Assessment of air quality and damage caused after an anthropogenic disaster in the city of Beirut.

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Abstract. Air pollution is an important cause of concern and has a significant impact on health as well as the environment. Air pollutants are released into the atmosphere by various sources, and the concentration in cities is mainly due to anthropogenic sources like emissions from industries, factories, vehicles, fossil fuel combustion, waste production, etc. But certain high episodes of air pollution can be witnessed in cities which can cause serious threats to human beings and the environment. Remote sensing is one of the sustainable measures, which allows the integration and presentation of useful information at various temporal and spatial scales. This tool can be helpful in understanding and managing natural disasters and man-made risks contributing to air pollution. Analyzing the cause of such high pollution episodes can help to take necessary steps to reduce the emissions, and damage or to take precautions to avoid man-made disasters. One such incident of an explosion of ammonium nitrate in a port had a long-lasting impact on the air quality in Beirut where the average concentration of air pollution already exceeds WHO threshold limits. This paper explores the concentration of aerosols and NO2, before and after the incident of an explosion that took place in Beirut. Assessment of the damage near the port caused by the explosion in Beirut was done using a change detection technique for which an algorithm was developed. Due to the non-availability of field data for the study area of Beirut, the algorithm was developed and validated for Chennai city and extended to Beirut. The aerosol and NO2 concentration data were extracted from sentinel-5p/TROPOMOI and validated with ground data through regression analysis. The results obtained from this study can be used as an early warning system and decision support system for mitigating loss due to the explosion.

Keywords: air pollution, aerosol, NO2, satellite data, damage assessment

1. Introduction.

Air pollution is a major environmental risk factor for poor health and causes about 2 million premature deaths worldwide each year [1]. Natural and anthropogenic activities are major sources of air pollution. There are 6 major criteria pollutants out of which the exposure to particulate matter (PM2.5) and nitrogen oxides (NOx) shows severe damage to health as well as often exceeding the World Health Organization (WHO) guidelines threshold limit [2,17]. Regular exposure to NO2 and aerosol has been linked to an increased risk of respiratory problems, cardiovascular disease along with lung cancer. It can also cause a myriad of short-term health issues such as respiratory infections, irritation of the eyes, nose, and headaches. In addition to health concerns, suspended particulates also reduce visibility
and contain harmful compounds which can cause environmental damage via dry or wet deposition.

There are different sources that add pollutants into the atmosphere reducing the air quality. Apart from these at times disasters or incidents that happen can leave a remarkable impact on air pollution [2]. The impact of fire smoke in the boreal forest showed an impact on the air quality in the US [3]. One such incident of explosion took place in Beirut, increasing the concentration of NO₂ and aerosol to an alarming level.

On August 4, 2020, nearly 3,000 tons of the highly combustible chemical compound (ammonium nitrate) exploded in Beirut's port [4], shooting a plume of orange smoke into the sky, followed quickly by a pressure wave that ripped through nearby buildings and blew out windows across the metropolis. In ordinary circumstances, ammonium nitrate is a fertilizer, but when placed under the stress of heat and pressure, it acts like a bomb. When ammonium nitrate explodes it releases toxic gases like nitrogen oxide (NOₓ) and ammonia gas and also emits particulate matter (PM). These gases, both harmful to the human respiratory system and the environment, in turn, break down and react with other chemicals. Nitrogen oxides, for example, when combined with other pollutants and sunlight form "bad ozone," a secondary pollutant, ozone at ground level. Regular monitoring and reducing the amounts of air pollution is therefore critical in this region.

Satellite remote sensing has a wide range of applications and one such application is retrieving data on air quality [5]. These techniques can be used to study spatial distribution, temporal variations, fine and coarse mode fraction, vertical distribution, etc. to derive sources, transportation, and interaction between pollutants and clouds [6,7,8]. The most significant factor is its ability to fill in gaps where ever the ground data information on air quality is the unavailability of sufficient monitoring stations. There are several air pollution retrieving satellites like MODIS, OMI, MISR, TOMS, AVHRR, MERIS, AATSR, etc. and algorithms are available. The improved resolution of TROPOMOI is expected to reduce the effect of spatial averaging compared to OMI and other coarse-resolution satellites [9]. This study aims to analyze the intensity of aerosol and NO₂ concentration from sentinel-5p/TROPOMOI and validate it. Also, to understand the impact of a disaster on the urban structure and human health.

2. Materials and Methods

The study explores the concentration levels of aerosol and NO₂ before and after the explosion in Beirut. Since the ground-based data was unavailable for Beirut, the satellite data and ground-based data from the Central Pollution Control Board (CPCB) for the city of Chennai were used for validation. Firstly, the ground-based data for PM 2.5, PM 10, and NO₂ were collected for the dates 12, 13, and 14th Jan 2021. The data was sourced from CPCB for the Chennai region. Then the satellite images of the Chennai region coinciding with the same dates were extracted from the Sentinel-5 Precursor mission instrument which collects data useful for assessing air quality. It uses the TROPOMI instrument which is a multispectral sensor that records the reflectance of wavelengths important for measuring atmospheric concentrations of pollutants. S5P is a near-polar sun-synchronous orbit satellite flying at an altitude of 817 km, with a swath width of approx. 2600 km, an along-track resolution of 7km, and daily global coverage [10]. The day-to-day variability of the data obtained from satellite and in situ measurements was found to be similar [9]. Here the data obtained are in the form of vertical column densities which are measured as mol/m³. Using a look-up table of altitude-
dependent air-mass factors (AMFs) the vertical column densities are converted before which the tropospheric and stratospheric slant column densities are separated from the total slant column using a data assimilation system based on the TM5-MP chemical transport model [9]. NO$_2$ measurements are available from the CPCB measurement database as hourly averaged concentrations in units of µgm$^{-3}$ for Chennai city. Regression analysis was used to evaluate the extent to which the satellite data can resolve ground-based estimates [11]. It involves analyzing the goodness of fit of the regression. One measure of goodness of fit is the coefficient of determination (R$^2$). Both satellite data and metrological data were combined to derive the correlation of NO$_2$, and AOD [12]. The integration of surface, satellite, and meteorological products and these products are added to form multiple linear regression (MVM) equations to estimate mass concentration [6].

Secondly, the concentration maps of Aerosol and NO$_2$ before and after the explosion of Beirut were prepared and analyzed. QGIS software was used for the visualization of maps. Thirdly damage assessment was done to identify the intensity of damage through a change detection technique. The satellite images obtained were processed and analyzed using the SNAP toolbox. To improve the accuracy of the results, both sentinel-1 (Radar data) and sentinel-2 (optical) data were used for pre-processing involving two major steps - Applying orbital file details and back geocoding. Then Terrain correction was carried out to correct the geometric distortions that lead to geolocation errors. It is done to move the image pixels into the proper spatial relationship with each other. The process of combining multiple images into a single image was done by layer stacking for which the images were re-sampled to have the same spatial resolution. Finally, the Change detection technique is used to estimate the damages caused by the explosion for which the algorithm was developed. The damages caused by the explosion are estimated by the change detection technique. The framework of the methodology followed in the study is given below in Fig. 1.

3. Study Area and Data Source

3.1 Study Area

Beirut is the capital and largest city of Lebanon. The latitude and longitude of Beirut, Lebanon 33° 53' 19.0680" N and 35° 29' 43.7280" E. Beirut is one of the most religiously, culturally, and economically diverse cities in the Middle East. Beirut is the third-largest city in the Levant region and the fifteenth-largest in the Arab world. Beirut covers an area of 19.8 km$^2$ and its metropolitan area is 67 km$^2$. Beirut is comprised 60% of the urban population of Lebanon. Beirut’s Population is almost five times the population of the second largest city in Lebanon, Tripoli. Now, it is estimated that the population has reached 2 million. Beirut has a warm climate with wet winters. The average temperature estimated in Beirut was 20.5 °C. The annual rainfall of Beirut is 845 mm per year. The precipitation difference between the driest and the wettest month is 196 mm. The driest and warmest months in Beirut in July and August respectively. The closest ocean to Beirut is the Mediterranean Sea. Fig 2 shows the location of Beirut city.
CONCLUSIONS

DATA

CPCB
PM 2.5 and NO₂ ground based data

Sentinel- 5P
Extracting S5P AOD and
Processing using python and Panoply

Sentinel-1&
PRE-
Coherence
Re-
Terrain
Subset
Layer
Collocatio

AOD, PM 2.5 and NO₂ regression plot
PM 2.5 and NO₂ map generation
Output AOD 
&NO₂ maps

ANALYSIS AND

CHANGE DETECTION

CONCLUSIONS

Fig 1: Methodology

Fig 2: Study area: Beirut
3.2 Data Source

The Aerosol optical depth (AOD) data from Sentinel-5p/TROPOMOI and NO$_2$ satellite data at two different wavelengths (388-354 nm, 388-340 nm) was studied on the 13$^{th}$ and 14$^{th}$ Jan 2021 for the Chennai region. The data was processed and maps were generated in panoply software giving a quantitative estimate of the concentration of pollutants present in a vertical atmospheric column from the ground to the top of the Atmosphere (TOA).

The values extracted are given as aerosol index (AI) and the graph was plotted against AI and scan line. The NO$_2$ concentration from the sentinel 5P was extracted through Python script for the dates 13$^{th}$ to 14$^{th}$ Jan 2021 for the Chennai region. The values extracted are given as mol/m$^3$ and the base map is generated using the matplotlib tool kit in Python. The quality of satellite observations was taken care of by “quality assurance value” (qa_Value) which provided an easy filter to remove less accurate observations. This study uses the Sentinel 1A, 1B and Sentinel 2A, 2B images for damage assessment. The images were downloaded from the ESA Copernicus SCI hub and necessary corrections are applied.

4. Selection of Input Parameters

4.1 Validation of data

The ground-based concentration of PM 2.5 and NO$_2$ was acquired from CPCB, Chennai for the dates 12$^{th}$ to 14$^{th}$ Jan. The concentration was found to be higher on 13$^{th}$ January 2020 as compared to the other two days. To check the accuracy of the result, a regression graph was plotted with the atmosphere (VCD) NO$_2$ data on the Y axis and ground level NO$_2$ on the X axis. Similarly, another regression graph was plotted with Aerosol Index (AI) on the Y axis and ground level PM 2.5 on the X axis. The results indicate the satellite-derived data can be a good substitute for the concentration levels acquired from the ground. The correlation graph for both pollutants has been shown in Fig 5 and Fig 6.

4.2 Analysis and Interpretation of Aerosol and NO2 in Beirut

The AOD and NO$_2$ concentration data from sentinel 5P at two different wavelengths (388-354 nm, 388-340 nm) was extracted for the dates 1$^{st}$ to 3$^{rd}$ August 2020 before the explosion. The explosion occurred on the 4$^{th}$ of August 2020 evening at 6.00 pm. The AOD and NO$_2$ concentration map generated data from the 5$^{th}$ to 7$^{th}$ of August 2020. About a month after another explosion and fire broke out. Similarly, the concentration maps over the period of other two consecutive months of both pollutants from 9$^{th}$ to 12$^{th}$ September 2020 and 4$^{th}$ to 11$^{th}$ November 2020 were prepared for analysis. The maps showing the major difference in concentration are shown in Fig 7 and Fig 8.

4.3 Damage Assessment in Beirut

For damage assessment, two sets of images before and after the explosion from sentinel 1 and sentinel 2 satellite was used for which a series of processing steps were applied with a snap toolbox. It estimates a constant range offset for each burst using a small block of data in the center of the burst and then it estimates a constant azimuth offset. Finally, the average of all the bursts is estimated to get the final constant range and azimuth offset. Co-registration of the product is created by keeping the same graph for which the coherence was estimated. Coherence is the process of estimating how well “correlated” the pixels are.
between the master and slave images used. Using the Coherence operator, the correlation between pixels is estimated. After estimating coherence in both images, it is stacked in order to be allowed to apply the Change Detection. The final step is to detect the changes between the two coherence images, and the result shows the damage caused due to the explosion. The products are re-projected so that we can insert them in QGIS for visualization and further results. Both the products are overlaid to identify what are all the buildings that were damaged due to the explosion in the Beirut port which is shown in Fig 9.

5. Results and Discussions

Before the assessment of the damage caused by the explosion, the satellite data was validated with ground-based data for the city of Chennai. The AOD concentration maps generated for the dates 13th and 14th Jan 2021 show the variation in values from -6.4 to 3.4, where the concentration was observed high on 13th Jan 2021. Also, the NO₂ concentration map generated for the dates 13th and 14th Jan 2021 showed that the concentration level was high on 13th Jan 2021. This could be mainly due to the Bogie festival being celebrated where old things are burnt as a part of the ritual [13]. The concentration of NO₂ was higher as compared to Aerosol due to the festival ritual.
To confirm the satellite data can be used as a good substitute for the ground-based data regression graph was plotted for both pollutants for the same dates of ground-based data. The graph for the NO$_2$ showed linear regression with a co-efficient of 0.806 and the AOD linear regression with a coefficient of 0.774. It indicated an excellent correlation between satellite and ground-based data [14,15].

Fig 5: Aerosol index at 354-388 nm Vs PM 2.5 in mg/m$^3$

Fig 6: Tropospheric NO$_2$ column Vs NO$_2$ in mg/m$^3$

Two pollution episodes, one before the explosion (1st -3rd August 2020) and the other one after the explosion (4th August- 7th August 2020) were considered. The AOD and NO$_2$ concentration maps that were generated clearly indicated the drastic increase in pollutant levels after the explosion. The aerosol concentration observed to be is less and the maximum aerosol index value is 2.3 before the explosion. The concentration map generated for the consequent months of September and November 2020 showed the impact of air quality in Beirut. The explosion had a significant reduction in air quality in Beirut between 6th August to 11th September 2020. The next consecutive month showed a gradual reduction in the levels indicating a period of at least 3 months for the pollutants to disperse.
For damage assessment, a direct comparison of high-resolution Google Earth imagery that was taken just after the explosion over the port of Beirut was carried out. The destroyed buildings can be observed in the image [16]. Both the change detection analysis of Sentinel-1 and Sentinel-2 shows a good correlation with the visual inspection of the high-resolution Google Earth imagery despite the difference in their spatial resolution. Also, throughout the month of August and September, the wind direction is predominantly in the west direction. Therefore, the pollution starts to travel in the South East direction, and the spread of the pollution covered the surrounding countries namely Jordan, Syria, and Israel. The spread covers an area of a 400 km radius.
6. Conclusions

The current study was carried out to find the variation in the aerosol and NO$_2$ concentration due to the explosion that occurred at the port of Beirut [17]. The massive explosion and regional transport of pollutants between 4$^{th}$ August to 11$^{th}$ November 2020 in Beirut was analyzed by integrating multiple satellite remote sensing products with surface observations.

Aerosol and NO$_2$ concentrations were monitored regularly and it took nearly a longer period of more than 3 months to get lesser concentration. When ammonium nitrate explodes it releases toxic gases like ammonia and nitrogen dioxide in large amounts when compared to particulate matter. Satellite-derived AOD and NO$_2$ vertical columns show an excellent correlation between ground-based PM 2.5 and NO$_2$. A damage assessment was carried out to estimate the damages caused by the explosion in and around the port area. The results obtained from this study can be used as an early warning system and decision support system for mitigating losses due to the explosion of ammonium nitrate.

Cloud cover proved to be a great limitation with the majority of the portions of AOD and NO$_2$ data unavailable on particular days and hence proved difficult during daily analysis. Only PM2.5 and NO$_2$ were considered for Air Quality analysis here, however, there are other pollutants such as PM10, CO, SO$_2$ etc., which can also be considered for further detailed analysis. Another possible development is the integration of satellite observation with ancillary datasets such as wind speed and wind direction. By adding ancillary datasets, it is possible to improve the accuracy of the result.

7. References


