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Experience in the quadcopter-based meteorological observations in the atmospheric boundary layer

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Abstract. Recent developments of the unmanned aerial vehicles (UAVs) opens wide opportunities for their application for in-situ meteorological measurements in the atmospheric boundary layer (ABL). In this study we consider the experience of ABL measurements with a mass-market quadcopter DJI Phantom 4 Pro, equipped with temperature, humidity, pressure and infra-red surface temperature sensors. The quadcopter was used during a field experimental campaign in the northern Russia in winter for several types of measurements: hovering near the automatic weather station for a verification (1); vertical transects within the lowest 500 m in order to obtain the vertical temperature profiles and compare them with observations of the microwave temperature profiler MTP-5HE (2); horizontal transects over an unfreezing polynya (3). Additional verification was performed near the high meteorological mast in Obninsk. Listed experiments have shown that quadcopter-based system is a promising and usable tool for ABL measurements. However, its application requires a multi-step data processing framework, which is presented in this study.

Introduction

Monitoring of the meteorological conditions (temperature, humidity, wind, etc.) inside the atmospheric boundary layer (ABL) is essential for various environmental applications. It is important for the understanding the processes of the surface-atmosphere interactions, which are often studied in the experimental campaigns. However, the measurements higher than a few meters above the ground require the usage of masts, which are heavy, expensive, limited in height and inflexible with respect to the changes in location [1,2]. The remote sensing equipment (e.g. SODARs, LIDARs or temperature profilers) is also expensive and has a lot of limitations [3–5].

Rapid development of unmanned aerial vehicles (UAVs) opens wide opportunities for meteorological measurements in the ABL. There are two main types of the UAVs: fixed-wing aircrafts and multirotor aircrafts (usually quadcopters or octocopters, further called as multicopters). The key advantages of the multicopters in comparison to fixed-wing UAVs are the maneuverability and abilities to hang in a fixed point and to takeoff or land in a confined space. Their disadvantages are the short flight time (usually no more than 30 minutes) and limited vertical and horizontal ranges of operation.

Recent hardware and software developments significantly improved the reliability and usability of multicopters and turned them to mass-marked devices, which could be easily operated by a user without special piloting skills. The multicopters are now widely used for the photo and video production,



cartography and various monitoring tasks, including the agricultural monitoring [6,7], creation the high-resolution digital elevation models [8,9], snow depth estimations [10] and monitoring of the land/water surface temperature using the infra-red thermal cameras and radiometers [7,11–13].

Both fixed-wing UAVs and multicopters are a promising tool for in-situ atmospheric measurements, e.g. for investigation of the vertical or horizontal distribution of the temperature, humidity, wind, turbulence, etc. The methodology of such measurements is developed and well-tested for the fixed-wing UAVs, which have been used in the wide number of studies [1,14–17]. The experience of the multicopter-based measurements is much smaller, probably due to their later appearance and stricter limitations in flight time and range. However, in contrast to fixed-wing UAVs, the multicopters are available to make strictly vertical profiles and to fly with a low speed, which reduces the sensors' inertia effect on measurements [2]. Due to the listed features, application of multicopters is especially promising for measurements near the surface and within the ABL.

Prior to our study, the multicopters have been used for in-situ atmospheric measurements in a few field campaigns, e.g. in [1], including the investigation of the vertical structure of the Singapore urban heat island [18] and the Antarctic ship-based campaign [2]. However, a lot of methodological issues of the multicopter-based in-situ measurements remained unsolved and discussed, including the questions about the optimal location of the sensor [6], effects of the sensor's inertia and atmospheric disturbances, induced by the quadcopter in flight.

In this study, we present the experience of the atmospheric measurements, made by a mass-market quadcopter DJI Phantom 4 Pro in winter conditions. The drone was equipped with meteorological sensors and used for the vertical and horizontal transects. The description of the system, its missions and data processing is given in Section 1, while results are presented and discussed in Section 2.

1. Data and methods

1.1. Design of the quadcopter-based measuring system

In our study we use a mass-market quadcopter DJI Phantom 4 Pro (Figure 1a). Its flight ceiling is limited to a height of 500 m, the horizontal range is 1-2 km and flight time on one battery is about 25 minutes. The drone was equipped with iMet-XF sensor package, manufactured by International Met Systems (<http://www.internetsystems.com>). It includes the main board with integrated pressure sensor and a number of external sensors: air temperature and humidity module EE03, NTC (Negative Temperature Coefficient) thermistor, infra-red (IR) surface temperature sensor and GPS receiver (Table 1). The package could be further extended by additional sensors.

Table 1. List and specifications of the sensors, used within the framework of iMet-XF system.

Sensor name and type	Manufacturer	Range	Accuracy	Response time
Pressure sensor (in iMet-XF main board)	International Met Systems	10–1200 hPa	±0.24 hPa	8 ms
Air temperature sensor (glass bead NTC thermistor with Shibaura PSB-S5 sensor)		-95–50 °C	±0.3 °C	1 s
Air temperature (T) and relative humidity (RH) module EE03 with a polymer-based capacitive humidity sensor HC103	E+E Elektronik	-40–80 °C (T) 0–95% (RH)	±0.3 °C (T), ±3 % (RH) at 20°C	1 s
Infra-red (IR) temperature sensor	Melexis	-50–125 °C	±0.3 °C	1 s
GPS Receiver (CAM-M8Q)	UBlox	-	-	-

The data from the sensors is collected to the main board, transmitted to a serial output with 1 second frequency and logged to MicroSD card using Logomatic v2 data logger (SparkFun Elektronik, <https://www.sparkfun.com/>). The system is powered from an external battery (5 VDC). The main board of iMet-XF, logger and battery are placed in a box, mounted to the chassis of the quadcopter (Figure 1b).

Effect of airflow on readings of temperature and pressure sensors is very important for airborne measurements. However, it is poorly investigated for multirotor UAVs. There is no common solution about the optimal location for the sensors with respect to a multicopter and its rotors. Mounting the

sensors on a horizontal tube well outside the downwash of the propellers [1] or on top of a vertical boom above the aircraft could reduce the influence from the rotor blades [2]. On the other hand, mounting the sensors just above or behind one of the rotors promotes a better ventilation [1]. In our study, NTC and EE03 sensors were placed at the end of a plastic tube behind a propeller close to each other (Figure 1c). After several flights, the NTC sensor was separated by ≈ 5 cm from EE03 and moved by a few mm out of its metal case. The IR temperature sensor was mounted at the central part of plastic tube and pointed to the surface. We have also tried to mount it to the camera gimbal in order to have it pointed strictly perpendicular to the surface, however the gimbal was not able to operate with any additional load.

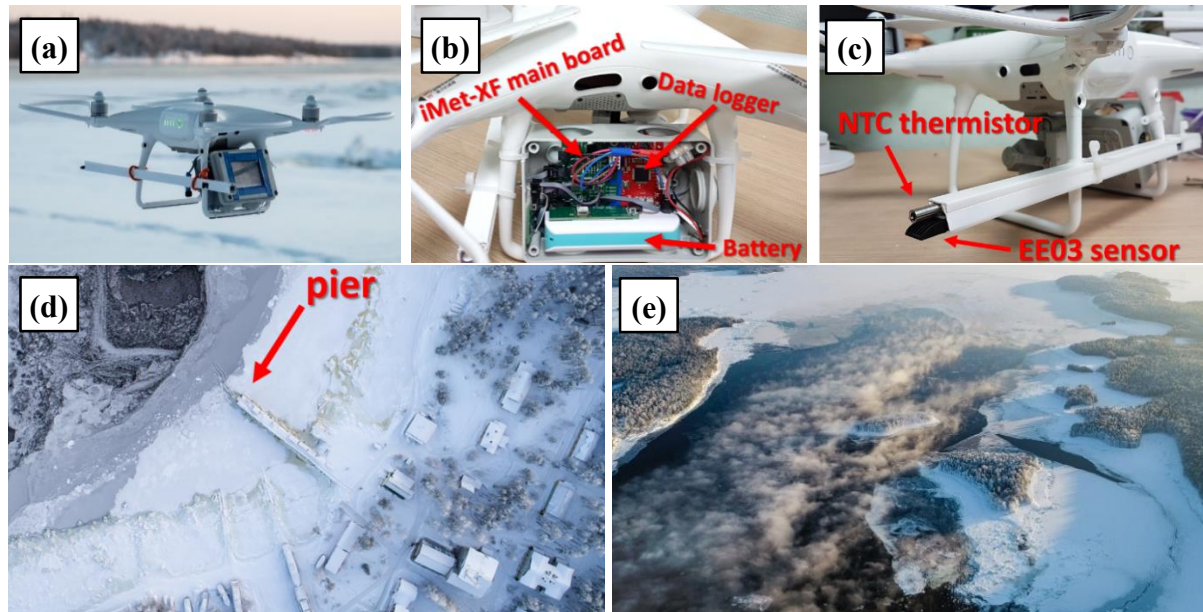


Figure 1. The equipped quadcopter in flight (a); the box with iMet-XF main board and data logger (b); initial mounting the NTC and EE03 sensors (c); aerial view to WSBS (d); aerial view to the polynya (e)

1.2. Experimental campaigns

1.2.1. White sea field campaign. The quadcopter was used in a field campaign, which took place at in Northern Russia White Sea Biological Station (WSBS) of Lomonosov Moscow State University, located at the coast of the White sea (66.554°N , 33.104°E) in February 2018. The campaign was aimed to the investigation of the turbulent fluxes within an inhomogeneous landscape and was organized mostly similar to a previous one [19]. Among the ground-based observation, the automatic weather station (AWS) Vaisala WX150 and MTP-5HE microwave temperature profiler MTP-5HE [20,3] were installed at the pier of WSBS (Figure 1d). MTP-5HE was used for the vertical temperature profile measurements in the lowest 1000 m with a 5-minute frequency and a vertical resolution 50 m. Different weather conditions were observed during the campaign, including the calm and clear anticyclonic weather with strong near-surface temperature inversions. The most of the flights were carried out during no-sunlight hours or in cloudy conditions, so the unshaded sensors were not affected by the direct solar heating.

The quadcopter was used for three types of measurements during the White sea campaign:

1. **Hovering flights at the fixed point** near the AWS at the pier (Figure 1d) were performed for calibration of the sensors and understanding the disturbances, induced by the flying quadcopter.
2. **Vertical transects** over the pier within the lowest 500 m were carried out twice a day from 3rd to 7th of February 2018 (10 flights in total) in order to obtain temperature and humidity profiles and to compare the temperature data with observations of the MTP5-HE profiler. Each flight included continuous ascent with a speed of ≈ 2 m/s, hovering at the top and descent with the same speed.
3. **Horizontal transects** over an unfreezing polynya were made at the different height in order to investigate the convective boundary layer that forms over the open water and its effect on the

temperature and humidity. The polynya was formed by the local currents in the Bolshaya Salma straight (Figure 1e) at the distance 300 m from the WSBS pier.

1.2.2. Obninsk campaign. Additional tests of the quadcopter-based measuring system were performed near Obninsk Meteorological Tower in Kaluga region of Russia (55.11 °N, 36.598 °E) at 11th March 2018. This tower has a height of 310 m and is equipped by temperature, humidity and wind sensors at the height of 2, 25, 73, 121, 217 and 301 m above the ground [21]. 10 vertical transects near the tower were made in one day. Among them, 6 were carried out in the same way as described above and 4 were carried out with lower ascent/descent speed (≈ 1 m/s) within the lowest 250 m. The temperature stratification was close to adiabatic during the Obninsk campaign. The sky was mostly covered by clouds, so the sensors were not affected by direct solar radiation.

1.3. Data processing

The developed data processing algorithm utilizes iMet-XF logs and the quadcopter flight logs, which are available using DJI Assistant software. The flight logs include a lot of parameters that characterize the state of the aircraft engines, navigation system, inertial measurement unit (IMU), etc. They are used for the determining of the takeoff/landing exact moments and as one of the sources of the altitude data.

1.3.1. Altitude determination. Two different methods of the altitude determination were considered. At first, the altitude data, determined by the IMU and further called as DJI altitude, is available in the flight logs. Secondly, the altitude could be derived from the iMet-XF pressure readings. We calculate it using an iterative method with a pressure-based vertical grid:

$$z_i = z_{i-1} - \Delta p / g \cdot \rho_i$$

where $\Delta p = 0.5$ hPa is the step of the vertical grid, $\rho_i = p_i / R \cdot T_i$ is air density, p_i and T_i are the pressure and air temperature (in K) for i^{th} level, $R = 287.058$ is specific gas constant for dry air. The average vertical temperature profile ($T_{i=1...n}$) is obtained based on the readings of the NTC sensor. For the vertical transects the averaging is made separately for ascending and descending flights.

The comparison between two methods has shown a significant excess of the DJI altitude over the pressure-based altitude, up to 10% for the coldest days (500 m against 450 m for a flight ceiling). This is not a surprise, because the DJI altitude is obtained using the built-in barometer and the temperature profile of standard atmosphere, which is characterized by a lower vertical pressure gradient. The further analysis utilizes the pressure-based altitude and vertical profiles, re-calculated for a grid with 5-m step.

GPS-determined altitude was not used due to low GPS accuracy in high latitudes.

1.3.2. Correction of the sensors' inertia. The inertia of the temperature and humidity sensors is a known problem of radiosondes [21,22] and UAV-based observations [2,23]. For the vertical transects, it could be solved by an averaging over the ascending and descending flights. However, more universal solution is required for horizontal transects and more complicated missions. For the temperature we propose a simple method of inertia correction based on the shift of the time series:

$$T_1(t) = T_0(t + \Delta t)$$

where T_0 and T_1 are raw and corrected time series, t is time and Δt is the value of the time shift. The optimal Δt values for NTC and EE03 sensors are investigated in the Section 2.2.

Additional correction was implemented to the relative humidity readings of EE03 module in order to take into account the correction for the thermal inertia. It is necessary, because the capacitive humidity sensor EE03 responds to absolute moisture content, while the calculation of the relative humidity utilizes the temperature readings. Resulting correction for the relative humidity is defined as:

$$RH_1(t) = RH_0(t + \Delta t_{EE03}) \cdot \frac{E(T_0(t))}{E(T_0(t + \Delta t_{EE03}))}$$

where Δt_{EE03} is inertia correction for the EE03 module (same as for temperature) and saturated water vapour pressure E is calculated according Mangus formula.

2. Results

2.1. Hovering flights near the AWS

A number of comparisons between the quadcopter-based sensors and the AWS were performed during the WSBS campaign. In two of them, the motionless measurements with the aircraft installed on a tripod were altered with hovering flights near the AWS. These experiments took place under different weather conditions (wind speed and near-surface lapse rate, see Table 2). Comparison between the temperature readings of the AWS (10-sec frequency) and the quadcopter-based sensors for 06.02.2018 is shown in Figure 2. The EE03 data is already unbiased with respect to the NTC data. The systematic bias ($\Delta T_{NTC}^{EE03} = T_{EE03} - T_{NTC}$) is 1.3 °C for the considered case and varies between 1 and 1.4 °C for other cases. The iMet-XF data is affected by the noticeable small-scale fluctuation, but in general follows the larger-scale variations, resolved by the AWS. Same pattern is observed for humidity (not shown). No systematic differences were found between in-flight and motionless conditions in terms of variability scale and biases (Table 2). We could suggest that the quadcopter-induced effects on temperature, humidity and their variations are much smaller than their natural variability.

Table 2. Weather conditions and statistical characteristics of the quadcopter-based in-flight (IF) and motionless (ML) measurements near the AWS. V_{AWS} is mean wind speed, γ_{MTP5} is a mean lapse rate in lowest 100 m according to MTP-5 data, σ means the standard deviation of temperature/humidity readings, Δ means the systematic biases between two indicated time series

Date	V_{AWS} [m/s]	γ_{MTP5} [°C/100 m]	σT_{NTC} [°C]		σT_{EE03} [°C]		σRH_{EE03} [%]		ΔT_{NTC}^{EE03} [°C]		ΔT_{AWS}^{NTC} [°C]		ΔRH_{AWS}^{EE03} [%]	
			IF	ML	IF	ML	IF	ML	IF	ML	IF	ML	IF	ML
06.02.2018	5.5	-0.78	0.58	0.57	0.51	0.50	0.51	0.50	1.31	1.35	-0.01	-0.07	-1.32	-0.77
07.02.2018	1.4	-0.47	0.12	0.11	0.10	0.08	0.10	0.08	1.16	1.13	-0.11	-0.19	-2.17	-1.72

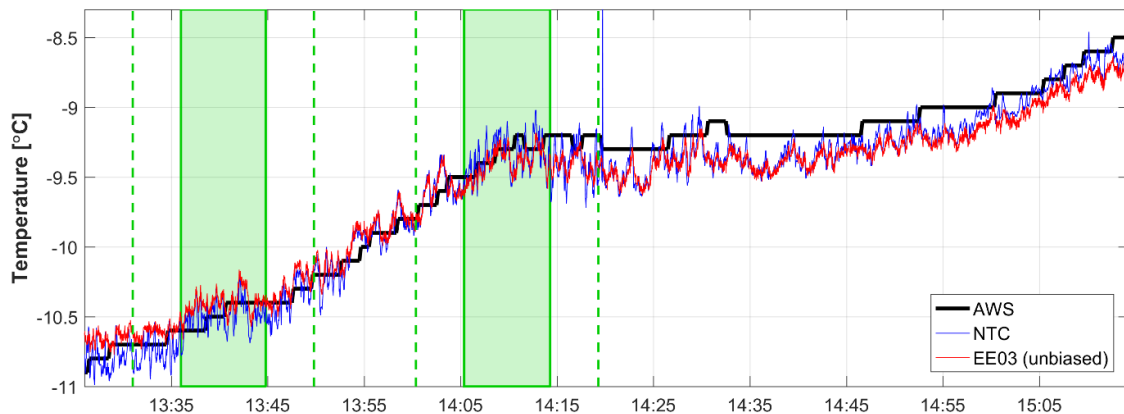


Figure 2. Comparison between temperature measurements, made by the AWS and a quadcopter in flight and in motionless conditions. Flight periods are indicated by green shading. Dotted lines indicate the periods, selected for the calculation of statistics for motionless conditions in Table 2.

2.2. Vertical transects

The vertical profile measurements, carried out at the WSBS and in Obninsk, were compared with reference observations (MTP-5 profiler and Obninsk tower). In addition, a comparison between ascending and descending profiles was performed in order to investigate the influence of the sensors' inertia, illustrated by Figure 3a-c for the temperature. The optimal values of the inertia correction Δt , defined in Section 1.3.2, were found separately for each flight by minimizing the following function:

$$F = \text{RMSD}(T_{EE03}^{asc}, T_{EE03}^{dsc}) + \text{RMSD}(T_{NTC}^{asc}, T_{NTC}^{dsc}) + \text{URMSD}(T_{NTC}^{asc}, T_{EE03}^{asc}) + \text{URMSD}(T_{NTC}^{dsc}, T_{EE03}^{dsc})$$
 where $\text{RMSD}(T_1, T_2)$ indicates the root-mean square difference between the profiles $T_1(z)$ and $T_2(z)$, URMSD indicates the unbiased RMSD , the superscripts *asc* and *dsc* indicate the ascending and descending profiles correspondingly, the subscripts indicate the type of the sensor.

The optimal Δt value depends on the type of sensor and on the method of its mounting. For the first 6 flights at the WSBS with initial sensors' mounting (Figure 1c), the mean Δt values are 8 and 10 sec for the NTC and EE03 correspondingly. The separation of the sensors from each other reduces the Δt values, especially for the NTC. The mean Δt values, averaged over the flights with separated sensors (4 at the WSBS and 10 in Obninsk), are 1 and 8 sec for the NTC and EE03. We have not found any dependence between the Δt values and ascend/descend speed or atmospheric stratification.

Corrected temperature profiles (Figure 3d-e) show a better agreement than the uncorrected ones (Figure 3a-c). Such improvement is confirmed by the RMSDs and correlation coefficients between the ascending and descending temperature and humidity profiles (Table 3). RMSDs for corrected temperature and humidity profiles are close to the declared accuracy of the sensors. Practically similar results were obtained using the optimal Δt values, determined separately for each flight (C1 mode in Table 3), and using the mean Δt values (C2 mode in Table 3).

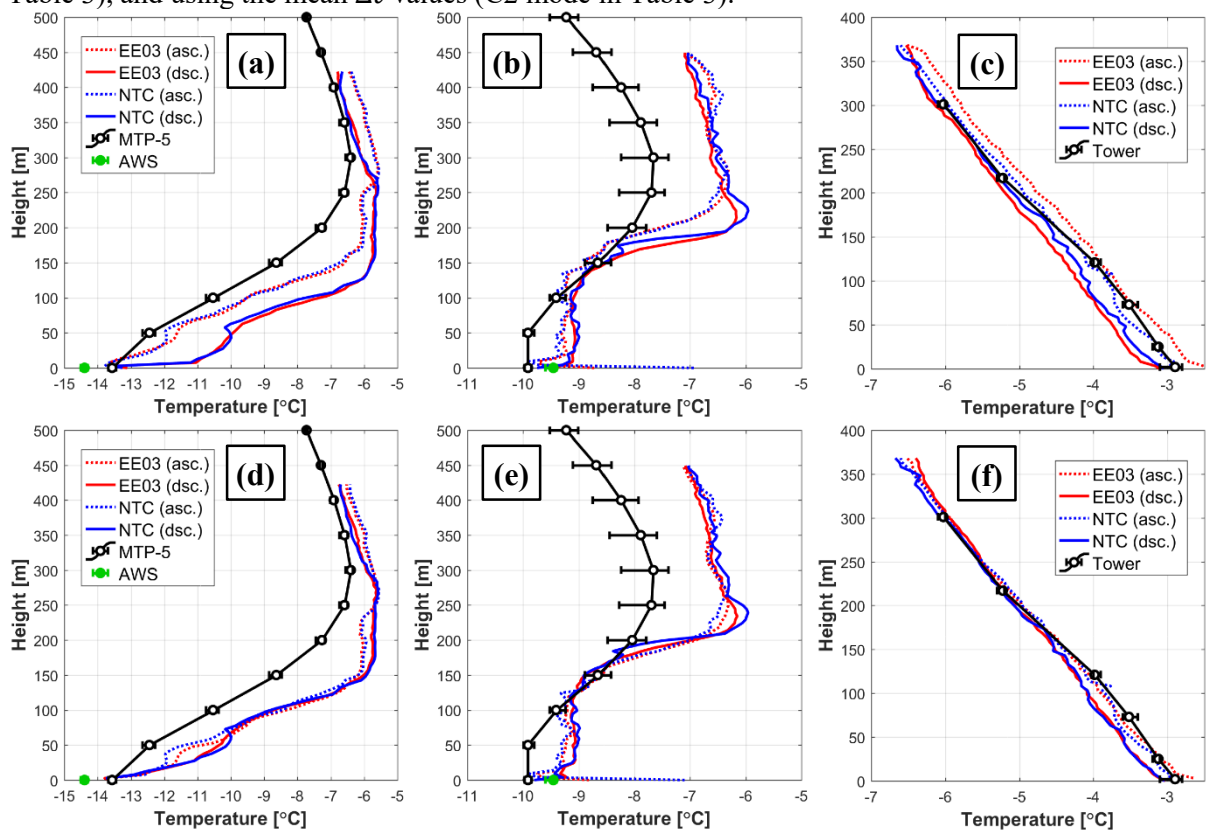


Figure 3. The ascending and descending vertical temperature profiles, restored from the uncorrected (a-c) and corrected (d-f) EE03 and NTC readings for two flights at WSBS (a, b, d, e) and one flight in Obninsk (c, f) in comparison to mean reference data (MTP-5 profiler or Obninsk tower). The horizontal whiskers indicate the range of variability for the reference data during the flight time. Inertia correction is performed using the mean Δt (C2 mode). EE03 data is unbiased.

Obninsk experiment has shown a good agreement between the quadcopter-based and tower measurements. The mean RMSD for temperature between both sensors on the quadcopter and tower data after all corrections is 0.33 °C, which is close to the declared accuracy of the sensors. The mean correlation coefficients exceed 0.97. Comparison for a humidity was not performed due to the gaps in the tower humidity measurements for the day of experiment. The comparison between the quadcopter-based measurements at WSBS and the data of MTP-5HE profiler shows worse results: the mean RMSD is ≈ 1.3 °C and the mean correlation coefficient is 0.77. However, the MTP-5 profiler is a remote sensing device and could not be considered as an ideal reference. Nevertheless, in-situ and remote sensing data agrees qualitatively about the presence of inversions and their height (Figure 3).

Table 3. Statistical parameters of the comparison (RMSDs and correlation coefficients R) between the ascending and descending temperature and humidity profiles, prepared with different approaches of inertia correction: without correction, with correction based on Δt values, determined separately for each flight (C1), with correction based on the mean Δt values (C2).

Campaign and sensors' mounting	Correction mode	T_{NTC}^{asc} vs T_{NTC}^{desc}		T_{EE03}^{asc} vs T_{EE03}^{desc}		RH_{EE03}^{asc} vs RH_{EE03}^{desc}	
		RMSD [°C]	R	RMSD [°C]	R	RMSD [%]	R
WSBS, sensors placed together	No correction	0.98	0.72	0.92	0.78	5.61	0.60
	C1	0.51	0.90	0.31	0.97	3.75	0.74
	C2	0.53	0.87	0.34	0.95	3.56	0.65
WSBS, sensors separated	No correction	0.32	0.87	0.51	0.68	2.60	0.48
	C1	0.28	0.93	0.38	0.88	2.17	0.55
	C2	0.31	0.89	0.40	0.85	1.96	0.59
Obninsk, sensors separated	No correction	0.25	0.98	0.36	0.99	2.56	0.97
	C1	0.23	0.98	0.18	0.99	0.88	0.98
	C2	0.25	0.98	0.19	0.99	0.83	0.97

2.3. Horizontal transects over the unfreezing polynya

Arctic polynyas receive considerable scientific attention due to their significant contribution to the wintertime Arctic heat budget [24]. Recent modelling studies indicate a need for more in-situ observations of the convective boundary layers (CBLs) that forms over the polynyas [25,26]. In our study we test the possibility to use a quadcopter for investigation of the temperature and humidity undulations within the CBL that develops over the polynya in the Bolshaya Salma straight and is frequently associated with formation of the low-level clouds (Figure 1e). 6 flights over the polynya were carried out during the WSBS campaign. Unfortunately, no clouds were formed over the polynya during these flights. Each flight included the horizontal transects at the height of 5, 10-20 and 40-50 m a.s.l. Flight routes and height were controlled manually, so the flight tracks are slightly different. Inertia corrections were applied as described above using the mean Δt values. In further analysis we consider the projections of the flight tracks to a line that goes from the WSBS pier crosses the strait (Figure 4).

To illustrate the preliminary results of this research we consider two cases with stronger (Figure 4b) and weaker (Figure 4c) temperature inversions (same cases as considered in Figure 3a and 3b). The IR surface temperature (ST) data allows to identify the polynya edges (Figure 4b-c, upper panels). Open water ST ($\approx -3^\circ\text{C}$) is slightly lower than a freezing point (-1.8°C), which could be explained by the presence of thin ice patches over the water. The ST is significantly cooler for the ice ($\approx -10^\circ\text{C}$) and snow-covered land (up to -15°C). The uncertainty about ± 25 m for the position of polynya's edges is caused by the differences between the flight tracks and by the inclination of the quadcopter.

All of the near-surface transects indicate a persistent increase of the air temperature up to 2°C above the polynya. A one solid temperature hotspot is found in two considered cases in the middle part of the polynya, closer to its southern edge. However, multiple hotspots are found in a few of other cases (not shown), which indicates the existence of the different convection regimes. The temperature hotspots are usually collocated with increase of humidity (Figure 4b-c, bottom panels). The horizontal transects higher than 20 m shows mostly homogeneous temperature distribution without any noticeable polynya-induced undulations. The same is observed for humidity with only one exception shown in Figure 1b. For this case with a strong inversion, a positive humidity disturbance is above over the polynya even at the height of 40 m. This results indicated that in spite of the absence of clouds, the thin CBL develops above the polynya. Its extent could be very roughly estimated as 20-40 m, which is in agreement with the depth of clouds that are formed in favorable conditions (Figure 1e), with previous estimates of the CBL height above the same polynya [27] and with modelling studies that propose the CBL height about 50-100 m even for polynyas with ≈ 1 km width [25,26].

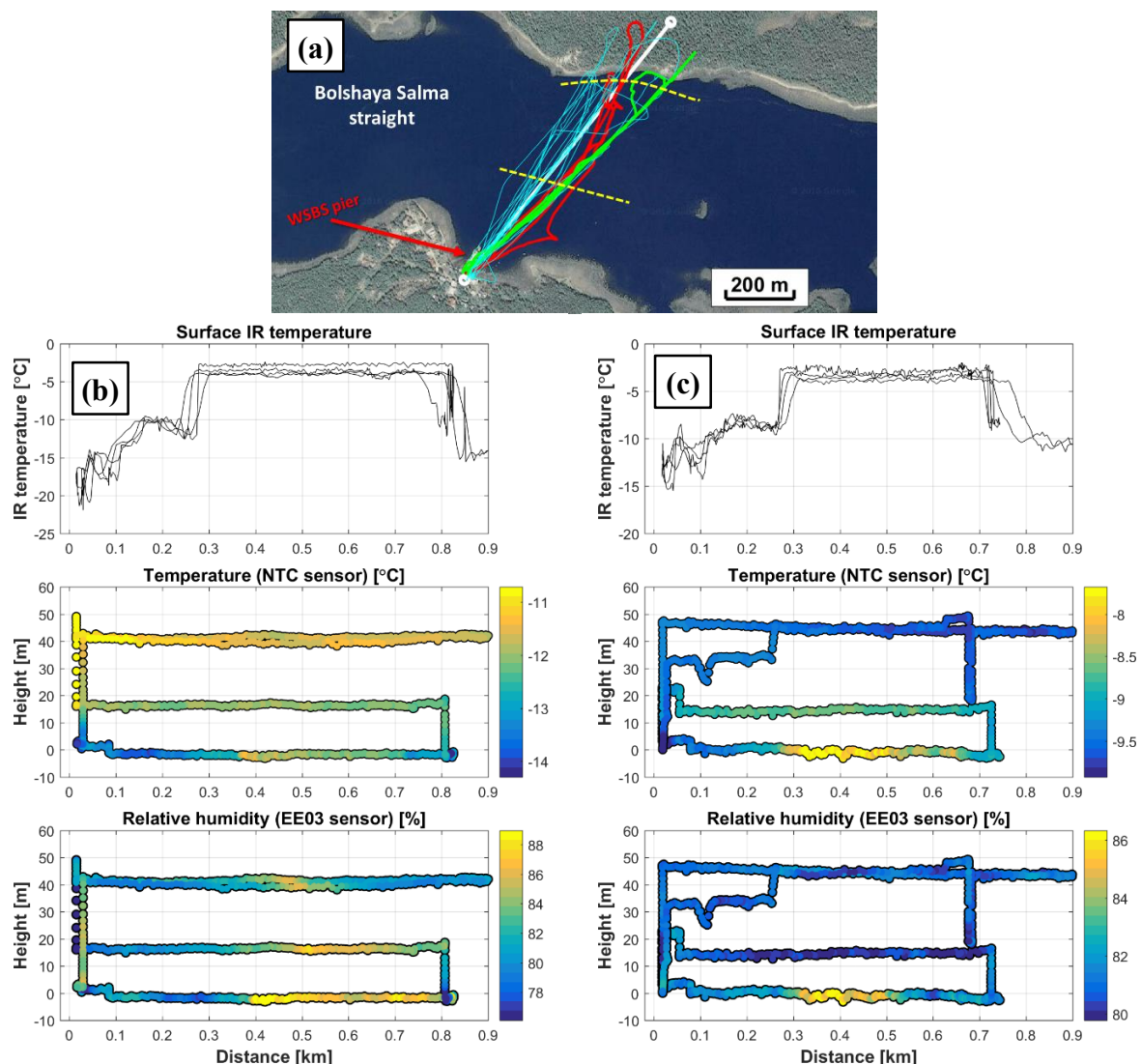


Figure 4. The tracks of all flights over the polynya that were carried out at the WSBS (a) with tracks of two considered flights (b,c) indicated by green and red color correspondingly. The yellow dotted lines indicate the approximate position of polynya's edges. For two considered flights, the distribution of IR surface temperature, air temperature and relative humidity is shown along the section that crosses the straight and is indicated by a white line in (a). Zero on the absciss axis is a take-off point near the pier.

3. Conclusion and outlook

Our study confirms that even a relatively cheap mass market quadcopter could be a useful tool for the meteorological measurements in the ABL. DJI Phantom 4 Pro quadcopter, equipped with iMet-XF meteorological sensors, have been successfully used for different types of measurements during the winter research campaign in the Northern Russia. In spite of the low temperatures and lower GPS accuracy in high latitudes, we have not faced any principal technical problems.

Comparison between the quadcopter-based and reference observation (MTP-5HE temperature profiler at the WSBS and the meteorological mast in Obninsk) has confirmed that a quadcopter could be successfully used for vertical temperature and humidity profile measurements and resolving the specific details that are missing in the remote sensing data. The quadcopter-based vertical profile measurements are especially promising due to an opportunity to restore a wind speed and direction data using the internal measurement unit of the aircraft [28], which will be tested in our next studies.

The horizontal transects over the polynya have shown an opportunity for in-situ measurements over the hard-to-reach areas and demonstrated the polynya-induced effects on temperature and humidity. Such experience opens wide opportunities for new experimental campaigns that could improve the general understanding of the atmospheric processes over the inhomogeneous landscapes such as forest lakes [19], polynyas [24–26] and urban areas [18,29], including and the Arctic cities, where pronounced wintertime urban heat islands have been recently discovered [30].

The analysis of the quadcopter-based measurements requires a detailed data processing framework, which should include the correction for sensors' inertia. The inertia could be significantly reduced by using the fast-response sensors (e.g. the NTC thermistor), but their improper mounting (e.g. as it is shown in Figure 2b) could strongly weaken the improvement. A simple correction for inertia, based on a shift of time series, significantly improves the agreement between the ascending and descending vertical temperature and humidity profiles. However, this method could fail in case of sharp temperature gradients, as it is shown by ascent and descent segments in Figure 4b. Therefore, there is an urgent need for more detailed theoretical understanding of the uncertainties of quadcopter-based measurements and development of more complicated corrections methods, such as proposed for a fixed-wind UAV in [23].

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References

- [1] Kral S T, Reuder J, Vihma T, Suomi I, O'Connor E, Kouznetsov R, Wrenger B, Rautenberg A, Urbancic G, Jonassen M O, Båserud L, Maronga B, Mayer S, Lorenz T, Holtslag A A M, Steeneveld G J, Seidl A, Müller M, Lindenberg C, Langohr C, Voss H, Bange J, Hundhausen M, Hilsheimer P, Schygulla M 2018 Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer (ISOBAR) – the Hailuoto 2017 campaign *Atmosphere* **9** 268
- [2] Jonassen M O, Tisler P, Altstädter B, Scholtz A, Vihma T, Lampert A, König-Langlo G, Lüpkes C 2015 Application of remotely piloted aircraft systems in observing the atmospheric boundary layer over Antarctic sea ice in winter *Polar Res.* **34** 1–15
- [3] Ezau I N, Wolf T, Miller E A, Repina I A, Troitskaya Y I, Zilitinkevich S S 2013 The analysis of results of remote sensing monitoring of the temperature profile in lower atmosphere in Bergen (Norway) *Russ. Meteorol. Hydrol.* **38** 715–22
- [4] Lang S, McKeogh E 2011 LIDAR and SODAR measurements of wind speed and direction in upland terrain for wind energy purposes *Remote Sens* **3** 1871–901
- [5] Beyrich F 1997 Mixing height estimation from sodar data – A critical discussion *Atmos. Environ.* **31** 3941–53
- [6] Roldán J J, Joossen G, Sanz D, del Cerro J, Barrientos A 2015 Mini-UAV based sensory system for measuring environmental variables in greenhouses *Sensors* **15** 3334–50
- [7] Patel P N, Patel M A, Faldu R M, Dave Y R 2013 Quadcopter for Agricultural Surveillance *Adv. Electron. Electr. Eng.* **3** 427–32
- [8] Ajayi O G, Salubi A A, Angbas A F, Odigure M G 2017 Generation of accurate digital elevation models from UAV acquired low percentage overlapping images *Int. J. Remote Sens.* **38** 3113–34
- [9] Voskresensky I S, Suchilin A A, Ushakova L A, Shaforostov V M, Entin A L, Ivanov M M 2018 Study of the landslide morphology based on GNSS data and airborne sounding (on the example of a section of the Protva river valley) [in Russian] *Eng. Surv.* **12** 50–7
- [10] Cimoli E, Marcer M, Vandecrux B, Bøggild C E, Williams G, Simonsen S B 2017 Application of Low-Cost UASs and Digital Photogrammetry for High-Resolution Snow Depth Mapping in the Arctic *Remote Sens.* **9** 1–29
- [11] Nishar A, Richards S, Breen D, Robertson J, Breen B 2016 Thermal infrared imaging of geothermal environments and by an unmanned aerial vehicle (UAV): A case study of the

- Wairakei - Tauhara geothermal field, Taupo, New Zealand *Renew. Energy* **86** 1256–64
- [12] Li F, Yang W, Liu X, Sun G, Liu J. 2018 Using high-resolution UAV-borne thermal infrared imagery to detect coal fires in Majiliang mine, Datong coalfield, Northern China *Remote Sens. Lett.* **9** 71–80
- [13] Demario A, Lopez P, Plewka E, Wix R, Xia H, Zamora E, Gessler D, Yalin A P 2017 Water plume temperature measurements by an unmanned aerial system (UAS) *Sensors* **17** 306
- [14] Spiess T, Bange J, Buschmann M, Vörsmann P 2007 First application of the meteorological Mini-UAV “M2AV” *Meteorol. Zeitschrift* **16** 159–69
- [15] Berman ESF, Fladeland M, Liem J, Kolyer R, Gupta M 2012 Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle *Sens. Actuators B Chem.* **169** 128–35
- [16] Boer G, Ivey M, Schmid B, Lawrence D, Dexheimer D, Mei F, Hubbe J, Bendure A, Hardesty J, Shupe M D, McComiskey A, Telg H, Schmitt C, Matrosov S Y, Brooks I, Creamean J, Solomon A, Turner D D, Williams C, Maahn M, Argrow B, Palo S, Long C N, Gao R S, Mather J 2018 A bird’s-eye view: Development of an operational ARM unmanned aerial capability for atmospheric research in arctic Alaska *Bull. Am. Meteorol. Soc.* **99** 1197–212
- [17] Wildmann N, Bernard S Bange J 2017. Measuring the local wind field at an escarpment using small remotely-piloted aircraft *Renew. Energy* **103** 613–9
- [18] Chow W, Ho D 2016 Investigating the vertical dimension of Singapore’s urban heat island through quadcopter platforms: an pilot study *Geophys. Res. Abstracts* 5690
- [19] Barskov K V., Chernyshev R V., Stepanenko V M, Repina I A, Artamonov A Y, Guseva S P, Gavrikov A V 2017 Experimental study of heat and momentum exchange between a forest lake and the atmosphere in winter *IOP Conf. Ser. Earth Environ. Sci.* **96** 012003
- [20] Kadyrov E N, Pick D R 1998 The potential for temperature retrieval from an angular-scanning single-channel microwave radiometer and some comparisons with in situ observations *Meteorol. Appl.* **5** 393–404.
- [21] Lokoshchenko M A, Korneva I A, Kochin A V., Dubovetsky A Z, Novitsky M A, Razin P Y 2016 Vertical extension of the urban heat island above Moscow *Dokl. Earth Sci.* **466** 70–4
- [22] Ivanov A, Katz A, Kurnosenko S, Nash N, Zaitseva N 1991 WMO International Radiosonde Comparison, Phase 3, Instruments and Observing Methods, Rep. No. 40
- [23] Jacobi C, Scherf A, Siemer A H, Roth R 1995 On the influence of sensor inertia on the estimation of turbulent fluxes from aircraft measurements *Boundary Layer Meteorol.* **76** 97–108
- [24] Burk S D, Fett R W, Englebreton R E 1997 Numerical simulation of cloud plumes emanating from Arctic leads *J. Geophys. Res. Atmos.* **102** 16529–44
- [25] Esau I N 2007 Amplification of turbulent exchange over wide Arctic leads: Large-eddy simulation study *J. Geophys. Res. Atmos.* **112** D08109
- [26] Vihma T, Pirazzini R, Fer I, Renfrew I A, Sedlar J, Tjernström M, Lüpkes C, Nygård T, Notz D, Weiss J, Marsan D, Cheng B, Birnbaum G, Gerland S, Chechin D, Gascard J C 2014 Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: A review *Atmos. Chem. Phys.* **14** 9403–50
- [27] Stepanenko V M, Debolsky A, Varentsov M I, Kuznetsov D, Zimin M 2011 Study of Atmospheric Convection Over the Arctic Ice Opening Applying Supercomputer Computations and High Resolution Satellite Data [in Russian] *Earth from Space* **10** 52–5
- [28] Neumann P P, Bartholmai M 2015 Real-time wind estimation on a micro unmanned aerial vehicle using its inertial measurement unit *Sens. Actuators A Phys.* **235** 300–10
- [29] Varentsov M, Wouters H, Platonov V, Konstantinov P 2018 Megacity-Induced Mesoclimatic Effects in the Lower Atmosphere: A Modeling Study for Multiple Summers over Moscow, Russia *Atmosphere* **9** 50
- [30] Konstantinov P, Varentsov M, Esau I 2018 A high density urban temperature network deployed in several cities of Eurasian Arctic *Environ. Res. Lett.* **13** 75007