ural'sk during a study of heat balance on the soil surface [31].

In the early 1970s, in order to prepare for measurements in the tropical Atlantic, Elagina designed a miniature optical hygrometer [31]. It was used in the TROPEX-72 and TROPEX-74 expeditions to estimate all components of thermal balance of the ocean surface in the tropics for the first time in the world [33, 34] (subheading 5). In February 1976, the turbulent fluxes of heat and water vapor over snow were measured

Fig. 13. Measuring system in operating position during the winter expedition in Koltushi (anemometer, hygrometer, and resistance thermometer).

together for the first time [35] (Fig. 13). These fluxes turned out to be oppositely directed: water vapor moves upward and heat flows downward.

During these experiments, we clarified that the correlation of variations in the temperature and absolute humidity, i.e., water-vapor density, reaches 0.9 and can be positive or negative. Correlation is positive in the summer at unstable stratification over the dry land, fresh water [30], and ocean [33, 34] (Fig. 14) and negative in the winter at a stable stratification above the snow [35]. According to the results of the International Turbulence Comparison Experiment of 1976 [12], this hygrometer was recognized as the best (Fig. 15).

5. STUDY OF HEAT EXCHANGE BETWEEN THE OCEAN AND THE ATMOSPHERE IN THE TROPICS

In the tropical Atlantic, the northeast trade wind is observed in the Northern Hemisphere and the southeast trade wind is recorded in the Southern Hemisphere. The convergence region of these flows is termed the Intertropical Convergence Zone (ICZ), which is always located in the Northern Hemisphere

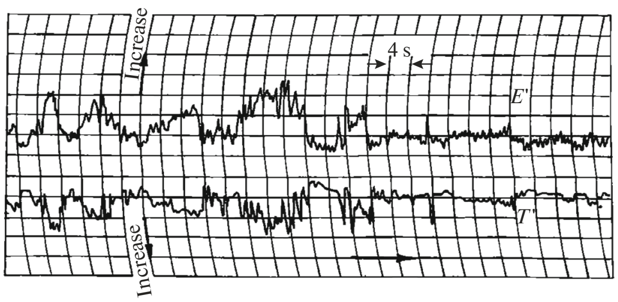

Fig. 14. Fragment of a synchronous record of temperature and humidity in the daytime at a height of 10 m in the trade-wind zone of the Atlantic.

and undergoes seasonal migrations from the extreme northern position in August to the extreme southern one in January—February.

The measurements during the 13th cruise of R/V *Akademik Kurchatov* in the Tropex-72 National Soviet Experiment were performed at point 7°19′ N, 20°52.3′ W. The ICZ center was located near 5° N, so that the measurement point was in the region of the northeast trade wind in the vicinity of its southern margin.

The measuring system was located at a height of 10 m (Fig. 16). It included the sensors of longitudinal u' and vertical w' velocity components, temperature T', and absolute humidity E'. To take into account the

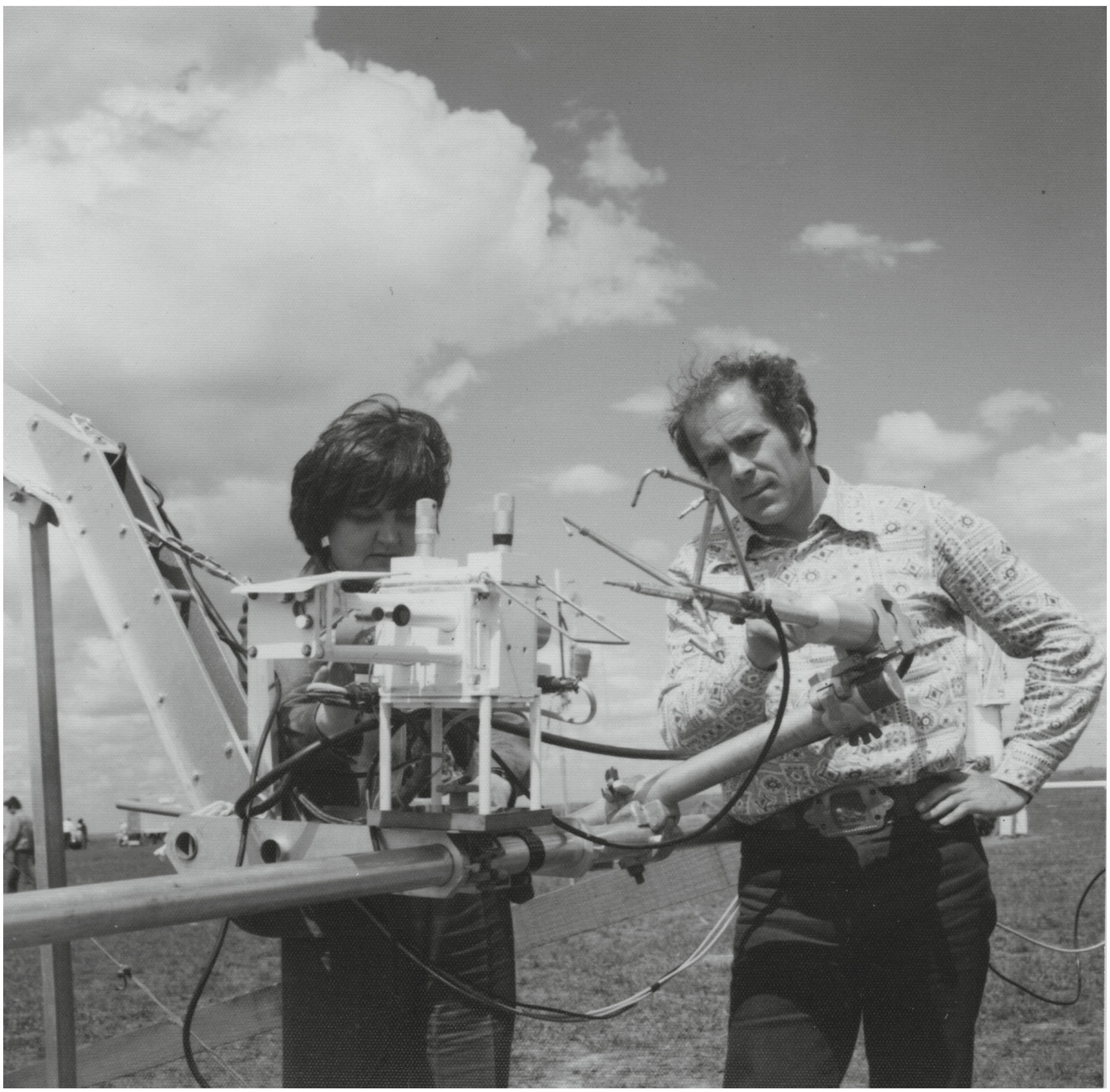

Fig. 15. L.G. Elagina and B.M. Koprov are mounting an acoustic anemometer and a hygrometer during the International Turbulence Comparison Experiment in Australia.

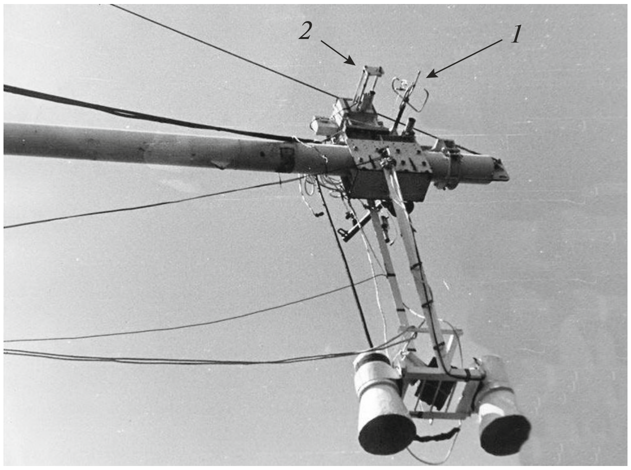

Fig. 16. Measuring system at a height of 10 m at the bowsprit of R/V *Akademik Kurchatov* during the TROPEX-72 expedition: anemometer (*1*) and hygrometer (*2*); an acoustic wave meter is shown below. View from below the boat.

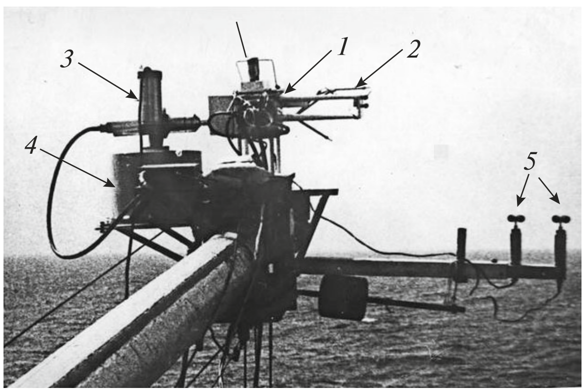

Fig. 17. Measuring system at the bowsprit of R/V *Akademik Kurchatov* during the TROPEX-74 expedition: hygrometer (*1*), anemometer (*2*), accelerometer (*3*), gyroplatform (*4*), and cup-type anemometers (*5*). View from the vessel's head.

effect of a vessel's motion on W', vertical acceleration ($\ddot{z}$), the velocity of oncoming flow U, and the angle of longitudinal motions φ of the vessel were also measured. The turbulent fluxes were calculated using analog multipliers immediately during measurements.

On August 7–21, 1972, a turbulent flux of sensible heat $q_T = c_p\rho\overline{w'T'}$ had a diurnal mean value of 6.7 W/m^2, and the flux of latent heat $q_E = L\overline{w'E'}$ was close to 67 W/m^2; thus, their average sum amounted to 74 W/m^2 [33].

On the second testing ground, the diurnal mean value of the flux of visible radiation absorbed by the ocean was 210 W/m^2 [36], and the average value of effective radiation of the ocean was about 26 W/m^2 [37]. As a result, the radiation balance on the ocean surface was estimated at 184 W/m^2. If we deduct the sum of turbulent fluxes of sensible and latent heat (74 W/m^2) from this amount, the value of diurnal mean heat flux absorbed by the ocean close will be 110 W/m^2.

In June–September 1974, measurements during the 19th cruise of R/V *Akademik Kurchatov* were taken at the equator at point 0° N, 23°30′ W. The ICZ center was found at the latitude of 5° N. This means that, in both cases, the measurement point was located in the trade-wind zone; but in 1972 it was northward of the ICZ center by 2° and, in 1974, southward of the ICZ center by ~5°.

To avoid the influence of the vessel's motions on the readings of the acoustic anemometer, a miniature gyroplatform was used in the 19th cruise (Fig. 17). The measurements were taken for turbulent fluxes of sensible and latent heat q_T, q_E, as well as the fluxes of total Q and reflected $F_{\uparrow 0}$ solar radiation and effective radiation $F(0)$. The turbulent fluxes were measured at 3:00 a.m.; 9:00 a.m.; 3:00 p.m.; and 9:00 p.m., local time. The fluxes of Q, $F_{\uparrow 0}$ radiation were measured continuously during daylight hours, and those of $F(0)$ radiation were measured at night time. For the daylight hours (9:00 a.m. and 3:00 p.m.), the values of $F(0)$ were found by empirical formulas [34].

The heat flux from the atmosphere to the ocean was approximately 130 W/m^2, which is close to the value of 110 W/m^2 obtained in 1972.

The net flux at the upper atmospheric boundary $F_H = S - F_{\uparrow H}$ is directed downward and amounts to 112 W/m^2 [33]. Here, S is the radiation flux penetrating through the system and $F_{\uparrow H}$ is the Earth's outgoing long-wave radiation.

Taking into account the roughness of the estimations accepted in the calculations, this value 112 W/m^2 is not too different from value 130 W/m^2, which was the above estimate for the flux from the atmosphere to the ocean. This means that the state of the atmosphere at the measurement point of 1974 was close to heat balance on average. Later on, the same conclusion was made if the value of $F_{\uparrow H}$ takes the value from the Atlas of Radiation Balance [38].

As for the flux of longwave radiation $F_{\uparrow H}$ flowing out from the upper atmospheric boundary (225 W/m^2), it turns out to be much greater than the sum of all energy fluxes flowing away from the ocean surface (130 W/m^2). To explain this, an assumption was made and evidenced in [39] and [40] on the flux of heat that is insufficient for balance moving into the latitudinal belt around the ICZ from the sides of the poles. The major component of this transport is a flux of latent heat of evaporation, which is known to be oriented from the poles to the ICZ [41]. This means that the separation of the global meridional heat flux into the atmosphere and ocean components may look like it is shown in Fig. 18.

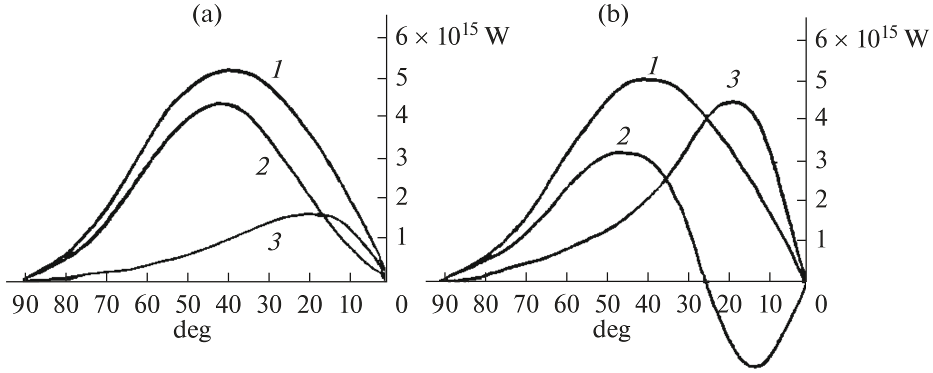

Fig. 18. Global meridional energy flux (*1*) and its atmospheric (*2*) and ocean (*3*) components. The ICZ width is taken as zero. (a) Data [41]; (b) the author's data [38].

This overview based on the data of direct measurements also relies on the tacit assumption of the steadiness and zonal homogeneity of turbulence and radiation fields in the trade-wind zone.

REFERENCES

1. A. M. Obukhov, *Turbulence and Atmospheric Dynamics* (Gidrometeoizdat, Leningrad, 1988) [in Russian].
2. A. S. Monin and A. M. Yaglom, *Statistical Hydromechanics*, Vol. 1 (Nauka, Nauka, 1965) [in Russian].
3. A. S. Monin and A. M. Yaglom, *Statistical Hydromechanics*, Vol. 2 (Nauka, Nauka, 1967) [in Russian].
4. S. I. Krechmer, "Study of micropulsations in the atmospheric temperature field," Dokl. Akad. Nauk SSSR **34** (1), 55–58 (1952).
5. S. I. Krechmer, "A technique for measuring micropulsations of wind velocity and temperature in the atmosphere," Tr. Geofiz. Inst., No. 24, 43–111 (1954).
6. M. Miyake, R. W. Stewart, R. W. Burling, L. R. Tsvang, B. M. Koprov, and O. A. Kuznetsov, "Comparison of acoustic instruments in atmospheric turbulent flow over water," Boundary-Layer Meteorol. **2** (2), 228–245 (1971).
7. L. R. Tsvang, B. M. Koprov, S. L. Zubkovskii, A. J. Dyer, B. Hicks, M. Miyake, R. W. Stewart, and J. W. Mcdonald, "A comparison of turbulence measurement by different instruments; Tsimlyansk Field Experiment 1970)," Boundary-Layer Meteorol. **3** (4), 499–521 (1973).
8. A. I. Dyer, I. R. Garratt, R. I. Francey, at al., "An international turbulence comparison experiment (ITCE-1976)," Boundary-Layer Meteorol. **24** (2), 181–209 (1982).
9. V. M. Bovsheverov, A. S. Gurvich, M. I. Mordukhovich, and L. R. Tsvang, "Instruments for the measurement of temperature and wind velocity pulsations as well as for statistical analysis of the measurement results," in *Transactions of the Institute of Atmospheric Physics, USSR Acad. Sci.: Atmospheric Turbulence* (AN SSSR, Moscow, 1962), No. 4, pp. 21–29 [in Russian].
10. L. G. Elagina, "Optical instrument for measuring turbulent pulsations of humidity," Izv. Akad. Nauk, Ser. Geofiz., No. 8, 1100–1107 (1962).
11. A. M. Obukhov, "On energy distribution in the turbulent flow spectrum," Izv. Akad. Nauk, Ser. Geogr. Geofiz., **5** (4), 453–466 (1941).
12. A. N. Kolmogorov, "The local structure of turbulence in an incompressible fluid at very large Reynolds numbers," Dokl. Akad. Nauk SSSR **30** (4), 299–303 (1941).
13. G. Batchelor, *The Theory of Homogeneous Turbulence* (Cambridge University Press, Cambridge, 1953; Nauka, Moscow, 1955).
14. A. S. Monin and A. M. Obukhov, "Main regularities if turbulent mixing in the atmospheric surface layer," Tr. Geofiz. Inst., No. 24, 163–187 (1954).
15. V. M. Bovsheverov and V. P. Voronov, "Acoustic weather-vane," Izv. Akad. Nauk, Ser. Geofiz., No. 6, 882–885 (1960).
16. B. M. Koprov and L. R. Tsvang, "Direct measurements of the turbulent heat flux onboard an aircraft," Izv. Akad. Nauk, Fiz. Atmos. Okeana **1** (6), 643–648 (1965).
17. S. L. Zubkovskii, "Frequency spectra of pulsations of the horizontal component of wind velocity in the surface layer of air," Izv. Akad. Nauk, Ser. Geofiz., No. 10, 1425–1433 (1962).
18. S. L. Zubkovskii and B. M. Koprov, "Experimental study of the spectra of turbulent fluxes of heat and momentum in the atmospheric surface layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **5** (4), 323–331 (1969).
19. V. M. Bovsheverov, B. M. Koprov, and M. I. Mordukhovich, "A three-component acoustic anemometer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **9** (4), 434–437 (1973).
20. S. L. Zubkovskii and M. M. Fedorov, "Experimental determinations of spatial correlation functions of the wind velocity field in the atmospheric surface layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **22** (9), 909–916 (1986).
21. V. M. Bovsheverov, A. S. Gurvich, V. I. Tatarskii, and L. R. Tsvang, "Instruments for statistical analysis of turbulence," in Proceedings of the Meeting on Stellar Scintillation Studies (AN SSSR, Moscow–Leningrad, 1959), pp. 26–32 [in Russian].
22. J. W. Telford and J. Warner, "Fluxes of heat and vapour in the lower atmosphere from aircraft observation," J. Atmos. Sci. **21** (5), 539–548 (1964).
23. V. P. Kukharets, "Spectra of turbulent momentum fluxes in the atmospheric boundary layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **12** (2), 200–203 (1976).
24. A. S. Gurvich and L. R. Tsvang, "On the spectral composition of turbulent heat flux," Izv. Akad. Nauk, Ser. Geofiz., No. 10, 1547–1548 (1960).

25. H. E. Cramer, F. A. Record, and J. E. Tillman, *Round Hill Turbulence Measurements*, Tech. Rep. ECOM 65-G10 (Massachusetts Institute of Technology, Cambridge, 1966).
26. H. S. Weiler and R. M. Burling, "Direct measurement of stress and spectra of turbulence in the boundary layer over sea," J. Atmos. Sci. **24** (6), 653–664 (1967).
27. A. K. Azad and J. Latham, "Electrification associated with the evaporation of water and ionic solution," J. Atmos. Terr. Phys. **29** (11), 1403–1410 (1967).
28. L. G. Elagina, "Optical instrument for measuring turbulent pulsations of humidity," Izv. Akad. Nauk, Ser. Geofiz., No. 8, 1100–1107 (1962).
29. L. G. Elagina, "On the measurement of frequency spectra of pulsations of absolute humidity in the atmospheric surface layer," Izv. Akad. Nauk, Ser. Geofiz., No. 12, 1860–1865 (1963).
30. L. G. Elagina and B. M. Koprov, "Measurement of turbulent flows of moisture and their frequency spectra," Izv. Akad. Nauk, Fiz. Atmos. Okeana **7** (2), 117–120 (1971).
31. L. G. Elagina, S. L. Zubkovskii, B. M. Koprov, and D. Yu. Sokolov, "Experimental study of heat balance on the soil surface," in *The Integrated Energetic Experiment (KENEKS)* (Gidrometeoizdat, Leningrad, 1973), pp. 38–45 [in Russian].
32. V. I. Gorshkov and L. G. Elagina, "New model of the IR hygrometer for measuring turbulent pulsations of humidity over the sea," in *TROPEKS-72* (Gidrometeoizdat, Leningrad, 1974), pp. 663–666 [in Russian].
33. Yu. A. Volkov, L. G. Elagina, B. M. Koprov, and T. K. Kravchenko, "Turbulent fluxes of heat and moisture and some statistical characteristics of turbulence in the near-water layer of air in the tropical zone the ocean," in *TROPEKS-72* (Gidrometeoizdat, Leningrad, 1974), pp 304–312 [in Russian].
34. Yu. A. Volkov, L. G. Elagina, B. M. Koprov, B. . Semenchenko, and E. M. Feigel'son, "On heat and moisture exchange on the equator," in *TROPEKS-74*, Vol. 1 (Gidrometeoizdat, Leningrad, 1976), pp. 389–393 [in Russian].
35. L. G. Elagina, B. M. Koprov, and D. F. Timanovskii, "Some characteristics of the atmospheric surface layer over snow," Izv. Akad. Nauk, Fiz. Atmos. Okeana **14** (9), 926–931 (1978).
36. K. V. Voitova and G. N. Mart'yanova, "Variability of solar radiation incoming from and reflected by the ocean surface in research test areas," in *TROPEKS-72* (Gidrometeoizdat, Leningrad, 1974), pp. 451–460 [in Russian].
37. B. A. Semenchenko and V. N. Nekrasov, "The role of effective radiation in the ocean heat balance in the intratropical convergence zone," in *TROPEKS-72* (Gidrometeoizdat, Leningrad, 1974), pp 506–510 [in Russian].
38. J. S. Winston and A. Gruber, T. I. Gray, et al., *Earth–Atmosphere Radiation Budget Analyses Derived from NOAA Satellite Data June 1974–February 1978*, Vol. 2 (National Environmental Satellite Service, Washington, DC, 1979).
39. B. M. Koprov, "The energy balance in the near-equatorial atmosphere and meridional heat transfer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **16** (1), 11–19 (1980).
40. B. M. Koprov, "On the estimates of meridional energy transfer by the atmosphere and ocean," Izv. Akad. Nauk, Fiz. Atmos. Okeana **18** (1), 30–37 (1982).
41. E. N. Lorenz, *The Nature and Theory of the General Circulation of the Atmosphere* (WMO, 1967; Gidrometeoizdat, Leningrad, 1970).
42. M. N. Budyko, *Heat Balance of the Earth* (Gidrometeoizdat, Leningrad, 1978) [in Russian].
43. V. M. Bovsheverov, A. S. Gurvich, S. O. Kochetkov, and S. O. Lomadze, "Measurement of the frequency spectrum of small-scale circulation of velocity," Izv. Akad. Nauk, Fiz. Atmos. Okeana **7** (4), 371–376 (1971).
44. B. M. Koprov, G. V. Azizyan, and V. V. Kalugin, "Spectra of velocity circulation in the atmospheric surface layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **23** (11), 1151–1158 (1987).
45. B. M. Koprov, V. V. Kalugin, and N. S. Thieme, "Turbulent flow of a vortex," Izv. Akad. Nauk, Fiz. Atmos. Okeana **30** (1), 13–17 (1994).
46. N. F. Elansky, B. M. Koprov, D. Yu. Sokolov, and N. Thieme, "Turbulent flow of ozone over steppe," Izv. Akad. Nauk, Fiz. Atmos. Okeana **31** (1), 109–114 (1995).
47. G. V. Azizyan and B. M. Koprov, "On the spatial and temporal structure of the temperature field in the atmospheric surface layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **21** (8), 815–823 (1985).
48. G. V. Azizyan, B. M. Koprov, and V. V. Kalugin, "The spectra of turbulent fluctuations of velocity in the dissipation range," Izv. Akad. Nauk, Fiz. Atmos. Okeana **25** (12), 1267–1271 (1989).
49. G. V. Azizyan, B. M. Koprov, and V. V. Kalugin, "On the microstructure of the temperature field in the dissipation range," Izv. Akad. Nauk, Fiz. Atmos. Okeana **28** (9), 917–925 (1992).
50. B. M. Koprov, S. L. Zubkovsky, V. M. Koprov, M. I. Fortus, and T. I. Makarova, "Statistics of air temperature spatial variability in the atmospheric surface layer," Boundary-Layer Meteorol. **88** (3), 399–423 (1998).
51. B. M. Koprov, V. M. Koprov, and T. I. Makarova, "Convective structures in the atmospheric surface layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana **11** (1), 109–114 (1995).
52. B. M. Koprov, V. M. Koprov, T. I. Makarova, and G. S. Golitsyn, "Coherent structures in the atmospheric surface layer under stable and unstable conditions," Boundary-Layer Meteorol. **111** (1), 19–32 (2004).
53. B. M. Koprov, V. M. Koprov, V. M. Ponomarev, and O. G. Chkhetiani, "Experimental studies of turbulent helicity and its spectrum in the atmospheric boundary layer," Dokl. Phys. **50** (8), 419–422 (2005).
54. B. M. Koprov, V. M. Koprov, M. V. Kurgansky, and O. G. Chkhetiani, "Helicity and potential vorticity in surface turbulence," Izv., Atmos. Ocean. Phys. **51** (6), 565–575 (2015).
55. B. M. Koprov, V. M. Koprov, O. A. Solenaya, O. G. Chkhetiani, and E. A. Shishov, "Technique and results of measurements of turbulent helicity in the stratified surface layer," Izv., Atmos. Ocean. Phys. **54** (2018) (in press).

Translated by L. Mukhortova