Investigations of the Atmospheric Moisture Contents Variations Using Ground-Based Microwave Radiometers

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Abstract. The method of microwave radiometry for investigations of the atmospheric water vapor and integrated cloud liquid water content is considered. Some results of experimental studies of temporal and spatial variations in the integrated water vapor and cloud liquid water contents using ground-based microwave radiometers during different meteorological conditions as well as during developments of dangerous weather phenomena are presented. The results of the experiments confirm the prospects of using microwave radiometric information for forecasting of dangerous weather events associated with the development of convective clouds and thunderstorms.

The method microwave radiometry allows to determine the atmospheric integrated water vapor, integrated cloud liquid, profiles of humidity and temperature of the atmosphere by means of ground-based microwave radiometers [1-5]. In modern research, more attention is paid to the research of mesoscale variations of the important meteorological parameters of the atmosphere for the weather forecasting and nowcasting, which can be carried out with the ground-based remote sensing (including using integrated methods of passive and active radar) [6, 7].

One of the tasks that is effectively solved using ground-based microwave radiometry is related to the measurement of integral characteristics of atmospheric moisture content, which include the integrated water vapor and integrated cloud liquid water content. Interest in studying the characteristics of atmospheric moisture content is associated with the huge role played by atmospheric water vapor in the formation of atmospheric processes, the development of weather hazards associated with clouds, the need to improve methods for forecasting weather hazards. The characteristics of atmospheric moisture content are extremely variable, so to improve the information support of forecasting dangerous weather events associated with clouds, it is important to use almost continuous measurements atmospheric parameters with high spatial-temporal resolution characteristics. In this paper, the method of microwave radiometry is used for experimental studies of temporal and spatial variations in the characteristics of atmospheric moisture content under various weather conditions, also during the development of dangerous weather phenomena associated with the convective clouds, precipitation, and thunderstorms.

1. Microwave radiometry for atmospheric moisture content sounding

The method of studying variations in the characteristics of atmospheric moisture content is based on the use of: methods for the separate determination of the integrated water vapor and integrated cloud liquid water content from measurements of a radio brightness temperatures at two frequencies in the ranges of about 20.6-22.23 GHz and 31-37 GHz; methods for determining the integrated cloud liquid content of a powerful convective clouds from measurements of the characteristics of radio-thermal radiation of
clouds in the spectral region of weak emission at 6-14 GHz and in atmospheric "windows" at frequencies 31-36 GHz.

The integrated water vapor and integrated cloud liquid are determined from:

\[
IWV = a_0 + a_1 \tau(v_1) + a_2 \tau(v_2)
\]

\[
ICL = b_0 + b_1 \tau(v_1) + b_2 \tau(v_2),
\]

where \(a_i, b_i\) - regression coefficients derived from models of cloudy atmosphere using radiosonde and aircraft data in Leningrad region. The optical thickness of the atmosphere determined from the measured brightness temperature using mean effective temperature of the atmosphere [2, 4]. Accuracy of determining the integrated water vapor of the atmosphere (in the absence of rain) is about 10%, and accuracy of determining the integrated cloud liquid is about 30%. Methodical issues of determining the moisture contents of the atmosphere were considered in [2, 5, 8]. Using an additional 75-95 GHz frequency range improves the ability to study low-liquid moisture in cloud [9].

Integrated cloud liquid estimation can be obtained from microwave radiometric measurements at one frequency:

\[
ICL = K_a(v,T_d)^{-1}[\tau(v) - \tau_d(v) - K_q(v)IWV],
\]

where \(\tau_d(v)\) - absorption of atmospheric oxygen; \(K_q, K_a\) - specific absorption coefficients of water vapor and cloud liquid, respectively. Two-frequency microwave radiometric sounding are used for effective investigations of convective clouds. Frequency range 30-38 GHz are used in the early stages of the development of convective clouds. Frequency range 6-14 GHz are used for studies of convective clouds (Cu cong, Cb) and super cooled zones of cumulonimbus. Error estimating of integrated cloud liquid is about 20-40%.

2. Microwave radiometers for investigation of the atmosphere

Microwave radiometers of the 22-60 GHz frequency range allow for up-to-date information on the state of the atmosphere in the mode of automatic all-weather observations [1, 3, 6, 10]. In the practice of meteorological observations Radiometrics corp., Radiometer-Physics GmbH, Attex and others meteorological microwave radiometers are used. The water vapor radiometer (WVR) designed by Institute of Applied Astronomy of Russian Academy of Sciences is known.

Characteristics of the microwave radiometers are used in experiments are shown in table 1. The radiometer WVR includes two independent radiometric channels (20.7 and 32 GHz). WVR allow us to study the atmospheric moisture contents in temporal scales from 10 s. The error in determining 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.

| Characteristics | WVR | CLR |
|-----------------|-----|-----|
| Centre frequency, GHz | 20.7; 32.0 | 9.3; 36.5(V,H) |
| Bandwidth, GHz | 0.25; 0.50 | 0.25; 0.50 |
| Sensitivity, K/sec⁴ | 0.1 | 0.3 |
| Beamwidth, level 3 dB, deg. | 7 | 1 |
| Sampling time, sec | 5 | 0.2 |
| Absolute accuracy, K | 1 | 2 |

The radiometer system CLR consists two scanning radiometers (9.3 and 36 GHz) with high angular resolution (less then 1 deg.) for determination of integrated cloud liquid of convective clouds.

3. Some results of experiments

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, thunderstorms 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.

3.1. Water vapor during thunderstorms

As an example, figure 1 presents time-series of atmospheric integrated cloud liquid (figure 1,a) and integrated water vapor (figure 1,b) derived from microwave radiometric measurements using WVR between July 12 and 15, 2008 in Voeikovo, Leningrad region. The figure 1,b also shows the values of integrated water vapor, obtained according to the radiosonde in Voeikovo. The thunderstorm front 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 on this day reached 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. The integrated water vapor obtained from measurements by WVR in the vicinity of the storm was more then 35-40 kg/m². However, during passage of the thunderstorm, the use of the equation (1) may not be correct, because in the beam of vision of the antenna may have been an area containing a large-drop fraction of cloud water droplets. According to the aerological data 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 second example demonstrates the time–series of the integrated water vapor during the period of intense thunderstorm development in July in the Turgosh Leningrad region, is given in figure 2. The figure also shows periods when meteorological radar 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 [4].

Figure 1. Time-series of integrated cloud liquid (a), integrated water vapor (b), and map of the meteorological radar MRL-5 July 14, 2008, Voeikovo Leningrad region
3.2. 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 CLR radiometer.

Example of evolution the integrated cloud liquid of convective cloud derived from radiometric measurements of microwave radiation using CLR radiometer in Turgosh Leningrad region are shown on figure 3. Figure shows temporal variability of integrated cloud liquid and multi-cell structure 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.
Figure 3. Evolution of the integrated cloud liquid from CLR 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 GMT

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

3.3. Water vapor and cloud liquid during passage atmospheric front

Research on temporal variability of water vapor and cloud liquid by using microwave radiometers revealed significant effects of synoptic processes in the atmosphere to change the water vapor and cloud liquid water contents. Figure 4 shows an example of variability of atmospheric integrated 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 15 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. Variations of the integrated cloud liquid water content during June 11 and June 12
was more then 2 kr/m². Such changes in the moisture content of the atmosphere are caused by the passage of a system of atmospheric fronts in the cyclone area.

3.4. Microwave radiometers and forecasting weather phenomena

The use of information on the profiles of humidity and temperature, integrated water vapor and cloud liquid water is important for improving the technology of early warning of the development of dangerous weather phenomena associated with clouds and thunderstorms. Ground-based microwave radiometers can significantly supplement the data of aerological sounding of the atmosphere, allowing to track the dynamics of processes occurring in the atmosphere.

Experimental studies of the atmosphere performed complex with the use of passive and active radar methods during the development of powerful convective clouds indicate the possibility of using microwave radiometric measurements of the atmospheric water vapor in the problem of ultra-short-term forecast of thunderstorm. The proposed version of the radiometric prognostic criterion for the development of thunderstorm has the form:

\[ K_{trb} = C_0 + C_1Q + C_2\Delta Q(\Delta t), \]  

(3)

where \( C_k \) – regression coefficients; \( Q \) – integrated water vapor; \( \Delta Q(\Delta t) \) – change of integrated water vapor over a time interval \( \Delta t \). Subject to \( K_{trb} > 0 \), dangerous phenomena associated with the development of thunderstorms are expected. The criterion determines the time “window” when the development of dangerous phenomena is likely. Preliminary testing of the developed microwave radiometric criterion showed that the advance forecast of dangerous phenomena associated with the development of powerful clouds and thunderstorms in the Leningrad region is 1-12 hours, and the justification about 76%.

Improvement of technology of early warning of development of dangerous weather phenomena is connected with application of methods of regional ultra-short-term forecast of dangerous weather phenomena on the basis of assimilation of heterogeneous meteorological information, including data of remote sensing of the atmosphere (ground microwave radiometers, Doppler radars, as well as satellite sounders).

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.

4. Appendices

Experimental microwave radiometric studies of atmospheric moisture contents performed in different meteorological condition as well as dangerous weather phenomena have confirmed the possibility of the microwave radiometers to measuring integrated water vapor and cloud liquid water content.

The use of two frequency radiometer at 9.3 and 36.5 GHz has been effective in the study of powerful convective clouds, the super cool zones of convective clouds, as well as on early stage of cloud development. 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. 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 result of experiments at the Geophysical Observatory Lehtusi demonstrated the possibilities of the novel water vapor radiometer designed of Institute of Applied Astronomy of the Russian Academy of Sciences to determine the characteristics of the atmospheric water content with high space-time resolution.

Further studies related to development in the practice of meteorological observations methods of microwave radiometric temperature and humidity sounding of the atmosphere for nowcasting and short-range forecasts of severe weather associated with clouds and precipitation.
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