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The 2016 Al-Mishraq sulphur plant fire: Source and health risk area estimation

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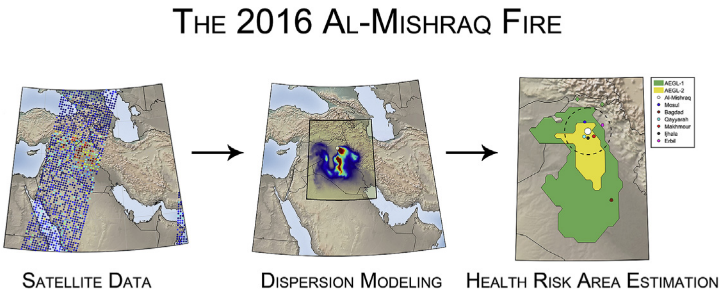
HIGHLIGHTS

- Scorched earth tactics creates foul air quality.
- The source term for the Al-Mishraq fire 2016 is estimated using satellite data.
- Dispersion simulation reproduced the atmospheric transport of the SO_2.
- The health risk area where exposure may have caused injuries to people was determined.
- Casualty estimates in good agreement with reported injuries south of Mosul.

GRAPHICAL ABSTRACT



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ABSTRACT

On October 20, 2016, Daesh (Islamic State) set fire to the sulphur production site Al-Mishraq as the battle of Mosul in northern Iraq became more intense. An extensive plume of toxic sulphur dioxide and hydrogen sulphide caused comprehensive casualties. The intensity of the SO_2 release was reaching levels of minor volcanic eruptions and the plume was observed by several satellites. By investigation of the measurement data from instruments on the MetOp-A, MetOp-B, Aura and Soumi satellites we have estimated the time-dependent source term to 161 kilotonnes sulphur dioxide released into the atmosphere during seven days. A long-range dispersion model was utilized to simulate the atmospheric transport over the Middle East. The ground level concentrations predicted by the simulation were compared with observation from the Turkey National Air Quality Monitoring Network. Finally, the simulation data provided, using a probit analysis of the simulated data, an estimate of the health risk area that was compared to reported urgent medical treatments.

1. Introduction

Scorched earth tactics are not a novel modus operandi in conflict situations. Although banned under Article 54 of Protocol I of the 1977 Geneva Conventions, it is regularly used as a warfare tactic, by both state actors and non-state actors. For instance, during the first Gulf War in 1991, retreating Iraqi forces set fire to over 600 oil wells as well as numerous oil filled low-lying areas, such as trenches.

Abbrevations: kt, Metric kilotonnes; UTC, Coordinated Universal Time; VCD, Vertical column densities data; DU, Dobson Units; NWP, Numerical weather prediction; MSE, Mean square error.

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More recently, and in particular since the beginning of the Mosul offensive, Daesh (Islamic State), have revived these tactics including deliberate oil fires and at least one attack on a chemical plant, namely the sulphur plant in Al-Mishraq which had one of largest sulphur deposits in the world (Zwijnenburg, 2016; Kalin, 2016; Al-yaseen and Niles, 2016; Sis, 2016). This is however not the first time the Al-Mishraq plant is set on fire, in an alleged act of arson it burnt in June 2003. Then the fire burned for approximately four weeks causing a release of ~600 kilotonnes (kt) SO_2 (Carn et al., 2004). The resulting toxic plume dispersed over a large area causing acute short term injuries in exposed military staff and population (Baird et al., 2012) and is possibly linked to long term adverse medical effects including constrictive bronchiolitis (USAPHC, 2012).

In the current situation, with the October 2016 advancement on Mosul, Daesh created a complex battle environment with the attack and fire at the Al-Mishraq sulphur plant combined with oil fires and the alleged use of chemical weapons (Deutsch, 2016). These acts resulted in an amplification of the already present humanitarian crises in the region. Moreover, humanitarian aid personnel and military deployed personnel were also affected thereof. This once again accentuates the need for accurate and timely health threat assessment in conflict areas.

In the ideal world, real-time air sampling and environmental monitoring would be conducted in theatre. This is however rarely the case due to the nature of conflict zones. At best, sampling could be conducted in the immediate environment of deployed troops. Nevertheless, reliable data are needed to obtain sound information regarding levels of pollutants and, if necessary, to formulate appropriate protective measures. To better inform medical intelligence (Wikström et al., 2016) such data could be supplied through dispersion modelling, but this requires a reliable source term, i.e. an assessment of the rate at which the pollutant is injected into the atmosphere. In this paper we show that remote sensing through satellite images of SO_2 can be utilized to provide a rapid source estimate for dispersion modelling. The dispersion model results are compared with air measurements from the Turkey National Air Quality Monitoring Network. As a final point we use the high resolution simulation data to estimate a health risk area by investigation of the health impact following the SO_2 exposure.

2. Satellite data

In absence of detailed in situ observations of the fire at the Al-Mishraq sulphur mine, satellite images provide the best basic data of the event. Today there exists a number of different systems that measure the SO_2 load in the atmosphere. NASA's Aura and Soumi satellites carry the Ozone Monitoring Instrument (OMI) (Levelt et al., 2006) and the Ozone Mapping and Profiler Suite (OMPS) (Pan et al., 2013), respectively. EUMETSAT's and ESA's satellites MetOp-A and MetOp-B constitute platforms for the instruments Global Ozone Monitoring Experiment-2 (GOME-2) (Hassinen et al., 2016). These satellites are polar orbiting meaning that they only probe the area of interest a short period of time on each lap around Earth. The two GOME-2 instruments complement each other with regards to field of view and closely related passage times. Iraq is covered around 07:00 (UTC) every day. Combining the two GOME-2 instruments' measurements gives a near complete coverage of the area of interest: the latitude-longitude box 30°E - 60°E, 20°N - 45°N. There may occur overlaps between the two GOME-2 observations which are resolved by using the mean value in these areas. In the same way Aura and Soumi complement each other and pass Iraq around 11.00 (UTC) every day adding one additional assembled field available for this study. This means that we have access to two separate assembled fields from two different systems, i.e., the first is constituted by the two GOME-2 instruments and the second is constituted by the OMI and OMPS instruments. This work incorporates qualitative data from all these four instruments.

SO_2 can also be detected in the thermal infrared spectrum, for example by the Spin Enhanced Visible and Infrared Imager (SEVIRI) system located on the satellite Meteosat-10 and the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the satellites Aqua and Terra. In contrast to MetOp-A, MetOp-B, Aura and Suomi, the Meteosat-10 satellite is indeed geostationary and SEVIRI covers the region of interest providing images every 15 min. We use the SEVIRI images for qualitative assessments of the source, however, as the accuracies of the infrared retrieval methods does not match those of the ultra-violets ones, like GOME-2 and OMI/OMPS (Corradini et al., 2009), we opt not to use SEVIRI for quantitative estimates of SO_2 loadings.

OMI, OMPS and GOME-2 all utilize hyperspectral imaging and study the solar backscatter radiation to detect aerosols and trace gases. Processed data (level 2 data) from the GOME-2 instruments are mediated via the Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring project (O3M SAF). Amongst the level 2 products available we find SO_2 vertical column densities data (VCD). The VCD values have been corrected for a number of physical and chemical phenomena that interfere with SO_2 remote measurements. Each data point represents a surface area of 40×40 km^2 and 40×80 km^2 for GOME-2 on MetOp-A and MetOp-B, respectively. Similar data can be readily acquired from the OMI and OMPS instruments processed into level 2 data by NASA. The pixel size for OMI and OMPS are 13×24 km^2 and 50×50 km^2, respectively. Unfortunately there are factors that cause uncertainties in the SO_2 measurements such as cloud coverage and interference between SO_2 and ozone (Fioletov et al., 2013) which imply that the target uncertainty for GOME-2 SO_2 measurements is ~50% (Hassinen et al., 2016) and similar uncertainties are present for the OMI/OMPS measurements (Li et al., 2017). The VCD values for SO_2 are given in Dobson units (DU), where 1 DU corresponds to 2.69×10^{20} molecules per square meter when the column is integrated vertically. The translation from sensor data to the corresponding concentrations in DU depends on the actual height of the SO_2 plume in the given column. The instruments cannot detect the height of the SO_2 plume and the concentration is therefore presented as four different values corresponding to four different assumed heights of the plume (1.0 km, 2.5 km, 6.0 km and 15.0 km for GOME-2 and 0.9 km, 3.0 km, 8.0 km and 18.0 km for OMI/OMPS). We have implemented a method where the plume height is differentiated over the region and we therefore interpolate the VCD value in each position to the local height of the SO_2 plume (where the local plume height is inferred from the dispersion model results as is discussed later). Further on, the datasets include quality flags and other information that indicate if data points may be subject to errors or increased uncertainties. All data points with any such indication have been removed in this analysis following recommendations from the data providers. For GOME-2 we use $\text{QualityFlag} = 0$ and the following limitations to improve the quality of the data points used: $\text{IndexInScan} \leq 2$ (only forward scans), $\text{ViewMode} = 256$ (only day measurements) and $\text{SolarZenithAngleCentre} \leq 75$ (only appropriate angle for the sun). For OMI/OMPS we require $\text{SolarZenithAngle} \leq 70$. Moreover, we remove the first two and the last two rows of each dataset for OMI and the first and last rows for OMPS which have been found to exhibit unresolved abnormalities. Only a small fraction of the provided points are excluded for any of these limitations leaving the vast majority of the data points available for the source term estimation.

Presence of clouds interferes with the measurements of SO_2 mainly due to the fact that the instrument is unable to detect the