ISSN 1068-3739, Russian Meteorology and Hydrology, 2013, Vol. 38, No. 10, pp. 715–722. © Allerton Press, Inc., 2013.
Original Russian Text © I.N. Ezau, T. Wolf, E.A. Miller, I.A. Repina, Yu.I. Troitskaya , S.S. Zilitinkevich, 2013, published in Meteorologiya i Gidrologiya, 2013, No. 10, pp. 93–103.

The Analysis of Results of Remote Sensing Monitoring of the Temperature Profile in Lower Atmosphere in Bergen (Norway)

I. N. Ezau[a, b], **T. Wolf**[a], **E. A. Miller**[c], **I. A. Repina**[d, e],
Yu. I. Troitskaya[b, d, f], and **S. S. Zilitinkevich**[b, g]

[a]*Nansen Environmental and Remote Sensing Center, Thormøhlens gate 47, Bergen, 5006 Norway*
[b]*Lobachevskii State University of Nizhny Novgorod, pr. Gagarina 23, Nizhny Novgorod, 603950 Russia*
[c]*Central Aerological Observatory, ul. Pervomaiskaya 3, Dolgoprudny, Moscow oblast, 141700 Russia*
[d]*Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia*
[e]*Russian State Hydrometeorological University, Malookhtinskii pr. 98, St. Peterburg, 195196 Russia*
[f]*Institute of Applied Physics, Russian Academy of Sciences, GSP-120, ul. Ul'yanova 46, Nizhny Novgorod, 603950 Russia*
[g]*Finnish Meteorological Institute, Erik Palménin aukio 1, Helsinki, 00560 Finland*

Received February 8, 2013

Abstract—Considered is the application of MTP-5 meteorological temperature profiler used for the remote sensing of vertical profiles of the air temperature in the planetary boundary layer and the lower one-kilometer layer of the atmosphere. The measurements were carried out in Bergen (Norway) in 2011–2012. The obtained dataset of temperature profiles has temporal resolution of five minutes and vertical resolution of 50 m. The MTP-5 data are complemented with the measurements of the air temperature and the wind taken at two automatic weather stations and with the measurements of the rain intensity made with the rain radar. Studied is the impact of meteorological conditions and precipitation on the MTP-5 readings. It is revealed that formation of a thin water film (of ice or, to a smaller degree, of sleet) on the surface of the sensor cover of MTP-5 has a significant impact on the data of the temperature monitoring. The removal of intensive precipitation (the precipitation rate is >0.2 mm/hour) improved the reliability and quality of the temperature profile monitoring. In particular, it is demonstrated that significant air pollution and stably stratified atmospheric conditions which lead to low temperatures are reliably monitored with this instrument.

DOI: 10.3103/S1068373913100099

INTRODUCTION

In the case of stable atmospheric stratification, when less dense and, hence, potentially warmer air layers are situated over the denser and cooler layers, the turbulent mixing is suppressed. This results in formation of thin planetary boundary layers (PBLs), in the increase in the concentration of admixtures in them, and in the significant decrease (increase) in the temperature of the surface air layer in the case of the negative (positive) heat balance on the surface [8, 13]. In addition, the height of PBL is limited by the superimposed atmospheric stratification over PBL [15] which can result in the development of PBL with the thickness of about 100 m even in the case of low stability near the surface. Moreover, having been formed for one or another reason, the stably stratified PBL has a trend towards the stability increase in the upper part; this weakens still more the transfer of the angular momentum from the free atmosphere to the underlying layers of PBL, suppresses the turbulence in PBL, and results in the further intensification of different severe weather phenomena in the surface air layer [7]. Stable stratification is rather widespread in nature. First of all, it is formed almost every night over the land surface. Stable PBLs are typical of the areas occupied by the water bodies which lower surface temperature is less than the air temperature; this is especially typical of the areas of cold oceanic currents and upwelling. In winter months, stably stratified PBLs are common over the ice-covered Arctic Ocean surface as well as in the anticyclones formed over the snow-covered continents. Nevertheless, the processes in such PBLs have been studied insufficiently, and, in particular, the problem of the adequate description of turbulent exchange in the surface layer has not been solved yet [4].

The monitoring of the stratification of the lower atmosphere and especially of PBL is an essential component of the systems of diagnosis and prediction of weather phenomena and the air quality. At present, such systems are based on numerical models of atmospheric circulation and admixture transport. These models apply the parameterization of turbulent mixing and of PBL height using a set of large-scale parameters and universal functions, in particular, the resistance laws considered in details in [5, 14–16]. The resistance laws enable to determine the profiles of the wind and temperature characteristics in PBL; however, there is a number of external parameters which should be determined from independent observations or obtained from large-scale meteorological models. In particular, one of the major external parameters is the potential temperature gradient in the free atmosphere over PBL, i.e., the superimposed stratification.

It seems to be difficult to determine the stratification in the upper part of PBL and in the lower atmospheric layer using the traditional observational tools. Routine aerological data come from the higher altitude than the typical thickness of stably stratified PBLs. As a rule, the vertical resolution of these data is insufficient to allow the inversion in the upper part of PBL. At the same time, the meteorological masts with the height of 200–500 m are unique objects which cannot be installed at any place, where the need in PBL monitoring arises. Under these conditions, the remote sensing with application of the enhanced version of MTP-5 meteorological temperature profiler [6, 11] enables to solve the problem of the temperature profile monitoring up to the height of 1000 m with the high spatial and temporal resolution.

One of the main difficulties of MTP-5 operation is associated with the formation of the water (ice or sleet) film on the surface of the sensor cover. It is known that under these conditions the measurement results provide the more isothermal temperature profile than the one measured with thermometers at the meteorological mast. The paper [9] compares the readings of MTP-5 and those of the thermometers at the meteorological mast in Obninsk for the cases with intensive precipitation observed during the summer 2009. Three typical cases of the temperature profile distortion were singled out, and in the case of intensive precipitation this distortion reached 2°C for the upper levels of the measurement.

Although the physical nature of the distortion of the temperature profile measured by MTP-5 is clear enough, the meteorological and climatic significance of distortions under concrete conditions of operation still remains unclear. In particular, to parameterize PBL in numerical prediction models and to construct statistical regression models of the air quality, it would be desirable to estimate the results of the remote sensing of the temperature profile under different meteorological conditions as well as the contribution of the temperature profile distortions to the averaged values of PBL stratification.

In the present paper, the results are presented of the analysis of the remote monitoring of the temperature profile in lower atmospheric layers in the valley, where Bergen (Norway) is located. The analysis is carried out using the temperature monitoring data for 2011–2012. Good meteorological equipment of the Bergen valley enables not only to carry out the analysis of the climatology of temperature profiles but also to compare the MTP-5 data with the independent temperature observations near the surface and at the higher levels on the slopes of the valley. Moreover, the simultaneous monitoring of precipitation with the meteorological radar enables to study the MTP-5 data sensitivity to the presence and intensity of precipitation.

BRIEF DESCRIPTION OF MTP-5 INSTRUMENT AND THE AREA AND CONDITIONS OF OBSERVATIONS

The MTP-5 modified meteorological temperature profiler (produced by NPO ATTEX, Russia, www.attex.net) was installed on the measurement site of the Geophysical Institute of University of Bergen on February 8, 2011. The MTP-5 has a certificate of confirmation of the measurement tool type Ru.C.32.002.A No. 45688 and CE international safety certificate. It was worked out for measuring temperature profiles from the level of installation to the height of 1000 m regardless of weather conditions. The instrument passed the series of international comparisons with different alternative measurement systems: radiosondes, RASS, meteorological masts, etc. [6, 12]. Following the results of the series of comparisons and tests in 2011, the instrument is included in the "Quality Assurance Guidance for the Collection of Meteorological Data Using Passive Radiometers" worked out by the U.S. Environmental Protection Agency [10]. Technical characteristics of MTP-5 are presented in the table.

The operation principle of MTP-5 is described in details in [1, 11]. The method is based on measuring the intrinsic heat radiation of molecular oxygen at the frequency of 60 GHz (the wave length is 5 mm) with the scanning radiometer. The radiation is measured in terms of the brightness temperature converted into the atmospheric temperature by means of solving the Fredholm equation of the first kind. This problem is mathematically incorrect, and the instability of its solution can be removed using the methods of statistical regularization. In the elevation method used in MTP-5, the correct retrieval of the temperature profile

Technical characteristics of MTP-5 profiler produced by NPO ATTEX

Characteristic	Value
Height range of the temperature profile measurement	0–1000 m
Vertical resolution of the data in the layer of 0–100 m	25 m
Vertical resolution of the data in the layer of 100–1000 m	50 m
Sensitivity (at the constant of the measurement time = 1s)	Not more than 0.1 K
Measurement accuracy (standard deviation (SD))	±(0.2–1.2)°C
Accuracy along the vertical	25%
Operational range of temperature	–50…40°C
Standard interval of measurements	5 minutes
Weight	25 kg
Power supply	220 V, 2 A, 50–60 Hz
Power consumption	
maximum	120 W
mean	60 W
Output voltage of the power unit	13.8 + 2 V, $I_{\text{out}} \leq 6$ A
Communication with the personal computer	RS232
Calibration	Automatic
Diagnostics	Automatic

requires that the radiation come from the atmospheric layer prespecified for each of measurement angles. In the opposite case, due to the regularization, the mathematical algorithm operates with the radiation coming from the smaller distance and not containing the information about the temperature of the layer. In case of the wave length of 5 mm, on the way to the receiver, radiation should experience the effects of reflection, absorption, and scattering on water and snow particles. These effects have been noted before and are partially characterized in [12]. As a rule, they cause a small (about 0.1°C) error in measurement results. More serious problems are caused by the formation of the water film on the sensor cover in MTP-5.

Figure 1 gives the idea of the external appearance, location, and orientation of the MTP-5 microwave radiation receiver during the measurements. The measurement site is located at the height of 45 m above the sea level and at the height of 33 m above the level of Bergen meteorological station (its conventional name is Florida). The measurement site and the station are equipped with many measuring instruments that enables to carry out the cross-sectional analysis of the quality of measurements and their sensitivity to different meteorological conditions. In the present paper, the quality was assessed by means of comparing independent temperature measurements using MTP-5 and temperature sensors by Aandera Data Instruments Company. The sensitivity of measurements was studied with respect to the amount and intensity of precipitation measured with the meteorological micro rain radar and with respect to the mean air temperature during the observation. The more detailed information about the instruments installed in the Geophysical Institute is presented on the website http://veret.gfi.uib.no/.

Besides the measurements on the Florida site, the temperature measurements on the slopes of Ulriken Mountain were used (the station with the conventional name Ulriken is located at the height of 602 m above the sea level or 557 m above the level of the instrument). This enabled to study the quality of the retrieval algorithm of the temperature profile in MTP-5 using the long series of observations at two levels.

The data obtained with MTP-5 from February 10, 2011 to September 1, 2012 were used for the statistical analysis. During this period, the measurements were carried out in the continuous mode with the spatial resolution of 50 m (the height range of 45–1045 m) and temporal resolution of five minutes (12 temperature profiles per hour, 288 profiles per day). Since other temperature measurements are of hourly resolution, the MTP-5 data were also averaged for each hour of observations. The one-hour intervals during which at least one failure in the operation of the instrument was detected were removed from the database.

In early September 2012, the resolution of the instrument was increased to 25 m in the lower 100 m of PBL. Although the preliminary analysis demonstrates that the quality of the temperature profile retrieval at least did not worsen, the authors do not have the sufficient statistics for the more detailed qualitative analysis.

Fig. 1. Meteorological temperature profiler produced by NPO ATTEX (Russia, www.attex.net). The instrument is installed on the measurement site of the Geophysical Institute of University of Bergen at the height of 45 m above the sea level. The image is dated from February 8, 2011.

ANALYSIS OF MONITORING RESULTS IN 2011–2012

One of the main problems of the monitoring of the air temperature profile using MTP-5 is the screening of radiation of oxygen molecules by the water drops on the surface of the sensor cover and, to a certain degree, along the direction of the measurement during intensive or durable precipitation. The climate of Bergen is characterized by the large amount of precipitation (the annual norm is 2260 mm) with the maximum in autumn (283 mm of precipitation in September). The precipitation mainly falls from the clouds with the cloud base below 1000 m. The use of the models of radio wave absorption demonstrates that the contribution of thick clouds with the water supply of 2 kg/m^2 and the cloud base of 300 m to the total error of the retrieval of the temperature profile from MTP-5 is 0.07°C only; this is commensurate with the measurement errors [2], because the water film on the protection cover can distort them rather significantly.

Figure 2 presents the diurnal course of the temperature profile in the case of precipitation. The considered day of September 6, 2011 is rather typical that enables to understand qualitative changes in the MTP-5 data caused by precipitation. Firstly, it can be noted that even small precipitation (for example, in the first half of the day) distorts considerably and dramatically the temperature profile although do not result in the absolutely isothermal stratification. Only the precipitation with the intensity of more than 2 mm/hour results in the practically complete isothermal stratification. Secondly, as clear from the figure, the intensity of precipitation is variable that leads to the partial retrieval of the temperature profile during the periods of low-intensity precipitation. However, such retrieval needs several consecutive scans (in the given example, up to three scans or up to 15–20 minutes). Therefore, the authors divided the observational time into one-hour periods without precipitation (dry periods), i.e., with the complete absence of precipitation during the observational hour, periods with small precipitation (moist periods), when total precipitation was less than 0.2 mm, and periods with precipitation.

It is clear from Fig. 3 that the measurement errors can be divided into four classes depending on the precipitation intensity. If there is no precipitation, the mean value of the difference between the data of the station and MTP-5 is minimal for the whole dataset and amounts to 0.83°C; this is in a rather good agreement with the results of other studies. In the case of small precipitation, this difference increases and reaches the maximum at the precipitation intensity of more than 2 mm/hour. Thus, it can be asserted that in the case of

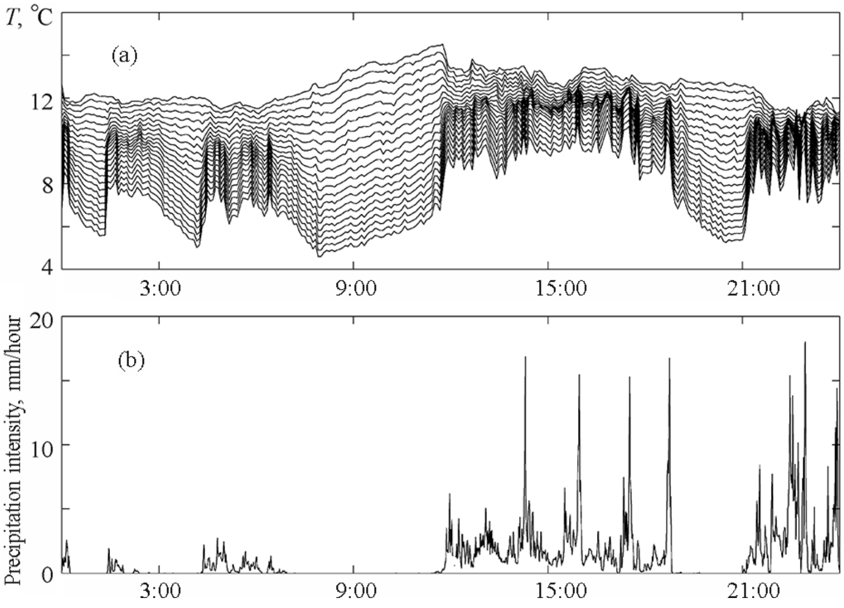

Fig. 2. Sensitivity of MTP-5 temperature profile to the presence and intensity of precipitation. (a) Diurnal variations of temperature on September 6, 2011 at the specified levels (the upper curve is 45 m above the sea level; further upwards, at every 50 m); (b) diurnal variations of precipitation intensity on the same day.

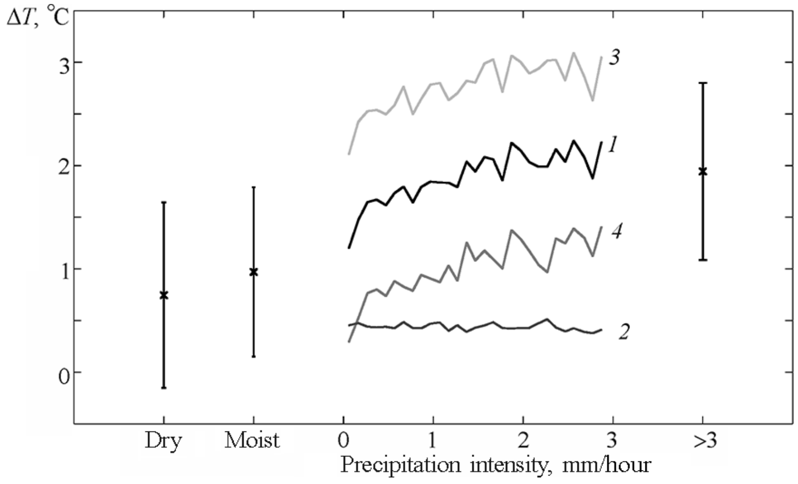

Fig. 3. Statistical analysis of the impact of the presence and intensity of precipitation on the difference $\Delta T = T_{\text{MTP-5}} - T_{\text{st}}$ at the Ulriken station level (602 m above the sea level and 557 m above the level of the instrument). Conditions without precipitation (dry) determine the mean (*1*) and the variance of the temperature difference between MTP-5 and the station due to the location of the station near the surface; (*2*) standard deviation (the value of SD/2 is presented) for the given range of precipitation intensity; (*3*, *4*) the mean minus and plus SD, respectively. Conditions without precipitation (dry), with the precipitation intensity of less than 0.2 mm/hour (moist), and with the precipitation intensity of more than 3.0 mm/hour are singled out into a separate category and are demonstrated in the form of signs and vertical lines defining one standard deviation.

such precipitation intensity, the surface of the protection cover is completely wet during the time between two consecutive scans of temperature profile.

The relationship between the difference in the temperature measured with MTP-5 and independent temperature sensor at the same level and the mean temperature in the hour of observations is presented in Fig. 4 (Florida station level, 45 m above the sea level) and Fig. 5 (Ulriken station level, 602 m above the sea level). As clear from the figures, there is a small mean deviation ($\Delta T = T_{\text{MTP-5}} - T_{\text{st}} = (-0.24 \pm 0.15)$°C) in MTP-5 readings at the lower level. This deviation as well as its variance for the hourly data does not practically de-

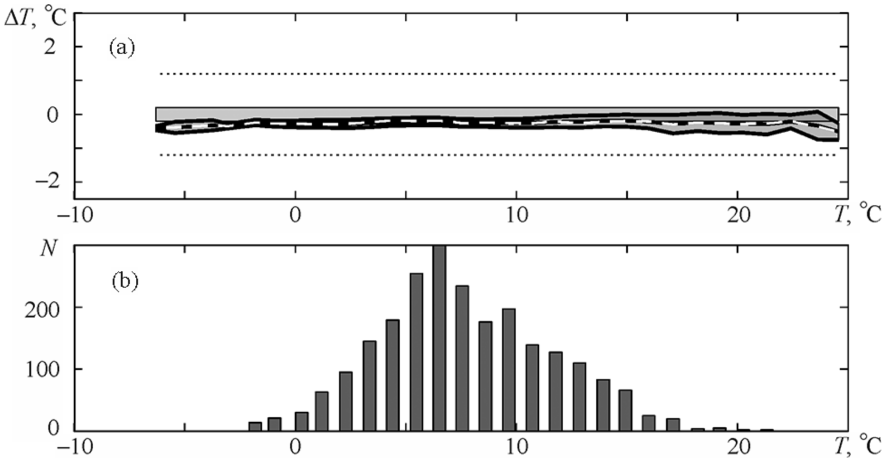

Fig. 4. Dependence of the temperature difference $\Delta T = T_{\text{MTP-5}} - T_{\text{st}}$ obtained from the measurements with MTP-5 and at Florida station (45 m above the sea level) on the mean temperature in the hour of observations. Permissible measurement errors of the instrument presented in the table are given in the form of the grey rectangular and the dotted lines. (a) Temperature difference for the hours with precipitation is shown with the black bold lines (the mean value in the temperature interval, by the dashed line and the mean ± SD, by the solid lines) and with the grey tint between them. Temperature difference for the hours without precipitation is shown with the white line (the mean only); (b) the number of one-hour intervals N during which the precipitation of more than 0.2 mm was registered for each specified temperature range.

pend on the temperature and precipitation. The value of the obtained deviation is comparable with the nominal accuracy of the instrument (0.2°C, see the table); however, these two values are of different origin. The instrument error is obtained for the ideal calibration conditions, whereas the obtained deviation characterizes the impact of specific local conditions of the instrument installation, in particular, the formation of surface inversions on the sloping surface of the valley. Due to the slope of the valley surface, the first level of temperature profile measurements has a smaller height above the surface than the instrument. Thus, the instrument receives the radiation from the levels being actually closer to the surface and, hence, being colder. This results in the negative difference between the temperatures registered with MTP-5 and the independent sensor, especially in the case of low mean temperature.

At the Ulriken station level, the mean temperature difference is $\Delta T = (0.66 \pm 0.91)$°C for the conditions without precipitation and $\Delta T = (1.2 \pm 1.0)$°C for the conditions with the precipitation of more than 0.2 mm/hour, i.e., MTP-5 regularly registers higher temperature than the station does. The increase in this difference can reach 5°C/km for the conditions with precipitation, i.e., actually, can reach the difference between the real moist-adiabatic and obtained isothermal temperature profiles in the case of precipitation. This difference can be explained by the increase in the number of isothermal temperature profiles in the case of precipitation. The climate in Bergen can be rather distinctly divieded into two weather-circulation regimes [3], that is, the regime of the zonal transport with the large amount of precipitation and the moderate air temperature and the regime of atmospheric blocking, when precipitation is practically absent and the temperature can be low (in winter) or high (in summer). This peculiarity of the Bergen climate is indicated in the nature of the dependence of the temperature difference on the hourly temperature. Figure 5a clearly demonstrates the typical “flexure” of the dependence towards the large values of the difference in the temperature range of 0–10°C. At the same time, if the temperature is below 0°C, when precipitation is mainly in the form of the snow and the water film does not cover the radiation receiver, the temperature difference stops depending on precipitation. This observation is in a good agreement with the results of [12], although the instrument registers the isothermal profile of temperature in the case of the sticking or rapid freezing of sleet.

Another interesting feature shown in Fig. 5a is that the MTP-5 measurements register the higher value of temperature at the Ulriken station level even during the periods without precipitation. In the case of the relatively low temperature in winter (below –5°C), there is no change in the sign of the difference as it could be expected judging from the idea that the surface of the slope is intensively cooled with the thin surface air layer at the negative wintertime heat balance. Such effect is really observed at the wind speed of less than 5 m/s. These cases are removed from the analysis. Thus, probably, there is a certain systematic error of the

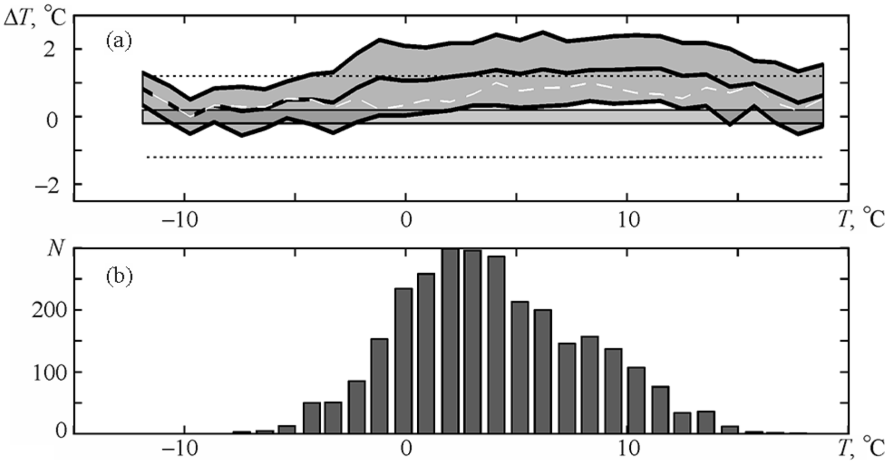

Fig. 5. The same as in Fig. 4 for Ulriken station (602 m above the sea level).

temperature profile which underestimates the temperature gradient approximately by 1°C/km. The temperature gradient underestimation means the slightly higher atmospheric stability according to the data of the instrument as compared with the really observed one. On the other hand, it should be taken into account that Florida and Ulriken stations are spaced apart, and the atmosphere, especially in the areas with the complex terrain, may not be flatly stratified.

CONCLUSIONS

The analysis of the large number of temperature profiles retrieved as a result of the remote sensing of the atmosphere with MTP-5 in 2011–2012 demonstrated that the instrument is reliable for monitoring the stratification of the lower atmosphere and PBL. The mean difference between the temperature profile retrieved from the data of the brightness temperature measurement and the profiles obtained from independent observations does not practically depend on meteorological conditions except the cases of heavy precipitation. The mean difference in the values of temperature was estimated at (–0.24 ± 0.15)°C at the level of the instrument installation and at (0.66 ± 0.91)°C at the Ulriken station level (557 m above the level of the instrument). These differences do not exceed the measurement errors presented in the passport of the instrument but in total give the slightly more stable atmospheric stratification than the real one. Since the thickness of PBL can be quite sensitive to the stratification of the free atmosphere [5, 15], this error should be taken into account when using the data of the temperature profile monitoring for the works on the air quality prediction and calibration of PBL parameterization in numerical models.

The major problem of the temperature profile monitoring with MTP-5 is the formation of the water film (of ice or, to a smaller degree, of sleet) on the sensor cover. The visible effect of such film in these measurements is the sudden transition to the partially or completely isothermal atmospheric stratification. Since the lower atmosphere is, as a rule, well mixed, in the case of precipitation the temperature profile error depends on the height as the moist adiabatic curve for the given temperature [7].

ACKNOWLEDGMENTS

This study was supported by a grant from the Government of the Russian Federation under contract No. 11.G34.31.0048 and the European Research Council Advanced Grant, FP7–IDEAS, 227915. Norwegian authors were supported by the Norwegian research council grants 196174/S30 and 191516/V30. Russian authors were also supported by the grant of Ministry of Science and Education No. 8833. We are particularly thankful to GC Rieber Foundation (Bergen) for long-term support of climate studies as well as personally to Prof. Joachim Reuder, Jan-Asle Olseth and Ole-Edward Grov for access to the meteorological data.

REFERENCES

1. E. N. Kadygrov, “Microwave Radiometry of Atmospheric Boundary Layer: Method, Equipment, and Applications,” Optika Atmosfery i Okeana, No. 7, **22** (2009) [Atmos. Ocean. Optics, No. 7, **22** (2009)].
2. A. V. Troitskii, *SHF Radiometry of the Earth’s Atmosphere*, Abstract of the Thesis for the Doctor Degree in Physics and Mathematics (Moscow, 1994) [in Russian].
3. I. N. Ezau, “Application of Cluster Analysis in the Studies of Inhomogeneities in Geophysical Fields,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **34** (1998) [Izv., Atmos. Oceanic Phys., No. 2, **34** (1998)].
4. Y. Cheng and W. Brutsaert, “Flux–Profile Relationships for Wind Speed and Temperature in the Stable Atmospheric Boundary Layer,” Boundary-Layer Meteorol., **114** (2005).
5. *EPA Quality Assurance Guidance for the Collection of Meteorological Data Using Passive Radiometers*, U. S. Environmental Protection Agency Region 10 Office of Environmental Assessment and U. S. Environmental Protection Agency Office of Air Quality Planning and Standards, FINAL 0611 (2011).
6. I. Esau, R. Davy, and S. Outten, “Complementary Explanation of Temperature Response in the Lower Atmosphere,” Environ. Res. Lett., **7** (2012).
7. I. Esau and S. Zilitinkevich, “On the Role of the Planetary Boundary Layer Depth in the Climate System,” Adv. Sci. Res., **4** (2010).
8. I. Esau and S. Zilitinkevich, “Universal Dependences between Turbulent and Mean Flow Parameters in Stably and Neutrally Stratified Planetary Boundary Layers,” Nonlinear Processes in Geophysics (The Special Issue “Turbulent Transport in Geosciences”), **13** (2006).
9. E. N. Kadygrov and D. R. Pick, “The Potential for Temperature Retrieval from an Angular-Scanning Single-Channel Microwave Radiometer and Some Comparison with in Situ Observations,” Meteorol. Appl., No. 5 (1998).
10. A. Koldaev, E. Miller, A. Troitsky, and S. Sarichev, “Experimental Study of Rain-induced Accuracy Limits for Microwave Remote Temperature Profiling,” in *WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, Helsinki, Finland, 30 August–1 September 2010*.
11. A. V. Troitsky, K. P. Gaikovich, V. D. Gromov, et al., “Thermal Sounding of the Atmospheric Boundary Layer in the Oxygen Band Center at 60 GHz,” IEEE Trans. on Geoscience and Remote Sensing, No. 1, **31** (1993).
12. 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 and Experiments,” J. Atmos. and Ocean. Technol., No. 7, **16** (1999).
13. S. S. Zilitinkevich and I. Esau, “Planetary Boundary Layer Feedbacks in Climate System and Triggering Global Warming in the Night, in Winter and at High Latitudes,” Geography, Environment and Sustainability, No. 2, **1** (2009).
14. S. S. Zilitinkevich and I. Esau, “Resistance and Heat Transfer Laws for Stable and Neutral Planetary Boundary Layers: Old Theory, Advanced and Re-evaluated,” Quart. J. Roy. Meteorol. Soc., **131** (2005).
15. S. S. Zilitinkevich and I. Esau, “Similarity Theory and Calculation of Turbulent Fluxes at the Surface for the Stably Stratified Atmospheric Boundary Layers,” Boundary Layer Meteorol., No. 2, **125** (2007).
16. S. S. Zilitinkevich, I. Esau, N. Kleeorin, et al., “On the Velocity Gradient in Stably Stratified Sheared Flows. Part 1: Asymptotic Analysis and Applications,” Boundary Layer Meteorol., No. 2, **135** (2010).