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Fog detection over sea based on multispectral analysis of satellite images

Wykrywanie mgieł nad obszarami morskimi na podstawie wielospektralnej analizy zdjęć satelitarnych

Janusz Jasiński, Karolina Krawczyk, Sławomir Pietrek

Military University of Technology, Faculty of Civil Engineering and Geodesy
Department of Geographic Information Systems
Wojskowa Akademia Techniczna, Wydział Inżynierii Lądowej i Geodezji,
Zakład Systemów Informacji Geograficznej
00-908 Warszawa, ul. S. Kaliskiego 2
e-mail: janusz.jasinski@wat.edu.pl, kkrawczyk@wat.edu.pl, spietrek@wat.edu.pl

Key words: meteorology, remote sensing, RGB composite imagery, differential imagery

Abstract

Detecting fog over sea, especially in early stages of its development, is extremely important due to the threats it imposes on sea navigation. Measurement and observation network in the areas is very thin and limited to single drifting buoys and information provided irregularly by the crews of ships. For these reasons, fog detection by means of remote sensing methods becomes especially significant. The paper presents possibilities to detect fog developing in the most difficult to detect cases – in the air cooling at night time – when it is not possible to sense in the visible light and when the thermal contrast between the fog and the underlying surface is lower than the thermal resolution of the IR images. Analysis of differential and RGB composite images produced from results of observation of the same meteorological objects obtained in various spectral bands reveals features unobservable in each of the bands separately. Using the EUMETSAT recommendations, algorithms of creating RGB composite images were developed in the Department of Geographic Information Systems and applied to images for analysis.

Słowa kluczowe: meteorologia, teledetekcja, kompozycje RGB, zobrazowania różnicowe

Abstrakt

Wykrywanie mgieł nad obszarami morskimi, zwłaszcza we wczesnych stadiach ich powstawania, jest niezwykle istotne ze względu na zagrożenie, jakie stanowią one dla żeglugi. Na obszarach tych sieć pomiarowo-obserwacyjna jest bardzo rzadka i ogranicza się do pojedynczych boi pływających oraz informacji przekazywanych nieregularnie przez załogi statków. Z tych powodów wykrywanie mgieł metodami teledetekcyjnymi nabiera szczególnego znaczenia. Artykuł przedstawia możliwości wykrywania mgieł powstających w najtrudniejszych do wykrycia przypadkach – w ochładzającym się w nocy powietrzu – gdy niemożliwa jest obserwacja w świetle widzialnym oraz gdy kontrast termiczny między mgłą i podłożem jest mniejszy niż rozdzielczość termalna zdjęć w podczerwieni. Analiza obrazów różnicowych oraz kompozycji barwnych złożonych z wyników obserwacji tych samych obiektów meteorologicznych wykonanych w różnych zakresach spektralnych ujawnia ich cechy niewidoczne w każdym z zakresów z osobna. Uwzględniając zalecenia EUMETSAT, w Zakładzie Systemów Informacji Geograficznej opracowano algorytmy tworzenia kompozycji barwnych i zastosowano je do analizowanych zdjęć.

Introduction

Fogs significantly influence miscellaneous human activities. Visibility reduced by fog may cause serious difficulties or even hazards in land, maritime and air transport. Sea navigation on more and more crowded routes and reservoirs becomes increasingly vulnerable to risks of collision. Hence, detecting fog, especially in early stages of its development, is extremely important due to the threats it imposes on all kinds of traffic.

Fog is a complex atmospheric phenomenon. Its development depends on multiple meso-scale processes including vertical turbulent mixing in the boundary layer of the atmosphere and radiation of the ground surface. The development depends also on macro-scale regional environmental factors and synoptic situation [1]. Furthermore, fog development is related with micro-scale physical processes of water droplets growth by water vapor condensation and droplets coagulation.

The complexity of fogs development and their significant spatial and temporal differentiation require diverse methods of atmospheric observations and measurements. Measurement and observation results from the ground meteorological observation network concern weather conditions identified in the vicinity of the observation site. Synoptic observations conducted at the weather stations provide only a local picture of the situation. Currently, fog analysis methods commonly use satellite data provided in wide spectrum of wavelengths and with high spatial and temporal resolution by the geostationary meteorological satellites. The HRV (High Resolution Visible) channel of the SEVIRI (the Spinning-Enhanced Visible and Infrared Image) scanner on the MSG (Meteosat Second Generation) satellite yields 1 km resolution at nadir for images acquired every 15 minutes.

Both fog and Stratus clouds are very close to the surface and their apparent temperature is similar which causes that they are hardly distinguishable from one another on satellite imagery. That is why the problems of fog and Stratus identification (distinguishing from the ground) are usually treated jointly [2]. The paper presents attempts to identify these on satellite images: on single spectral channel images, on differential images derived from two spectral channels and selected RGB composite images produced from a few spectral channels.

Interpretation of MSG single spectral channel imagery

Upper parts of Stratus and fog are observed as uniform areas on the geostationary satellite images, e.g. in channels 1 through 11 of the MSG while high resolution channels (e.g. MSG HRV channel) may show some elements of the fog or Stratus top structure. Some features facilitating detection of fog or Stratus (or even distinguishing between them) on satellite images result from the conditions in which they develop [3, 4, 5]:

– fog and Stratus developing in valleys often have the shape of the surrounding terrain; the lightest part of the image of them lies along the valley axis where the fog and Stratus layer thickness is the greatest;
– fog and Stratus developing over sea yield a smooth area with soft boundaries in the images;
– advection fog or Stratus have regular contours while radiation fog contours are more irregular and sharper than Stratus contours due to greater influence of the terrain form;
– it is more likely to observe movement of Stratus than of fog in animated series of satellite images.

Fog and Stratus detection is based on the properties of their influence on solar radiation in the visible and infrared wavelength ranges [3, 4, 5, 6, 7, 8]:

– reflectivity in the VIS0.6 visible range (MSG channel 1) is proportional to the Stratus or fog layer thickness and its water content – they usually appear in the image as clearly seen white or light grey areas, however, they are not distinguishable from snow cover underneath;
– reflectivity in the NIR1.6 near infrared range (MSG channel 3) is greater for fog and clouds containing smaller water droplets than for clouds containing ice crystals and larger water droplets – fog and Stratus appear white or light grey while snow cover and other clouds are significantly darker;
– emissivity in the IR10.8 infrared range (MSG channel 9) is a function of the temperature of the emitting surface – fog and Stratus, with their tops having nearly the same temperature as the ground below, are presented as grey or dark grey and usually cannot be distinguished from the ground;
– solar radiation reflected by the Earth/atmosphere and radiation emitted by the Earth/atmosphere are recorded in the IR3.9 infrared range (MSG channel 4). Daytime images include both solar and Earth radiation while nighttime images only the Earth one. Earth surface emissivity in this channel is different from the emissivity of the fog or Stratus at the same temperature which is used to distinguish them from the ground on nighttime images – the radiation temperature of the ground occurs to be higher, hence the fog or Stratus are presented as lighter grey in the image.

Interpretation of MSG differential imagery

Differences in the reflectivity and emissivity characteristics of ground surface and fog or Stratus may be utilized to produce differential images from images in various spectral channels. Differential images for nighttime fog or Stratus detection are usually produced from the IR3.9 and the IR10.8 channels. Fog or Stratus emissivity is smaller in the IR3.9 channel than in the IR10.8 channel [4, 6, 9] and the radiation temperature differences in these channels are usually of the order of a few degrees. The IR3.9 channel range (3.48÷4.36 μm) includes also the range of CO_2 absorption (4.2 μm) and it is necessary to make corrections for it [10]. Therefore, universal radiation temperature difference ranges (IR3.9 – IR10.8) indicating fog or Stratus may not be defined (Fig. 1).

In cases of low values of radiation temperature in the IR3.9 channel (e.g. in winter in high latitude areas), the relation between the radiance of the objects and their temperature is non-linear which causes that even slight changes in the radiance value result in significant changes in the radiation temperature, unlike in other spectral ranges (e.g. IR8.7, IR10.8, IR12.0 channels). In such atmospheric conditions, in the IR3.9 channel the radiation temperature is measured with lower accuracy than in other channels. This noise, reaching the value of 2 K, reduces the thermal contrast between the surface and fog or Stratus and thus limits the applicability of the images in this channel to detecting fog and Stratus. Instead of the IR3.9 channel, the IR8.7 channel is then usually used to produce the differential images [4, 9], however, the radiation temperature difference with respect to the IR10.8 is not so significant.

Interpretation of MSG RGB composite images

The R, G and B components of the RGB composite images consist of single spectral channel images or differential images. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) operating the MSG satellites recommends a few RGB composite images for fog and Stratus interpretation. Table 1 presents a selection of MSG RGB composite images that may be applied to detecting fog and Stratus. Unfortunately, most of these RGB composite images cannot be produced without access to EUMETSAT sophisticated software. Images are available at the EUMETSAT website, however, they are not archived. Using the EUMETSAT recommendations, algorithms of creating RGB composite images were developed in the Department of Geographic Information Systems of the Military University of Technology.

The following RGB composite images were developed using the Readmsg.exe application (available from EUMETSAT at [11]):

1) RGB 03,12,12 based on the HRV Fog (Table 1): images from channel 3 (NIR1.6) and channel 12 (HRV). In this case the entire ranges of the specific channels were used instead of the

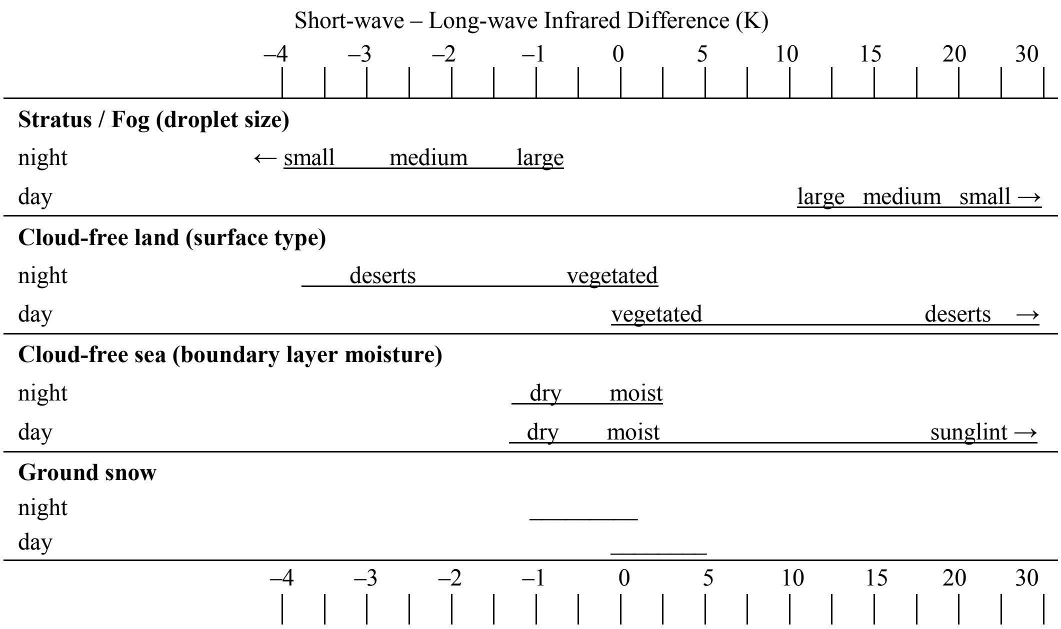
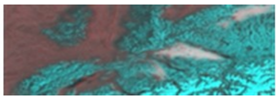


Fig. 1. Diagram showing representative ranges of the brightness temperature difference (BTD) between two spectral channels – short-wave and long-wave infrared (plot reproduced from [12])

Rys. 1. Schemat przedstawiający charakterystyczne zakresy różnic temperatury luminancyjnej pomiędzy dwoma kanałami spektralnymi – podczerwieni krótko- i długofalowej (opracowanie na podstawie [12])

Table 1. A selection of MSG RGB composite images for detection of fog and Stratus (compiled from [4, 5, 13, 14, 15, 16])
Tabela 1. Wybrane kompozycje barwne zdjęć z satelity MSG do detekcji mgieł i chmur Stratus (na podstawie [4, 5, 13, 14, 15, 16])

RGB composite image name	Spectral channels (or differential images) assigned to the R, G and B components of the composite			Fog or Stratus color	Time
	R (red)	G (green)	B (blue)		
03,02,01 Natural Color	NIR1.6	VIS0.8	VIS0.6		Day
02,04r[1],09 Day Microphysics	VIS0.8	IR3.9r	IR10.8		Day
02,03,04r Day Solar	VIS0.8	NIR1.6	IR3.9r		Day
10-09,09-04,09 Night Microphysics	IR12.0 –IR10.8	IR10.8 –IR3.9	IR10.8		Night
3,12,12 HRV Fog	NIR1.6	HRV	HRV		Day
12,12, 9i[2]	HRV	HRV	IR10.8		Day

[1] **r** – only the solar reflected radiation in channel 4 is used and the radiation emitted by the Earth and the atmosphere is skipped.
[2] **i** – inverted image in which the pixel values increase with the temperature of the object in the image.

recommended by the EUMETSAT selection of sub-ranges (70% of channel 3);

2) RGB 02,03,04r based on Day Solar (Table 1): images from channel 2 (VIS0.8), channel 3 (NIR1.6) and channel 4 (IR3.9). Similarly, the entire ranges of the specific channels were used (Day Solar recommends using only the solar reflected radiation in channel 4 and skipping the radiation emitted by the Earth and the atmosphere).

Fog and Stratus reflect a similar amount of radiation in all the components of the RGB composite described in 1) above. High brightness in the HRV channel results from significant thickness of the layer and water content of fog or Stratus. They consist of water droplets which yields increased reflectivity also in the NIR1.6 channel. Fog or Stratus are white and slightly pink in the composite image (e.g. Fig. 4). Stronger absorption of radiation by ice crystals (in channel 3) enables distinguishing between water and ice fog or clouds, as well as distinguishing them from snow cover.

Reflectivity in the IR3.9 channel increases with decreasing dimensions of fog or Stratus elements and is greater for water droplets than for ice crystals. Fog and Stratus are thus brighter – white or light grey – in the images than high clouds. In the RGB composite 2) images, fog or Stratus appear as smooth and light, slightly greenish areas (e.g. Fig. 5). They significantly differ from the ground surface (blue), snow (pink) and medium and high level clouds (orange).

Detection of fog and Stratus on satellite images[1]

September 29, 2011. Fog developed in the vicinity of the south-west coast of Scandinavia at night on September 29, 2011 and was observed until afternoon. Fog and Stratus detection at night using single spectral images is difficult because of small radiation temperature differences between them and the surface (Fig. 2a and b). However, they may be interpreted on the differential image produced from the IR3.9 and IR10.8 channels (Fig. 2c). To analyze the value of the differences for fog or Stratus, a square area was selected (Fig. 2d). The color pixels indicate radiation temperature difference values in the range from –8K through –11K which is characteristic for fog or Stratus composed of small dimensions water droplets.

[1] 2 images through 12 presented in the paper were processed in Readmsg.exe [11] using data from [17].

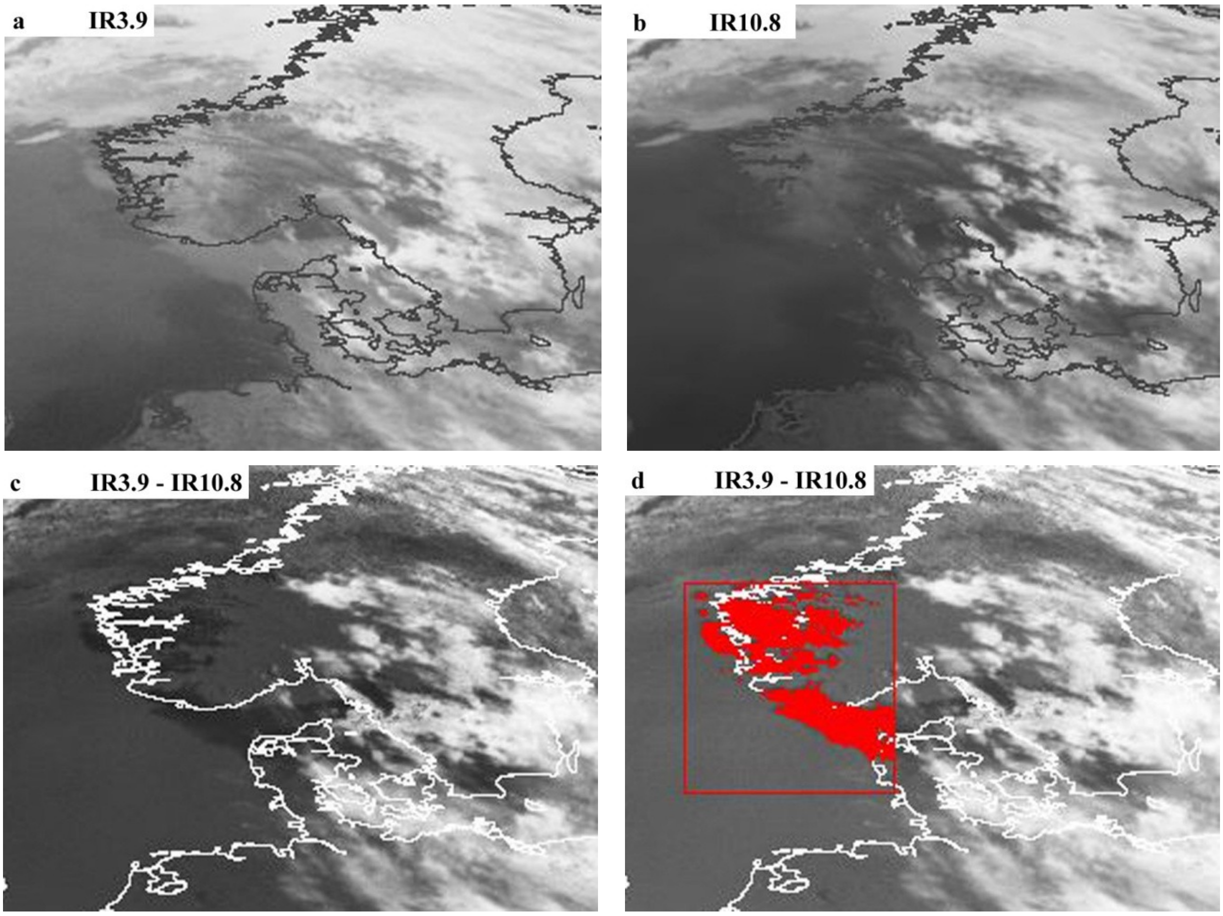


Fig. 2. Fog / Stratus at night. MSG-2 and differential images, September 29, 2011 at 5.00 UTC
Rys. 2. Mgły / Stratus w porze nocnej. Zobrazowania MSG-2 i różnicowe, 29 września 2011 r. 5.00 UTC

HRV high resolution visible images were used for the daytime analysis of the fog and Stratus. They are clearly visible as white or light grey (Fig. 3a). In the IR3.9 channel image fog and Stratus are grey or dark grey (Fig. 3b) due to significant reflectivity. Figure 3c proves that the IR10.8 channel images are not appropriate for detecting fog or Stratus because of their very small thermal contrast with respect to the ground. The (IR3.9 – IR10.8) differential image is shown in figure 3d in which the fog and Stratus are observed as lighter area against the darker background. The radiation temperature difference in these channels at daytime is positive. It increases with increasing Sun elevation and decreasing dimensions of the water droplet of Stratus or fog. Yellow pixels in figure 3e indicate the radiation temperature difference range of 6K through 18K.

Figures 4 and 5 show RGB composite images produced respectively according to the following algorithms:

- RGB 03,12,12 from channel 3 (NIR1.6) and channel 12 (HRV);
- RGB 02,03,04 from channel 2 (VIS0.8), channel 3 (NIR1.6) and channel 4 (IR3.9).

In figure 4 fog and Stratus are observed on September 29, 2011 at 11 UTC as smooth light pink areas clearly distinct from the brown land and dark blue water. Higher reflectivity of fog and Stratus in the IR3.9 channel results in smooth light green areas in the RGB composite image in figure 5 clearly distinct from the orange areas of medium and high level clouds and navy blue water.

April 17, 2011.

A vast area of fog and Stratus is observed over southern part of the Baltic Sea along the Polish coastline on April 17, 2011. They are clearly seen as a light smooth patch in the HRV image at 12.00 UTC (Fig. 6a). In this case, common analysis of HRV images, differential images (Fig. 6d and e) and RGB composite images (Figs 7 and 8) significantly facilitates detection of fog and Stratus which on commonly used single channel images (Fig. 6b and c) are hardly recognizable. In the differential image (IR3.9 – IR10.8) yellow pixels indicate two conditions: radiation temperature values in the IR10.8 channel image are higher than 270K and the radiation temperature value difference between the IR3.9 and the IR10.8 channel images is within the range of 12K through 23K.

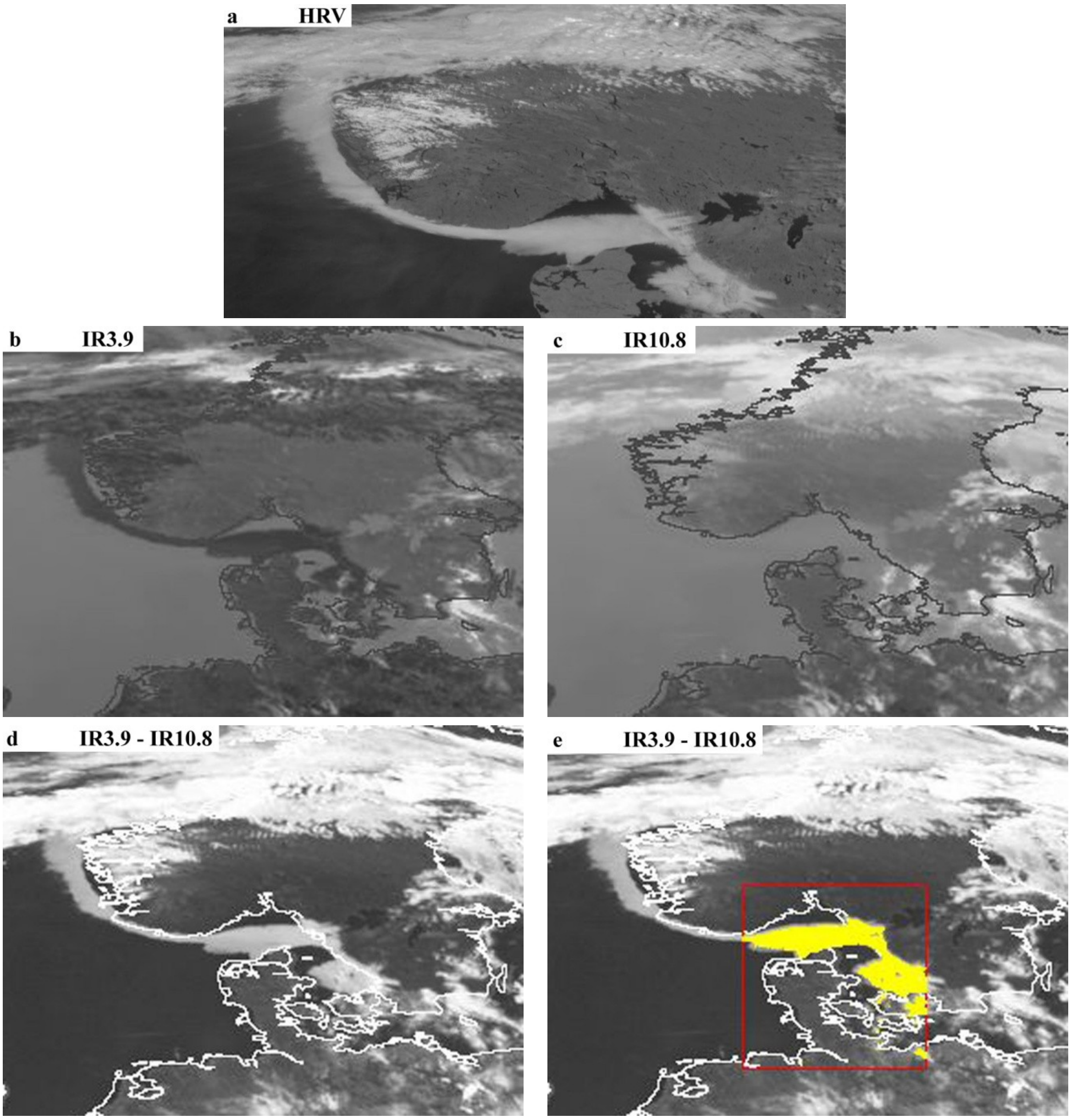


Fig. 3. Fog / Stratus at day. MSG-2 and differential images, September 29, 2011 at 11.00 UTC
Rys. 3. Mgły / Stratus w porze dziennej. Zobrazowania MSG-2 i różnicowe, 29 września 2011 r. 11.00 UTC

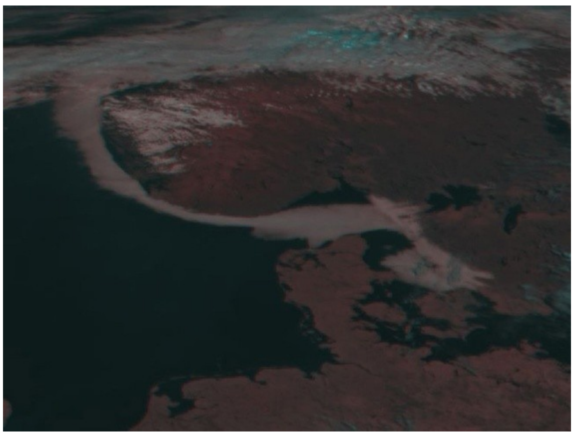


Fig. 4. Fog / Stratus. MSG-2 RGB 03,12,12 composite image, September 29, 2011 at 11.00 UTC
Rys. 4. Mgły / Stratus. Kompozycja barwna RGB 03,12,12, MSG-2, 29 września 2011 r. 11 UTC

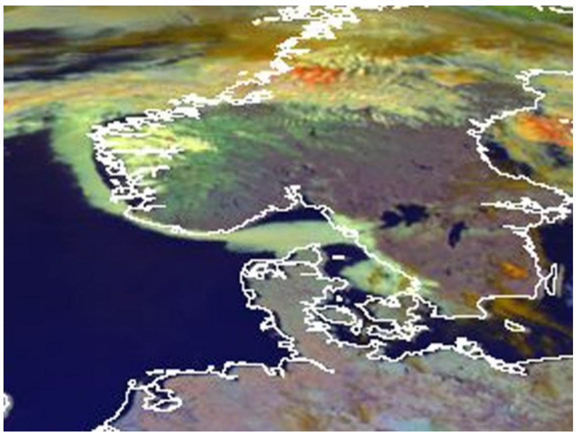


Fig. 5. Fog / Stratus. MSG-2 RGB 02,03,04 composite image, September 29, 2011 at 11.00 UTC
Rys. 5. Mgły / Stratus. Kompozycja barwna RGB 02,03,04, MSG-2, 29 września 2011 r. 11 UTC

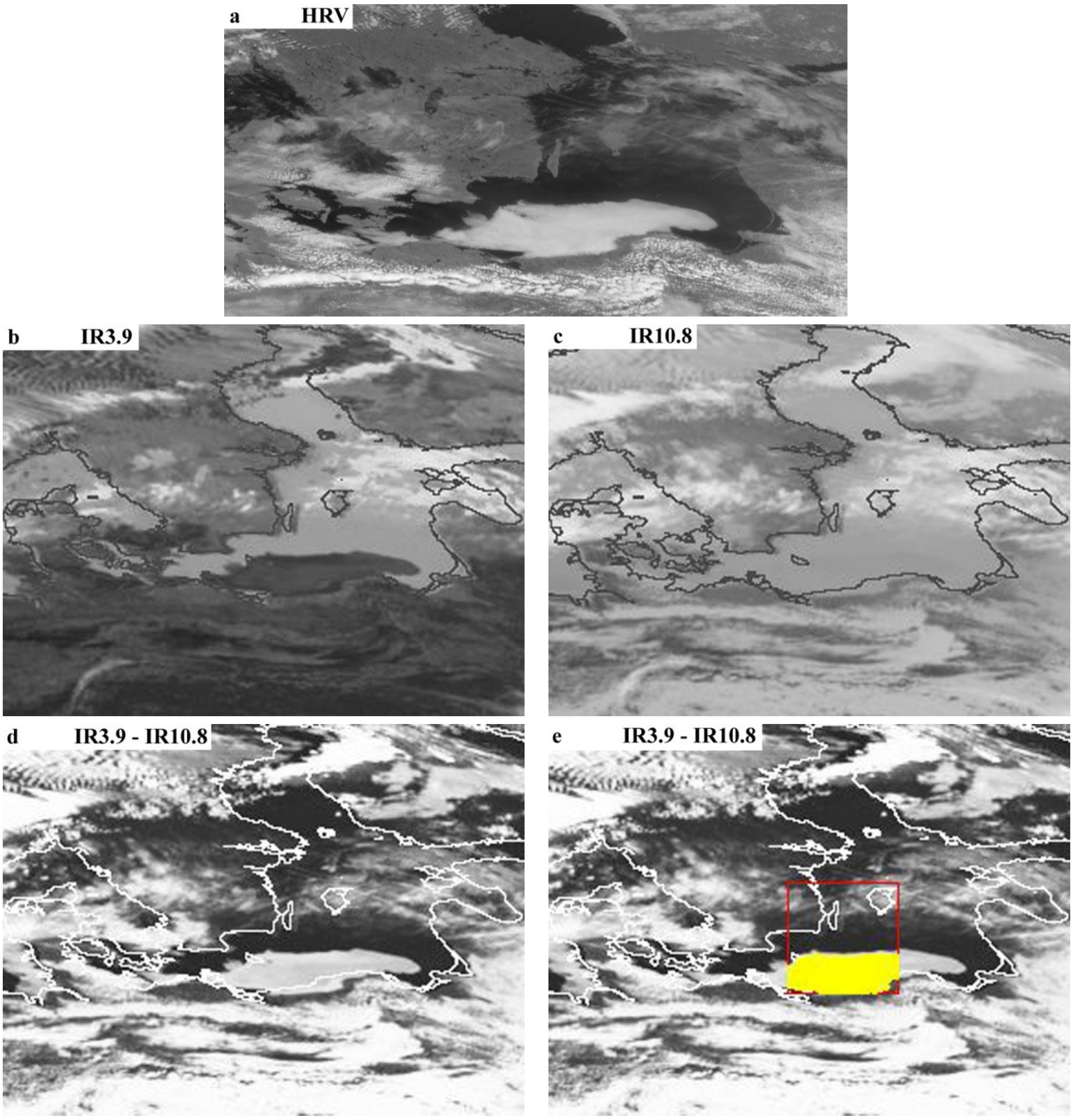


Fig. 6. Fog / Stratus at day. MSG-2 and differential images, April 17, 2011 at 12.00 UTC
Rys. 6. Mgły / Stratus w porze dziennej. Zobrazowania MSG-2 i różnicowe, 17 kwietnia 2011 r. 12 UTC

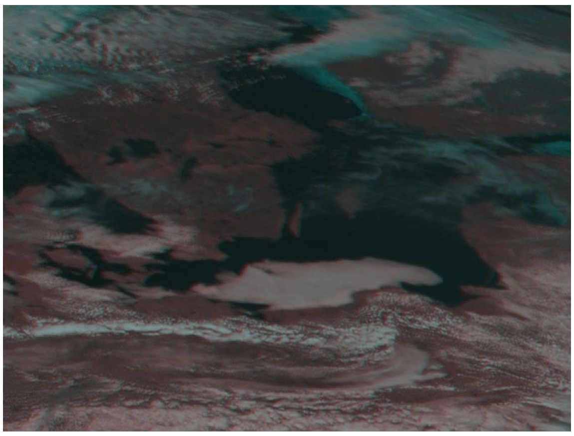


Fig. 7. Fog / Stratus. MSG-2 RGB 03,12,12 composite image, April 17, 2011 at 12.00 UTC
Rys. 7 Mgły / Stratus. Kompozycja barwna RGB 03,12,12, MSG-2, 17 kwietnia 2011 r. 12 UTC

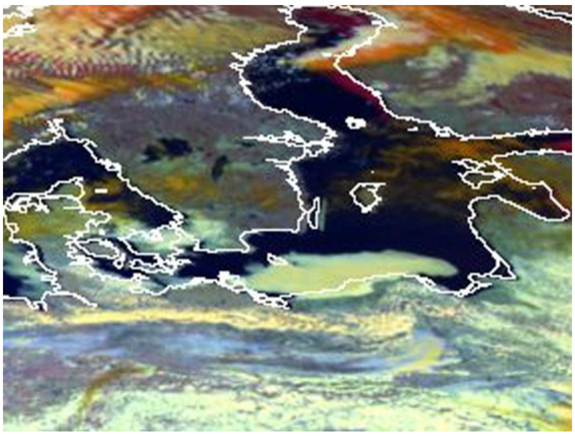


Fig. 8. Fog / Stratus. MSG-2 RGB 02,03,04 composite image, April 17, 2011 at 12.00 UTC
Rys. 8. Mgły / Stratus. Kompozycja barwna RGB 02,03,04, MSG-2, 17 kwietnia 2011 r. 12 UTC

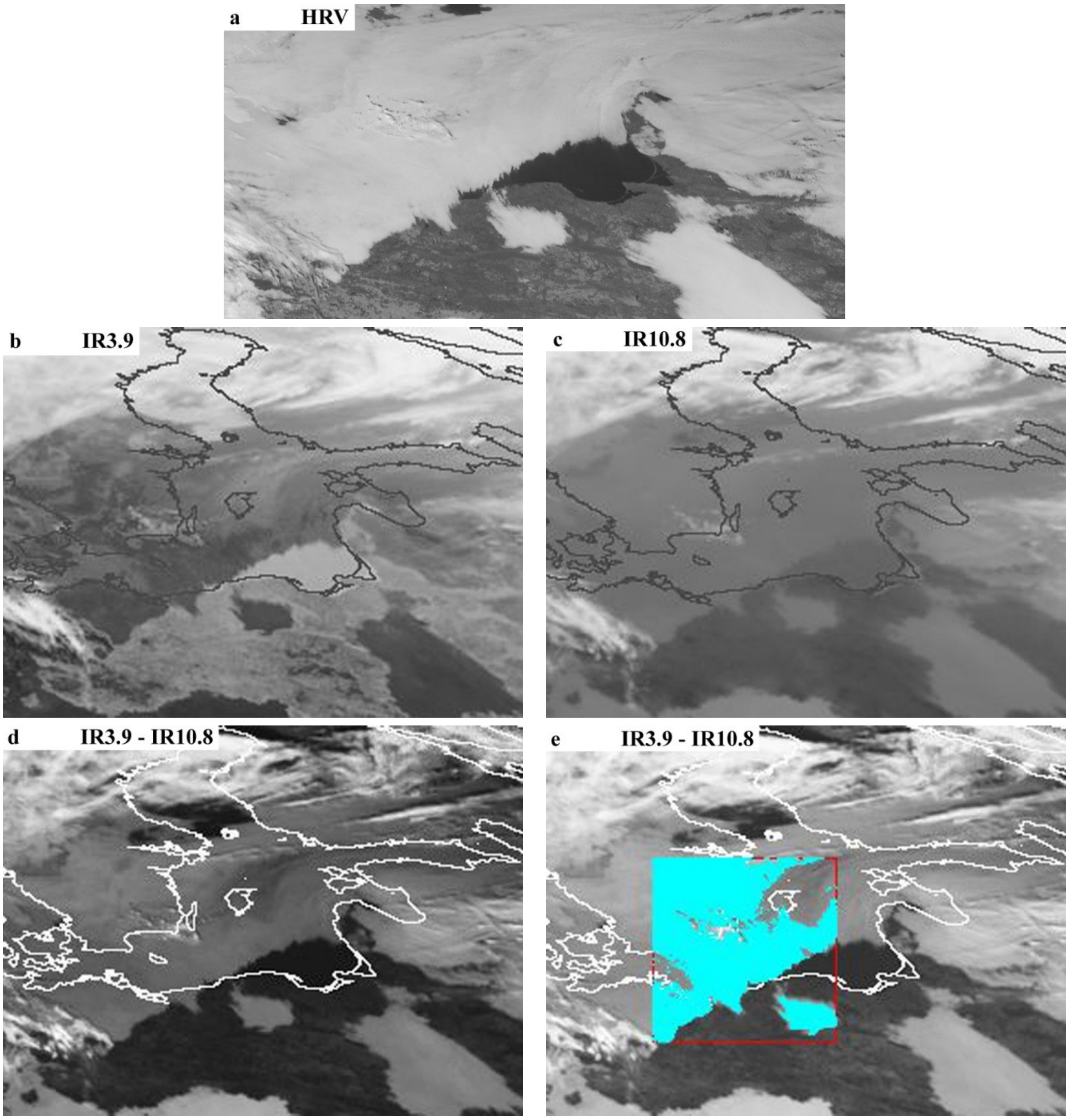


Fig. 9. Fog / Stratus at day. MSG-2 and differential images, November 2, 2011 at 12.00 UTC
Rys. 9. Mgły / Stratus w porze dziennej. Zobrazowania MSG-2 i różnicowe, 2 listopada 2011 r. 12 UTC

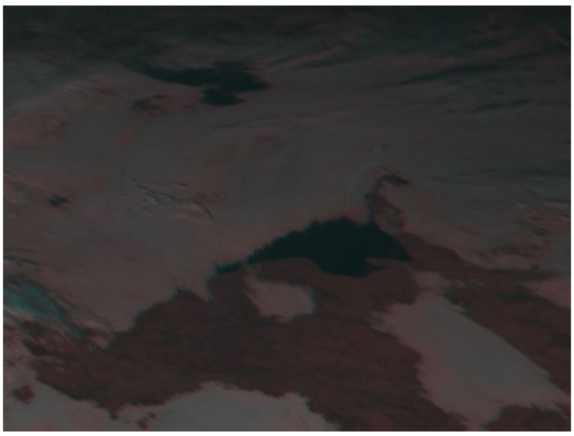


Fig. 10. Fog / Stratus. MSG-2 RGB 03,12,12 composite image, November 2, 2011 at 12.00 UTC
Rys. 10. Mgły / Stratus. Kompozycja barwna RGB 03,12,12, MSG-2, 2 listopada 2011 r. 12 UTC

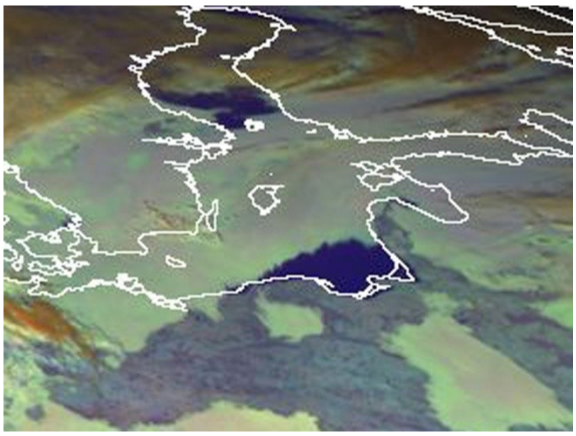


Fig. 11. Fog / Stratus. MSG-2 RGB 02,03,04 composite image, November 2, 2011 at 12.00 UTC
Rys. 11. Mgły / Stratus. Kompozycja barwna RGB 02,03,04, MSG-2, 2 listopada 2011 r. 12 UTC

November 2, 2011.

Fog and Stratus developed in a shallow layer of humid and relatively warm air under a temperature inversion observed over a significant part of Poland, Scandinavia and the Baltic Sea. The situation was analyzed on both, daytime (12 UTC) and nighttime (19 UTC) images.

Fog and Stratus are visible in the HRV channel image as a vast smooth area with a sharp contour (Fig. 9a). They are also quite clearly visible in the IR channels, especially in the IR3.9 channel (Fig. 9b). The differential images (Fig. 9d and e) and the RGB composite images (Fig. 10 and 11) strongly confirm fog and Stratus in the analyzed area. Blue pixels in figure 9e indicate that the radiation temperature values in the IR10.8 channel image are higher than 270K and the radiation temperature value difference between the IR3.9 and the IR10.8 channel images is within the range of 6K through 16K.

At nighttime differential images (Fig. 12c and d) of the radiation temperature differences have negative values. Navy blue pixels in figure 12d indicate the area where the temperature differences are in the range of –8K through –11K.

Conclusions

Effective application of satellite images to fog and Stratus detection requires profound knowledge concerning the characteristics of the specific spectral channels of the satellite scanners and the processes of the electromagnetic radiation and Earth / atmosphere interaction. Appropriate wavelength ranges – spectral channels – are selected from the spectrum in which radiation interaction with cloud particles, air molecules or ground surface is observed.

First general information about fog and Stratus is derived from characteristic features of the objects observed in the image: shape, dimension, structure and texture, as well as the object's location with respect to the Earth surface. During daytime, visible channels images are commonly used with the high resolution HRV one being especially informative.

More detailed methods of fog and Stratus analysis in satellite images are mainly related with analysis of reflectivity and radiation temperature values recorded for each image pixel. Taking into account characteristics of reflectivity and emissivity of various ground surfaces, aerosols, clouds and hydrometeors, as well as knowledge concerning radiation

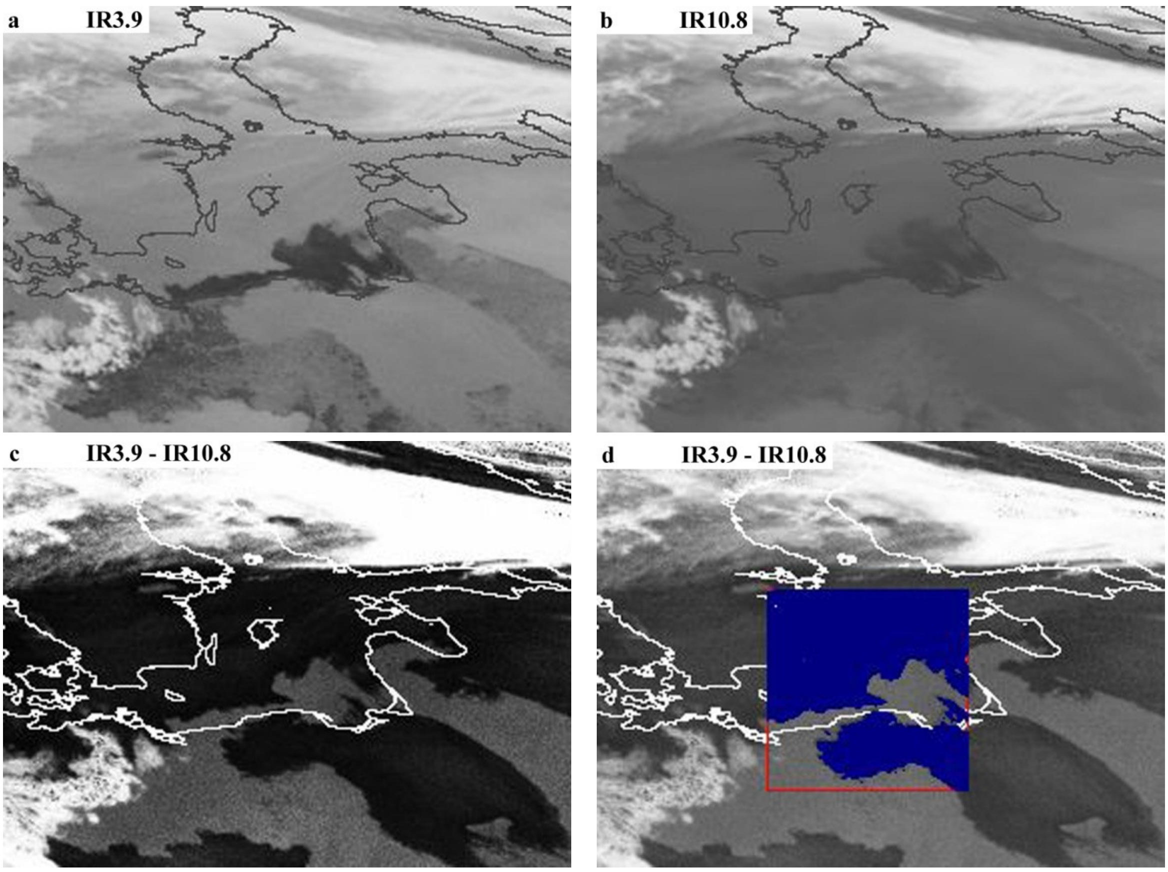


Fig. 12. Fog / Stratus at night. MSG-2 and differential images, November 2, 2011 at 19.00 UTC
Rys. 12. Mgły / Stratus w porze nocnej. Zobrazowania MSG-2 i różnicowe, 2 listopada 2011 r. 19 UTC

absorption in the atmosphere, miscellaneous products, like differential images and RGB composite images, are derived to facilitate detection and recognition of phenomena and observation of their features. These data constitute a source of information which is otherwise unavailable (invisible) in single spectral channel images.

The above presented application of MSG satellite images to fog and Stratus detection and interpretation is a part of research conducted in the Department of Geographic Information Systems of the Faculty of Civil Engineering and Geodesy of the Military University of Technology. The research is aimed to define areas of application of simplified algorithms for creating differential images and RGB composite images to detection and recognition of low layer clouds and hydrometeors using satellite data available at the LRIT user stations. The receiving station at the Department provides a limited set of satellite images (5 out of the 12 MSG-2 spectral channels), therefore the idea is to construct the algorithms using only these data.

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