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Letter

Impact of Hurricane Ida on Nitrogen Oxide Emissions in Southwestern Louisiana Detected from Space

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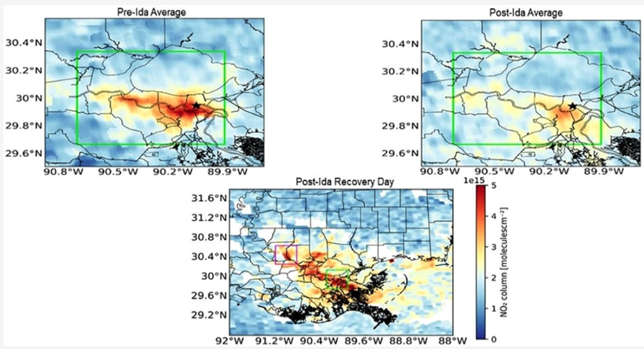
ABSTRACT: Hurricane Ida made landfall on August 29, 2021, in southwestern Louisiana and devastated the region's industrial landscape. Its disruptions to atmospheric composition were detected by the TROPOspheric Monitoring Instrument (TROPOMI). This study quantifies NO_2 spatial changes and estimates top-down NO_x emissions for two cities impacted by Hurricane Ida, New Orleans and Baton Rouge. Considering the difference in NO_2 lifetime pre- and post-Ida, top-down derived NO_x emissions for each impacted city saw decreases in NO_x emissions of ~40% and ~80% for New Orleans and Baton Rouge, respectively. However, a significant increase in the TROPOMI NO_2 level was seen during the posthurricane period, occurring only on September 2, 2021, where potential causes of such deviation are attributed to hurricane recovery actions. When this date is excluded from post-Ida averages, the NO_x emission estimates are further decreased by ~80% and ~92% for New Orleans and Baton Rouge, respectively. Short-lived extreme weather events and their accompanying preparatory and recovery actions are unique drivers of change in NO_x emissions. This study demonstrates the use of satellite products to provide a quick emission analysis of areas affected by such events and illustrates the necessity of understanding their influence on atmospheric pollutants.



KEYWORDS: *NO_x, NO_2, TROPOMI, hurricane, Louisiana*

1. INTRODUCTION

Hurricane Ida made landfall on the Louisianan Gulf Coast on August 29, 2021, as a category 4 hurricane with maximum sustained winds of 150 mph.[1] After landfall, the hurricane progressed northward where the eye approached the state's largest cities, New Orleans and Baton Rouge.[2] Hurricane Ida became one of the strongest hurricanes to hit Louisiana, just behind Hurricane Katrina, which devastated Louisiana in 2005.[3]

Hurricane Ida created life-threatening storm surges, heavy rainfall, and intense winds.[4] Southeast Louisiana's electric grid was severely impacted, where approximately 1 million customers experienced electrical power outages.[5,6] It took approximately 2 weeks for the New Orleans and Baton Rouge urban areas to achieve normalcy, while it was not until late September for rural and harder-hit areas to experience full electrical restoration.[5,7] The region is home to a diverse landscape of industrial and commercial complexes, including offshore oil and natural gas production, shipping ports, and petrochemical refineries, all of which are significant contributors to anthropogenic air pollutants such as nitrogen oxides ($NO_x \equiv NO + NO_2$).[8] With the hurricane and delay of power restoration, it is expected that the anthropogenic emission patterns in the region changed. This change provides a unique opportunity to examine the impact of hurricanes on the anthropogenically produced NO_x emissions in the Gulf of Mexico region.

In addition to the direct disruption of hurricanes described above, NO_x emissions are also expected to differ from "normal" during the recovery stage when air quality regulations are waived, emission control strategies are inoperable, and auxiliary power generators, infamous for a lack of emission controls, are employed.[9−12] There is limited knowledge about how the atmospheric composition changes due to recovery efforts, as many airborne or ground-based air quality monitoring systems may go offline due to damage incurred or lack power due to the event. Satellite retrievals have the greatest potential to fill the gap because they are consistently available before and after extreme events and can unveil hurricane-driven emission changes. Here, we quantify how Hurricane Ida impacted anthropogenically produced NO_x emissions, using recent

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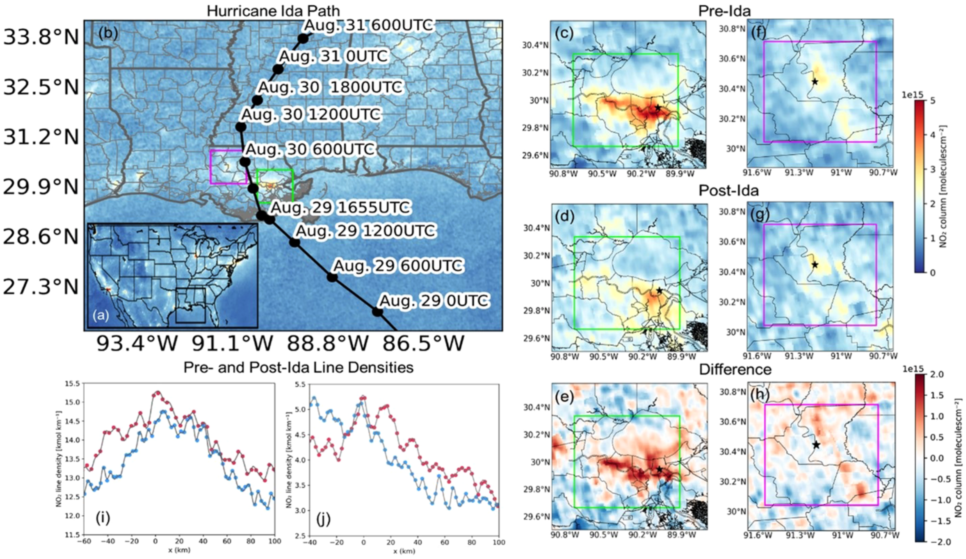

Figure 1. (a) Average TROPOMI tropospheric NO_2 column density over the continental United States oversampled to a resolution of 0.01° × 0.01° during August 2021. The black box indicates the area shown in panel b. (b) Region of southeastern Louisiana impacted by Hurricane Ida. Best track for Hurricane Ida in black with time stamps. Green and pink squares delineate New Orleans and Baton Rouge, respectively. Average five-day TROPOMI tropospheric NO_2 column density oversampled to a resolution of 0.01° × 0.01° over (c−e) New Orleans and (f−h) Baton Rouge: (c) New Orleans pre-Ida average, (d) New Orleans post-Ida average, (e) difference between panels c and d, (f) Baton Rouge pre-Ida average, (g) Baton Rouge post-Ida average, and (h) difference between panels f and g. The line densities for the domains before source interference is reduced are shown in panel i for New Orleans and in panel j for Baton Rouge. Red circles indicate pre-Ida line density values, blue circles post-Ida line density values, and gray lines the resulting filtered values.

satellite observations. Such an analysis is important as hurricanes will become more frequent and intense due to global climate change and a full understanding of their impact is necessary.[13−16] Despite some efforts made to understand how hurricanes change natural NO_x emissions,[17,18] to the best of our knowledge, no prior study investigated the effects of hurricanes on anthropogenically produced NO_x emissions.

This study presents a quantitative analysis of top-down derived NO_x emission changes in two urban areas in Louisiana, New Orleans and Baton Rouge, affected by Hurricane Ida. An exponentially modified Gaussian (EMG) function is utilized to estimate the NO_x emission changes to illustrate its use for quick quantification of the complex emission dynamics caused by short-lived extreme weather events.[19−30] The results shown here are from the first analysis quantifying hurricane-driven emission changes of anthropogenically produced NO_x using the EMG function.

2. MATERIALS AND METHODS

2.1. TROPOMI and ERA5. We employ NO_2 retrievals from the TROPOspheric Monitoring Instrument (TROPOMI) to observe spatial changes in NO_2 and derive NO_x emission estimates for two main cities and hubs of industrial activity impacted by Hurricane Ida, Baton Rouge and New Orleans (Figure 1). For this study, we use TROPOMI's tropospheric NO_2 vertical column densities version 2.02 (S1).[31] A physics-based oversampling process was employed to resample TROPOMI observations to a regular grid of 0.01° (S2).[32] European Center for Medium-range Weather Forecast (ECMWF) ERA5-Interim products are utilized (S3).[33] Wind fields from the surface to approximately 500 m are averaged for use in the EMG function.[19,23,27,29] The choice of wind data directly affects lifetime and emission estimates; given the short time scale, systematic errors will largely cancel out in relative emission changes. To match TROPOMI's overpass time of 13:30 local solar time (LST), wind fields are linearly interpolated temporally and spatially to match TROPOMI pixels.

2.2. Dates. TROPOMI does not require long temporal averages for quality emission analyses.[23,34,35] We build off this short time scale approach and use a total of only 10 TROPOMI overpasses. Five days pre- and post-Ida provided sufficient quality retrievals for analysis and observations of the direct effects of Hurricane Ida. We average the selected dates creating two separate analysis periods: pre-Ida (August 19−25, 2021) and post-Ida (August 31 to September 10, 2021) (S5). The date of Hurricane Ida's landfall (August 29, 2021) as well as four days prior and one day following are excluded because these days did not pass the criteria employed for overpass selection due to cloud obstruction or exclusion from quality controls (S4 and Table S2). Pre-Ida is defined as representing "normal" conditions as no preparatory measures were enacted during this time.[36−38] Post-Ida is the subsequent quality retrievals after Hurricane Ida made landfall.

2.3. Line Densities. Pre- and post-Ida TROPOMI NO_2 columns were rotated around the city center (S5) to align mean wind in the x-direction.[21,22,29,30] To observe plume evolution, line densities were determined by integrating the NO_2 tropospheric vertical column densities in the across wind direction, for the interval of 100 km in the downwind direction, which roughly corresponds to 4 times the e-folding distance for a lifetime of 3 h and a mean wind speed of 2 m s^{-1}. The fit interval in the upwind direction is set to be 40 km, under half the e-folding distance to ensure the plumes from the two domains do not mix. The area analyzed was sufficient for covering the industrial and commercial landscape while capturing the full plume of each domain.

To take advantage of the EMG function, a Gaussian shape is required from the resulting line densities to show spatial smoothing of the exponential downwind plume decay. Due to the short time frame of our analysis, a smooth Gaussian shape is not produced in the five-day averaged line densities (Figure 1f,j) and previous line density fitting methods for regions with multiple sources cannot be employed.[27] To achieve quality fits, the influence of multiple sources is reduced, leaving only the main urban plume in question (S8). By fitting each period's mean vertical column density relative cumulative frequency curve with a piecewise linear function, we produced threshold points (Figure S9). For each period, the highest threshold point is applied, removing NO_2 concentrations below the threshold which could be emission contributions from small anthropogenic and natural sources, as well as the free tropospheric background. With source interference reduced, the mean spatial pattern of the main NO_2 burden is revealed allowing for its analysis (Figure S9).

2.4. Mean Effective Lifetime and NO_x Emission Estimates. With the primary NO_2 burden revealed, a convolutional filter is applied to line densities employed in mean effective lifetime calculations. This filter smooths line densities for improved fitting but conserves the spatial pattern produced by the multiple sources captured in the main NO_2 burden (S7). The resulting smoothed line densities are related to the city center and fit with an EMG function (eq S1) for the determination of the mean effective lifetime ($\tau_{effective}$) (eq S2).[27] Filtered line densities are representative of the NO_2 downwind plume evolution with a high level of agreement as shown in panels f and j of Figure 1.

The estimation of the total NO_2 mass is constructed from the line densities where filtering is not applied to represent the NO_2 magnitude directly (S7).[26] These line densities are fit again with the EMG function, where resulting parameters from the fit lead to NO_x emission estimates (E_{NO_x}) (eq S3). Estimated integrated uncertainties range for lifetimes from 44% to 48% and for emission estimates from 51% to 55%; the specifics of uncertainty estimations are included in S10.

3. RESULTS

3.1. Spatial Changes. Figure 1 shows the spatial distribution of the TROPOMI NO_2 vertical column density across the five-day average for both cities affected by Hurricane Ida. Distinct spatial pattern differences are observed with post-Ida averages compared to pre-Ida (Figure 1e,h), while line densities (Figure 1i,j) expose downwind plume variability driven by the hurricane. Variations could be due to changes in the emission pattern driven by recovery actions or even possible natural NO_x increases experienced after hurricane periods[18,39] (Figure S13). A reduction in the observed TROPOMI NO_2 vertical column density between the periods is clear, with New Orleans and Baton Rouge experiencing 5.25% and 1.40% decreases, respectively.

Post-Ida results exposed abnormal patterns in NO_2 vertical column densities over the entire southwestern Louisiana region on September 2, 2021, as shown in Figure 2. Our investigation showed the probable cause of this behavior was a part of recovery efforts (S6). On September 2, 2021, the Department of Energy released 1.5 million barrels of crude oil from the Strategic Petroleum Reserve to ExxonMobil's Baton Rouge refinery for the alleviation of fuel shortages caused by Hurricane Ida.[40−42] The refinery produced and supplied fuel to the local Louisiana market through marine transportation along the Mississippi River, as pipelines and other delivery modes were inactive due to power outages.[40,43] This recovery

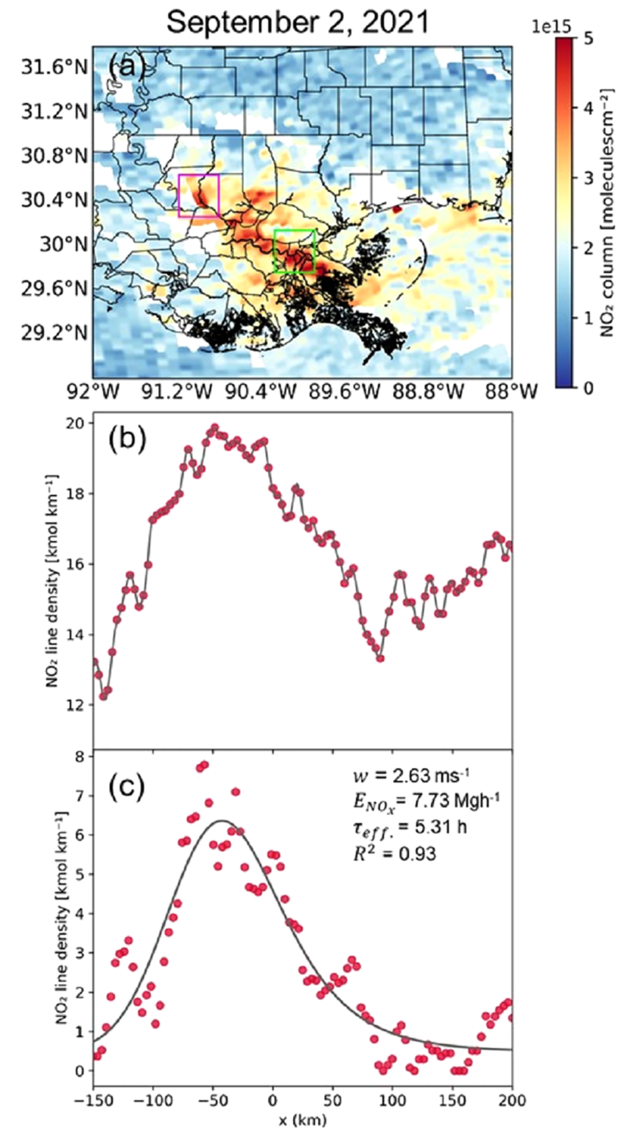

Figure 2. (a) TROPOMI tropospheric NO_2 column density over the Hurricane Ida-impacted region for September 2, 2021. Green and pink squares delineate New Orleans and Baton Rouge, respectively. (b) Line densities before below threshold NO_2 removal and (c) above threshold line densities (red) with an EMG fit (gray).

effort resulted in an exceptional increase in the observed NO_2 vertical column density due to the pressing need to distribute fuel for restoration. When this anomalous date is removed from post-Ida averages, the NO_2 vertical column density is decreased further, with New Orleans seeing an ∼20% decline and Baton Rouge seeing an ∼11% decline (Figure S4).

3.2. Mean Effective Lifetime and NO_x Emission Estimate Changes. The changes in NO_2 column densities from TROPOMI between pre-Ida and post-Ida periods may not be taken directly as changes in NO_x emissions as we find the mean effective lifetime of NO_2 differs between the two periods. The mean effective lifetimes pre-Ida (1.73 ± 0.3 h for New Orleans and 1.44 ± 0.2 h for Baton Rouge) and post-Ida (2.32 ± 0.2 h for New Orleans and 2.87 ± 0.5 h for Baton Rouge) are related to wind speeds, where post-Ida effective lifetimes increased following increased wind speeds (Table S3), consistent with the work of Valin et al.[30] Our estimated lifetimes are similar to previously reported lifetimes for

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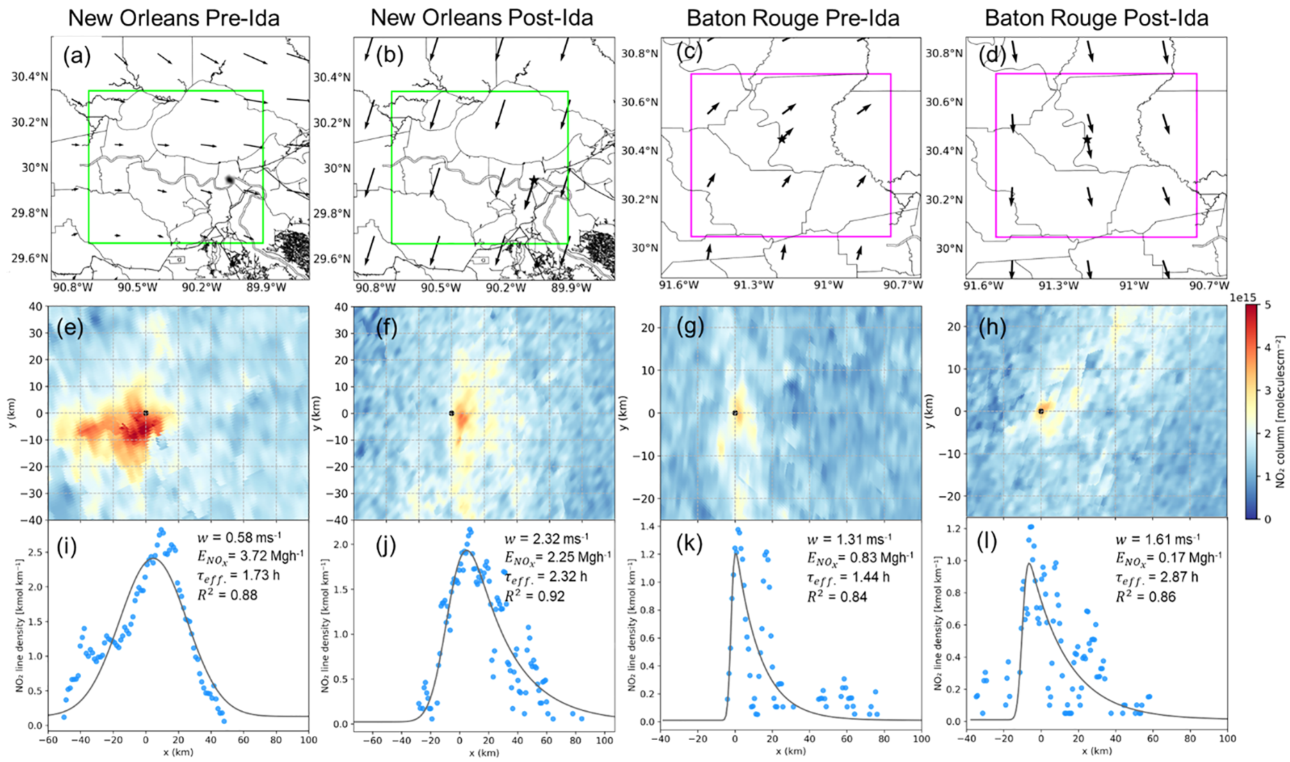

Figure 3. ECMWF ERA5-Interim mean wind speeds and directions with city center mean wind fields included at the black star for (a) New Orleans pre-Ida, (b) New Orleans post-Ida, (c) Baton Rouge pre-Ida, and (d) Baton Rouge post-Ida. Black arrows indicate the wind direction, and the length of the arrow is proportional to the wind speed. Wind-aligned average five-day mean TROPOMI tropospheric NO_2 column densities for (e) New Orleans pre-Ida, (f) New Orleans post-Ida, (g) Baton Rouge pre-Ida, and (h) Baton Rouge post-Ida. Above threshold line densities (blue) with EMG fits (gray) for (i) New Orleans pre-Ida, (j) New Orleans post-Ida, (k) Baton Rouge pre-Ida, and (l) Baton Rouge post-Ida.

summer (May−September) averages that range from 1 to 7 h.[19−23,26−30,43] As wind speeds are higher in the post-Ida periods (Table S3), there are corresponding increases in the mean effective lifetimes of 34.10% and 99.31% for New Orleans and Baton Rouge, respectively. The September 2 emission event's mean effective lifetime is found to be 5.31 ± 0.8 h, indicating support for observing a higher mean effective lifetime at higher NO_x concentrations.[27,30] However, this relationship is not held throughout our analysis and could simply be attributed to the nonlinearity in NO_x chemistry.[27]

TROPOMI-derived NO_x emission estimates between pre- and post-Ida exposed Hurricane Ida's impact on the anthropogenically produced NO_x emissions in the afflicted region. The average NO_x emission estimate pre-Ida [3.72 ± 0.2 Mg h^{-1} for New Orleans and 0.83 ± 0.1 Mg h^{-1} for Baton Rouge (mean ± standard deviation)] is larger than the post-Ida estimate (2.25 ± 0.1 Mg h^{-1} for New Orleans and 0.17 ± 0.2 Mg h^{-1} for Baton Rouge), leading to ∼40% and ∼80% decreases in NO_x emissions for New Orleans and Baton Rouge, respectively. As shown in Figure 3i−l, there are decreases in maximum line density values from 2.8 kmol pre-Ida to 2.2 kmol post-Ida for New Orleans and from 1.4 kmol pre-Ida to 1.2 kmol post-Ida for Baton Rouge.[44]

Substantial deviations in TROPOMI-derived NO_x emissions estimates were seen on September 2, 2021. A single TROPOMI overpass was used to calculate this day's emissions, which produced an estimated NO_x rate of 7.73 ± 0.7 Mg h^{-1}. When the September 2 emission is excluded in the post-Ida NO_x emission estimates, rates are decreased to 0.77 ± 0.2 Mg h^{-1} for New Orleans and 0.11 ± 0.1 Mg h^{-1} for Baton Rouge. This means ∼80% and ∼92% declines in NO_x emissions from pre-Ida to post-Ida for New Orleans and Baton Rouge, respectively. The difference in post-Ida mean estimates resulting from the single date of September 2 can be interpreted as the strong effect of hurricane ramifications on anthropogenically produced NO_x emissions. Our analyses suggest that recovery efforts after hurricanes can significantly alter the local atmospheric composition and lead to emission spikes in an already suffering region.

3.3. Comparison with Other Estimates. We assess the validity of derived top-down estimates of NO_x emissions with the comparison of current bottom-up estimates (S9). The top-down estimate for New Orleans pre-Ida (3.72 ± 0.2 Mg h^{-1}) is in reasonable agreement with the U.S. Environmental Protection Agency's (EPA's) National Emission Inventory (NEI) 2017 NO_x emissions of 3.49 Mg h^{-1}, while pre-Ida Baton Rouge derived estimates are lower than the NEI 2017 estimate of 2.28 Mg h^{-1}. Because the NEI estimate is an annual approximation, it does not reflect the specific emission variations seen during Hurricane Ida and does not capture total emission changes due to COVID-19. The EPA's Continuous Emission Monitoring Systems (CEMS) continuously tracks air pollutants emitted hourly by U.S. power plants. Here, this emission inventory is used to relatively assess the top-down estimates. The New Orleans CEMS 2021 NO_x emissions pre-Ida (4.29 Mg h^{-1}) and post-Ida CEMS estimate of 1.04 Mg h^{-1} reveal a difference of 3.25 Mg h^{-1}. When September 2 emissions are excluded, top-down derived NO_x estimates for New Orleans exhibit a similar difference of 2.95 Mg h^{-1}. The pre-Ida CEMS 2021 NO_x emission estimate for

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Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

Baton Rouge of 0.29 Mg h^{-1} and the post-Ida estimate of 0.25 Mg h^{-1} exhibit a difference of 0.04 Mg h^{-1}. TROPOMI-derived NO_x estimates for Baton Rouge do not share a similar difference but are one order of magnitude higher than that of CEMS estimates. Poor agreement for Baton Rouge could be attributed to the increased uncertainties observed in the EMG fit in addition to methodological uncertainties (S10). In addition, the Baton Rouge region is dominated by industries that report emission values only to NEI and are not included in CEMS estimates (Figure S12). Thus, large uncertainties in reporting practices could be the cause of the poor agreement seen with the bottom-up inventories.[45]

4. DISCUSSION

Short-lived extreme weather events, like hurricanes, are unique drivers of changes in anthropogenically produced NO_x emissions. Hurricane Ida changed emission patterns in southeastern Louisiana, which led to decreases in TROPOMI-derived NO_x emissions rates of ∼40% and ∼80% for two cities impacted by the hurricane, New Orleans and Baton Rouge, respectively. Preparatory and recovery efforts are significant industrial emissions events that can generate dozens or even hundreds of tons of emission per hour.[39] Given the continued urbanization of the United States and the anticipated increase in the number of hurricanes, understanding their relation to anthropogenically produced emissions is critical.

We demonstrate that quickly derived emission estimates utilizing satellites can fill a gap where surface-based monitoring networks are unavailable and can aid in the development of potential emission mitigation strategies that balance necessary preparation or recommencing activities. With the impending release of NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO),[46] its increased temporal resolution can provide improved observations of how short-lived extreme events can change anthropogenically produced atmospheric pollutants, improving our understanding of how humans are influencing the atmospheric composition.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.2c00414.

> Figures and tables, rationale for the period and September 2, 2021, description of satellite observations, overpass selection, oversampling method, meteorological data, bottom-up emission inventories, details of methods for background removal, top-down mean effective lifetimes, emission derivation, bottom-up emission estimates, and uncertainty of our top-down mean effective lifetime and NO_x emission estimates (PDF)

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Author Contributions

Y.W. conceived the research idea. K.S. developed the oversampling algorithm. T.L. conducted data analysis. All authors helped to edit the text of the manuscript.

Notes

The authors declare no competing financial interest.

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Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX