Use of an optical rain gauge in a system of monitoring severe weather phenomena

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Abstract. Phenomena of convective origin (tornadoes, squalls, thunderstorms, heavy precipitation, and large hail) occur more often than the other natural phenomena causing huge economic damage. Analysis of weather events in recent years shows that the most dangerous meteorological phenomena in the Russian Federation (40% of total events) are extreme rainfall events (heavy rain, long rain, shower, hail, and thunderstorm). Modern systems for environmental research, monitoring, and prompt detection of severe weather phenomena must contain instruments for precipitation measurement that meet modern requirements for quantity and quality of meteorological information. Liquid precipitation measurements require receiving the following real time information: presence of precipitation, intensity (mm/h), start time and duration of precipitation, and total amount per day (mm). The measuring instrument must determine the type of precipitation (rain, snow, hail/large hail, mixed precipitation) with accuracy comparable to the results of visual observation. In addition, the device must provide an autonomy operation as part of autonomous meteorological systems (without any maintenance) and means of remote transmission, storage, and processing of measurement data with various averaging times and sets of measured characteristics. An optical precipitation gauge called OPTIOS, developed at IMCES SB RAS, fully complies with these requirements.

1. Introduction
Among the natural phenomena that cause huge economic damage and lead to loss of life, phenomena of convective origin (tornadoes, squalls, thunderstorms, heavy rainfall, and large hail) are leaders in the frequency of occurrence. Against the background of climatic changes the number of registered disasters increases in many regions of Russia [1]. These severe phenomena are caused by the passage of well-developed cumulonimbus clouds, where strong vertical air flows (up to 30 m/s) occur. In the cumulonimbus clouds and at a distance from them conditions for icing, strong turbulence, and aircraft lightning strikes can be formed. Near the underlying surface one can observe a wind speed increase with gusts of more than 30 m/s, vertical wind shift, hail, heavy rain, and heavy snow. The lifetime of cumulonimbus clouds is, on average, 1.5 hours and the speed of movement can be 100 km/h or more. At the same time, some cumulonimbus clouds have a characteristic size of about 10 km. Often these clouds are masked in the fields of layered cumulus or high layered clouds. These features make it difficult to detect cumulonimbus cloudiness and forecast emergency situations that it causes.
2. Detection of severe weather phenomena
A new method for detecting cumulonimbus cloudiness has been developed at IMCES SB RAS. It is based on the definition of distortion of the surface electric field during the passage of clouds of this type [2]. On the basis of this method, an automatic complex for the automated system of online detection of severe weather phenomena of convective origin was designed. The basis of the complex is an ultrasonic automatic weather station AMK-03 [3]. The station provides measurement of meteorological parameters (temperature, air humidity, atmospheric pressure, wind speed and direction taking into account the vertical component speed) with high time resolution. In addition to the measurement of the basic meteorological parameters of the surface layer, AMK-03 is used to evaluate standard statistical and turbulent characteristics, structural and autocorrelation functions of turbulent temperature fluctuations, and wind speed components. The developed complex includes an electric fluxmeter to measure the atmosphere electric field and a precipitation gauge to derive precipitation characteristics. The spatially distributed system of such complexes, which transmits meteorological information to the data processing center, allows monitoring of the main meteorological characteristics. Analysis and summarizing of the received information provide the capability of detection of adverse and severe weather events at least in 1-3 hours, depending on the system configuration. Each measuring complex included in the system can be supplemented with sensors that allow covering the entire list of severe weather phenomena issued by the Russian Hydrometeorological Center. This system is being developed in order to clarify, supplement and, in certain cases, replace the weather radar data and radar networks, as well as to improve the justification of local short-term weather forecasts.

Analysis of the natural hydrometeorological phenomena in recent years (1991-2015) shows that most severe weather phenomena registered in the Russian Federation (more than 40% of the total number of severe weather phenomena) are concerned with extreme precipitation (heavy rain, long rain, rain, hail, and thunderstorm) [4]. Intensive rainfall can cause flooding, soil erosion, and landslides. Heavy snowfalls and snowstorms block transport, cause damage of buildings, power lines, and provoke avalanches. Despite the importance of timely information on the characteristics of precipitation, now these data can be obtained only from the network of hydrometeorological stations of Roshydromet. The spatial resolution of this network is hundreds of kilometers, and the temporal resolution of the meteorological measurements is 3 hours. Another approach to determine the characteristics of precipitation is establishing a network of Doppler weather radars (DWRs). However, the existing projects for the DWRs network development are being implemented too slowly and, as a result, they do not provide the formation of a system for continuous monitoring of the entire populated area of the country.

3. Precipitation measurements
Since severe weather phenomena are characterized as fast progress with a short lifetime, the rain gauge must be highly sensitive for maximum efficiency of precipitation detection and duration determining. To meet the requirements for the liquid precipitation measurement data, the following information must be obtained in real time: the presence of precipitation, the intensity of precipitation (mm/h), the exact start time and duration of precipitation, and the total amount per day (mm). The device should determine the precipitation type (rain, snow, hail, mixed precipitation) with an accuracy comparable to the results of visual observation. In addition, the device should provide autonomous operation as part of the automatic meteorological complex (without any maintenance by the observer) and the possibility of remote transmission, storage, and processing of measurement data taking into account the broad requirements for the averaging time and sets of necessary characteristics.

To solve the tasks more effectively, a new automatic optical precipitation rain gauge OPTIOS [5] was used when developing the automatic system of online detection of severe weather phenomena of convective origin. It is based on the principle of obtaining and analyzing shadow images of precipitation particles.
The device specifications meet all of the above requirements. The sensitivity to the precipitation amount (not worse than 0.0001 mm) allows one to ensure the accuracy of determining the presence of precipitation, the time of precipitation beginning and finishing, fundamentally unattainable with the rain gauges that are traditionally used at stations of the Roshydromet network. The ability to register even a single precipitation particle makes possible real time monitoring of smallest changes in the precipitation intensity. The ability to estimate the fall velocities and average sizes of precipitation particles allows OPTIOS to determine the precipitation type with high accuracy [6]. In addition, the device capabilities can be used to estimate the kinetic energy of falling precipitation particles. This information is necessary to predict the effects of storm precipitation on soil erosion and damage caused by large hailstones. The ability to count the number and to measure the sizes of snowflakes allows OPTIOS to estimate the intensity of snowfall which, in combination with the information about the air temperature and wind speed obtained from the AMK-03, allows prediction of snow drifts and a critical reduction of visibility.

4. Field test results
To test the device capabilities, prototypes of the optical rain gauge OPTIOS were tested at the meteorological site of IMCES SB RAS during the summer-autumn seasons of 2015-2018. To verify the results of the measurements, a standard O-1 precipitation gauge and a tipping-bucket type precipitation gauge Davis Rain Collector (RC) were used. The instruments arranged at the meteorological site are shown in Figure 1.

![Figure 1](image)

**Figure 1.** Precipitation measurement at the meteorological site of IMCES SB RAS.

One of the results of simultaneous measurement of high intensity ($I$) precipitation using the OPTIOS and RC rain gauges is shown in Figure 2. The measurements were carried out on 15.06.2016. One can see that the gauges demonstrate a good coincidence in $I$ values. The deviation of the values obtained by the OPTIOS and RC at some points can be explained by a lower resolution of the tipping-bucket rain gauge in the amount of precipitation (0.2 mm), which does not allow the RC to measure accurately the precipitation intensity and to determine the precipitation start and end times. The result of the precipitation amount measurement for the selected time interval is 3.99 mm and 3.96 mm for the OPTIOS and RC, respectively.

The precipitation that falls from cumulonimbus clouds in hail form is most dangerous. Traditional rain gauges do not allow reliable determination of the presence of hail and its characteristics.
The optical precipitation gauge OPTIOS is capable of detecting and determining the size of hailstones, even in the presence of concomitant rain precipitation. Figure 3 presents the particle size distribution in rain precipitation accompanied by hail. The event was registered on 09.07.2016 at 18:49-18:52 (1267 particles were detected). The particle size distribution curve has a typical shape for large raindrops with a maximum at 1.5 mm. It has a gentle continuation to the region of larger particles and is not limited by the size range of liquid precipitation particles. The capabilities of the device to determine the precipitation type are presented in [6].

5. Conclusions
The modern systems developed for environmental research and, in particular, for monitoring and online detection of severe weather phenomena must include precipitation gauges that meet modern
requirements for quantity and quality of available meteorological information. The optical precipitation gauge OPTIOS fully complies with these requirements.

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References
[1] Porfiriev B N 2015 Economics of natural disasters *Herald of the Russian Academy of Sciences* **86** 1-11
[2] Pustovalov K N and Nagorskiy P M 2018 Response in the surface atmospheric electric field to the passage of isolated air mass cumulonimbus clouds *J. Atm. Sol.-Ter.* **172** 33–9
[3] Azbukin A A et al 2012 AMK-03 Automatic weather stations, their modifications and applications *Sensors and systems* **3** 47-52
[4] Elemental hydrometeorological phenomena on the territory of Russia in 2015 Available at: http://meteo.ru/index.php?option=com_content&view=article&id=620:chrezvychajnye-situatsii-v-rossii-2015&catid=118:chrezvychajnye-situatsii-v-rossii
[5] Kalchikhin V V et al 2016 Detection of Microstructure Characteristics of Liquid Atmospheric Precipitation with the Optical Rain Gage *Atm.Ocean. Opt.* **29** 304–7
[6] Kalchikhin V V et al 2016 Determination of precipitation type on to the results of the optical microstructural characteristics measurements *Atm.Ocean. Opt.* **29** 654–7