Tracking of smoke plumes generated by Kuwaiti's oil wells fire, using model based image analysis

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ABSTRACT:

A study was carried out to assess the relation between the observed environmental damages in Iran during and after 1991, and the environmental contamination caused by the Persian Gulf War in Kuwait. Special attention is given to the use of Remote Sensing (RS) data and Geographic Information System (GIS) methods. Field observations in Iran and the region were used for verification and identification purposes. In this study, 1267 NOAA-AVHRR images from four satellites that were transmitting data during 1991 (NOAA-9, 10, 11 and 12) were used for tracking smoke plumes of Kuwait's oil fires to the coast and territory of Iran.
The study concludes that the available data supports the assumption that smoke, soot and black and acid rains from Kuwait reached the territory of Iran. Application of model based image analysis and GIS permitted a quantitative and qualitative estimate of the smoke concentration over the Persian Gulf area.
During the peak period of the fires, the wells were emitting about 5,000 tons of greasy soot and smoke daily. It has been reported that there were about 225 smoky days in total during 1991. If we take in average about 4,000 tons of smoke daily (80% of 5,000 tons), then we have: given the accumulated output of the oil well fires of 4,000 tons/day * 225 days = 900000 tones and not considering smoke drifting on the image boundaries. It is estimated that about 0.37 * 900000 = 333000 tones of oil and oil related pollutants were transported by air from the Kuwaiti oil well fires to the territories of Iran, where 0.37 is the integrated smoke density over Iran relative to the integrated smoke density over the whole image.
As a conclusion, this study demonstrated how remote sensing and GIS data could be used to track smoke plumes of Kuwait's oil fires of the 1991 Persian Gulf War to the coast and territory of Iran. The results are in part qualitative (inspection of visual patterns) and in part provide quantitative information in conjunction with other data.

1. INTRODUCTION

Two specific events that occurred during the Persian Gulf War have made a severe impact upon the environment in the region. Late January 1991 millions of barrels of crude oil were released into the Persian Gulf from tankers and oil terminals located off the coast of occupied Kuwait. Less than a month later nearly 700 Kuwaiti oil wells, storage tanks, refineries and facilities were blown up and set on fire. An estimated nine hundred million barrels of oil were burned or spilled onto the land during the following 9 months generating trails of smoke and soot over several hundreds of miles. This caused the intrusion of massive quantities of smoke (soot), sulphur dioxide, nitrogen oxides and unburned hydrocarbons into the atmosphere (Jenkinks, 1991 a, b) [1]. The spread of soot and particulate matter took place within a large area as stated in WMO Report
It is not easy to assess the full impact that these events have had and still may have on the local and regional ecosystems. However, it may be expected that their effects will linger on for many years to come. The impacts in the Persian Gulf from the war are certainly among the heaviest environmental pressures incurred in recent times (Price, 1993) [2].

2. Method

2.1 Image data selection and pre-processing

The data have been pre-processed for sensor radiometric calibration and georeferencing by National Centre for Atmospheric Research of USA (NCAR).
As the data vary by time of the day, sunangle, average amount of haze in the sky, an additional radiometric calibration

is needed. For a selected test area which had no obstruction by clouds or smoke and for which the groundcover was constant, for each image a linear radiometric correction was applied which mapped the histograms of the reference areas located in the Saudi desert to the same mean and standard deviation as a reference date. The script used as procedure is presented in [3, Annex F].
In order to reduce the amount of processing a selection of all data has been made on the following criteria:
For the purpose of the detection and estimation of smoke and smoky clouds:
- Channel 2, the near infrared must have sufficient incoming radiation.
- Shadow and shading effects caused by clouds and mountains should be at a minimum.

The selection criteria are met by Midday images.
There were some limitations for generation of reference image for estimation of smoke density. Having no fully clouded free images for the time before the Gulf War in the available dataset was a major problem in generating the reference image. Bad quality of numbers of the available NOAA-AVHRR images also was one of the restrictions on selecting images that could be used in making the reference image.
For making the reference image, some sub windows of the images from May and June period also were used, so because of smoke and soot deposition in those periods, the smoke density estimation would be already underestimated.

2.2 Introduction to model based image analysis, the integration of sparse ship and ground observations with densely sampled NOAA data

In the context of the problem of assessing the damage caused by the oil during the Gulf War, the role of the analysis of the NOAA satellite images is to solve a transportation problem.
The role of image analysis is to calibrate the transportation models involved and to provide a spatial dense sample set of the estimated concentration of the pollutants.
The available external data consists of sparse samples at the receiving side, sparse meteorological data for the initialization of the transport equations and some estimates of the material flow as a function of time at the sources.
Model based image analysis relates the ground observations through an explicit model to the spatial patterns detected in the digital images, and transforms the image data to estimated parameters for the amount of oil derived pollutants. The ground observations are used to calibrate the models such that the models produce a minimum error / maximum likelihood estimate prediction of the ground observations at the given ground sample points.
The quality of the model fitting is derived from the residual errors between model and ground observations after a best fit.
The major transportation model is transport by air in the form of soot, oily or greasy smoke and mixtures of haze and cloud with oil derived pollutants.
For aerial transport, the required wind field data at some isobaric intervals could not be made available. The alternative was to estimate the smoke density as a function of space and time. The spatial density of smoke is accumulated over observation time. The accumulated smoke density is calibrated against point samples at ground observations, providing a dense sample of predicted accumulated load of pollutants at and between the observations at ground stations.

2.3 Model for estimation of the accumulated smoke concentration

Goal: estimation of total amount of pollutants transported by air from the Kuwaiti oil fires to the territory of the Iran. The product to be delivered is an accumulated smoke density map calibrated to the source-input data and available ground observations.
<u>Pre-processing</u>
Before the transportation models can be inverted, it is necessary to correct the remotely sensed data for undesirable geometric and radiometric effects. An important criterion for the quality of the pre-processing is that objects with constant properties should show constant parameters of the statistical models (such as mean vector and covariance matrix) that relating objects properties to RS measurements.
In view of the large amount of data a selection has to be made of data suitable for the purpose. This is treated under " pre-processing of data".
The model used here links the reflectance in the near infrared channel to the estimated smoke concentration by assuming that photons over land are mostly absorbed by smoke particles, while the combination of smoke and water particles produces an additional reflectance over the high absorption of NIR radiation by water.

smoke-fraction(t) = 1 – SQRT(Reflection(t)/Reflection. Scene Land).

Over water bodies the approximate model is:
smoke-fraction(t) = (Reflection(t) – haze x Reflection Cloud)/Reflection Smoke ,

For all scene elements on land, a reference reflection value (a function of cover class, slope and sunangle) was derived, called "reference image".
The detection problem consists of detecting clouds or haze by the rule:

IF smoke-fraction <0 THEN cloud or haze i.e. smoke_fraction =0.

The estimated pollution load is derived from a fit of the sum_over (t) of smoke-fraction (t) spatial distribution to observed point samples of soot and oily deposits.
In this phase of the study it was not possible to automatically detect and trace smoke clouds going through the condensation level, forming clouds and eventually producing black rain.
As mentioned preprocessing and data selections were performed. Radiometric correction was based on parametric histogram matching (mean and standard deviation) over a cloud and smoke free area (West of Kuwait).

Considerable effort was spent on the generation of reference reflectance data for the land area. Minimum and maximum operators plus manmade context masks were used to remove cloud, snow, haze and smoke from a sequence of images.

Estimating the smoke-concentration over water required a manual fitting of the haze level such that the smoke pattern over land matched the pattern over water.

3. TRACKING OF SMOKE PLUMES AND SOOT

The image dated March 11, 1991 shows a smoke plume over the Gulf and Saudi Arabia; however, differentiating between the fire sources and the smoke is difficult on this Band 2 image. Therefore, Band 3 of the NOAA-AVHRR sensor, which is very suitable for detection of fires, was used for detection of the burning oil wells. The Kuwait oil wells fires show a clearly visible colour on band 3. It should be indicated that there are two major fire sources, one to the North and the other one to the South of Kuwait City (Plate 1).

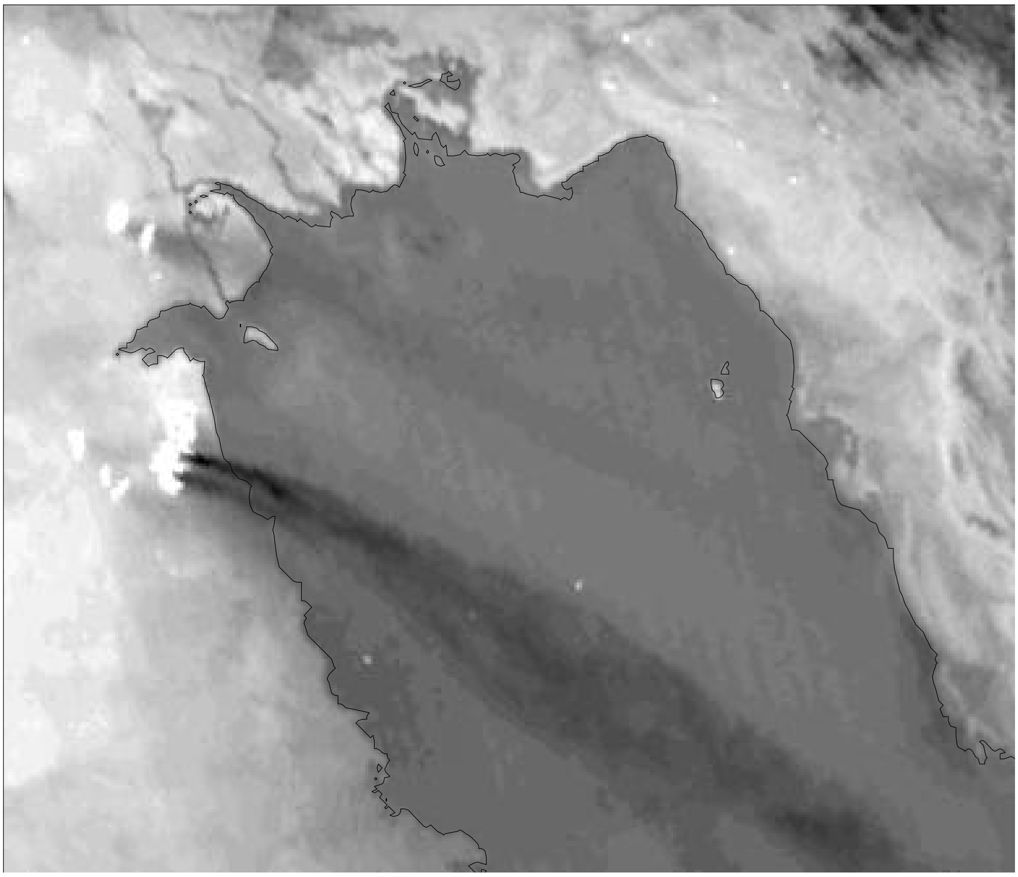

Plate 1: Oil field fires is appeared in white spots (SCWMRC, February 1998)

The smoke plumes over the Persian Gulf were steered by the wind direction, so that different altitudes, they were moved into various directions. The direction of the smoke movement was eastward (towards the Iran) during March and April 1991.

NOAA-AVHRR images of the period from May 13, 1991 to July 13, 1991 indicate the movement and persistence of smoke over Iran. Smoke is clearly visible over Iran, particularly over the provinces of Bushehr, Khuzestan, and over the coastal zone of Iran.
On June 14, 1991, the wind was stable and decreased in force compared to the preceding days, so heavy smoke and soot concentrated over the Northern part of the Persian Gulf, particularly over Abadan, Shadegan, Mahshahr (48°31' E and 30°.53' N) in Iran as well as over Kuwait itself.

On June 15, 1991 the wind direction changed to South and Southwest, so heavy smoke and soot concentrations were distributed over Bushehr and Southern Khuzestan as well as over the Iran-Iraq border area. In spite of the dispersion of the smoke over this large area, high concentrations of heavy smoke were still visible over the Shadegan and Abadan areas, as can clearly be observed on the NOAA, band 1 image dated June 15, 1991.

A colour composite image of band 1, 2 and 3 (RGB), of June 15, 1991 shows a smoke plume that extends to the Iran-Iraq border (Plate 2). The source of this smoke (the burning wells near Kuwait City) can be clearly distinguished on this colour composite image. After a few days of variable wind directions, a more stable southwestern wind established for the period June 20 to June 24, 1991. Consequently, smoke and soot was moved to the interior of Iran. NOAA-AVHRR images of this period (June 21 and June 22, 1991) show smoke and soot over Iran, particularly over Ahwaz (the capital of Khuzestan) and the Fars province, as well as over the areas of Abadan and Shadegan.

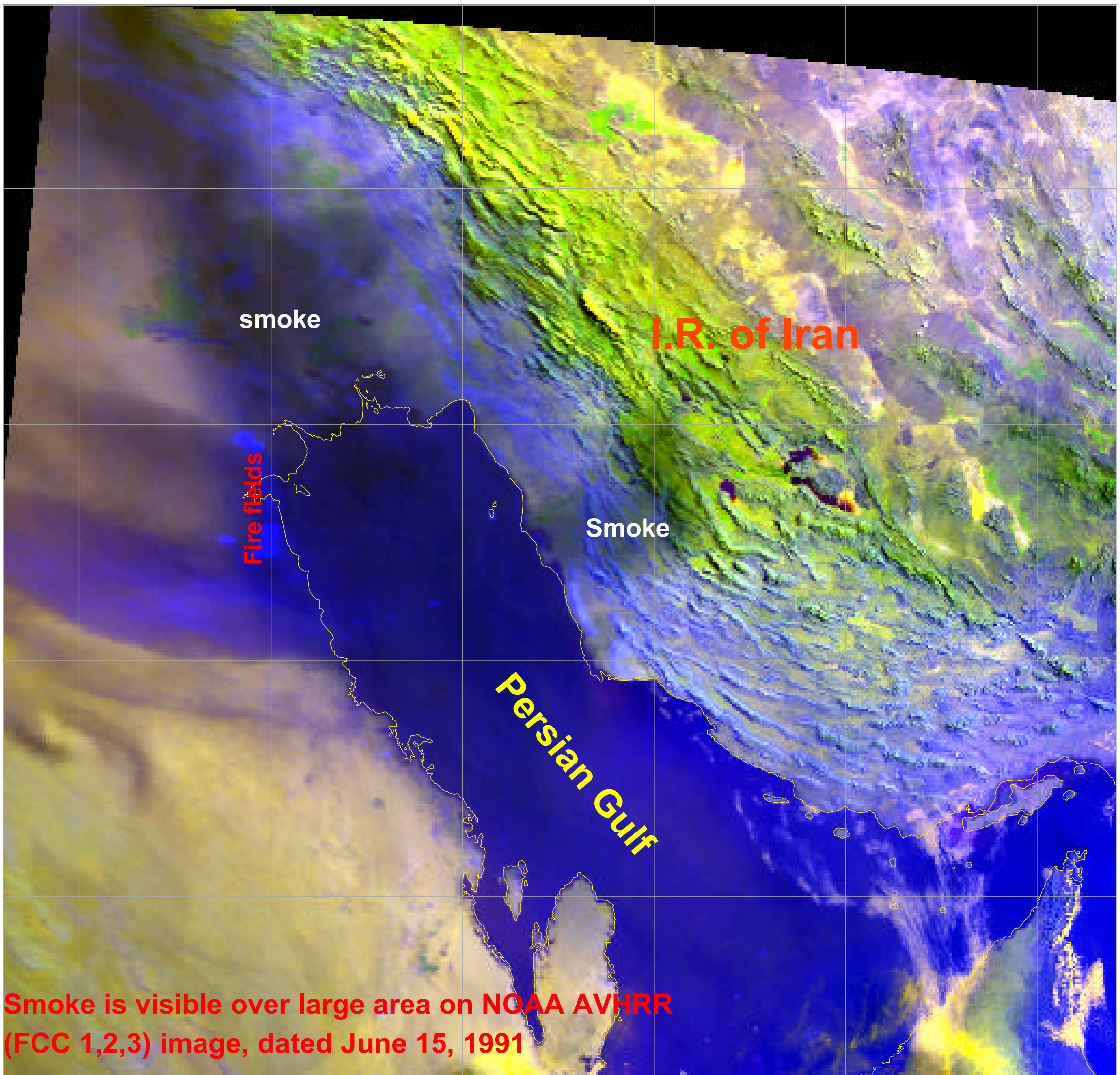

Plate 2: False Colour Composite Image Band 1, 2 and 3 (RGB) shows smoke intrusion over Iran. Dated June 15, 1991 (After SCWMRC, 1998)

Analysis of a sequence of SPOT multispectral and panchromatic images has been carried out to find confirmation of soot deposition in the area of Shadegan, in the Imam Khomeini major shipping port and in the surrounding marshlands. A SPOT multispectral image, acquired before the Gulf war (July, 1990 XS), shows clear lands without any soot (Plate 3a). Visual comparison of this image with an image taken just after the war (July 14, 1991 Pan) Plate 3b shows that the contrast between adjacent fields and between other soil-related features has diminished considerably. It is assumed that this is due to soot deposition in the Shadegan and Mahshahr areas. After matching the histograms of the above-mentioned images, specific windows were selected for detailed spectral analysis.
Comparing the histograms of the selected windows of the images of 1991 and 1992, a significant decrease in the percentage of reflectance can be clearly distinguished in the SPOT panchromatic image of 1991. More research is required to determine whether this decrease in reflectance of the land surface can indeed be attributed to the soot deposition observed in the field. In such research the possibilities of a seasonal effect and of rainfall should also be taken into account. In addition, from the previous visual analysis of the smoky NOAA_AVHRR images during May and June 1991, can be concluded that the Shadegan and Mahshahr areas are predominantly covered by smoke clouds.

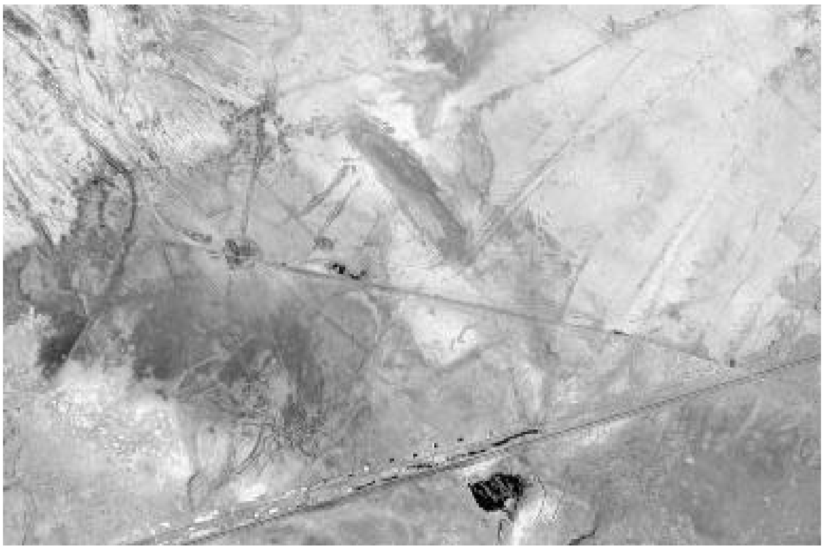

Plate 3a: sub window of SPOT image (XS, (B1+B2)/2), indicates smoke and soot free land in Shadegan area, Iran, Aug. 28, 1990

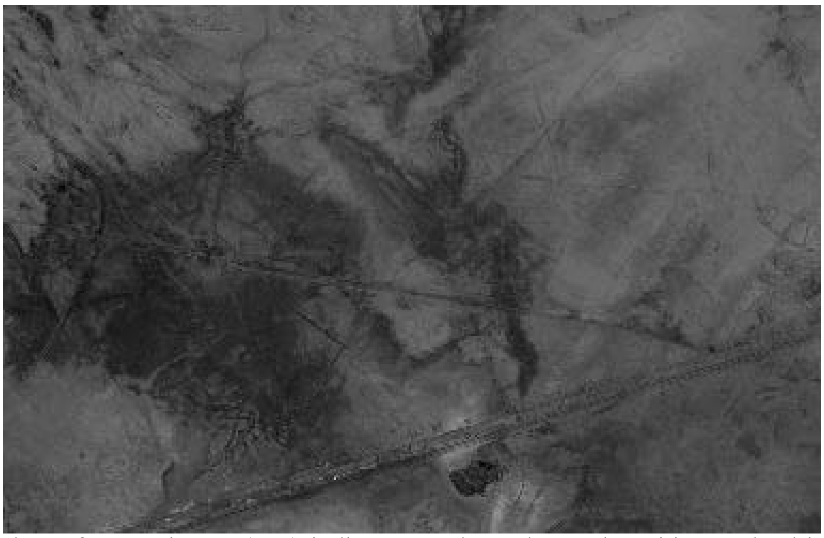

Plate 3b: sub window of SPOT image (Pan) indicates smoke and soot deposition on land in Shadegan area, Iran, July 14, 1991

3.1 Density of smoke and soot estimation, using satellite images over the territory of Iran

After performing analysis and calculations on full series of proper available NOAA-AVHRR images the following results have been obtained.
Density of smoke coverage over the Persian Gulf area was estimated, using digital image processing and smoke detection model, for whole smoky period (nine months).

A few samples on application of model for smoke density estimation and obtained results are presented by plate 4 and 5.

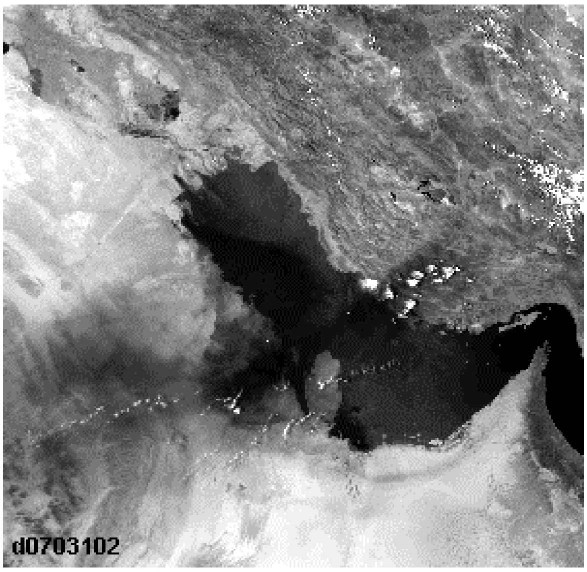

Fig 4a

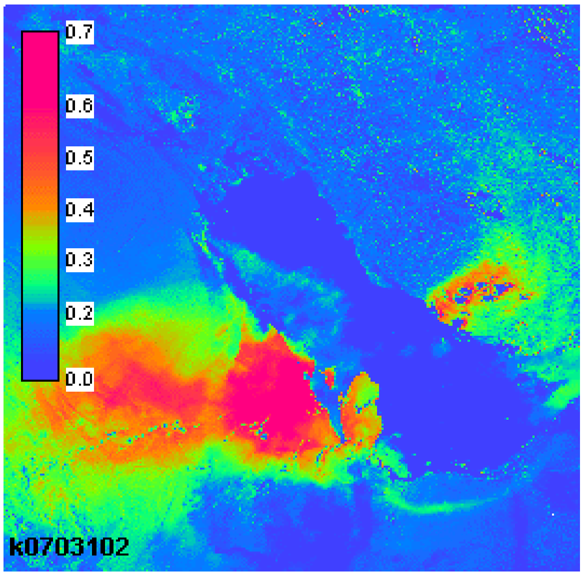

Fig4b

Fig 4a A sample of midday smoky image acquired on 03 July 1991 which is used for smoke density estimation.
Fig 4b A sample of results obtained from execution of model on midday smoky image acquired on 03 July 1991. Extent of smoke generated from Kuwait's oil well fires with different levels of concentration is presented in different colors.

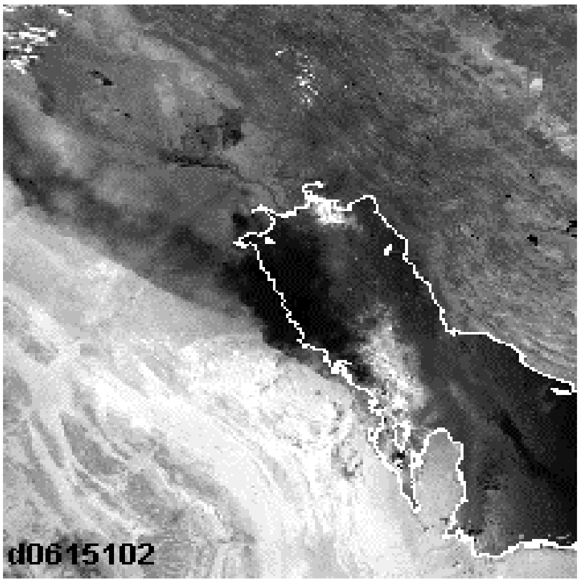

Fig 5a

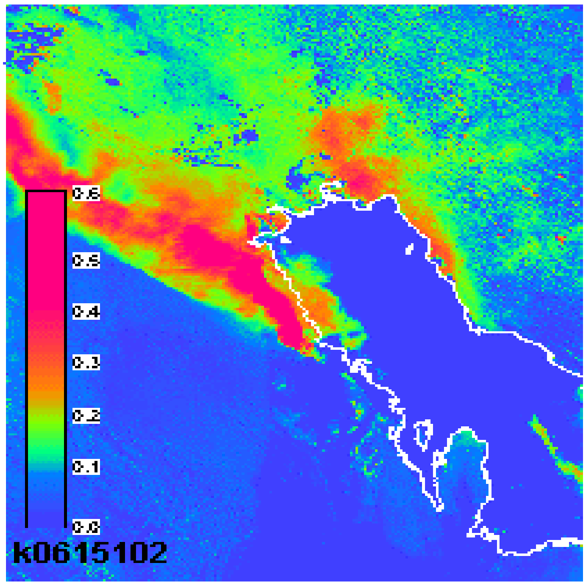

Fig 5b

Fig 5a A sample of midday smoky image acquired on 15June1991 which is used for smoke density estimation.
Fig 5b A sample of results obtained from execution of model on midday smoky image acquired on 15 June1991 for the Persian Gulf area. Extent of smoke generated from Kuwait's oil well fires, with different levels of concentration is presented in different colors.

A unique output called Cumulative estimated smoke density over the whole period of pollution in 1991, is presented by Plate 6.
The estimated smoke density also converted to the other sort of presentation. First, based on considering the frequency histogram of smoke density, the daily estimated smoke density maps were sliced and classified into the no smoke, light smoke; moderate and heavy smoke classes [3, Annex D-1].
The estimated smoke density maps also were used for smoke persistency calculations. In this respect smoke density maps were converted to the sort of bitmaps showing existence or absence of smoke, without considering density of smoke. As a result, accumulating the smoke persistency maps led to prepare the monthly smoke persistency for each month of 1991.

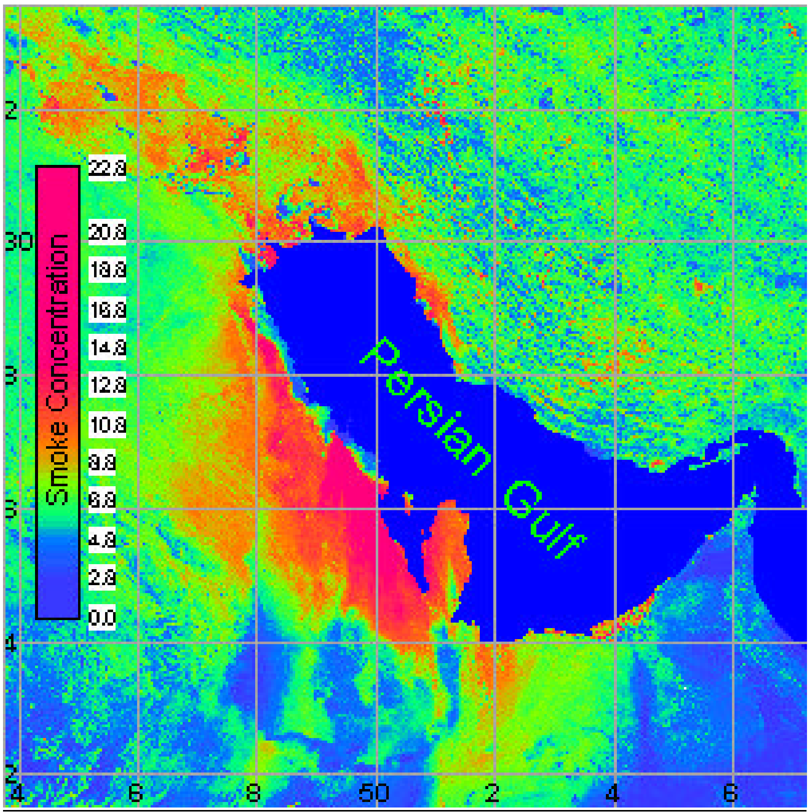

Plate 6: cumulative estimated smoke density over 1991, using mid-day infrared images for whole period of burning Kuwaiti oil wells.

In the following a model was chosen for quantitative estimation of smoke density over the Iranian territory during 1991.
<u>Model assumption:</u>
The accumulative estimated smoke density map over the territory of Iran is considered as a base data layer for smoke and soot calculation for Iranian territory. In this respect the following activities were carried out:

Calculating the area (i.e. the area covered by the image data) integrated smoke density by multiplying the smoke density values by the relevant number of pixels.

Assume, the integrated smoke density values is “C”, each smoke density value is “V” and number of pixels is “N”
$C = \Sigma V_i * N_i$

This equation gives an overall smoke density over the studied area. Considering the frequency histogram of the smoke density values over the Iranian territory, the same calculation was carried out for the inland area of Iran either excluding, the Persian Gulf area or including it.
Such calculation including the Gulf surface led to the following results.

CO = Overall area integrated smoke density =7 878925 units

CI = area integrated smoke density over Iran = 3051435 units

Atmospheric pollution fraction over Iran (RI) = CI/CO*100 = 38%
The same calculation excluding the Gulf surface gave following result.

CO = 6444405
CI =2424040
RI =CI/CO*100 = 37%

4. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the analysis carried out during this study indicate that indeed the consequences of the Gulf War are felt, and the following conclusions can be drawn:

- Application of model based image analysis permitted a qualitative and quantitative estimate of the smoke concentration over the Gulf area, using an accumulated smoke density map for the land reflection model over 1991. With the use of model based image analysis, it was estimated that 37 percent of the total amount of air pollutants emitted over 1991 came to the Iranian territory.
- During the peak period of the fires, the wells were emitting about 5,000 tons of smoke daily. Let's assume that we have about 225 smoky days in total during 1991. If we take in average about 4,000 tons of smoke daily (80% of 5,000 tons), then we have: Given the accumulated output of the oil well fires of 4,000 tons/day * 225 days = 900000 tones and not considering smoke drifting on the image boundaries. It is estimated that about 0.37 * 900000 = 333000 tones of oil and oil related pollutants have been transported by air from the Kuwaiti oil well fires to the territories of Iran, where 0.37 is the integrated smoke density over Iran relative to the integrated smoke density over the whole image (see plate 6) for estimated smoke concentration map over the Gulf area during the 1991).

The available field observations and remote sensing data confirm that smoke and soot from the burning oil wells in Kuwait reached large parts of the territory of Iran during 1991. The smoke drifting on the image boundaries was not considered in this study and for a qualitative and quantitative estimation of the smoke concentration over Iran, we need a extended image window like GAC NOAA_AVHRR images.

Evaluation:
The residual error after best fitting the accumulated smoke concentration to the ground sample data is a quality criterion in the same sense as the confusion matrix as used in maximum likelihood methods. The maps, showing persistence of heavy and light smoke over the Persian Gulf region is also verifies the accuracy and reliability of the obtained results met by this study.

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- Ir. P. Geerders, Environment/Coastal zones management specialist
- W. Bakker, BTW, Image Processing Specialist

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