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A study of coastal convective clouds using meteorological radar data

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Abstract

The paper presents the results of study of convective cloud development over land and sea. The study was based on data from the Gdańsk-Rębiechowo radar and upper air sounding from the Łeba aerological station. Radar data from the classical channel were analyzed for the atmosphere scanned at 6 elevation angles of the antenna beam. Vertical profiles of the atmosphere along selected paths presenting radiolocation reflectivity in the detected cloud structures were produced using the recorded radiolocation reflectivity. Conclusions concerning the cloud structure, the physical state of water in the clouds and the thermodynamic state of the atmosphere were formulated as the results of comprehensive analysis of the radar and upper air sounding data. The obtained values of selected parameters and indices were used to quantitatively describe selected physical processes and to formulate forecasts concerning weather phenomena that might pose threats to land, air and sea transport as well as for some industrial and agricultural branches. The developed method of radar and aerological data processing will be applied to further studies of convective clouds in other regions. It will also enable to assess the impact of environmental conditions on the development of convective processes.

Introduction

Contemporary meteorological radars, in addition to classic radars, are employed to detect areas of clouds and precipitation and to enable the study of wind fields. Radars emit horizontal and vertical electromagnetic impulses in beams of 1° width. The power of the radar echo is measured in the classic channel, which is the basis for determining the radiolocation reflectivity of meteorological objects (hydrometeors). The Doppler channel data are analyzed with respect to frequency and the results enable to quantitatively describe the wind field using the derived Doppler frequency shift of the radar echo with respect to the initial frequency of the emitted electromagnetic impulse.

Information systems adopted to process the radar data include computational procedures that utilize empirical relations developed on the basis of measurements conducted during numerous field research experiments.

As for any other atmospheric remote sensing data, the radar data interpretation should take into account the limitations resulting from the technical properties of the radar itself (e.g. antenna beam width, impulse length, receiver threshold sensitivity etc.) and the properties of the studied objects, e.g. heterogeneity of the cloud's structure (extended spectrum of the particles' sizes, various states of water, turbulence, etc.).

The impact of the environmental conditions on the development of convective clouds is an important issue to be taken into account. The type of underlying surface (sea, land) and its orography, and in some cases the infrastructure, are of special importance.

The analysis of results was based on retrieved upper air sounding data since there was no possibility to conduct a comprehensive study of the atmosphere in which the radar data might be verified using direct measurements. Therefore, the study of convective clouds had to be carried out in situations (region and time) in which the upper air soundings were truly representative.

The results of a comprehensive analysis of radar and upper air sounding data may be used to detect and monitor hazardous weather phenomena related with convective clouds (storms, heavy precipitation, hail), as well as gusty wind zones, meso-cyclones and meso-anticyclones, and convergence and divergence areas in the wind fields.

These weather phenomena induce conditions that may pose threats to many fields of human activity, with special impact on land, air and sea transport as well as for some industrial and agricultural branches.

Basics of radar data application to atmospheric studies

The scattering of electromagnetic waves, having wavelength λ, due to clouds and precipitation particles of the diameter D_i depends on the effective scatter surface, σ_i, of a single spherical particle:

$$\sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6 \quad (1)$$

where K is a function of the complex refraction coefficient of the material (water, ice or mixture).

The value of $|K|^2$ in normal conditions was established for water droplets (0.93) and ice crystals (0.197) using results of measurements conducted during numerous field experiments.

The effective scatter surface of a volume unit of a meteorological object is the sum of the effective scatter surfaces of all particles within the volume. For a homogenous cloud (consisting of only water droplets or only ice crystals) the value of $|K|^2$ is constant and the effective scatter surface of a volume unit, $\sigma_{\text{vol. unit}}$, is given by:

$$\sigma_{\text{vol.unit}} = \frac{\pi^5}{\lambda^4} |K|^2 \sum_{i,\text{vol.unit}} D_i^6 \quad (2)$$

The last element of equation (2) is the radiolocation reflectivity, Z, of a meteorological object. Its value depends on the object's size and contents, as well as on its microstructure, i.e. on the spectrum of particles' sizes and their concentration in the object (e.g. in a cloud or precipitation):

$$Z = \sum_{i,\text{vol.unit}} D_i^6 \ [\text{mm}^6/\text{m}^3] \quad (3)$$

Relation (3) is valid for cloud or precipitation particles that comply with the Rayleigh approximation, i.e.:

- they are spherical and of diameters significantly smaller than the emitted radar wavelength;
- they are of the same state of matter;
- they fill the entire space of the emitted radar beam.

The range of Z values for clouds or precipitation is very wide (e.g. for developed convective clouds it may vary between 10^4 and 10^7 mm^6/m^3) (Geçer, 2005), therefore, it is convenient to apply the logarithmic scale and express the values in the so called decibels of the radiolocation reflectivity, dBZ, calculated according to:

$$Z_e[\text{dBZ}] = 10 \log Z \quad (4)$$

where Z_e is the effective radiolocation reflectivity, i.e. the radiolocation reflectivity of a virtual cloud composed of water droplets for which the radar echo has a power, P_r, equal to the radar echo of the real cloud.

The radar equation for a meteorological object located at a distance R from the radar has the following form:

$$P_r = C_r \frac{Z_e}{R^2} \quad (5)$$

where C_r is the radar constant (the meteorological potential of the radar), whose value depends on technical parameters of the radar (Büyükbas et al., 2005).

Convective cloud phenomena recognition using radar data

Hail and storm may be recognized by means of an analysis of the vertical profile of radiolocation reflectivity. The radar echo measures the maximum height of a convective cloud. The value of the maximum radiolocation reflectivity and its height indicate the intensity of the phenomena related with the cloud. It may be assumed that when the maximum radiolocation reflectivity in an area exceeds the value of 40 dBZ, and the height of the radar echo exceeds the value of 5 km, then it is highly probable that the radar echo is related to a cloud accompanied by a storm (or at least to a cloud with strong convection).

Storms are often recognized using an algorithm based on radar echo heights (with minimum radiolocation reflectivity of 4 dBZ) – H_m [km] and maximum radiolocation reflectivity Z_m [dBZ].

Its parameter value Y is calculated according to the following formula:

$$Y = H_m \frac{Z_m - 18}{10} \quad (6)$$

The range of the parameter values indicating storm is determined individually for specific regions. In the area of Poland, the radar echo is related to a storm when $Y > 30$ (Szturc, 2004).

The procedure for hail detection (ZHAIL) uses data of radiolocation reflectivity concerning cloud layers above the 0°C isotherm (freezing level). The altitude of the freezing level may be determined using the results of an upper air sounding. Development of the ZHAIL algorithm was based on the Waldvogel algorithm. The hail occurrence criterion is fulfilled if the H_{45} altitude from which the radiolocation reflectivity value exceeds 45 dBZ and the H_o altitude of the 0°C isotherm are related as follows:

$$H_{45} > H_o + 1.4 \text{ km} \quad (7)$$

In practice, the Waldvogel criterion issues “false alerts” quite often.

The results of the ZHAIL algorithm calculations enable to determine, depending on the H_{max} altitude of the maximum radiolocation reflectivity, various levels of hail alerts. For the commonly applied radiolocation reflectivity threshold of 45 dBZ, the alert levels are defined as (Moszkowicz & Tuszyńska, 2006; Tuszyńska, 2011):

$H_{max} > H_{45}$ – light hail;
$H_{max} > H_{45 + 5\text{ dBZ}}$ – moderate hail;
$H_{max} > H_{45 + 10\text{ dBZ}}$ – heavy hail.

Synoptic situation in the southern region of the Baltic Sea on July 7th, 2014

On July 7th, 2014 the weather over the southern part of the Baltic Sea and its eastern coast was determined by a ridge related with a vast high-pressure area from Scandinavia. A cold front with developing waves influenced the western part of the area (Figure 1).

The analysis concerned a cloud development observed around noon in the coastal area of the Łeba region. At 12 UTC the upper air sounding data from the Łeba aerological station indicated that the air mass advection from the ground to the altitude of about 700 m was arriving from the east and veering from southeast to west-east and upwards, becoming westerly at the altitude of about 6 km. The advection speed was about 10–15 km/h. At altitudes of 10 to 11.2 km it increased to 30–35 km/h.

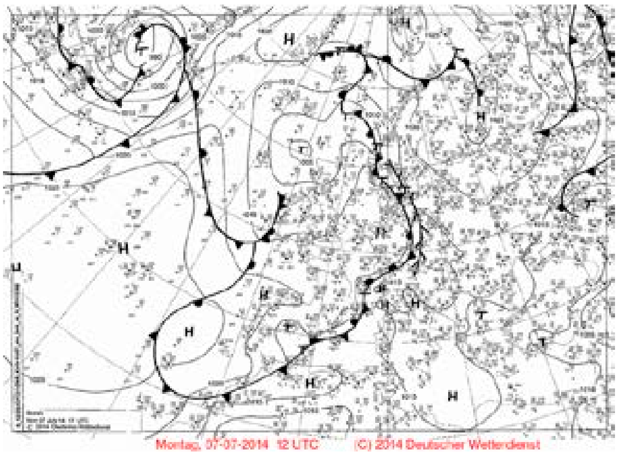

Figure 1. Surface weather chart with synoptic situation on July 07, 2014 at 12 UTC (wetter3, 2014)

Study of convective cloud development in coastal regions using radar data

Convective cloud development in a coastal region was analyzed using data from the Gdańsk–Rębiechowo airport radar. Radar data from the classic channel, acquired by scanning the atmosphere at the antenna beam elevation angles of 0.5°, 1.4°, 2.4°, 3.4°, 5.3° and 7.7°, were used in the research. The radar data and processing software (RAPOK) were acquired from the Institute of Meteorology and Water Management.

The cloud development study was initiated with analyses of the data of July 7th, 2014 at 11.40 UTC. The analysis of the radar data obtained by scanning the atmosphere at the lowest elevation angle of 0.5° indicated that there were two convective cells in the region of Łeba (Figure 2). The cloud further away from the radar developed over the sea, while the closer one developed over land.

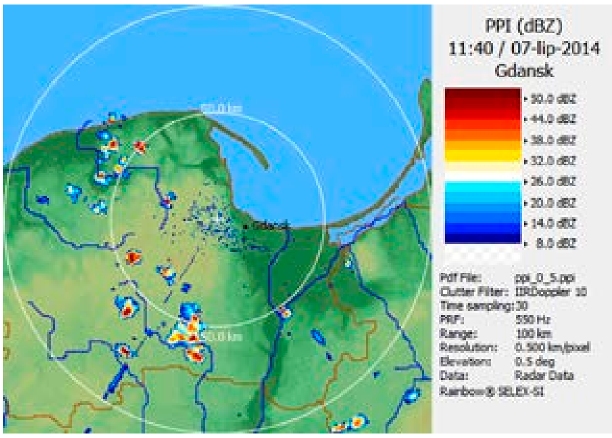

Figure 2. Radar image of horizontal distribution of maximum radiolocation reflectivity recorded for the scanning elevation angle of 0.5° by the Gdańsk-Rębiechowo radar on July 07, 2014 at 11.40 UTC

The maximum height of both clouds (8 and 6 km, respectively), their horizontal dimensions at the altitude of about 3 km (about 5 and 2 km, respectively) and the maximum values of radiolocation reflectivity (42 dBZ and 27 dBZ, respectively) were determined using vertical cross-sections of the radar echoes (Figure 3).

At 12.00 UTC the analyzed clouds merged into one convective cell with the radar echo height at about 11 km, a horizontal dimension of about 10 km and a maximum value of radiolocation reflectivity of 50 dBZ (Figure 4).

The maximum development of the convective cloud was observed at about 12.30 UTC. The cloud top reached the lower part of the tropopause (12 km) and the cloud developed a clearly visible incus

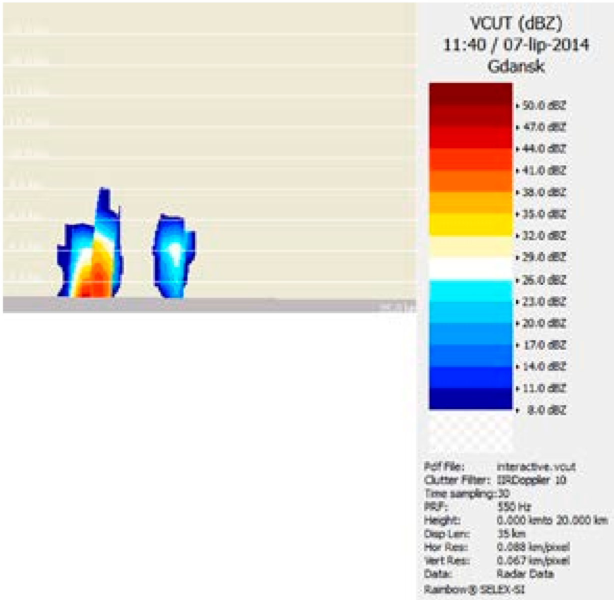

Figure 3. Vertical cross-section of the radar echoes recorded by the Gdańsk-Rębiechowo radar on July 07, 2014 at 11.40 UTC

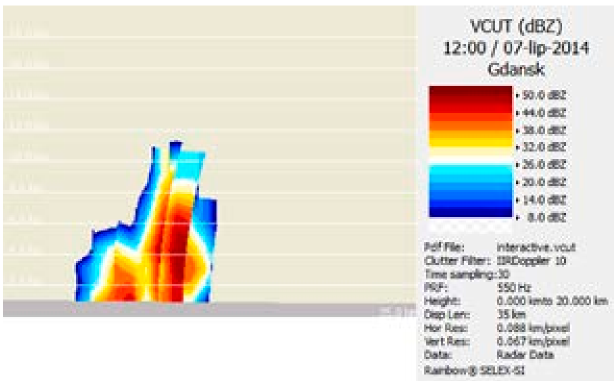

Figure 4. Vertical cross-section of the radar echoes recorded by the Gdańsk-Rębiechowo radar on July 07, 2014 at 12.00 UTC

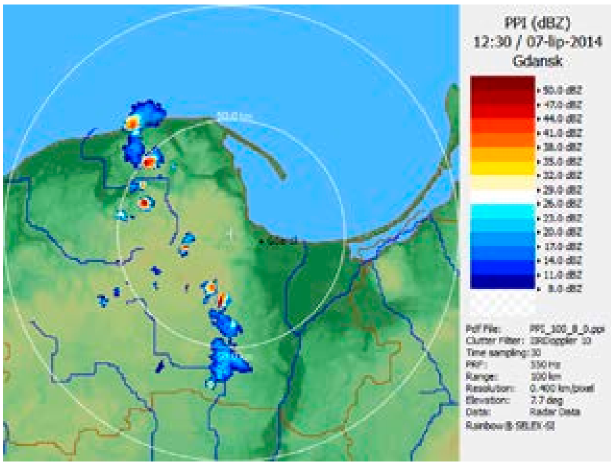

Figure 5. Radar image of horizontal distribution of maximum radiolocation reflectivity recorded for the scanning elevation angle of 7.7° by the Gdańsk-Rębiechowo radar on July 07, 2014 at 12.30 UTC

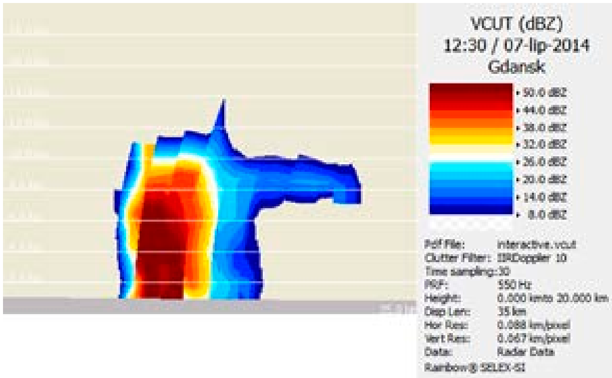

Figure 6. Vertical cross-section of the radar echoes recorded by the Gdańsk-Rębiechowo radar on July 07, 2014 at 12.30 UTC

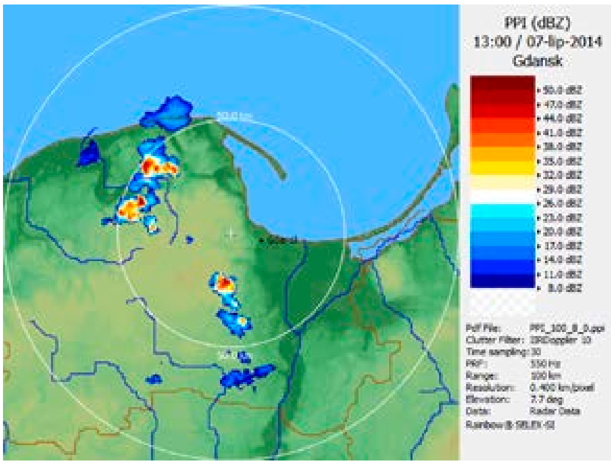

Figure 7. Radar image of horizontal distribution of maximum radiolocation reflectivity recorded for the scanning elevation angle of 7.7° by the Gdańsk-Rębiechowo radar on July 07, 2014 at 13.00 UTC

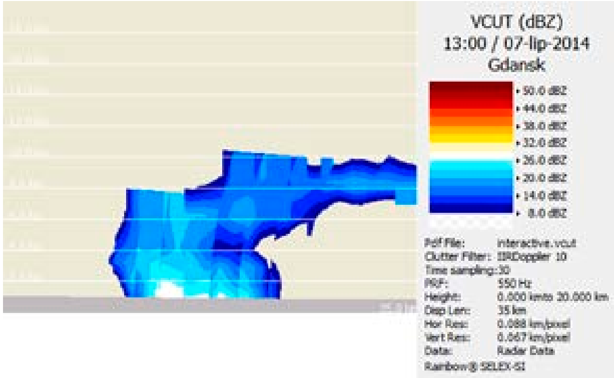

Figure 8. Vertical cross-section of the radar echoes recorded by the Gdańsk-Rębiechowo radar on July 07, 2014 at 13.00 UTC

(in the layer between 7 and 10 km) (Figure 6). The diameter of the incus cloud under the tropopause exceeded 20 km (Figure 5).

Analysis of the radar data at 13.00 UTC indicated that the studied cloud started to decay. The radar image acquired by scanning the atmosphere at the antenna beam elevation angle of 7.7° still showed the tops of the radar echo from the cloud shifted slightly to the east (Figure 7). Analysis of the vertical cross-section of the radar echo indicated that the incus was at an altitude of about 10 km while its horizontal dimensions remained unchanged; however, the maximum value of radiolocation reflectivity decreased to 20–26 dBZ (Figure 8).

Quantitative analysis of the convective clouds development process

Analysis of the convective cloud development was conducted using the Gdańsk-Rębiechowo radar data acquired from measurements made on July 7th, 2014 between 11.40 and 13.00 UTC at 10-minute intervals. Upper air sounding data acquired from the Łeba station on July 7th, 2014 at 12.00 UTC were also used.

The maximum radiolocation reflectivity changes for antenna scans at beam elevation angles between 0.5° and 7.7° are presented in Figure 9. The maximum radiolocation reflectivity observed for the scanning elevation angles between 0.5° and 5.3° increased in the period from 11.40 UTC (measurement #1) to 12.00 UTC (measurement #3). The radiolocation reflectivity reached its maximum values for all scanning angles in the period from 12.00 UTC to 12.30 UTC (measurement #6). In the same time interval, the maximum radar echo at the highest elevation angle (7.7°) was also recorded. In the phase of maximum cloud development, at the antenna beam elevation angle of 3.4°, the maximum radiolocation reflectivity of 54 dBZ was recorded at an altitude of about 4 km. Vertical development of the cloud was also observed until it reached the tropopause (12 km), along with increasing values of radiolocation reflectivity of the radar echo height from 24.5 to 42 dBZ. Between 12.30 UTC and 13.00 UTC (measurement

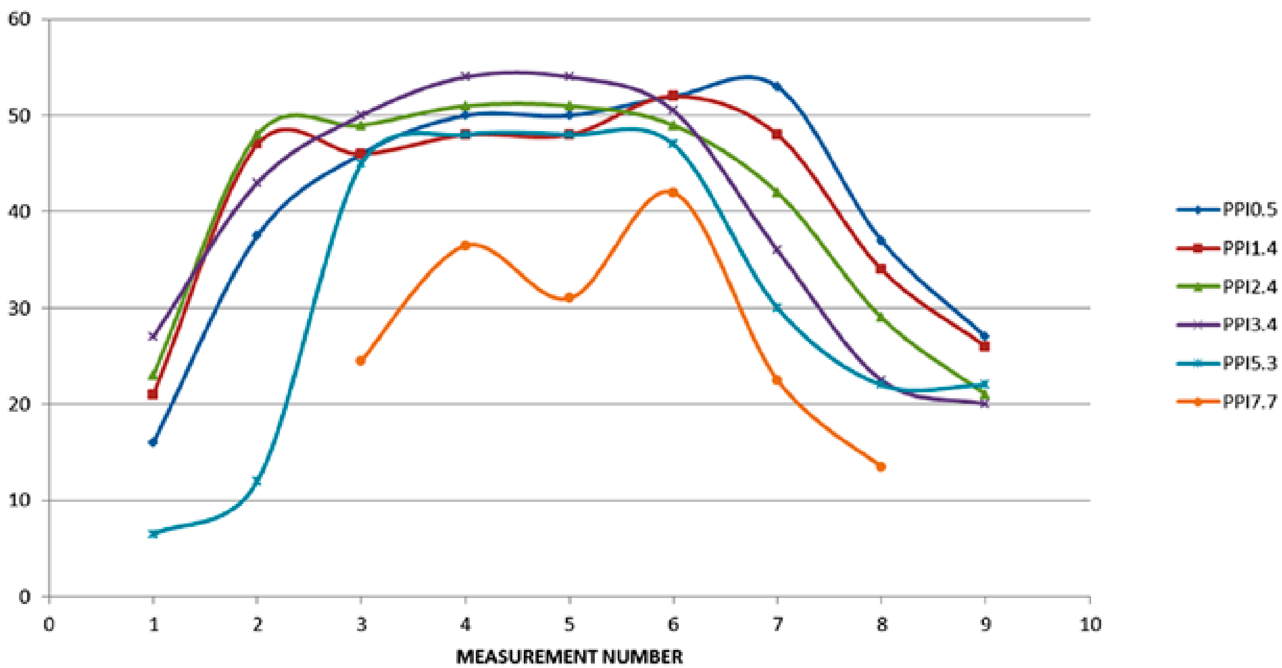

Figure 9. The maximum radiolocation reflectivity changes for antenna scans at beam elevation angles between 0.5° and 7.7° on July 7th, 2014 between 11.40-13.00 UTC

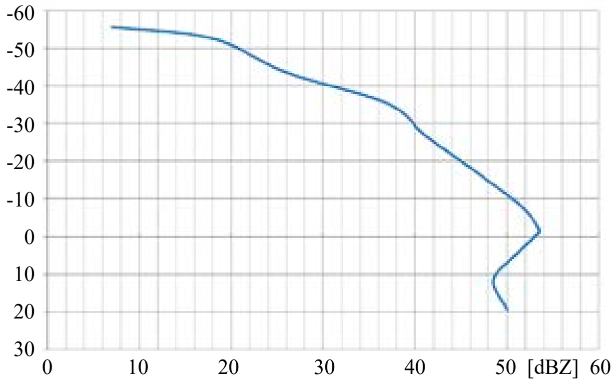

Figure 10. The maximum radiolocation reflectivity changes with temperature. Radar data of July 7th, 2014 at 12.30 UTC, upper air sounding data at 12.00 UTC

#9) the beginning of cloud dissipation was observed, along with rapidly decreasing values of radiolocation reflectivity to 27–22 dBZ and decreasing altitude of the cloud tops to 10 km.

Vertical profiles of maximum radiolocation reflectivity changes were determined to assess the structure of the cloud. The vertical profile of air temperature along the vertical axis was derived from upper air sounding data (Figure 10).

In the lower part of the cloud, composed of water droplets of various sizes, up to the 0°C isotherm level (3.6 km), the radiolocation reflectivity increased up to 54 dBZ. The large values of radiolocation reflectivity were due to the increasing size of water droplets, beyond the limit assumed for cloud droplets and up to the range of size of rain droplets. In radar meteorology, water droplets with radius larger than 100 µm are considered as rain droplets (Moszkowicz & Tuszyńska, 2006).

At higher altitudes, a gradual decrease of radiolocation reflectivity, up to 48 dBZ, was observed in the freezing layer with air temperature between 0°C and –12°C (5.8 km). This part of the cloud is a mixture of water droplets, super cooled water and ice crystals. The physical state of cloud particles significantly influences radiolocation reflectivity, which is related with the change of the effective scatter surface of the particles (1).

Above the –12°C isotherm the value of radiolocation reflectivity significantly decreases to 7 dBZ, which is related with varying concentration of ice crystals (1), (2).

The radar and upper air sounding data were used to the derive values of parameters and indicators (Table 1) that describe the thermodynamic state of the atmosphere. They are also used to formulate forecasts concerning weather phenomena that may pose threats to land, air and sea transport.

Analysis of the measurement results and meteorological observations at the Łeba station indicate that there was a storm in the vicinity of the station between 12.00 and 13.00 UTC.

Conclusions

Radar data are a reliable source of information about the state of the atmosphere and developing processes. Cloud system studies should use raw radar data acquired by scanning the atmosphere at selected antenna beam elevation angles. Radar products commonly available in weather data exchange networks, in most cases, do not enable to conduct quantitative analysis of the radar echoes.

It is important to take into account the impact of environmental and microclimatic conditions on the studied processes in order to obtain reliable results of radar data processing. Further research including

Table 1. Parameters describing convection conditions and weather phenomena occurrence probability for the region of the Łeba station in the afternoon of July 7th, 2014

Parameter	Value	Interpretation
Radar data		
Y Algorithm	43.2	Radar echo from the thunderstorm cloud
ZHAIL Algorithm	$H_{max} > H_{45+5\,dBZ}$	Moderate hail
Upper air sounding data		
Showalter Index – SSI	–1.14°C	Increased probability of thunderstorm
Convection Index – LI	–1.86°C	Thunderstorm possible (when strong forcing occurs)
Global Index – TT	50°C	Single intensive thunderstorms
Whaitinge Index – K	34.30	Probability of thunderstorm – 60 to 80%
Convective Available Potential Energy – CAPE	360.50 J/kg	Weak convection
Equilibrium Level – EL	241.83 hPa	Convective cloud height – ~10 900 m
Free Convection Level – LFC	770.13 hPa	Strong convection
Richardson Number – R_b	29.66	Conditions favorable to supercells formation

comparison and verification of radar data against direct measurements, upper air soundings and satellite data is necessary to increase the reliability of the computational results that qualitatively and quantitatively characterize the specific processes and weather phenomena.

The interpretation of radar measurements requires consideration of the influence of the atmosphere on electromagnetic wave propagation (atmospheric refraction). It is also necessary to take into account the impact of radar technical parameters on the results. The selected beam width and emitted impulse length cause an in increase, with increasing distance from the radar, in the measured geometric dimensions of the observed elements of the atmosphere (to which the radiolocation reflectivity is related).

Digital processing applied to radar echoes enables to determine additional characteristics of the state of the atmosphere, e.g. detecting turbulence, recognizing weather phenomena classes, intensity of precipitation and water sums over a selected region.

For operational hydrometeorological support, an important feature of radar measurements is the capability of covering an area of about 30,000 km^2 in real time with high temporal resolution (practically continuous measurement cycles).

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