A new algorithm for the detection of plumes caused by industrial accidents, based on NOAA/AVHRR imagery

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Abstract. The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellites may be used for detecting plumes caused by industrial accidents through the combined use of the visible (0.58–0.68 μm), near infrared (0.72–1.10 μm) and thermal infrared (11.5–12.5 μm) channels of the AVHRR. In this study a model algorithm is developed to identify pixels which correspond to plumes caused by industrial accidents. The novelty of the algorithm is that it combines the visible, the near infrared and the thermal infrared AVHRR channels in order to produce a two-dimensional feature space image in which the plumes can be detected and monitored. The algorithm was evaluated for four industrial accidents: in Enschede, the Netherlands on 13 May 2000; in Genoa, Italy on 13 April 1991; in Lyon, France on 2 June 1987 and in Kalohori, Greece on 24 February 1986. The effectiveness and reliability of the algorithm was found to be satisfactory in all case studies.

1. Introduction

In 1982 the Commission for the European Communities (CEC) issued Directive 82/501/EEC regarding Major Accident Hazards of Certain Industrial Activities (this Directive is often known as the Seveso Directive). The scope of the Directive was to minimize the risk of major accidents arising from industrial activities and to limit the resulting consequences of such accidents for man and the environment. Later accidents at Bhopal, India and at the Sandoz plant in Basle prompted the extension of the scope of the Directive. Additional substances were brought within its scope and greater emphasis was given to the storage of hazardous material. In 1996 the Seveso Directive was replaced with the more complete Seveso II Directive (96/82/EEC).

In recent years, and due to a number of incidents involving fires in industrial installations and warehouses, research has been oriented towards the definition of the properties and of the amount of the plume particulates generated by different

The aerosols of a plume produced by an industrial fire can be classified broadly into two main categories: the first is the dense plume category, consisting of areas with heavy aerosol loading, which are found over the broad disaster region. The second is the haze-like plume which has been transported by meteorological conditions to several kilometres from the site of the accident. Similar plume dispersions take place during forest fires (Andrae et al. 1988, Cahoon et al. 1992, Prins et al. 1998).

In several studies, (Ferrare et al. 1990, Kaufman et al. 1990, Kaufman et al. 1992, Cahoon et al. 1994) satellite data have been used for the analysis of the emitted smoke in order to quantify the gaseous output from forest fires. This technique relies upon the premise that if atmospheric aerosol concentrations are measurable by a satellite sensor, then the mass of CH$_4$, CO and other trace gases within a plume can be estimated using empirically derived correlations. The plume particulate may be detected by satellite sensors due to scattered radiation. However, satellite images have not been widely used in atmospheric dispersion studies for two main reasons: firstly, they are not well suited for the detection of atmospheric pollution because satellite sensors are generally not tuned to the absorption bands of the pollutants; and secondly, the spatial resolution of satellite data is too low for the study of plumes produced in local scale pollution episodes. The plume reflectance in the visible part of the spectrum is a function of its aerosol particle optical thickness and of its liquid water content. In particular, aerosols scatter the reflected short-wave radiation, thus they can be detected in the visible channel of a satellite sensor if it has the appropriate spatial resolution. Landsat Thematic Mapper (TM) has the advantage of a spatial resolution of about 30 m, consequently TM channel 1 (centred at 0.48 $\mu$m) may be used for plume detection. The disadvantage of TM is that Landsat data are collected every 16 days over a given area. However it is an interesting tool for studying aspects of atmospheric diffusion, such as the shape and the spread of plumes as a function of distance from the source (Desiato and Ciminelli 1991).

In order for a plume to be identified in the thermal infrared range, it must contain particles radiating as grey bodies. This condition is fulfilled by a plume in which water is condensed and the plume looks like a low cloud. It should be mentioned that a temperature contrast of the plume with the surface background is unlikely to support clear identification except in exceptional circumstances of very cold ground.

2. Theoretical background

Several research studies indicate that, despite the existing limitations, it is possible to investigate some aspects of plume dispersion using satellite images. Brimblecombe et al. (1978) used Landsat MSS data to study the shape and to draw probability contour maps of plumes emitted in the area of Derby, UK; Viswanadham and Torsani (1982) used 11 Landsat MSS images presenting plumes originated in eastern Cabo Frio, Brazil, to estimate the lateral dispersion and to evaluate the horizontal eddy diffusivity coefficient over a water surface. Scorcer (1988) outlined the usefulness of short visible wavelength NOAA/AVHRR and CZCS images for the observation of air pollution. Desiato and Ciminelli (1991) used Landsat TM images presenting
Remote sensing of plumes caused by industrial accidents

Chung and Le (1984) examined the feasibility of using satellite imagery to detect large-scale pollution episodes. Cahoon et al. (1994) used NOAA/AVHRR imagery to examine the development and spatial distribution of the severe 1987 forest fires in northern China and southern Siberia. In their analysis, false colour composites were produced with AVHRR channels 1, 2 and 4 to distinguish between smoke plume, snow, low clouds, high clouds, water, unburned vegetation and burned forest.

Kaufman et al. (1990) proposed two methods to obtain information about the emission products from biomass burning in Amazonia. Both techniques are based on the analysis of NOAA/AVHRR imagery (1 km resolution) and depend on the detection and count of fires using data from channels 3 and 4. Ackerman and Toon (1981), Kaufman (1987) and Fraser et al. (1984) related the carbon content of the plume to the single scattering albedo, as well as to the light extinction of the plume. Kaufman and Nakajima (1993) showed that smoke reduces the effective cloud droplet radius of bright clouds; but they also showed that smoke decreases the cloud reflectance due to absorption of sunlight by black carbon that is part of the smoke. Kaufman and Fraser (1997) showed that smoke particles increase the reflectance of thin or moderately thick clouds.

Christopher and Chou (1997) used a combination of spectral and textural measures in order to separate visually the plume aerosols from the underling background. The normalized AVHRR channel ratio (1–4)/(1 + 4) was first used to produce an image. This image was then used to compute several textural measures for a 9 pixel × 9 pixel window (Welch et al. 1988, Trovinkere et al. 1993, Christopher et al. 1996).

Baum and Trepte (1999) proposed a grouped threshold method for scene identification in NOAA/AVHRR imagery that may contain clouds, fires, smoke plumes or snow. The philosophy of the approach was to build modules, with each module consisting of groups of spectral threshold tests that were applied concurrently to each image pixel. The purpose of each group of tests was to identify uniquely a specific class in the image, such as a smoke plume. Practically, each class was identified using its spectral signature in a three dimensional feature space which was developed by overlying three different images of the scene: the first image represents the 0.63 μm reflectance of the scene (resulting from channel 1), the second represents the 11 μm brightness temperature of the scene (resulting from channel 4) and the third represents the 3.7–11 μm brightness temperature difference of the scene (resulting from channels 3 and 4).

Bandinelli and Carla (1992) used an hourly sequence of METEOSAT infrared images to detect and monitor an extended plume caused by the major fire on the large oil-tanker ‘Heaven’ in the gulf of Genoa. In this accident, several onboard tanks exploded and a great quantity of crude oil and gasoline burned, releasing in the atmosphere a dense plume.

In this study, the developed algorithm carries the advantages of a multispectral analysis and provides valuable results for the detection of plumes caused by major industrial accidents.

3. Data and methodology

The data used in this study are AVHRR high resolution images from NOAA-9, NOAA-11 and NOAA-14. AVHRR has a spatial resolution of 1.1 km at the

plumes originating from power stations in North and Central Italy, to study plume dispersion over the sea.
Nadir, a temporal resolution of approximately six hours (for both the ascending and descending NOAA nodes), and a swath coverage of 2700 km. AVHRR records incoming radiation in five spectral channels (µm): 0.58–0.68 (visible), 0.72–1.10 (near infrared), 3.55–3.93 (mid-infrared), 10.5–11.3 (thermal infrared) and 11.5–12.5 (thermal infrared). The four case studies examined in this work are for 13 May 2000 (14:44 UTC); 13 April 1991 (12:42 UTC); 2 June 1987 (13:55 UTC) and 24 February 1986 (12:55 UTC). The first date refers to the massive explosion in a firework factory in the town of Enschede (The Netherlands); the second refers to the major fire on the large oil-tanker ‘Heaven’, moored in shore near the oil terminal of the port of Genoa (Italy); the third refers to the Lyon industrial accident at the Shell refineries (France), whereas the latter date relates to the Kalohori industrial accident at the Jet Oil refinery (Greece).

The images used were available in NOAA Level 1-b format and were structured in 10-bit (1024-grey level) words. Initially, all images were geometrically corrected using a sample of Ground Control Points (GCPs) for each image in combination with the Level-1b meta-data information. Subsequently a common projection system was used for all AVHRR images, whereby images were calibrated, the calibration procedure being based on the conversion of digital numbers of the image to brightness temperature values for the infrared channels and to reflectance values for visible and near infrared channels with the use of the equations given in the NOAA Polar Orbiter Data Users Guide (Kidwell 1997) in combination with lookup calibration tables from the Satellite Ground Receiving Station of the University of Dundee.

A model algorithm was then developed, its main element being the definition of a two-dimensional feature space image as resulting from a combination of AVHRR channels 1, 2 and 5. Such a feature space is needed for the discrimination of pixels that contain plumes caused by industrial accidents from those that may contain clouds or the underlying surface. The AVHRR image of 13 May 2000 (14:44 UTC) was used for the development and the calibration of the algorithm, whereas the remaining three images were used for the application and evaluation of the algorithm. In particular, the two-dimensional feature space image was developed by superimposing two images, each one representing a pseudo-channel image resulting from the respective normalized ratios \((5–1)/(5+1)\) and \((2–1)/(2+1)\) of AVHRR channels 1, 2 and 5.

The first normalized ratio (hereafter CLD) takes into account the received radiation in AVHRR channels 1 and 5. It is given by the following formula (Chrysoulakis and Cartalis 2000):

\[
\text{CLD} = \frac{\text{Channel 5} - \text{Channel 1}}{\text{Channel 5} + \text{Channel 1}}
\]  

(1)

Clouds strongly reflect the short-wave solar radiation; consequently the records of AVHRR channel 1 which correspond to cloudy pixels correspond to high reflectance values. In general, cloud top temperatures are low; consequently the records of channel 5 which correspond to cloudy pixels correspond to relatively low brightness temperature values. Plumes generally have lower spectral reflectivities in the visible and higher temperatures than clouds. Only low level clouds (fair weather cumulus or stratus clouds) may obtain the same or warmer temperatures than plumes. Therefore, the records of channel 1 which correspond to pixels that contain plumes correspond to lower reflectance values in comparison to the respective records.
which correspond to cloudy pixels. Furthermore, the records of channel 5 which correspond to pixels that contain plumes correspond to higher brightness temperature values as compared to the records which correspond to cloudy pixels. It is very hard to separate clouds from plumes using only channel 5 when there are low-level clouds in the vicinity of the plumes. As a result, in the absence of low-level clouds, CLD values should have an upper limit for cloudy pixels and a lower limit for pixels that contain plumes.

The value of CLD was calculated for each pixel in the AVHRR image of 13 May 2000, producing a range of values from 0 to 1. CLD was used for the discrimination of pixels that contain plumes from those that contain clouds and for the masking (filtering) of cloudy pixels.

Visual inspection and histogram analysis of CLD images indicated that values smaller than 0.85 correspond to cloudy pixels, while values greater than 0.85 correspond to pixels which contain plumes. Therefore, plumes and clouds due to their different spectral signatures in pseudo-channel CLD can be identified and separated in a CLD image. In particular the CLD value of 0.85 may be used as a threshold for the discrimination of pixels that contain plumes from those that contain clouds. Accordingly, a cloud mask was applied by setting the digital numbers of all cloudy pixels in the image to the value of zero.

The second normalized ratio is known as the Normalized Difference Vegetation Index (NDVI) (Lillesand and Kiefer 1987, Rao et al. 1990, Sabins 1996). It takes into account the received radiation in AVHRR channels 1 and 2:

\[
NDVI = \frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}}
\]

For aerosols there is a rapid decrease in aerosol optical thickness (therefore reflectance) from the visible to near infrared. Although there is a rapid decrease in optical depth of plumes from the visible to the infrared, the difference of near-infrared reflectance minus visible reflectance (channel 2 − channel 1) is much lower for plumes than for the background surface, due to the existence of vegetation. For land surfaces covered by vegetation, the spectral reflectivity in the near infrared is much higher than that in the visible range; therefore NDVI values should be relatively high. As a result, and assuming that clouds are masked, NDVI threshold can be used to separate plumes from the underlying surface. In the case of plume dispersion over water, the plume can be also separated because pure water has negative NDVI values and absorbs almost all incident near-infrared radiant flux.

The value of NDVI was calculated for each pixel in the image, producing a range of values from −1 to 1. It is used, in this study, for the discrimination of pixels that contain plumes from those corresponding to the underlying surface, as well as for the masking of pixels that contain water bodies.

Visual inspection and histogram analysis of NDVI images indicated that positive values correspond to pixels that contain plumes and land surfaces, whereas negative values correspond to pixels that contain water surfaces. As a result, plumes, land surfaces and water surfaces obtain different spectral signatures in pseudo-channel NDVI; thus they can be identified and separated in an NDVI image. Subsequently, a mask for water surfaces was applied by setting the digital numbers of all pixels in the image that contain water bodies to zero. It should be mentioned that the algorithm does not take into account the spectral signature of clouds in
pseudo-channel NDVI, because all cloudy pixels are filtered by applying the CLD cloud mask.

In order to develop and calibrate the algorithm, the spectral signatures of plumes, clouds, land surfaces and water surfaces in both pseudo-channels CLD and NDVI were defined based on the AVHRR image of 13 May 2000 (14:44 UTC), which refers to the massive explosion in a firework factory in the town of Enschede (The Netherlands). Since the image was geometrically corrected, the pixels corresponding to the plume were defined using the coordinates of the accident’s site. Pixels which contained clouds, land surfaces and water surfaces were also identified. Mean CLD and NDVI values of pixels that contained each element (plume, cloud, land, water) are presented in table 1. These values correspond to the coordinates of the centre of the position of each element in the two-dimensional feature space as developed by superimposing the images of two pseudo-channels NDVI and CLD. Figure 1 shows a graphical representation of the two dimensional feature space; the $x$-axis is set to NDVI values, whereas the $y$-axis is set to CLD values. Relative positions of plumes, clouds, land surfaces and water surfaces are also presented in figure 1. It is obvious

Table 1. Mean CLD and NDVI values of pixels that contain plumes, clouds, land surfaces and water surfaces as resulted from the AVHRR image of 13 May 2000 (14:44 UTC). These values correspond to the coordinates of the position centres of each element in the NDVI–CLD space.

<table>
<thead>
<tr>
<th></th>
<th>CLD</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plumes</td>
<td>0.90</td>
<td>0.29</td>
</tr>
<tr>
<td>Clouds</td>
<td>0.64</td>
<td>0.15</td>
</tr>
<tr>
<td>Land surfaces</td>
<td>0.88</td>
<td>0.70</td>
</tr>
<tr>
<td>Water surfaces</td>
<td>0.93</td>
<td>−0.21</td>
</tr>
</tbody>
</table>

Figure 1. Graphical representation of the NDVI–CLD space. Relative positions of plumes, clouds, land surfaces and water surfaces are presented. Each element holds a different area of the NDVI–CLD space, which is the basis of its identification. The dashed line represents the CLD threshold of 0.85.
in this figure that each element covers a different area. Consequently, the model algorithm is able to identify plumes by detecting the positions of the corresponding pixels in the NDVI–CLD space.

The stages of the model algorithm are presented graphically in figure 2. Initially, the values referring to channels 1, 2 and 5 were extracted from the geometrically corrected AVHRR image. During the calibration procedure, digital numbers were converted to brightness temperature values for channel 5 and to reflectance values for channels 1 and 2. Then, the pseudo-channels CLD and NDVI were developed, whereby a cloud mask was applied to the CLD image and a water mask was applied to the NDVI image (FILTER1 in figure 2). During the latter process, the CLD values of pixels corresponding to clouds and the NDVI values of pixels corresponding to water surfaces were set to zero. The algorithm located all pixels with zero values in the CLD image and nullified the values of the respective pixels (pixels with the same coordinates in the common projection system) in the NDVI image and vice versa (FILTER 2 in figure 2). During the latter process the values of pixels corresponding to clouds and to water surfaces were set to zero in both CLD and NDVI images and the superimposition of the two double-masked images took place (LAYER STACK in figure 2). The superimposition was achieved by creating a pseudo-coloured RGB image of CLD, NDVI, 0; where the double-masked CLD pseudo-channel was set to RED, the double-masked NDVI pseudo-channel was set

Figure 2. Stages of the algorithm developed for the detection and monitoring of plumes caused by industrial accidents on the basis of NOAA/AVHRR imagery.
to GREEN, and all values of the BLUE channel were set to zero. This pseudo-coloured image represents the two-dimensional NDVI–CLD feature space in which plumes are detected and monitored. According to figure 1, the CLD values of pixels that contain plumes are high, whereas the NDVI values are relatively low. Consequently, plumes should appear a dark red colour in the pseudo-coloured image. Similarly, the CLD values of pixels that contain land surfaces are high as well as their NDVI values. Therefore, land surfaces should appear a green colour in the pseudo-coloured image.

4. Results

The algorithm was applied to the AVHRR image of 13 May 2000; in this image the plume was well located. The algorithm was also applied to the other three AVHRR images (13 April 1991, 2 June 1987 and 24 February 1986), i.e. in images where the exact positions of the respective plumes were unknown. Therefore, the reliability and the accuracy of the algorithm were evaluated on the basis of the latter three images. In all cases the final product of the algorithm was a pseudo-coloured RGB image (CLD, NDVI, 0), which represented the two-dimensional NDVI–CLD feature space. Pixels corresponding to the plumes appeared a dark red colour; thus they could be easily detected and separated in each pseudo-coloured image. Pixels corresponding to clouds or to water surfaces appeared in black, whereas pixels corresponding to land surfaces appeared a green colour. Since all images were geometrically corrected, the coordinates corresponding to the detected plumes were compared with the respective coordinates of the accidents sites in order to estimate the accuracy of the algorithm.

In figure 3, a pseudo-coloured image is presented, resulting from the application of the algorithm to the AVHRR image of 13 May 2000. The pixels in red in the vicinity of Enschede area correspond to the plume caused by the massive explosion in the firework factory. These pixels can be easily separated in the NDVI–CLD space, therefore the plume is detected and monitored.

![Figure 3. Pseudo-coloured RGB image (CLD, NDVI, 0), resulting from application of the algorithm to the AVHRR image of 13 May 2000 (14:44 UTC). This pseudo-coloured composition represents the two-dimensional NDVI–CLD feature space. The pixels in heavy red in the vicinity of Enschede area correspond to the plume caused by the massive explosion in the firework factory.](image-url)
Figure 4 shows a pseudo-coloured image resulting from the application of the algorithm to the AVHRR image of 2 June 1987. The pixels in red in the vicinity of Lyon area correspond to the plume caused by the accident in the Shell installations. The plume is detected well and monitored with the use of the NDVI–CLD space.

Figure 5 presents a pseudo-coloured image resulting from the application of the algorithm to the AVHRR image of 13 April 1991. The pixels in red over the gulf of Genoa correspond to the plume caused by the major fire on the oil-tanker ‘Heaven’. These pixels can be more easily separated in the NDVI–CLD space as the plume is dispersed over the sea. The pixels corresponding to the sea appear in black, thus a homogenous background is developed. The enhanced contrast between the plume and its background has resulted in the plume being more easily detected and monitored.

5. Error analysis and evaluation of the algorithm

In order to re-define the domains of the spectral signatures for plumes, clouds, land surfaces and water surfaces in the NDVI–CLD space, a statistical analysis was performed taking into account the results of the model algorithm for all mentioned case studies. Each domain is allocated the area occupied by each element (plumes, clouds, land surfaces, water surfaces). Therefore, the goal of this analysis is to specify the overlapping percentage among these areas. Zero or low overlapping indicates that pixels corresponding to each element can be absolutely separated, which implies that the accuracy of the algorithm is high. Consequently, the overlapping percentage among these areas in the NDVI–CLD space is a measure of the reliability of the model algorithm, as it represents its efficiency to separate pixels corresponding to plumes, clouds, land surfaces or water surfaces in a pseudo coloured RGB image (CLD, NDVI, 0).

Mean and standard deviation values of CLD and NDVI for pixels that contain

![Figure 4. Pseudo-coloured RGB image (CLD, NDVI, 0), resulting from application of the algorithm to the AVHRR image of 2 June 1987 (13:55 UTC). This pseudo-coloured composition represents the two-dimensional NDVI–CLD feature space. The pixels in heavy red in the vicinity of Lyon area correspond to the plume caused by the accident at the Shell installations.](image-url)
Figure 5. Pseudo-coloured RGB image (CLD, NDVI, 0), resulting from application of the algorithm to the AVHRR image of 13 April 1991 (12:42 UTC). This pseudo-coloured composition represents the two-dimensional NDVI–CLD feature space. The pixels in heavy red over the gulf of Genoa correspond to the plume caused by the major fire on the oil-tanker 'Heaven'.

Plumes, clouds, land surfaces and water surfaces based on overall available AVHRR images were calculated and are presented in Table 2. Mean values correspond to the coordinates of the centres of the areas occupied by each element in the NDVI–CLD space. The size and the boundaries of each area could be accurately defined by applying the algorithm to a wide number of case studies. In the present study, the standard deviation values, which are presented in Table 2, are used in order to estimate the size and the boundaries of each area. Therefore the position (in the NDVI–CLD space) of a pixel that contains a cloud, a plume and land or water may be located with probability 68.27% in the area which is outlined in both the CLD and NDVI axes by the mean value, with standard deviation from the mean at ±1.

Accordingly:

Table 2. Mean and standard deviation values of CLD and NDVI for pixels that contain plumes, clouds, land surfaces and water surfaces as resulting from the AVHRR images of 13 May 2000 (14:44 UTC), 13 April 1991 (12:42 UTC), 2 June 1987 (13:55 UTC) and 24 February 1986 (12:55 UTC). Mean values correspond to the coordinates of the position centres of each element. Standard deviation values are related to the dispersion of each element in the NDVI–CLD space.

<table>
<thead>
<tr>
<th>Element</th>
<th>CLD Mean</th>
<th>CLD Standard deviation</th>
<th>NDVI Mean</th>
<th>NDVI Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plumes</td>
<td>0.90</td>
<td>0.05</td>
<td>0.28</td>
<td>0.13</td>
</tr>
<tr>
<td>Clouds</td>
<td>0.66</td>
<td>0.22</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>Land surfaces</td>
<td>0.89</td>
<td>0.06</td>
<td>0.58</td>
<td>0.22</td>
</tr>
<tr>
<td>Water surfaces</td>
<td>0.93</td>
<td>0.04</td>
<td>−0.22</td>
<td>0.05</td>
</tr>
</tbody>
</table>
The position of a pixel that contains a plume can be located with probability 68.27% in the NDVI–CLD area which is bounded by an ellipse. The coordinates of the midpoint between the two centres of curvature of the ellipse are defined by the mean NDVI and CLD values for plumes from table 2 (0.28 and 0.90). The major axis of the ellipse is parallel to the NDVI axis and its length is equal to two NDVI standard deviations for plumes \((2 \times 0.13 = 0.26\) units of length), whereas the minor axis is parallel to the CLD axis and its length is equal to two CLD standard deviations for plumes \((2 \times 0.05 = 0.10\) units of length).

The position of a pixel that contains a cloud can be located with probability 68.27% in the NDVI–CLD area which is bounded by an ellipse. The coordinates of the midpoint between the two centres of curvature of the ellipse are defined by the mean NDVI and CLD values for clouds from table 2 (0.14 and 0.66). The major axis of the ellipse is parallel to the CLD axis and its length is equal to two CLD standard deviations for clouds \((2 \times 0.22 = 0.44\) units of length), whereas the minor axis is parallel to the NDVI axis and its length is equal to two NDVI standard deviations for clouds \((2 \times 0.15 = 0.30\) units of length).

The position of a pixel that contains land surface can be located with probability 68.27% in the area of the NDVI–CLD space which is bounded by an ellipse. The coordinates of the midpoint between the two centres of curvature of the ellipse are defined by the mean NDVI and CLD values for land surfaces from table 2 (0.58 and 0.89). The major axis of the ellipse is parallel to the NDVI axis and its length is equal to two NDVI standard deviations for land surfaces \((2 \times 0.22 = 0.44\) units of length), whereas the minor axis is parallel to the CLD axis and its length is equal to two CLD standard deviations for clouds \((2 \times 0.06 = 0.12\) units of length).

The position of a pixel that contains pure water surface can be located with probability 68.27% in the NDVI–CLD area which is bounded by an ellipse. The coordinates of the midpoint between the two centres of curvature of the ellipse are defined by the mean NDVI and CLD values for water surfaces from table 2 \((-0.22\) and 0.93). The major axis of the ellipse is parallel to the NDVI axis and its length is equal to two NDVI standard deviations for water surfaces \((2 \times 0.05 = 0.10\) units of length), whereas the minor axis is parallel to the CLD axis and its length is equal to two CLD standard deviations for clouds \((2 \times 0.04 = 0.08\) units of length). Only pure water is considered in this study; this is due to the fact that the reflectance of natural water depends upon sediment and therefore its reflectance in the visible as well as in the near infrared could be high; in this case water ellipse could overlap other ellipses.

The ellipses for plumes, clouds, land surfaces and water surfaces in the NDVI–CLD space are presented graphically in figure 6. The relative positions of these areas are related to the efficiency of the algorithm to separate pixels corresponding to each element in a pseudo coloured RGB image (CLD, NDVI, 0), with probability 68.27%. All unmasked pixels in such a pseudo coloured image must have an NDVI value greater than 0 and a CLD value greater than 0.85.

The pixels which are covered partially by two or more elements ('mixed' pixels) are located outside of the ellipses or belong to more than one ellipse in figure 6. For these pixels the efficiency of the algorithm may be less than 50% because it depends
Figure 6. The encircled areas correspond to the value domains for plumes, clouds, land surfaces and water surfaces in the NDVI–CLD feature space. The relative positions of these areas indicate that the separation of pixels corresponding to each element can be satisfactorily achieved using the respective spectral signatures.

on the percentage of the pixel being covered by each element. The spatial resolution of a satellite sensor plays the most important role regarding the existence of 'mixed' pixels. For instance such pixels exist in AVHRR images due to the low spatial resolution of the sensor.

The model algorithm was evaluated by examining two parameters: (a) its efficiency for 'real event' detection; and (b) its ability for 'false alarm' rejection. The term 'real event' describes the situation when a plume exists in the satellite image and the algorithm detects the respective pixels. The term 'false alarm' describes the situation when the algorithm has classified some pixels as pixels that contain a plume, but there is no plume in the respective area of the satellite image.

The efficiency of the algorithm for 'real event' detection may be reduced by the following parameters: (a) cloud cover; (b) absorption of radiation by the atmospheric water vapour; and (c) AVHRR scanning geometry which causes pixel overlapping in many cases. In all case studies the efficiency of the algorithm for 'real event' detection was excellent (see figures 4 and 5). However, CLD values less than 0.85 are possible for pixels that contain plumes (i.e. a plume that partially covers the pixel); in these cases the algorithm fails because the respective pixels are filtered. If the CLD threshold was set to a value less than 0.85 in order to keep the respective pixels unfiltered, the ability of the algorithm for 'false alarm' rejection would decrease. This is because in the latter case, if there are low broken clouds or low-level clouds in the image, they will not be filtered, and will be classified as plumes.

The ability of the algorithm to reject 'false alarms' is reduced in the following cases: (a) when there are low-level clouds in the vicinity of plumes; (b) when the edges of extended cloud systems partially cover some pixels of the satellite image; (c) when there are broken clouds with CLD values greater than 0.85; and (d) when there are small clouds covering areas less than the spatial resolution of AVHRR. The reason is that the CLD threshold of 0.85 fails in cases where pixels are partially
covered by clouds (small cloud or edge of extended cloud system). The radiation coming from these areas is a combination of the radiation reflected at the land surface and at the clouds as well as of the thermal radiation emitted from the land surface and from the clouds; therefore the CLD values for the respective pixels are greater than 0.85. These pixels are mixed, corresponding neither to land surfaces nor to plumes. In addition, low-level clouds may obtain CLD values greater than 0.85. If the CLD threshold was set to a value greater than 0.85 in order to filter these mixed pixels, the ability of the algorithm for ‘false alarm’ rejection increases, but the efficiency of the algorithm for ‘real event’ detection decreases. This is because in the latter case some of the pixels corresponding to plumes are filtered.

6. Conclusions
The detection of a plume in a satellite image relates to its dispersion, optical thickness and temperature structure, as well as to the spatial resolution of the satellite sensor. The methodology proposed in this study is based on the development of a model algorithm which produces a two-dimensional feature space image in order to discriminate pixels that contain plumes from those that may contain clouds or the underlying surface. The two-dimensional feature space is generated by combining the normalized ratios \( \frac{5-1}{5+1} \) and \( \frac{2-1}{2+1} \) of AVHRR channels 1, 2 and 5. The first normalized ratio (named CLD) takes into account the received radiation in the visible and thermal infrared. It is used for discrimination of pixels that contain plumes from those that contain clouds, and for masking of cloudy pixels. The second normalized ratio (the well known NDVI) takes into account the received radiation in the visible and near infrared. It is used for discrimination of pixels that contain plumes from those corresponding to the underlying surface, as well as for masking of pixels that contain water bodies. The final product of the algorithm is a pseudo-coloured RGB image (CLD, NDVI, 0), which represents the two-dimensional NDVI–CLD feature space. This pseudo-coloured image is developed by superimposing the two images which represent the pseudo-channels NDVI and CLD. Pixels corresponding to plumes appear in a heavy red colour, in order to be detected and monitored in the pseudo-coloured image.

The AVHRR image of 13 May 2000 was used for the development and the calibration of the algorithm, whereas the images of 13 April 1991, 2 June 1987 and 24 February 1986 were used for the evaluation of the algorithm. The algorithm was evaluated by examining two parameters: (a) its efficiency for ‘real event’ detection and (b) its ability for ‘false alarm’ rejection. Since all images were geometrically corrected, the inspection was based on the comparison of the coordinates of the detected pixels with the (known) coordinates of the sites where industrial accidents occurred. In all case studies the efficiency of the algorithm for ‘real event’ detection was satisfactory. The ability of the algorithm for ‘false alarm’ rejection was poor in the following cases: (a) when the edges of extended cloud systems partially covered some pixels of the satellite image; (b) when there were low level or broken clouds; and (c) when there were small clouds which covered an area less than the spatial resolution of AVHRR.

The effectiveness and reliability of the algorithm may be improved if it is combined with other sources of information, such as knowledge of the existence of a fire caused by an industrial accident. Such information may be retrieved by the application of a fire detection algorithm in the AVHRR images. In this case, the implementation
of the Sevezo Directive may be supported with respect to operational plans for the abatement of major industrial hazards.

References


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