Improving early warning methods for thunderstorm processes through the integrated use of active and passive radar techniques

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Abstract. The article examines the methodical aspects of the integrated use of passive and active radar to improve early warning methods for the development of powerful convective clouds and thunderstorm processes. Some results of complex experimental studies of the atmosphere and convective clouds in the Leningrad region are presented with the use of meteorological radar and ground-based microwave radiometers. Particular attention is paid to the use of microwave radiometry to separate the content of vapor moisture in the atmosphere and liquid water in the clouds, as well as the use of a comprehensive method of passive-active radar to determine the super cool water of powerful convective clouds. Prospects for improving technologies for predicting weather hazards associated with clouds and precipitation are connected with the use of a complex of radiophysical means of the Geophysical Observatory of the Mozhaisky Military Space Academy.

1. Introduction
To improve the systems of warning about the development of dangerous atmospheric weather phenomena (powerful convective clouds, thunderstorms, etc.) the use of modern radio physical methods and remote means of monitoring the state of the natural environment is of great importance. Promising methods are active and passive radar, which allow to receive information about the state of the atmosphere (profiles of humidity and temperature), as well as on the characteristics of clouds (liquid water content, etc.) and precipitation [1-6]. Comprehensive studies of cloud characteristics are needed in connection with the development of thunderstorm cloud models and technologies for their modification [7-8]. The aim of the work was to generalize the results of the completed complex experiments with the use of active and passive radar, aimed at researching the moisture parameters of the atmosphere and cloud liquid water content in various weather conditions, including during dangerous weather events, in particular to improve the method of forecasting thunderstorm processes.

2. Complexing active and passive radar methods for sounding of the atmosphere
The development of methods based on the joint use of active and passive radar complexes became particularly important for the study of cloud and precipitation in meteorology in the mid-1960s and early 1970s [4]. The main task of meteorological radar is to alert to dangerous weather events associated with clouds (rain, thunderstorm, hail, tornado, etc.). In the meteorological radar stations of the storm warning network, information is given on radar reflectivity, precipitation intensity, height of upper and lower cloud boundaries, dangerous phenomena (thunderstorm, downpour, hail), data on the speed and direction of movement of clouds.
The method of ground microwave radiometry allows to determine the integrated water vapor, cloud liquid water, the profiles of humidity and air temperature in the troposphere [2, 9-11]. The joint use of passive and active radar provides new opportunities for determining the medium liquid water profiles of convective clouds, water supply in the supercooled part of convective clouds, and precipitation intensity. The passive-active method has advantages (compared to the classical radar method) to improve the accuracy of cloud water and precipitation intensity. Ways to improve the method of preventing the development of thunderstorm processes are determined by the use of complex methods of passive and active radar to alert the parameters of the atmosphere and clouds [10].

The method of preventing thunderstorm processes includes two techniques, the first, detection and recognition of areas of increased liquid capping moisture in the hypothermia part of the cloud with the help of passive-active radar, and second, control the meteorological parameters of the atmosphere using microwave radiometers to determine the content of vapor moisture in the atmosphere and to identify favorable conditions for the development of powerful convective clouds and thunderstorms. The modern version of the passive-active radar was developed on the basis of Doppler meteorological radar DMRL-C by Lianozovo Electromechanical Plant (LEMZ Division, Moscow) with the participation of the authors. For the study of super cooled water in convective clouds, some of the benefits compared to the C-band may have X-band.

Ground-based microwave radiometers allow for significant complementary atmospheric aerological sensing data, allowing us to track the dynamics of atmospheric processes. The use of information on the content of water vapor in the atmosphere is important for improving early warning technology about the possible development of dangerous weather events. For example, the paper proposes a microwave radiometric criterion for cloud and precipitation development based on a joint analysis of radar information and microwave radiometric data on the content of water vapor in the atmosphere during the development of dangerous weather events associated with the development of powerful convective clouds and thunderstorms.

Prospects for further improvement of early warning technology for the development of dangerous weather events are associated with improvements in regional ultra-short-term forecasting technologies based on the assimilation of remote atmospheric sensing data, including microwave radiometric, Doppler radar, satellite and other types of heterogeneous meteorological information.

Method of microwave radiometry for control of the atmosphere are based on measurements of a radio brightness temperatures at frequencies in the ranges of about 20.6 -22.23 GHz and 31-37 GHz to derive integrated water vapor and integrated cloud liquid water content [10]. Microwave radiometric method for determination the cloud liquid content of convective clouds are based on interpretation measurements of clouds radiation characteristics in the spectral region at 5 -14 GHz and at 31- 36 GHz. Uncertainty of estimating the cloud liquid water content in convective cloud is about 20-40%.

3. Microwave radiometers for moisture sounding

Ground-based microwave radiometers are used in experiments for the study of atmospheric moisture parameters of a cloudy atmosphere in Leningrad region are follow as:

- The dual frequencies at 20.7 (or 22.23) and 36 (or 32) GHz water vapor radiometer (WVR) to study the atmospheric moisture contents in zenith with temporal resolution of 1 min. The uncertainties of determination the integrated water vapor of the atmosphere is about 0.5-1 kg/m², and cloud liquid water contents is about 0.03 kg/m².
- The microwave radiometer system at 9.3 and 36 GHz for determination of integrated cloud liquid of convective clouds. Resolution of a scanning antenna are used in radiometer system is about of 0.3 and 1 degree at 36 and 9.3 GHz, respectively. Temporal resolution of radiometric data is 0.3 s. Microwave radiometer at 36 GHz is a dual polarisation (vertical and horizontal) radiometer.

4. Results of comprehensive research of a cloudy atmosphere using passive and active radar

Experimental investigations of the atmospheric moisture content using microwave radiometers have been carried out since mid-1960s in Leningrad region. Microwave radiometric research were usually part of comprehensive studies of dangerous weather phenomena, convective clouds, thunderstorms,
which were conducted at the field experimental base of the Voeikov Main Geophysical Observatory in Turgosh, based on the Research Center for Remote Sensing of the Atmosphere in Voeikovo, and at the Geophysical Observatory of the Mozhaisky Military Space Academy in Lehtusi, Leningrad Region. One of the most important tasks of the experiments was to study dangerous weather phenomena, convective clouds, thunderstorm to improve the methods of forecasting dangerous weather events based on the use of various means of remote sensing of the atmosphere, including methods of active and passive radar.

4.1. Water vapor during thunderstorms

As an example, figure 1 presents time-series of integrated water vapor and integrated cloud liquid derived from microwave radiometric measurements using WVR between July 12 and 15 2008 in Voeikovo, Leningrad region. The thunderstorm was observed on July 14, 2008 in Leningrad region. According to the weather radar MRL-5 (wave length is 3.2 cm), the height of the upper boundary of clouds reached 10-13 km. The radar reflectivity area at 18:50 UTC was more than 3 000 km² (figure 1 c). The thunderstorm accompanied by downpours, squalling winds and intense discharges of lightning. Variation of ground electrical field July 14 2008 in Voeikovo is more then 1.5 kV/m during 2 hour (figure 1 d). The integrated water vapor derived from measurements by WVR in the vicinity of the storm was more then 35-40 kg/m² (figure 1 b). According to the data of a radiosonde at Voeikovo, after the passage of the front, there is a decrease in temperature in the boundary layer of the atmosphere by 3-7 °C, a decrease in the relative humidity of the air in different layers of the atmosphere and a decrease in integrated water vapor.

The example demonstrates the time-series of the integrated water vapor during the period of intense thunderstorm development in July 1996 in the Turgosh Leningrad region, is given in figure 1 a. The figure also shows periods when meteorological radar MRL-2 (wave length 3.2 cm) and atmospheric-electric observations detected the development of powerful convective clouds and zones of the electrical activity. Experiments have shown that variations in the integrated water vapor of the atmosphere in the vicinity of the thunderstorm can significantly exceed the variations of the integrated water vapor observed for the unperturbed atmosphere.

The results of complex experiments using active and passive radar showed the possibility of using information of the microwave radiometers to build a microwave radiometric prognostic criteria of the development of dangerous weather events associated with the development of clouds [10].

Figure 1. Time series of integrated water vapor (a) and integrated cloud liquid water (b) between of 12 to 15 July 2008, map of the meteorological radar MRL-5 July 14 2008 (c), ground electric field at July 14 2008 in Voeikovo Leningrad region.
4.2. **Cloud liquid water contents variations in convective clouds**

In experiments on the study of a convective clouds, the method of determining of the integrated cloud liquid water contents of convective clouds from the results of measurements of the characteristics of radio-thermal radiation at frequencies about 9.3 and 36.5 GHz was used. The use of a radiometric channel at 36.5 GHz has been effective in the study of the super cool zones of convective clouds and clouds at an early stage of their development. The measurement technique is to conduct angled elevation and azimuth measurements of the characteristics of radio-thermal radiation of clouds using a scanning narrow-minded antenna of the two channel microwave radiometer.

Example of evolution the integrated cloud liquid of convective cloud derived from radiometric measurements of microwave radiation using two frequency radiometer in Turgosh Leningrad region are shown on figure 3. Figure shows temporal and spacial variability of integrated cloud liquid water content of a convective cloud on a stage of dissipation. On the map (figure 3 a) grown in the 15:41 two cells are distinctly allocated integrated cloud liquid which was about 10 kg/m$^2$, in 15:55 (figure 3 c) the two cells were transformed into a single cell with integrated cloud liquid around 8 kg/m$^2$, in 16:08 (figure 3 e) integrated cloud liquid not exceed 1.6 kg/m$^2$.

Experiments indicate the possibility of local zones of super cool liquid water at the top of the convective cloud at altitudes of 6-9 km with a characteristic spatial size of about 1-2 km and a life time of less than 5 min. The detected short-term levels of radiation polarization from the super cool zones of powerful convective clouds at 36.5 GHz may be associated with dynamic factors and the orientation of cloud particles in the cloud's electric field.

Experimental study of the integrated water vapor in the atmosphere by microwave radiometers during the development of dangerous weather phenomena associated with the development of powerful convective clouds, precipitation, thunderstorms, shows that the integrated use of remote sensing methods and means of passive and active radar atmosphere may improve the chance and prognostic forecasts of a convective clouds and precipitation [10]. Capabilities to use the microwave radiometric data in weather forecasting and nowcasting tasks are discussed in work [11-14].

![Figure 2](image-url)
Figure 3. The integrated liquid water content map of convective cloud from microwave radiometric measurements in Turgosh Leningrad region. Time (h:m:s): a) 15:41:50; b) 15:48:46; c) 15:55:37; d) 16:01:50; e) 16:08:16.

Figure 4. Time-series of integrated cloud liquid water content and integrated water vapor measured by WVR between June 10 and 12, 2018, Lehtusi Leningrad region.
4.3. Water vapor and cloud liquid during passage atmospheric front

Figure 4 shows an example of variability of atmospheric water vapor and integrated cloud liquid water contents measured by the WVR in June from 10 to 12 2018 in Lehtusi, Leningrad region. It can be seen that between June 10 and 11 there was an increase in the integrated water vapor of the atmosphere in the interval of 14 to 27 kg/m². Qualitatively, microwave radiometric measurements of atmospheric water vapor are consistent with observations of the radiosonde station at Voeikovo. The decrease in atmospheric moisture content according to radiosonde data on June 12 was about 14.3 kg/m². Temporal variations of the integrated cloud liquid water content during June 11 and June 12 was more than 2 kg/m². Such changes in the atmospheric moisture content are caused by the passage of a atmospheric fronts in the cyclone area.

4.4. Microwave radiometers and forecasting weather phenomena

Further research into improving the information support of nowcasting and ultra-short-term forecasting of weather hazards associated with convective clouds, precipitation and thunderstorms is linked to the integrated use of the radio physical methods and instruments of the Lehtusi Geophysical Observatory, also including the use of microwave radiometers for humidity and temperature sounding of the atmosphere.

5. Appendices

The ultra-short-term forecast of powerful convective clouds based on the integrated use of passive and active radar is improved. As a result of the experimental studies of convective clouds at different stages of development, original results were obtained on the mutual location of areas of maximum radar reflectivity, cloud water content and areas of increased turbulence; found to have hypothermia at high altitudes. Further development of technologies of ultra-short-term forecasting of dangerous weather events associated with convective clouds is planned to be carried out on the basis of radiophysical means of the Geophysical Observatory of the Mozhaisky Military Space Academy.

Acknowledgments

The work was supported by a grant of Russian Science Foundation (Project 21-19-00378), https://rscf.ru/project/21-19-00378/

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