ISSN 1068-3739, Russian Meteorology and Hydrology, 2014, Vol. 39, No. 12, pp. 838–846. Allerton Press, Inc., 2014.
Original Russian Text V.P. Yushkov, 2014, published in Meteorologiya i Gidrologiya, 2014, No. 12, pp. 76–88.

INSTRUMENTS, OBSERVATIONS, AND PROCESSING

What Can Be Measured by the Temperature Profiler?

V. P. Yushkov

Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991 Russia, e-mail: yushkov@phys.msu.ru

Received June 6, 2014

Abstract—The ability of the ground-based microwave temperature profiler to retrieve the lapse rates in the lower part of the atmospheric boundary layer is verified by analyzing the long-term observation series. It is demonstrated that if the stratification of the whole boundary layer is either unstable or sufficiently homogeneous, measured and retrieved with a mast lapse rates are quite similar. If the stratification is stable, the retrieval algorithms require correction. Demonstrated is the potential for the more accurate retrieving of the temperature gradient over the surface layer by means of the angular scanning. This enables using the data of temperature profilers for estimating the boundary layer stability and the Monin–Obukhov scale.

DOI: 10.3103/S1068373914120097

1. INTRODUCTION

Recent decades are notable for the wide spread of high-tech instruments for remote measurements based on the physical principles which have not been used in meteorology before. Certainly, each new instrument is calibrated and compared with traditional measurements; however, the meteorological parameters characterized by high spatial and temporal variability and measured by different methods may not correspond to each other in the spatial and temporal averaging and in the sensitivity and dynamic range. The random variability of meteorological characteristics in the atmospheric boundary layer (ABL) is the well-known phenomenon that attracts the attention of the hundreds of researchers of atmospheric turbulence [16]; however, this natural random variability is not always taken into account when comparing the traditional and new methods of measurements. New instruments which also have the indirect measurement principle can contain the large absolute but small differential error and, hence, need permanent routine calibration. The calibration carried out in the laboratory or ideal environment (over the plane surface in summer) may not correspond to the regime of routine measurements or to the conditions of a special experiment.

The present paper analyzes the potential of the MTP-5 scanning temperature profiler which is rather widely used at the network of meteorological observations in Russia [2, 4, 5, 9]. The calibration of such high-tech instruments is the compulsory condition for their operation at meteorological stations; however, such calibration sometimes uses not meteorological but radio-engineering criteria (frequency, pass band, and sensitivity). Producers strive for keeping within the rather tough framework of manuals for meteorological measurements; however, these manuals were issued rather long time ago and are not focused on new measurement methods and the instrument potential. The paradoxical situation arises when a new instrument can measure characteristics not standardized in meteorological regulations; however, the accuracy of these measurements cannot be assessed using the rated criterion. The producers of high-tech equipment are interested in the stressing of the advantages of their instruments; however, when comparing the measurements by different methods and revealing systematic errors, the reason for these errors is not always obvious if the measurement instrument is considered as "the black box." Meteorologists often believe that traditional measurement methods are more accurate than new ones and do not take into account the difference in measurement principles. Under conditions of pronounced turbulent variability in the ABL new instruments can often measure the characteristics not measured by traditional equipment.

The objective of the present paper is to demonstrate the accuracy of the temperature gradient retrieval with profilers, to outline the ways of increasing this accuracy, and to assess how the accuracy of temperature gradient retrieval can be connected with the spatial resolution of temperature profilers. The data of long-term routine measurements with the MTP-5 temperature profiler are compared with the data of parallel contact measurements at the meteorological mast. The accuracy of the measurement of lapse rates in the lower part of the ABL by the profiler is estimated. The characteristics of the variability of the gradients measured with profilers of different spatial resolution are compared. The method is proposed for estimating the thermal instability in the lower part of the ABL, the Richardson balance number, and Monin–Obukhov scale [6].

2. MEASUREMENT PRINCIPLE AND THE EXPERIENCE OF CALIBRATION OF MICROWAVE PROFILERS

Temperature profilers such as MTP-5 [28] are the scanning VHF receivers of atmospheric self-radiation in the frequency band of ~60 GHz (5 mm) [8, 25]. The intensity of the received signal at the input of the receiving antenna in absorption and emission lines of oxygen molecules depends on the temperature and density of the medium at the typical absorption scale. In the case of the sensing from the ground this scale is ~300 m. If temperature varies with height at this scale, then, additionally assuming the horizontal homogeneity of the temperature field, one can solve the inverse problem of the retrieving of averaged temperature profiles [7].

In the present paper, the accuracy is studied of the retrieval of temperature profiles at the reception of radiation only in the center of this wide absorption band. The reception in the central part of the band is easier from the point of view of technical realization and has higher sensitivity to small variations of temperature [18, 25]. The sensing on the "wings" of the band of 60 GHz and in other frequency bands enables one to retrieve the temperature profile up to the height of several kilometers as well as the humidity profile and integral content of water vapor and liquid water in the clouds [21, 26]. Physical principles of the operation of microwave profilers are well known to radio physicists; however, a number of important questions arise at using such instrument in meteorological practice; the present research focuses on their study.

The conclusions made in the present paper are based on the long-term (2008–2012) round-the-clock and year-round measurements of temperature profiles in the urban environment (Moscow, MSU, the Vorob'ovy Hills) and in the country, at Zvenigorod scientific station of the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (ZSS IAP RAS) as well as in the Central Aerological Observatory (CAO). Temperature profiles in the ABL were retrieved up to the height of 600 m using the MTP-5 temperature profiler. The data of these measurements were published in [3, 20]. Synchronous contact measurements of temperature with ultrasonic anemometers (USA-1, METEK GmbH [29]) were carried out at two levels (6 and 56 m) in the country and at the height of 50 m above the ground and 20 m above the mean roof level (over the building of the MSU Department of Physics) in the urban environment.

Unlike the rather short periods of the intensive comparison with the data of measurements at high-altitude masts such as in Obninsk [1], Boulder [27], or Lindenberg [14], the long-term continuous measurements enable one to study how the accuracy of temperature gradient retrieval varies in different seasons at different diurnal amplitude of surface gradients. Such routine automatic measurements at meteorological masts can be recommended for the routine calibration as well as for the adaptation of algorithms of temperature profile retrieval to the concrete measurement point.

The experience of calibration of temperature profilers [14, 18, 24, 27] demonstrates that the deviation of retrieved temperature profiles in the case of the comparison with the data of upper-air sounding is 0.6–1 C (the standard deviation) and depends little on the height (before 1000 m). The comparison of retrieved temperature profiles with the measurements at the masts is also a traditional method of calibration of these instruments. Such comparisons demonstrate that the error of temperature profile retrieval in the ABL is close to homogeneous (before 300 m) and amounts to about 1 C [1, 14, 27]. More optimistic estimates demonstrate that the accuracy of the temperature profile retrieval in the lower part of the ABL (before 100 m) is equal to 0.3 C [15] and less; more cautious researchers keep to the estimate based on the standard deviation (rms) equal to 1 C and more [14, 27]. The estimates of errors vary depending on the duration, time, and place of comparison and depending on the used retrieval algorithms. Significant differences in the estimates of errors can also be associated with the constant enhancement of the technology of remote measurement of temperature: using the narrower directional pattern [17] and several sounding frequencies [23] and with the improvement of the algorithms of retrieval using attendant upper-air data [24].

Some comparisons carried out under the most inconvenient conditions for the temperature profile retrieval, demonstrate differences between local measurements and retrieved values of temperature equal to 2 C and more [11]. For example, such differences can be formed in raised inversions or at the mixing of different air masses (in the case of breezes). Such error is absolutely unacceptable for the comparison of measurements at close points, for example, for the assessment of the intensity of urban heat island and its vertical extent. In this case, a new way to increase the accuracy of the comparison of close measurements should

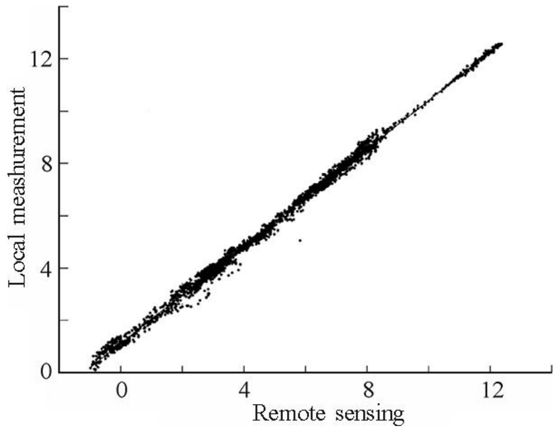

Fig. 1. An example of the comparison of temperature from the data of local and remote measurements at the zero level in Moscow on November 1–9, 2010. The parameters of linear regression $y = ax + b$ are the following: $a = 0.928$ 0.001, $b = 1.137$ 0.006. Standard deviation (rms) is 0.16 C.

be sought. Brightness temperature has the initial maximum accuracy for temperature radiometers; therefore, the comparison of this indirect integral characteristic measured, for example, "at zenith" or "at horizon" at close points is more accurate than the comparison of retrieved values of temperature.

As the research demonstrated, the use of attendant measurements at the masts (even not high ones) enables one to achieve much higher accuracy by means of introducing the correction coefficients, i.e., taking account of the systematic error. In Fig. 1, an example is presented of the comparison of local acoustic and remote averaged measurements of temperature at the zero level (the level of instrument installation). The mutual linear regression enables achieving the root-mean-square error of measurements with the temperature profiler equal to 0.16 C. It should be noted that this comparison was carried out in the urban environment being notable for the pronounced spatial variability of temperature. Even in this case, the accuracy of measurements can be much higher than the rated one. Correction coefficients reveal the significant deviation of the regression line from the single line and characterize the systematic measurement error as well as its variations. It should be noted that such linear regression is not a fitting. The need in the correction is defined by the fact that the temperature profilers measure radiation temperature in the lower layer of 50 m even in the case of the sounding in the horizontal direction whereas the vertical variations of temperature in this lower layer of 10–50 m are more significant, especially in the case of the stable stratification [16].

The analysis demonstrated that if some instrumental components of the error of both acoustic anemometers and temperature profilers are not taken into account, this can really result in differences exceeding 2 C and more: acoustic anemometers used for the comparison have the considerable constant systematic error which varies at the switching-on of the heating of sensors during the cold season. The control sensor of the profiler can be overheated in hot weather if the instrument is installed on the roof of the building and ventilation is insufficient. The overheating of the body of a meteorological mast results in additional errors in mast sensor measurements. In the case of measurements in the urban environment, the local features of the measurement point with the spatial scale of less than 300 m gain in high importance. Therefore, the introduction of correction coefficients enables one to take into account indirectly the factors which can hardly be foreseen during the development of the instrument. The regular comparison of the instruments taking part in long-term routine measurements in their location and in the mode of their use is an essential condition of the increase in the accuracy of such measurements.

3. TEMPERATURE GRADIENTS IN THE LOWER PART OF ABL

Although the closeness of compared values of temperature is the basic criterion for assessing the accuracy of the profiler, the important meteorological characteristic of the ABL is the parameter of temperature stratification, the lapse rate. The temperature stratification in the boundary layer can change rather quickly both with height and time; therefore, the upper-air radio sounding (twice a day) does not seem to be an acceptable instrument for the continuous monitoring of the boundary layer. The measurement of temperature stratification in the ABL in "the dead area" of upper-air radio sounding but above the surface layer of constant flows where the analytic formulae of the Monin–Obukhov similarity theory are not already true, is the main objective and the basic advantage of the use of temperature profilers. The continuous monitoring is needed for estimating the accuracy of parameterization of the turbulent transfer of momentum and heat in numerical models and for assessing air pollution over the cities. In some technical problems, for example, for providing aircraft landing safety, such monitoring has no competitors. Therefore, the comparison of measurements of lapse rates and their variability with height is the major element of calibration of temperature profilers. It is well known that the aperture of the receiving antenna defines the area for which the measured brightness temperature is averaged. This averaging scale defines to a significant degree the typical scale of vertical temperature inhomogeneities which can be retrieved with the microwave profiler. Such typical averaging scale for MTP-5 selected by the producer is 50 m. Therefore, temperature profiles of this type are not able to measure the logarithmic profile of temperature in the surface layer or to register thin inversion layers with significant lapse rates frequently observed using captive balloons [13] or sodars (acoustic radars) [12].

Up to now the algorithms of temperature profile retrieval have been mainly focused on achieving the homogeneous minimum of absolute errors of retrieval of temperature but not of its gradients because this characteristic is present in meteorological manuals. Besides, stability requirements for solving the inverse problem of temperature profile retrieving make them smoother, and this does not always correspond to the real profile. Thus, profilers rather retrieve the most probable vertical distribution of temperature than the actual one.

The accuracy of temperature measurement equal to 0.5 C is sufficient for classic meteorological problems whereas this error should be divided into the systematic (along the vertical) and random components for assessing thermal stratification that affects the turbulence in the ABL and defines the transfer of heat, momentum, and pollutants to the free atmosphere. For example, if the error is random, the formal assessment of the accuracy of temperature measurement equal to 0.7 C at the distance between the adjacent measurement levels equal to 50 m results in the estimate of the root-mean-square error of lapse rates equal to 1 C/50 m or 2 C/100 m that is absolutely inadmissible for meteorological problems as it exceeds the difference between the isothermal and adiabatic stratification by twice.

Infrequent launches of radiosondes do not enable studying to a sufficient degree the dependence of lapse rate retrieval error on the diurnal course of stratification. Besides, radiosondes have the significant random error in the lower part of the ABL (to 2–3 C (see [22])) associated with the fact that the radiosonde measurements are carried out instantly when flying by the corresponding height mark whereas the profiler retrieves spatially averaged and smoothed profiles according to the used algorithm.

The comparison of lapse rates measured by the profiler with the continuous series of contact measurements at two levels gives the detailed behavior pattern of measurement errors. Figure 2a provides the example of the comparison of lapse rates during several days in summer in the case of anticyclonic weather with the daytime convection and nocturnal cooling. It is clearly observed that in the daytime lapse rates in the lower part of the ABL are determined by the temperature profiler quite satisfactorily. At the presence of cloudiness at night (June 20), the lapse rate measured by acoustic anemometers is simulated by the temperature profiler with sufficient accuracy. However, in the case of fair weather, radiation cooling, and stable stratification in the lower part of the ABL (at positive lapse rates of more than 1 C/100 m), the estimates of lapse rates based on the data of contact measurements and the profiler differ considerably.

This example also agrees with other in situ comparisons at meteorological masts which demonstrate the systematic underestimation of lapse rates at stable stratification [14]. The errors of temperature profile retrieval at stable stratification are well known to the developers [25] because they proceed from the measurement principle. The revealed systematic error may depend on the used algorithm of temperature profile retrieval and measurement strategy. However, there is no research giving the accuracy characteristics of the estimation of lapse rates. Some examples of the comparison of temperature gradients based on measurements at meteorological masts do not provide the complete picture so far.

Can the diagnosis of the stably stratified ABL be improved using the scanning profiler measurements? The direct comparisons of the difference in brightness temperature measured at the angles of 1 and 3 to the horizon answer this question. In Fig. 2b, the comparison is presented of temporal variations of this difference reduced (using the linear regression) to the temperature difference at the height of 6 and 56 m. It is clear that this difference correlates well with positive lapse rates in the lower part of the ABL according to contact measurements. The difference in brightness temperature in the case of sounding at small angles is not certainly an accurate characteristic of the lapse rate in the surface layer; however, the high degree of their correlation indicates that the temperature profiler not only can measure average temperature in the lower 50-m layer but can also give the more accurate estimate of its thermal stratification.

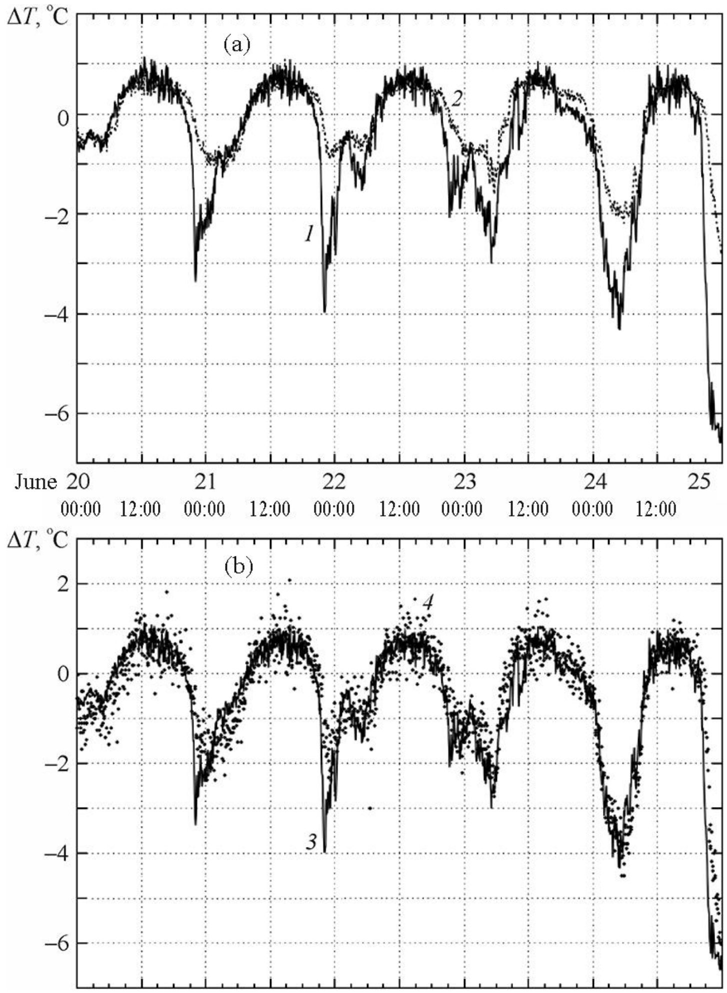

Fig. 2. An example of the comparison of (a) temperature gradients ΔT (the difference between measurements at the heights 0 m and 50 m) in the lower part of the ABL as derived from (*1*) differential contact and (*2*) remote measurements and (b) (*3*) difference in the temperature measured at the mast and (*4*) difference in brightness temperature measured by the profiler at small elevation angles of 1° and 3°. Countryside, June 20–25, 2010 (ZSS IAP RAS). The difference in brightness temperature is reduced to the difference in local measurements (°C/50 m) using linear regression.

This stratification can also be expressed through the dimensionless criterion $(c_p/g)(\partial T/\partial z)\big|_{z\to 0}$ if difference in the values of brightness temperature measured at the angles of 1° and 3° and reduced to the difference in the values of temperature between the standard height of 2 m and the height of 100 m, is taken as the measure of the temperature gradient near the surface but above the surface layer (where the laws of the similarity theory are true). As known, the linear approximation of the temperature profile above the surface layer at stable stratification corresponds to the Monin–Obukhov theory. At unstable and quasineutral stratification, this estimate corresponds to the observed difference in the values of temperature, i.e., characterizes the temperature jump across the surface layer of constant flows. It should be noted that the use of the Monin– Obukhov theory above the surface layer is hampered significantly (for example, see [10]).

Using this stratification balance criterion, the Richardson number can also be assessed if, besides thermal stratification, the wind speed is measured at the special mast or at the meteorological station (at the height of 10 m):

$$\mathrm{Ri} = \frac{g}{T_0}\frac{\partial T}{\partial z}\Big/\left(\frac{\partial U}{\partial z}\right)^2 \sim \frac{g}{T}\frac{\Delta T}{\Delta z}\bigg|_{z\to 0}\frac{H_{10}^2}{U_{10}^2},$$

where U_{10} is the average wind speed at the height of 10 m (H_{10}). Although this balance estimate characterizes the turbulent mixing in the ABL qualitatively only, it enables assessing the relationship between the

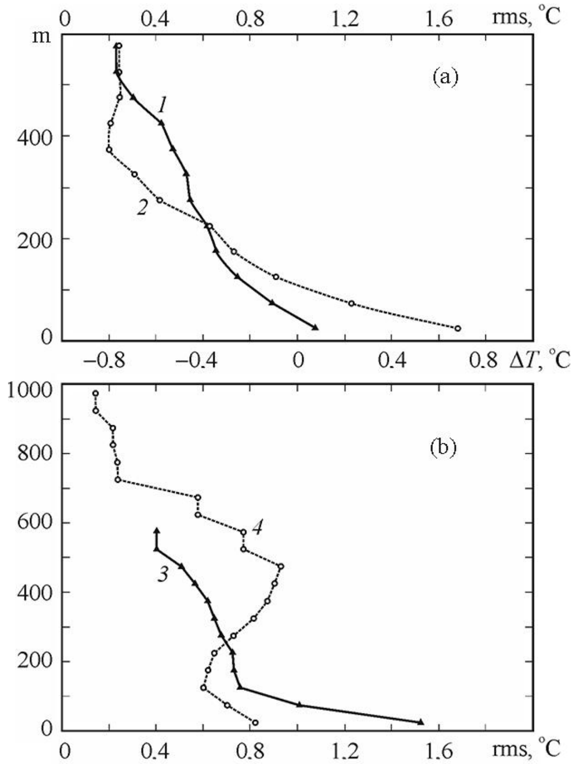

Fig. 3. Examples of (a) vertical variations of (*1*) the mean lapse rate $\overline{T}$ and (*2*) its standard deviation (rms) according to the measurements of the MTP-5 profiler in June 2010 (ZSS IAP RAS) and (b) comparison of the standard deviation of the lapse rate from February 12 to March 12, 2010 according to the measurements of two remote sensing instruments with different ranges of measurement height: (*3*) MTP-5 (ZSS IAP RAS) and (*4*) MTP-5HE (Dolgoprudny).

heat flux in the lower part of the ABL and mechanic mixing. Using this simple characteristic, it is possible, for example, to compare the model computations with in situ observations. The similar index-based estimation is also possible for the Monin–Obukhov scale:

$$L_{\mathrm{MO}} \quad \frac{\mathrm{Ri}}{z}^{1} \sim U_{10}^{2}\Big/\frac{gH_{10}}{T_0}\,\frac{T}{z}\Big|_{z\quad 0}$$

with the accuracy up to the certain empirical constant.

4. VARIABILITY OF LAPSE RATES AND ERRORS OF TEMPERATURE PROFILE RETRIEVAL

The systematic error of temperature profile retrieval is not constant along the vertical and depends on synoptic conditions and, for example, on the time of the day. The estimation of correlation between the errors of temperature measurement at different levels could be the consistent statistical approach; however, such data have not been given in the papers dealing with the calibration of microwave profilers. Since comparisons with measurements at large heights were not carried out in the present research, the natural variability of lapse rates was analyzed using the data of remote measurements. The synoptic variations of lapse rates for the long observation period were computed. One summer month was taken as the test period. At the same time, the stratification of the ABL (especially in the lower part) at the mid-latitudes of Russia varies more significantly. Lapse rates were computed between adjacent levels with the step of 50 m. In Fig. 3a, the profiles are demonstrated of the mean values of lapse rates and their variations in June 2010. It is clear that the spread in the values of lapse rates above 300 m becomes small that can indicate the errors of lapse rate retrieval at large height.

The variations of temperature at rather large height (above 200 m) cause small contribution to the variations of brightness temperature at the input of the receiving antenna of MTP-5. Although this signal exceeds the sensitivity threshold of the instrument, it can also be compared with the natural random variability at the antenna input, namely, the heating of the instrument body or external control sensor; the variations in the band of solar spectrum at the cloudiness variability; the temporal nonstationarity and spatial inhomogeneity of the temperature field, etc. Since the algorithms of temperature profile retrieval should take account of all this noise, the retrieved profiles are characterized by the high degree of smoothness. Rapid variations of thermal stratification at the height of hundreds of meters observed and registered by radiosondes, captive balloons, and sodars (using the variations of turbulence intensity) are considered at the profiler input as random variations and are filtered by the retrieval algorithm (see [14], Fig. 6).

The comparison between the variances of lapse rates at the large height measured by the profilers of two "generations" revealed the same. In Fig. 3b, the computation is presented of the profiles of variance of lapse rates for two profilers: MTP-5 with the sounding height of 600 m and MTP-5HE with the sounding height up to 1000 m. These measurements were carried out synchronously at the IAP RAS Zvenigorod scientific station (Zvenigorod) and Roshydromet CAO (Dolgoprudny). The distance between the measurement points is less than 100 km. The similar monthly mean variability of lapse rates could be expected above 300 m. However, the profile of variations of lapse rates in these synoptically close points differs considerably if instruments with different modifications are used.

So significant differences can be explained through the understanding of the atmospheric stratification structure. For example, in the case of the unstable stratification of the ABL, the gradients of potential temperature within the convective mixing layer are very low [19]. However, this convective mixing layer shields the more stable inversion layer with small thickness. This layer can be situated at different heights depending on the convection intensity. The height of this layer is the key (steering) parameter of the convective boundary layer but it also goes beyond the boundary of the upper range of measurements of a temperature profiler [16]. Therefore, the profiler actually measures not real but the most expected or most probable temperature gradient at the upper boundary.

In view of this, the question arises: should the reference points of temperature profile retrieval be located evenly? The accumulated experience of measurements demonstrates that it is reasonable to take the height range between the retrieval points proportional to $T/\ _{Tz}$, where T is the error of temperature retrieval; is the coefficient defining the ratio of the random error to the total one; $_{Tz}$ is the characteristic of the natural variability of vertical gradients of temperature T_z (standard deviation). The key points of temperature profile retrieval for MTP-5 can be defined as 400, 200, 100, 50, and 0 m. Then, the difference in the retrieved values of temperature in the upper part of the ABL, between 200 and 400 m, will demonstrate simultaneously the mean lapse rate in this layer. The error of the retrieval of this lapse rate will be about 1 C/200 m. In other words, the sensitivity of the profiler to temperature variations at large height should be agreed with the natural variability of lapse rates which dictates reasonable requirements to their measurement.

5. CONCLUSIONS

MTP-5 temperature profilers have the potential that goes far beyond the rated estimates. However, the use of these opportunities requires the understanding of physical principles of the instrument operation.

Firstly, the absolute error of temperature retrieval can be significantly reduced as a result of the combination of remote and control contact measurements above the surface layer. Measurements at meteorological masts make this possible. The use of the simple linear regression enables taking account of systematic errors associated with the measurement principle, significant averaging scale of a temperature profiler, and inhomogeneity of underlying surface at the measurement point.

Secondly, the temperature profiler enables measuring the effective index of stratification in the ABL $(c_p/g)(\ T/\ z)\big|_{z\ \ 0}$ at the conventional boundary of the surface layer of constant flows or the logarithmic temperature jump in the surface layer. This dimensionless parameter can also be used for verifying the model forecasts. The synchronous measurement of the wind speed at the observation point also enables assessing the Monin–Obukhov scale.

Thirdly, the errors of lapse rate retrieval in the upper part of the ABL need the agreement between the profiler sensitivity and discreteness of retrieval levels. The great number of height levels does not automatically mean the higher accuracy of lapse rate measurement. The smaller number of retrieval levels can make the estimation of average lapse rates in the upper part of the ABL more reliable. Such approach is similar to the certain degree to the use of the finite element method, when the retrieved temperature in each height range is characterized by two independent parameters: the average value and the lapse rate.

The indubitable advantages of new high-tech instruments for meteorological measurements include the continuity of measurements (such measurements can be carried out for years) and high mobility in the case of special measurements (expeditions). At the same time, the development of new modifications of such instruments needs the regular calibration of these measurements in order to keep the continuous series being homogeneous.

ACKNOWLEDGMENTS

In conclusion, the author would like to express his gratitude to the colleagues who contributed a lot to the present research: E.H. Kadygrov for the promotion of microwave radiometers in Russia and for the attentive treatment of the author's questions; A.B. Troitskii for his remarks, regular consultations, and goodwill; E.A. Miller for his attention, active participation in all initiatives, and huge work on the promotion of microwave radiometers at the Roshydromet network and all over the world. The author believes that new high-tech methods of meteorological measurements have a reliable future. The author would also like to thank G. Kurbatov for his assistance in the organization of measurements at the MSU Department of Physics and at ZSS IAP RAS. The author especially thanks M.A. Kallistratova for support and exactingness.

REFERENCES

1. A. S. Vyazankin, E. N. Kadygrov, N. F. Mazurin, et al., "Comparison of Temperature Profiles and Inhomogeneity Structure Obtained from a Microwave Radiometer and a Tall Meteorological Mast," Meteorol. Gidrol., No. 3 (2001) [Russ. Meteorol. Hydrol., No. 3 (2001)].
2. V. A. Gladkikh, A. E. Makienko, E. A. Miller, and S. L. Odintsov, "The Study of Parameters of the Atmospheric Boundary Layer under Urban Conditions by Means of Local and Remote Diagnostics, Part 2: The Air Temperature and Heat Flow," Optika Atmosfery i Okeana, No. 11, **23** (2010) [Atmos. Oceanic Optics, No. 11, **23** (2010)].
3. G. I. Gorchakov, E. N. Kadygrov, V. E. Kunitsyn, et al., "The Moscow Heat Island in the Blocking Anticyclone during Summer 2010," Dokl. Akad. Nauk, No. 5, **456** (2014) [Dokl. Phys., No. 5, **456** (2014)].
4. E. N. Kadygrov, I. N. Kuznetsova, and G. S. Golitsyn, "The Heat Island in the Boundary Atmospheric Layer over a Large City: New Results Based on Remote Sensing Data," Dokl. Akad. Nauk, No. 4, **385** (2002) [Dokl. Phys., No. 4, **385** (2002)].
5. I. N. Kuznetsova, E. N. Kadygrov, E. A. Miller, and M. I. Nakhaev, "Characteristics of Lowest 600 m Atmospheric Layer Temperature on the Basis of the MTP-5 Profiler Data," Optika Atmosfery i Okeana, No. 10, **25** (2012) [Atmos. Oceanic Optics, No. 10, **25** (2012)].
6. A. S. Monin and A. M. Obukhov, "Main Regularities of Turbulent Mixing in Atmospheric Surface Layer," Trudy GeoFIAN, **24** (1954) [in Russian].
7. A. P. Naumov, N. N. Osharina, and A. V. Troitskii, "Ground-based Microwave Thermal Sounding of the Atmosphere," Izv. vuzov. Radiofizika, No. 1, **42** (1999) [Radiophysics and Quantum Electronics, No. 1, **42** (1999)].
8. A. V. Troitskii, "Remote Determination of Atmospheric Temperature from Spectral Radiometric Measurements in the 5-mm Line," Izv. vuzov. Radiofizika, No. 8, **29** (1986) [Radiophysics and Quantum Electronics, No. 8, **29** (1986)].
9. M. N. Khaikin, E. N. Kadygrov, and I. N. Kuznetsova, "Influence of High Aerosol Concentration on the Thermal Structure of the Atmospheric Boundary Layer," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 6, **42** (2006) [Izv., Atmos. Oceanic Phys., No. 6, **42** (2006)].
10. V. P. Yushkov, "The Wind Speed Shear in the Case of Stable Stratification and the Scales of the Similarity Theory," Meteorol. Gidrol., No. 12 (2013) [Russ. Meteorol. Hydrol., No. 12, **38** (2013)].
11. S. Argentini, I. Pietroni, C. Gariazzo, et al., "Temperature Profiles by Ground-based Remote Sensing and in Situ Measurements," in *IOPConference Series: Earth and Environmental Science*, No. 1, **1** (IOP Publishing, 2008).
12. S. Argentini, I. Pietroni, Mastrantonio, et al., "Characteristics of the Night and Day Time Atmospheric Boundary Layer at Dome C, Antarctica," EAS Publ. Series–EDP Sciences, **25** (2007).
13. B. B. Balsley, R. G. Frehlich, M. L. Jensen, et al., "Extreme Gradients in the Nocturnal Boundary Layer: Structure, Evolution, and Potential Causes," J. Atmos. Sci., No. 20, **60** (2003).
14. S. Crewell and U. Lohnert, "Accuracy of Boundary Layer Temperature Profiles," IEEE Trans. Geosci. and Remote Sensing, No. 7, **45** (2007).
15. V. V. Folomeev, E. N. Kadygrov, E. A. Miller, et al., "Advanced Microwave System for Measurement of ABL Thermal Stratification in Polar Region," in *Proceedings of WMO Techn. Conferense on Meteorological Instruments and Methods of Observations* (Helsinki, Finland, 2010).
16. J. R. Garratt, *The Atmospheric Boundary Layer* (Cambridge Univ. Press, Cambridge, 1992).
17. E. Kadygrov, E. Miller, V. Nekrasov, et al., "MTP-5PE—New Instrument for Temperature Profiling in Polar Region," in *Proceedings of the 9th International Symposium on Tropospheric Profiling, September 3–7, 2012, L'Aquila, Italy.*

18. E. N. Kadygrov and D. R. Pick, "The Potential Performance of an Angular-scanning Single-channel Microwave Radiometer and Some Comparisons with in Situ Observations," Meteorol. Appl., **5** (1998).
19. J. C. Kaimal and J. J. Finnigan, *Atmospheric Boundary Layer Flows: Their Structure and Measurement* (Oxford University Press, 1994).
20. M. A. Kallistratova, R. D. Kouznetsov, V. F. Kramar, and D. D. Kuznetsov, "Profiles of Wind Speed Variances within Nocturnal Low-level Jets Observed with a Sodar," J. Atmos. Oceanic Technol., No. 9, **30** (2013).
21. U. Löhnert and S. Crewell, "Accuracy of Cloud Liquid Water Path from Ground-based Microwave Radiometry. Part I: Dependency on Cloud Model Statistics," Radio Sci., **38** (2003).
22. U. Löhnert, S. Crewell, O. Krasnov, et al., "Advances in Continuously Profiling the Thermodynamic State of the Boundary Layer: Integration of Measurements and Methods," J. Atmos. Oceanic Technol., No. 8, **25** (2008).
23. U. Löhnert and O. Maier, "Operational Profiling of Temperature Using Ground-based Microwave Radiometry at Payerne: Prospects and Challenges," Atmos. Meas. Tech., **5** (2012).
24. U. Löhnert, E. van Meijgaard, H. K. Baltink, et al., "Accuracy Assessment of an Integrated Profiling Technique for Operationally Deriving Profiles of Temperature, Humidity, and Cloud Liquid Water," J. Geophys. Res. Atmos., **112** (2007).
25. A. V. Troitsky, K. P. Gaykovich, E. N. Kadygrov, et al., "Thermal Sounding of the Atmosphere Boundary Layer in Oxygen Absorption Band Center at 60 GHz," IEEE Trans. Geosci. and Remote Sensing, No. 1, **31** (1993).
26. E. R. Westwater, S. Crewell, and C. Mätzler, "Surface-based Microwave and Millimeter Wave Radiometric Remote Sensing of the Troposphere: A Tutorial," IEEE Geosci. and Remote Sensing Newsletter (2005).
27. E. R. Westwater, Y. Han, V. G. Irisov, et al., "Remote Sensing of Boundary Layer Temperature Profiles by a Scanning 5-mm Microwave Radiometer and RASS: Comparison Experiments," J. Atmos. Oceanic Technol., **16** (1999).
28. http://attex.net/RU/mtp5.php.
29. http://www.metek.de/product-details/usonic-3-scientific.html.