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Section: Environmental protection

Multispectral satellite data application to hazardous convection monitoring

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Abstract

Satellite remote sensing technology development induced new capabilities of investigating various atmospheric phenomena and processes. Among the most dangerous and causing the greatest losses are phenomena related with strong convection, e.g. Cumulonimbus development with thunderstorms, hail, downpour, strong turbulence and icing zones, downbursts, squalls or wind shear. Although phenomena related with convection are sometimes limited in space and change rapidly, they develop harsh weather conditions and often endanger life by instantaneous floods, fires of premises and infrastructure caused by lightning, damages to forests and crops due to hurricane winds or hail.

Convective clouds and phenomena sometimes cover areas too small to be observed at meteorological stations and reported in standard weather charts due to large distances between the stations. Satellite data provide valuable information for detection of such phenomena. Images acquired by the SEVIRI radiometer from a geostationary orbit and by the MODIS spectroradiometer from a polar orbiting satellite are the main source of data for this research. VIIRS data are also used in the experiment. The sensor, installed on the Suomi NPP, is a new generation of imaging instruments for satellites replacing the NOAA series.

The comprehensive analysis concerned interpretation of single channel satellite images and multispectral ones composed of differential images and color compositions of appropriately selected sets of spectral channels. The analyses were also complemented with information derived from dispersion diagrams which enables to assess the internal structure of the clouds, phase of water and cloud particles size, and hence to assess the prevailing processes in the cloud for identifying its development.

The developing techniques of combining satellite images compositions with emission, absorption and scattering characteristics of various grounds, aerosols and clouds for identifying objects provide a new quality for hazardous convection monitoring. The methods described in the paper may be successfully used in hazardous weather phenomena warning systems.

Keywords: remote sensing; convective clouds; multispectral satellite data; Moderate-resolution Imaging Spectroradiometer (MODIS); Visible Infrared Imaging Radiometer Suite (VIIRS); Spinning Enhanced Visible and Infrared Imager (SEVIRI).

1. Introduction

Proper assessment of the conditions conductive to convective clouds development and related weather phenomena is of special importance in preparing an accurate weather forecast for various applications. Intensive convective processes, including Cumulonimbus clouds with thunderstorms, hail, rainstorms, strong turbulence and icing, downdrafts, squalls and wind shears, develop rapidly in relatively limited areas, however, the weather conditions are severe and often dangerous. Occurrence of convective clouds, characterized by sudden and fast development, may interfere with outside activities, making work in the sports, entertainment and recreation sector difficult for the entrepreneurs. Weather conditions related with convective clouds development may also influence and significantly complicate aircraft piloting. Sometimes, they make aircraft flights infeasible, force delays in tasks schedules and significantly influence the airport, aircraft, maintenance personnel and customers safety. Convection related phenomena often lead to instant floods, buildings and technical infrastructure fires caused by lightning, property and forests damages caused by hurricane winds or crops losses caused by hail. In extreme cases, these events occur together in fairly small areas resulting in huge material losses and even victims.

Dependent on the intensity of the convective currents, the clouds are accompanied by miscellaneous weather phenomena. Weak convection developing shallow Cumulus clouds is no significant threat for humans. Turbulence and limited visibility are observed in the clouds, while in spring and fall light icing may also occur. These influence only aircraft during flight. Strongly developed deep Cumulus clouds are already a real threat. Moderate and intensive icing may occur in the parts of

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the clouds where the temperatures are below the water freezing level. Visibility in clouds is drastically reduced, while intensive turbulence and strong vertical currents exceeding 10–15 m/s in both directions are observed in and around clouds.

The most severe and hazardous (especially with respect to aircraft flight) weather phenomena occur in Cumulonimbus and they include [1, 2]:

- extreme turbulence in the form of chaotic air motions, mainly 3-D vortices moving with various velocities, caused by strong ascending and descending air currents which speed is 10–15 m/s at the cloud base and usually 20–30 m/s inside, and exceeding 60 m/s in extreme cases,
- extreme icing developing in layers where the temperature is between 0 °C and –12 °C,
- intensive shower precipitation reducing visibility and lowering the cloud base down to 100 m and below; with the most dangerous hailstones exceeding a few centimeters in diameter,
- strong winds, often squalls, typically with sudden changes of speed and direction; resulting in damages when the wind speed significantly exceeds 20 m/s,
- whirlwinds (more and more often observed in Poland), strong air vortices with close to vertical and often bent axis, developing under the clouds in hot air and conditions of extreme instability of the atmosphere; wind speed in the vortices of usually a few dozen meters in diameter may exceed 50 m/s;
- severe thunderstorms with lightning.

Detection and monitoring of areas of convective clouds and related weather phenomena is therefore an indispensable part of planning of various activities. Local weather observations and intuition are not sufficient because the convective clouds development is rapid and takes place in a limited area. For these reasons, satellite images are a valuable source of data for detection and interpretation of the phenomena. This paper presents possibilities to apply some of the current remote sensing methods to detecting and monitoring these meteorological objects.

2. Methods and material

The complexity of the development process and significant spatial and temporal variability of convective clouds is a reason why satellite data are commonly used to analyze these meteorological objects. Advances in satellite remote sensing technology widened the scope and capabilities of research, however, proper data interpretation is still often a problem. There are currently many satellite systems delivering images of various spatial, spectral, radiometric and temporal resolutions. Geostationary satellites data are commonly used in meteorology because of their good temporal resolution, so important for monitoring hazardous weather phenomena and issuing warnings. More detailed information concerning the atmosphere because of better spatial resolution is provided by polar orbiting satellites. They have, however, a significant limitation with respect to poor temporal resolution. Terra, Aqua and Suomi NPP polar orbiting satellites provide data including the area of Poland two times a day each at constant periods of the day (Table 1).

Images recorded by the SEVIRI radiometer – the scanner of the Eumetsat second generation geostationary satellites (MSG) – are the basic source of data for this research. SEVIRI provides images in 12 spectral channels every 15 minutes (Table 2). MSG satellites have belonged to the basic operational system of European and African meteorological services since 2002. Currently, it is the MSG-3 satellite at 0° longitude and latitude. The spatial resolution of its 11 spectral channels is 3 km at nadir and over 5 km in the mid-latitudes while the high resolution visible channel (HRV) provides images with the resolution of 1 km at nadir and over 3 km in the mid-latitudes.

Data of 1 km nadir resolution acquired by the MODIS spectroradiometer (Moderate Resolution Imaging Spectroradiometer) were also used to detect convective phenomena. These multispectral optical and mechanical scanners are installed onboard Terra and Aqua polar orbiting satellites which are elements of the Earth Observing System. MODIS has been providing images of global and regional scale processes in the atmosphere, cryosphere and on land and ocean surfaces for over ten years. High radiometric and spectral resolution of the data (36 channels), advanced systems of radiometric calibration installed onboard the EOS satellites and orbit stabilization within ±5–10' enable to acquire homogenous observation series which provide meteorologists and climatologists with new opportunities to investigate meteorological elements and phenomena [3].

Table 1. Time of flight of Terra, Aqua and Suomi NPP polar orbiting satellites over Poland [4]

Satellite	Time frame
Terra	09:05–10:45 UTC
	19:40–21:15 UTC
Aqua	00:15–01:50 UTC
	10:30–12:20 UTC
Suomi NPP	10.25–12.05 UTC
	00.05–01.35 UTC

Table 2. Spectral channels of the SEVIRI radiometer and their corresponding channels of the MODIS and VIIRS spectroradiometers [3, 5, 6]

SEVIRI (MSG)			MODIS (Terra/Aqua)			VIIRS (Suomi NPP)		
Band number	Central wavelength [μm]	Spatial resolution (nadir) [km]	Band number	Central wavelength [μm]	Spatial resolution (nadir) [km]	Band number	Central wavelength [μm]	Spatial resolution (nadir) [km]
1 (VIS 0.6)	0.635	3	1	0.645	0.25	SVM5	0.672	0.750
						SVI1	0.640	0.375
2 (VIS 0.8)	0.810	3	2	0.859	0.25	SVM7	0.865	0.750
						SVI2	0.865	0.375
3 (NIR 1.6)	1.640	3	6	1.640	0.50	SVM10	1.610	0.750
						SVI3	1.610	0.375
4 (IR 3.9)	3.900	3	20	3.750	1	SVM12	3.700	0.750
						SVI4	3.740	0.375
			21	3.959	1			
			22	3.959	1			
			23	4.050	1	SVM13	4.050	0.750
5 (WV 6.2)	6.250	3	27	6.715	1			
6 (WV 7.3)	7.350	3	28	7.325	1			
7 (IR 8.7)	8.700	3	29	8.550	1	SVM14	8.550	0.750
8 (IR 9.7)	9.660	3	30	9.730	1			
9 (IR 10.8)	10.800	3	31	11.030	1	SVM15	10.760	0.750
						SVI5	11.450	0.375
10 (IR 12.0)	12.000	3	32	12.020	1	SVM16	12.010	0.750
11 (IR 13.4)	13.400	3	33	13.335	1			
12 (HRV)	Broadband (about 0.4 – 1.1 μm)	1						

VIIRS data were also experimentally used in the research. This sensor is installed onboard the Suomi NPP satellite which is the basis of the Joint Polar Satellite System (JPSS). JPSS was started in 2011 to replace the National Polar-orbiting Environmental Satellite System (NPOESS) program. The main aim of the NPOESS program was to combine civilian and military requirements concerning operational monitoring of the atmosphere. After years of ineffective cooperation of three agencies: NASA, NOAA and US Defense Department and spending billions of dollars, the project was assessed to be a failure and it was cancelled. A remainder of it and a hope for filling the gap was the NPOESS fleet demonstrator – the NPP spaceship (NPOESS Preparatory Project). The satellite (with the VIIRS spectroradiometer) was launched on October 28, 2011, and in January of 2012 it was renamed "Suomi National Polar-orbiting Partnership" (Suomi NPP), in memory of Verner E. Suomi „the father" of satellite meteorology. It is necessary to mention that the satellite is still in the phase of test procedures. The VIIRS data are ameliorated and the process will probably continue for a few years which is quite typical for all satellite missions. However, it does not implicate giving up processing and using the data [7].

Imagery acquired from the satellite systems provides especially valuable data enabling to detect and recognize convective clouds in various stages of their development. Comprehensive analysis of geostationary satellites data of high temporal resolution and polar orbiting satellites data of high spatial resolution enables to assess the internal structure of the cloud cover, and in this way – assess the prevailing processes in clouds and finally forecast their development for hazardous weather phenomena warning systems.

Analysis of reflectance and brightness temperature data recorded in image pixels were used in the research to detect and monitor convective phenomena. Information about clouds was also obtained from the analyses of characteristic shapes of the cloud systems, dimensions, internal structure and relations concerning location of specific cloud types. The research concerned data at the following processing levels: 1.5 for the MSG (Level 1.5 High Rate SEVIRI image data) and 1B for the Terra/Aqua and Suomi NPP (Level 1B) [8, 9, 10]. McIDAS 1.4 and MSGView software were used to process the images [11, 12].

3. Results

The research included developing a scheme based on single spectral channel images, differential images and color compositions of images acquired from the radiometers for multispectral analyses of remote sensing data. This scheme is guidance for convective cells development monitoring (Fig. 1).

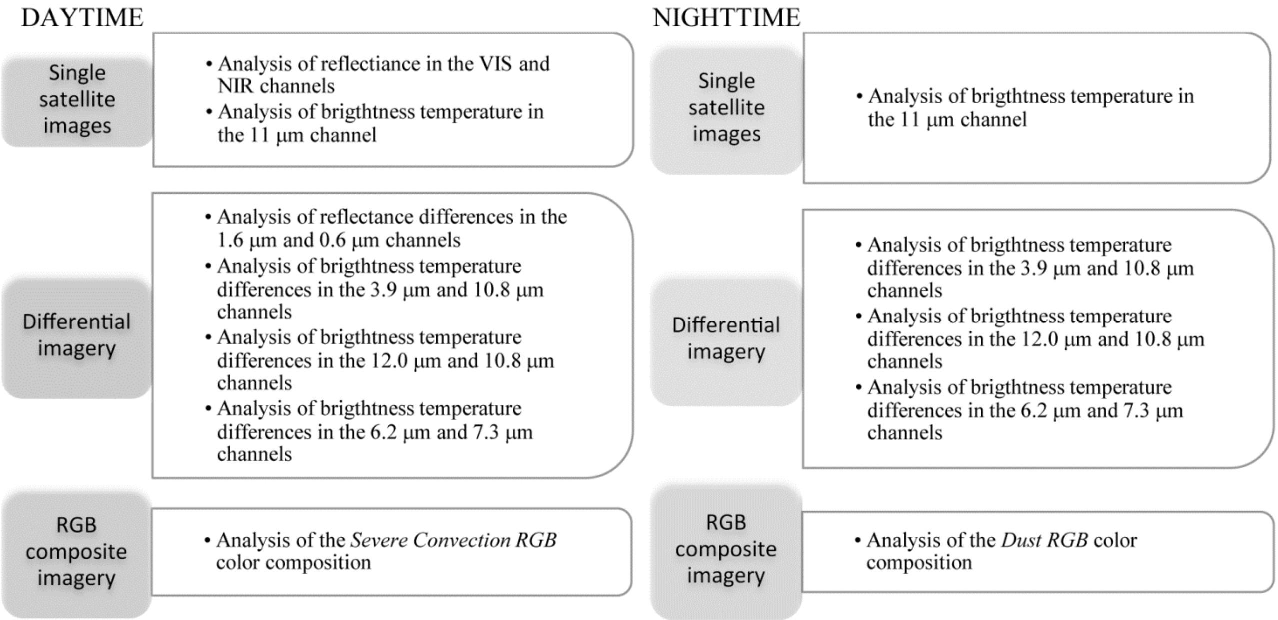

Fig. 1. Detection scheme developed for convective cells monitoring

Detection and monitoring of convective phenomena may usually be realized using single channel satellite images. Availability of data from several or even a few dozen channels provides wide potential of atmospheric processes analyses. They are based on application of the visible channel images [13]. Images acquired from the MODIS and VIIRS spectroradiometers and SEVIRI radiometer in the HRV channel are especially useful for analyses of the convective cloud tops structure. The convective clouds structure distinguished by very high reflectance is clearly visible in Figure 2. It is characteristic of deep clouds of high water content and composed of small water droplets. Shadows and areas of varying albedo enable to identify the spatial structure of the cloud cover. It is also possible to recognize Cirrus clouds which are often related with convective cells in their advanced stage of development. Cirrus clouds in the form of incus (anvil shape) are observed in the visible channel images as elongated streaks. Applying images acquired in the near infrared band of the spectrum (e.g. 1.6 µm) provides a useful supplement of the information concerning convective processes in the atmosphere. These images indicate first of all the state of water in the clouds [14]. Ice crystals strongly absorb solar radiation in this spectral band, hence convective cells which to a significant degree are built of ice crystals have visibly smaller values of reflectance in comparison with clouds in lower parts of the troposphere. Comparing images in the visible and near infrared bands may indicate the prevailing processes in the cloud.

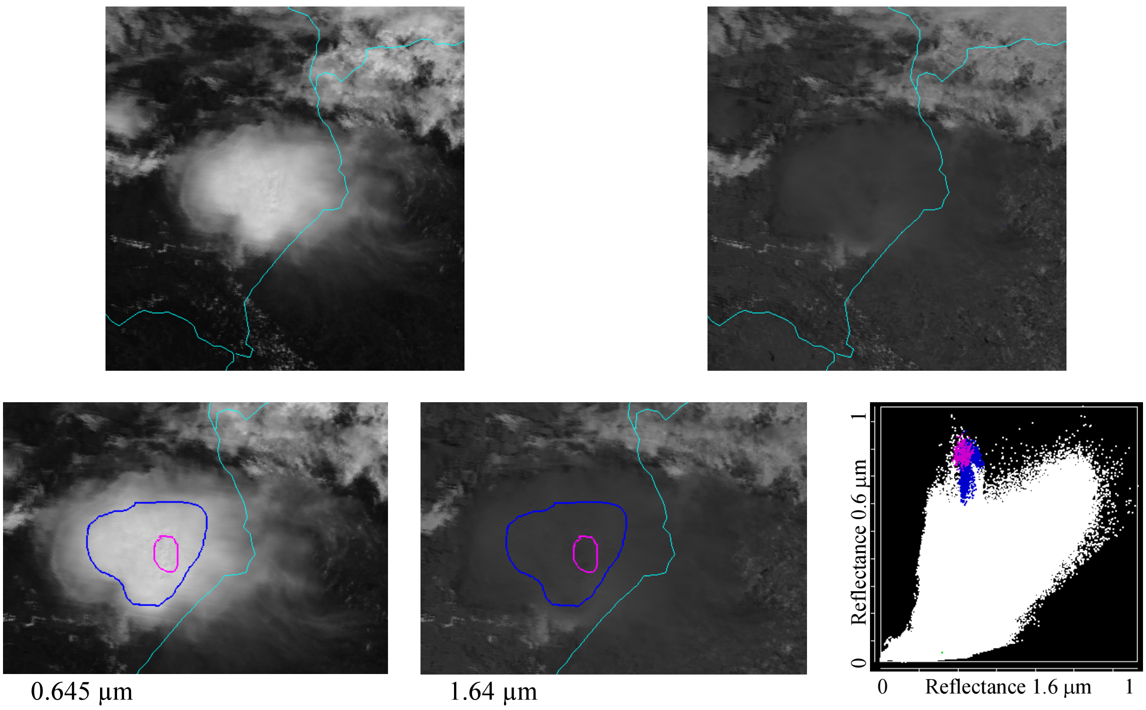

Fig. 2. Storm in eastern part of Poland. June 18, 2013, 9.10 UTC, MODIS (Terra). The core of the convective cell is indicated in the dispersion diagram – the highest reflectance in 0.6 µm band and low reflectance in the 1.6 µm band (data and software source: [9, 11])

Images acquired in the 11 µm bands (channel 31 of MODIS, SVM15 and SVI5 of VIIRS, 9 of SEVIRI – see Table 1) are sources of data concerning temperature of tops of the emitting objects and they enable to differentiate the altitude of the cloud tops. Increasing brightness on consecutive IR images indicates that the cloud tops temperature decreases in the areas which is interpreted as increasing cloud tops altitude. The coldest parts usually indicate the core of the thunderstorm cell (Fig. 3). Application of the data is even better justified for detection of convective phenomena at night time when the satellite sensors receive only radiation emitted by the Earth and the atmosphere.

Preparing and interpreting differential images of appropriately selected sets of spectral channels was a significant part of the research concerning analyses of processes developing in clouds. Propositions of differential images for detection of convective phenomena are presented in Table 3 [15, 16, 17, 18]. Differential images proposed in rows 2 through 4 in the table are important for monitoring convection at night when high resolution visible images are not available.

Table 3. Differential images for convection monitoring

	SEVIRI	MODIS	VIIRS	Applications	Time
Recommended differences	3 (NIR 1.6) – 1 (VIS 0.6)	6 (1.64) – 1 (0.645) →Terra 7 (2.13) – 1 (0.645) → Aqua	SVM10 – SVM5 SVI3 – SV1	optical thickness, phase, particle size	day
	4 (IR 3.9) – 9 (IR10.8)	20 (3.75) – 31 (11.03)	SVM12 – SVM15 SVI4 – SVI5	optical thickness, phase, particle size, emissivity	day and night
	10 (IR12.0) – 9 (IR10.8)	32 (12.02) – 31 (11.03)	SVM16 – SVM15	optical thickness	day and night
	5 (WV6.2) – 6 (WV7.3)	27 (6.715) – 28 (7.325)	–	overshooting tops	day and night

Results of applying the recommended and presented in Table 3 sets to images acquired by the Aqua satellite on July 21, 2012 at 12.10 are presented in Figure 4. A mesoscale convective system was observed south-west of Poland and it continued to develop in the afternoon. The system is characterized by high reflectance in the 0.645 µm band; in its southern part the reflectance value exceeds 0.8. Significant negative values of the reflectance observed in the 7 (2.13 µm) – 1 (0.645 µm) image additionally indicate existence of large ice crystals in the clouds. It is confirmed in the 20 (3.75 µm) – 31 (11.03 µm) differential image. A significant part of the clouds system is characterized by the values of the differences smaller than 40 K which indicates weak convective currents. The differences of the brightness temperature are greater than 40 K in the south-eastern part of the analyzed mesoscale convective system which indicates existence of small ice crystals and extremely strong convective processes in the clouds. The differences of the brightness temperature in the 32 (12.02 µm) – 31 (11.03 µm) image of values of about 0 K indicate that the cloud system extends through the entire troposphere, and positive values of the difference 27 (6. 715 µm) – 28 (7.325 µm) in the system's south-western part make detection of the core of the whole convective system easier.

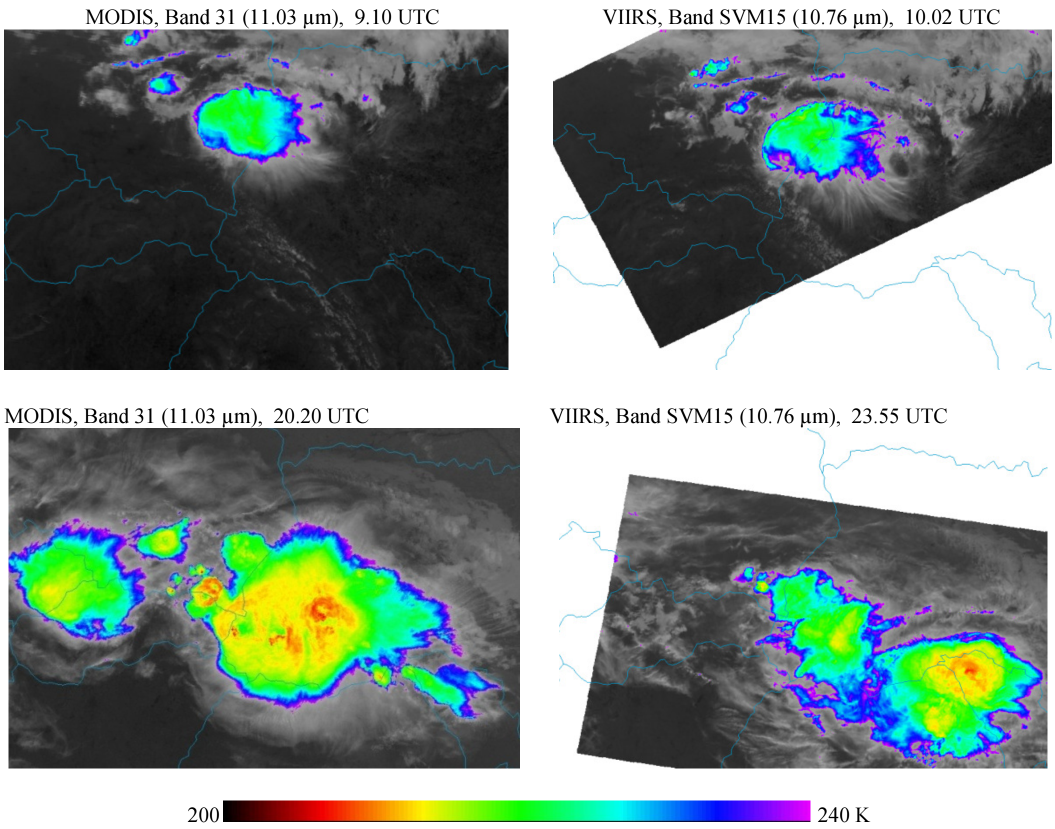

Fig. 3. Storm in eastern part of Poland. June 18, 2013, MODIS (Terra) and VIIRS (Suomi NPP) (data and software source: [9, 10, 11])

Color compositions produced by transparent combining images appointed to the RGB components are especially helpful in recognizing and interpreting properties of the convective processes in clouds. The compositions are obtained by combining single spectral channel images and / or differential images. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) running the Meteosat satellite system recommends a set of color compositions for interpreting convective phenomena [15, 18, 19, 20, 21]. The *Severe Convection RGB* color composition made of three differential images (Table 4) is especially recommended for day time interpretations. It may be produced using data acquired by both the SEVIRI radiometer and the MODIS spectroradiometer (VIIRS does not sense in the water vapor absorption band). This composition enables to recognize the cloud development stages – from the early development to dissipation. Good temporal resolution of the MSG images makes them especially useful for this purpose. The results of applying the *Severe Convection RGB* color composition to processing MSG satellite images of June 18, 2013 are presented in Figure 5. The images sequence shows intensive development of convective clouds systems in a vast area in central and southern parts of Poland.

Table 4. Severe Convection RGB: recommended range and enhancement [20, 21]

Beam	Channel		Range	Gamma
	SEVIRI	MODIS		
Red	WV6.2-WV7.3	Ch 27 (6.715) – Ch 28 (7.325)	–30 ÷ 0 K	1.0
Green	IR3.9-IR10.8	Ch 20 (3.75) – Ch 31 (11.03)	0 ÷ 50 K	0.5
Blue	NIR1.6-VIS0.6	Ch 6 (1.64) – Ch 1 (0.645)	–70 ÷ +20 %	1.0

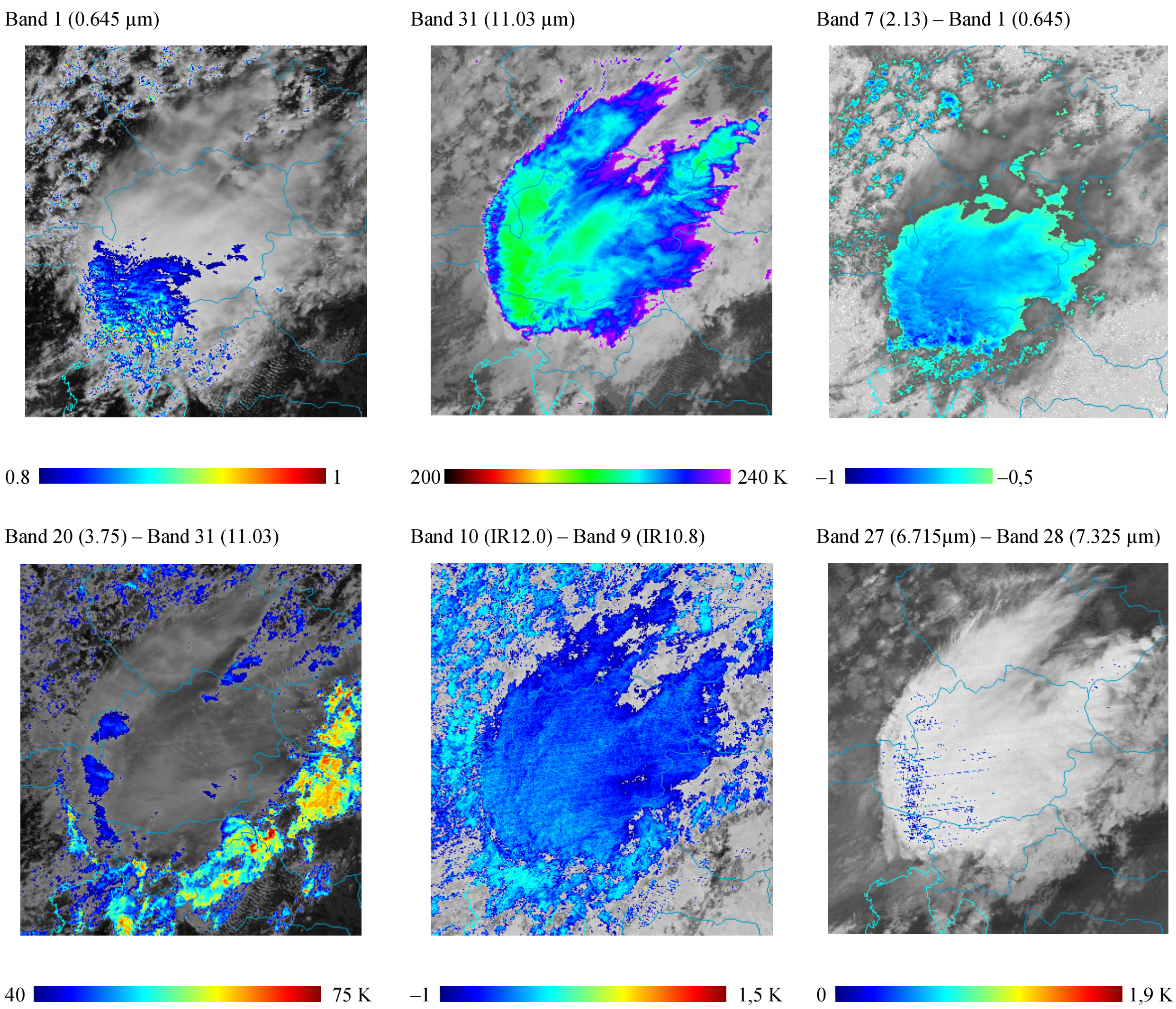

Fig. 4. Storm in Central Europe. July 21, 2012, 12.10 UTC, MODIS (Aqua) – an overall view in the VIS and IR bands and the brightness temperature difference products (data and software source: [9, 11])

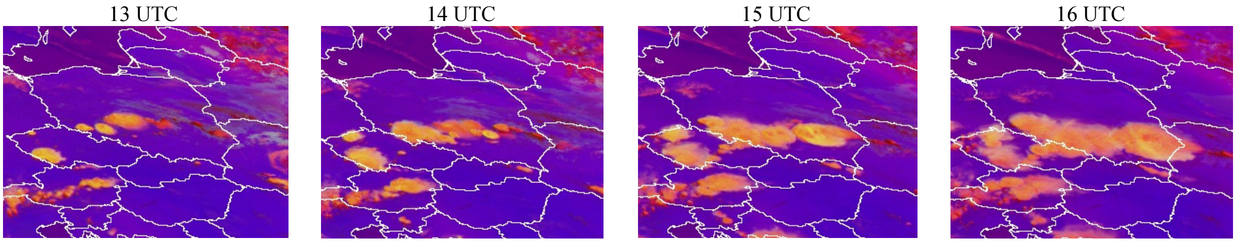

Fig. 5. Convective cells development in central and southern Poland. June 18, 2013, MSG-3, RGB WV6.2 - WV7.3, IR3.9 - IR10.8, NIR1.6 - VIS0.6 (data and software source: [8, 12])

Dispersion diagrams provide detailed characteristics concerning radiation dispersion, absorption and emission from objects in the atmosphere in various spectral ranges. They enable to derive information about the internal structure of convective clouds, phase of water and cloud particles size. Dispersion diagrams presented in Figure 6 were prepared for satellite images of June 18, 2013 at 9 UTC and 13 UTC. They show significant differences in intensity of convective processes in the analyzed cloud systems. The red dots in the red frame in the dispersion diagram at 9 UTC indicate that the convective processes fade and large ice crystals appear in the upper part of the cloud in weakening vertical currents in the cloud (IR3.9 – IR10.8 < 40 K).

Dispersion diagram at 13 UTC shows that the convection development is dynamic. The red dots in the red frame indicate that large ice crystals dominating in weak vertical currents (IR3.9 – IR10.8 < 40 K) give way to small ice crystals developing in strong convection (IR3.9 – IR10.8 > 40 K) indicated by numerous yellow dots. Yellow dots in the yellow frame indicate that the clouds developed to higher parts of the troposphere and they may also develop towering tops in extremely strong convective processes (WV6.2-WV7.3 is about 0 K).

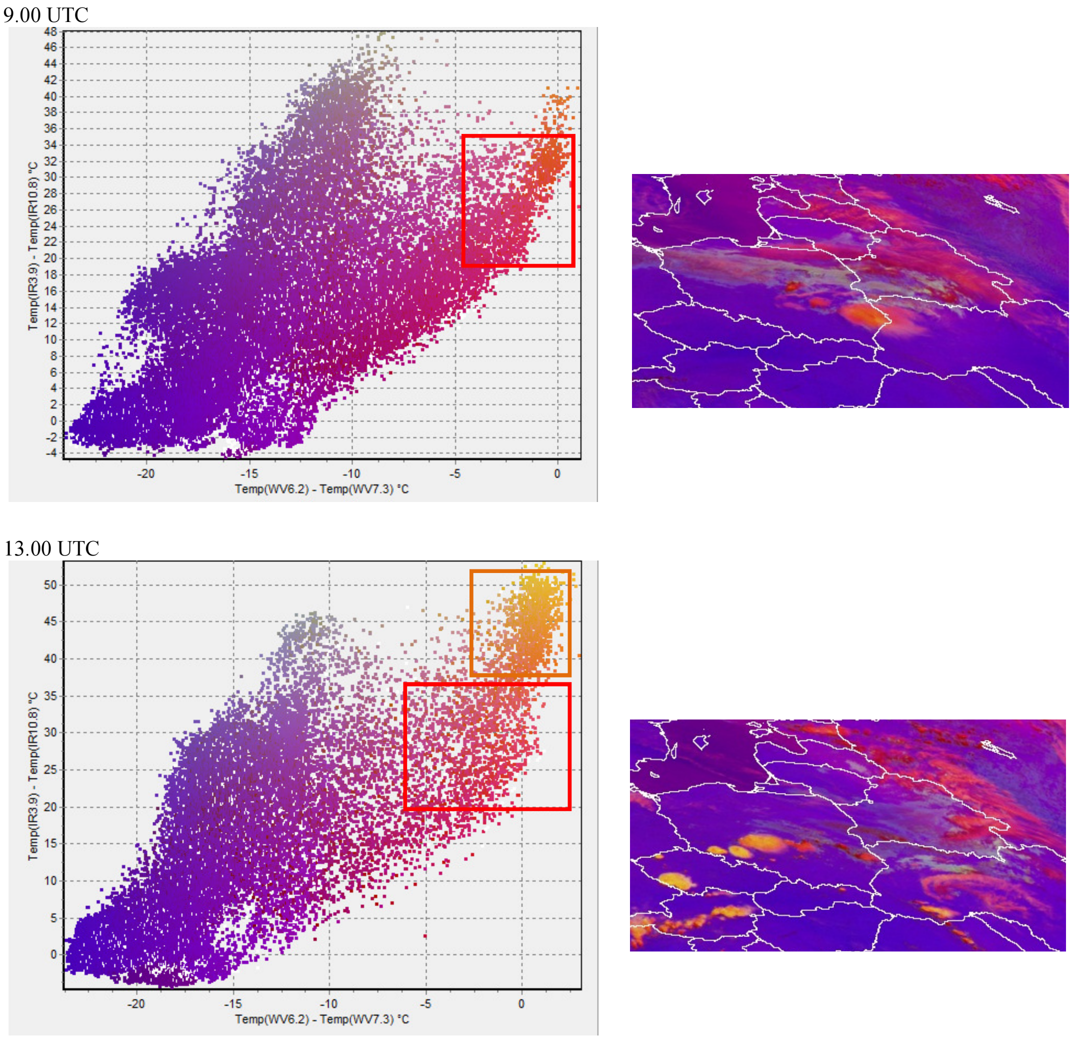

Fig. 6. Dispersion diagrams for convective cells. MSG, June 18, 2013, 9 UTC and 13 UTC (data and software source: [8, 12])

The *Dust RGB* color composition is recommended for convective phenomena detection at night time. The components of the composition and the properties of the specific channels are presented in Table 5. The *Dust RGB* color compositions prepared using SEVIRI and MODIS data of June 13, 2013 are presented in Figure 7. Characteristic red color of convective clouds is related with large value of the red component which is the result of significant optical thickness of the clouds. In such situations, the values of IR12.0 – IR10.8 and Ch32 (12.02 μm) – Ch31 (11.03 μm) differences are positive. Low temperatures of convective cloud tops result in small share of the blue component in the analyzed composition and it is also similar for the green component. It indicates that no significant differences concerning spectral properties of convective cells are observed in the 8.5 μm and 11 μm bands.

Table 5. Dust RGB: recommended range and enhancement [20, 21]

Beam	Channel			Range	Gamma
	SEVIRI	MODIS	VIIRS		
Red	IR 12.0-IR 10.8	Ch 32 (12.02) – Ch 31 (11.03)	SVM16-SVM15	–4 ÷ +2 K	1.0
Green	IR 10.8-IR 8.7	Ch 31 (3.75) – Ch 29 (8.55)	SVM15-SVM14	0 ÷ +15 K	2.5
Blue	IR 10.8	Ch 31 (11.03)	SVM15	+261 ÷ +289 K	1.0

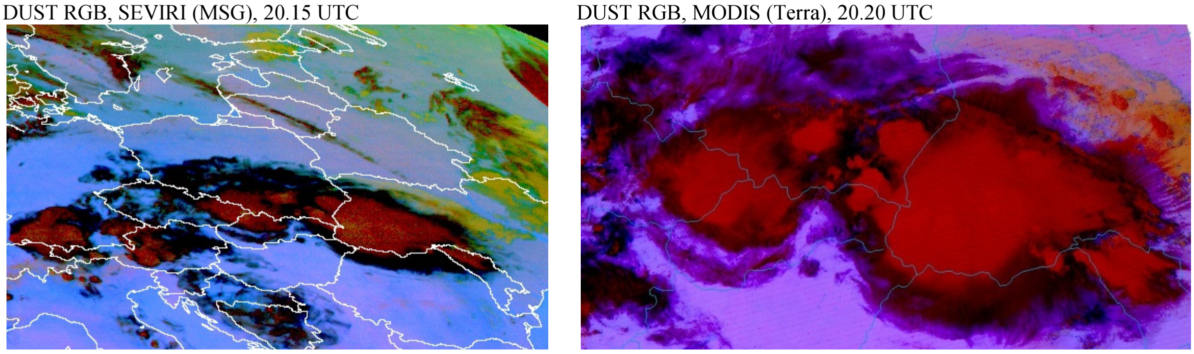

Fig. 7. Convective cells in southern Poland. June 18, 2013, night time

4. Discussion

The research concerned the problem of application of data from three satellite radiometers – operational SEVIRI and two experimental and research ones (MODIS and VIIRS) to convective phenomena detection. The images from the systems are different in terms of projection, resolution (mainly temporal and spatial) and coverage. Investigating rapidly developing convective clouds systems requires high temporal resolution data. This requirement is fulfilled by geostationary satellites images, e.g. from the MSG. In case of the polar orbiting satellites (Terra, Aqua, Suomi NPP) the acquired information is much less frequent. However, the images have better spatial resolution which is of great importance for mesoscale phenomena interpretation. Furthermore, spatial resolution of geostationary satellites images gets worse with distance from the nadir. Therefore, polar orbiting satellites data are an important supplement in investigating dynamics of convective phenomena.

Although changes in brightness in satellite images seem to contain most of the information concerning the analyzed objects, the proposed method of analysis of reflectance and brightness temperature of the specific pixels in the image occurs to be the most appropriate for investigating convection. The specialized interpretation enables to derive information about the analyzed processes from images of the radiation dispersed and emitted by the Earth and the atmosphere in various spectral ranges. However, the skill to interpret the characteristic shapes, sizes, internal structure and relations concerning layout of various cloud types is also important.

Comprehensive analysis of visible and infrared images as well as application of the recommended here differential images facilitate recognizing the properties of convective cloud systems which in single spectral channel images could not be unambiguously interpreted. Combining satellite images into color compositions provides new effective tools for the analyzed phenomena monitoring.

Information derived from analyses of the detected and monitored convective phenomena may be an effective element of the decision making support systems for managing preventive activities. These activities may include deploying specialized personnel and equipment in advance to areas of forecasted threats, prevention concerning controlling traffic in urban areas subjected to intensive precipitation, issuing warnings about strong and gusty wind, rerouting air and sea traffic, suspending jobs vulnerable to lightning (handling petrol and flammable materials, jobs done on high objects and in open areas, e.g. in crops fields and play grounds). Frequent acquisition of satellite images enables detection of convective phenomena in early stages of their development and early initiating appropriate procedures of issuing warnings.

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