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The impact of the 2005 Gulf hurricanes on pollution emissions as inferred from Ozone Monitoring Instrument (OMI) nitrogen dioxide

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A B S T R A C T

The impact of Hurricanes Katrina and Rita in 2005 on pollution emissions in the Gulf of Mexico region was investigated using tropospheric column amounts of nitrogen dioxide (NO_2) from the Ozone Monitoring Instrument (OMI) on the NASA Aura satellite. Around New Orleans and coastal Mississippi, we estimate that Katrina caused a 35% reduction in NO_x emissions on average in the three weeks after landfall. Hurricane Rita caused a significant reduction (20%) in NO_x emissions associated with power generation and intensive oil refining activities near the Texas/Louisiana border. We also found a 43% decrease by these two storms over the eastern Gulf of Mexico Outer Continental Shelf mainly due to the evacuation of and damage to platforms, rigs, and ports associated with oil and natural gas production.

1. Introduction

The 2005 Atlantic hurricane season was the most active and destructive on record. Both Hurricanes Katrina and Rita reached Category 5 strength on the Saffir–Simpson Hurricane Scale though they were each Category 3 at landfall (Graumann et al., 2005; Beven et al., 2008). Katrina made landfall on August 29 in southeastern Louisiana and Mississippi, claiming about 1800 lives, severely damaging approximately 320 million large trees (Chambers et al., 2007) and causing an estimated \$81 billion in damage (Blake, 2007). Rita made landfall on September 24 in the less populated region of southwestern Louisiana.

Hurricanes Katrina and Rita damaged or destroyed many sources of pollution, including power generation, oil refining, and oil/gas production, along the Gulf of Mexico's coast from eastern Texas to Alabama. About 1.8 million customers lost power because of Katrina and 250 000 customers were still without power by the time Rita made landfall (OE, 2005a). After Rita, 1.6 million customers were without power (OE, 2005b). Most of the major deepwater ports along the Gulf coast were operating at or near pre-Katrina levels by the end of 2005, except for the Port of New Orleans (AAPA, 2005). The hurricanes caused widespread damage to oil and gas infrastructure in the Gulf of Mexico Outer Continental Shelf (GOM OCS) (OE, 2005a,b), which accounts for 30% of oil and 22% of natural gas produced in the United States (U.S.) (DNV, 2007). The Louisiana Offshore Oil Port (LOOP), which handles 13% of foreign oil imports, resumed operation in early November 2005.

In this manuscript, we quantify the impact of Hurricanes Katrina and Rita on emissions of nitrogen oxides (NO_x) as inferred from tropospheric column amounts of nitrogen dioxide (NO_2) from the Ozone Monitoring Instrument (OMI) (Levelt et al., 2006). We show that the changes in the distribution of pollution emissions as inferred from the column amounts are consistent with the locations of NO_x sources damaged by the hurricanes and that the data product can be useful for assessing the impact of natural disasters and monitoring the progress of recovery. Satellite measurements of tropospheric column amounts of NO_2 have been widely used to constrain surface emissions of NO_x (e.g., Martin et al., 2003, 2006).

2. OMI NO_2 observations

The OMI is an UV/Vis imaging spectrometer; the basic algorithm for the retrieval of total column and tropospheric NO_2 is described by Boersma et al. (2007). The Aura satellite was launched in July 2004 and crosses the equator at approximately 1345 local time. NO_2 fitting was performed in the spectral window 405–465 nm. Here, we use tropospheric column amounts of NO_2 from the DOMINO

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(Dutch OMI NO_2) product v1.02 (Boersma et al., 2007, 2009). We gridded the product to a horizontal resolution of 0.25° latitude by 0.25° longitude using only data with effective cloud fractions less than 30%. The retrieval of cloud fractions is described by Sneep et al. (2008). A number of recent studies (Boersma et al., 2009; Huijnen et al., 2009; Zhou et al., 2009) indicate that OMI retrievals are positively biased, most likely with a magnitude of 0–30% irrespective of season. This is confirmed by comparisons with in situ aircraft NO_2 profiles from the INTEX-B campaign over the southeastern United States (Boersma et al., 2008; Hains et al., in press, 2010) and by year-round comparisons with in situ surface NO_2 measurements in Mississippi, Alabama, and Georgia (Lamsal et al., in press). The bias is significantly reduced when using improved surface albedos (derived from OMI) and observed NO_2 profiles rather than simulated a priori NO_2 profiles in the retrieval.

We removed from our analysis four days (i.e., August 4, 14, 15 and 16, 2005) as the contributions from lightning to the tropospheric column amounts over our study region were as high as ~55% of surface sources within 1 h of the overpass time and as high as 35% in the 6 h before the overpass. We estimated the lightning source using data from the National Lightning Detection Network (NLDN), which detects cloud-to-ground flashes (Biagi et al., 2007; Beirle et al., 2006). To account for intracloud flashes, we used a gridded climatology of intracloud to cloud-to-ground flash ratios (Boccippio et al., 2001). We assumed a production per flash of 500 mol NO/flash (Ott et al., 2010). Typically, it is difficult to discriminate this source from surface sources over polluted regions using the OMI data (Martin et al., 2007; Beirle et al., 2009).

3. Impact of the Hurricanes on sources of NO_x

3.1. Impact on OMI tropospheric column amounts of NO_2

The tracks of Katrina and Rita are shown in Fig. 1. Fig. 2 shows the column amounts for the pre-Katrina (August 1–26, 2005) and post-Rita (September 27 – October 17) periods and the differences between them. The pre-Katrina period had higher column amounts (as much as 40–50% higher) over a large area from eastern Texas to Alabama that extended about 250 km inland and 150 km out to sea (Fig. 2c). Simulated column amounts correlate nearly linearly with NO_x emissions in summer in the U.S. (Martin et al., 2006), so that the inferred percent decreases in surface source emissions are expected to be similar to those in the column amounts. However, the decrease in NO_x emissions may impact the lifetime of NO_2 through feedbacks in the hydroxyl radical (Stavrakou et al., 2008).

Mean differences of the column amounts between pre-Katrina, post-Katrina/pre-Rita (September 1–21, 2005), and post-Rita periods are shown in Fig. 3. Fig. 3a shows the difference between the post-Katrina/pre-Rita and pre-Katrina periods, which is, in effect, the impact of Katrina on emissions. Fig. 3b is the same as Fig. 3a, but for the post-Rita minus the post-Katrina/pre-Rita period, which is, in effect, the impact of Rita on emissions. In general, the impact of Rita (Fig. 3b) on column amounts within the GOM OCS was less, except near where it made landfall, than the impact of Katrina because of the extensive damage to NO_x sources by Katrina that existed before Rita made landfall as discussed below. We calculated differences in columns for the following regions, defined in Fig. 2c: the New Orleans/Gulfport area (boxes 2 and 3) near where Katrina made landfall, the Port Arthur/Lake Charles area (box 1) near where Rita made landfall, and the GOM OCS region (box 4) where there is a high density of oil and gas extraction activities. The column amounts over the New Orleans/Gulfport area decreased by about 35% after Katrina made landfall; column amounts over the GOM OCS dropped by 40% (Fig. 3a). For the Port Arthur/Lake Charles area, column amounts were not significantly different in the post-Katrina/pre-Rita period as the region did not experience damaging winds and storm surges from Katrina (Fig. 3a). Column amounts decreased about 20% in the Port Arthur/Lake Charles area after Rita made landfall as compared to the post-Katrina/pre-Rita period, reflecting the damage there to power generation and oil refining operations (Fig. 3b). The combined impact of the hurricanes (i.e., the post-Rita minus pre-Katrina periods) is shown in Fig. 3c.

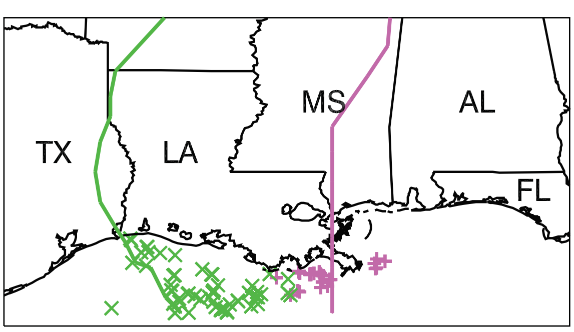

Fig. 1. The locations of platforms destroyed by Katrina (magenta plus signs) and Rita (green cross signs). The tracks of Katrina and Rita are shown as magenta and green lines, respectively.

3.2. Impact on coastal sources

In New Orleans and on the Mississippi coast (boxes 2–3 in Fig. 2c) where Katrina made landfall, the column amounts in the post-Rita period were 24% and 27% lower, respectively, than in the pre-Katrina period. There was a 14% decrease in the region near the Texas/Louisiana border, which includes the cities of Port Arthur and Lake Charles (box 1), where Rita made landfall. Fig. 4 shows the number of customers without power in Louisiana, Mississippi, and Texas (OE, 2005a,b). The number of customers still without power at the end of October reflects those homes and businesses which were catastrophically damaged, particularly in New Orleans. Rita made landfall in a region with intense oil refining activities. Fig. 4 shows the reduction in refinery capacity as the refineries shut down in preparation for Rita's landfall. Even by the end of October, normal operations had not resumed at all refineries.

3.3. Impact on inland sources

The column amounts were typically lower in the post-Rita period in counties declared disaster areas for individual and public assistance by the federal government, as delineated in Fig. 2c. Twenty-one counties in southeastern and 15 counties in southwestern Louisiana were declared disaster areas due to Katrina and Rita, respectively (FEMA-1603-DR-LA; FEMA-1607-DR-LA). Forty-nine counties in Mississippi and 11 counties in western Alabama were also declared disaster areas for Katrina (FEMA-1604-DR-MS; FEMA-1605-DR-AL). Some of the inland damage was associated with tornadoes spawned by the hurricanes (Knabb et al., 2006; NOAA, 2006).

3.4. Impact on offshore sources

Fig. 3a shows that the column amounts in the pre-Katrina period were higher offshore over a broad region extending from the Texas/Louisiana border to Alabama, which is associated with damage to oil rigs and platforms in the GOM OCS region. The column amounts decreased by 40% over the ocean (box 4 in Fig. 2c)

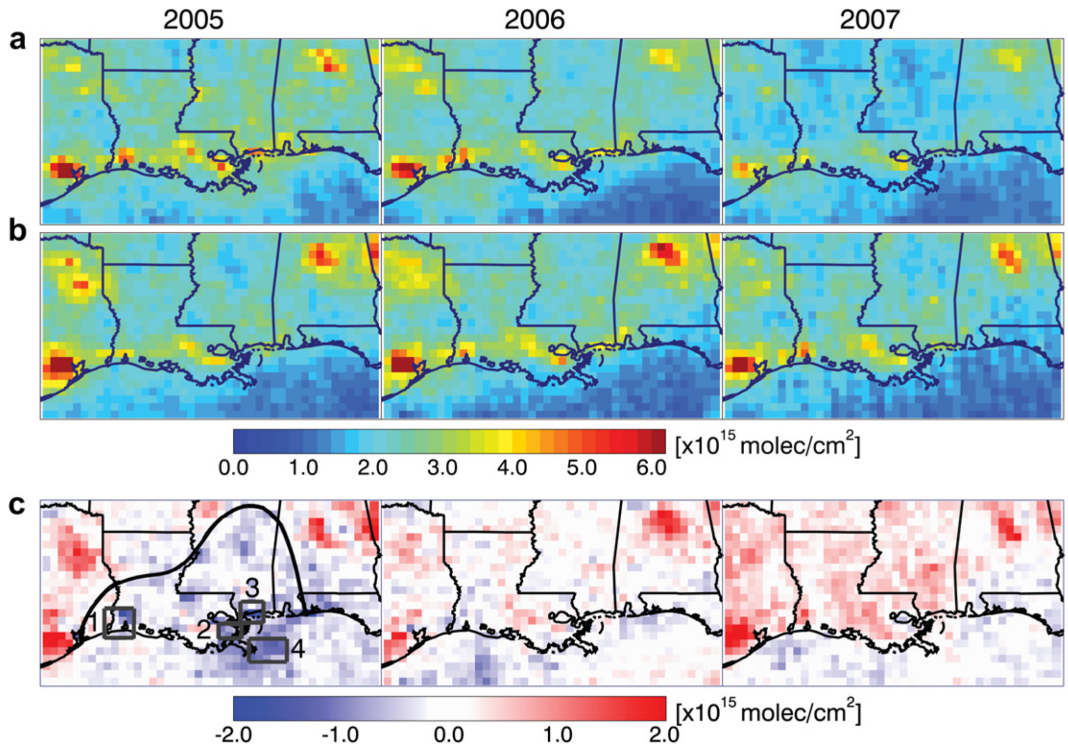

Fig. 2. (left column) a) The mean OMI tropospheric column amounts of NO_2 ($\times 10^{15}$ molec cm^{-2}) for the pre-Katrina period (August 1 to 26, 2005). b) The same as a), but for the post-Rita period (September 27 to October 17). c) The difference between the two periods (i.e., post-Rita minus pre-Katrina). Box 1: Port Arthur, Texas, and Lake Charles, Louisiana, 2: New Orleans, Louisiana, 3: Gulfport, Mississippi and 4: the GOM OCS. The area inside the thick black line indicates those counties designated as federal disaster areas for individual and public assistance. (middle column) The same as the left column, but for 2006. (right column) The same as the left column, but for 2007.

after Katrina as compared to the pre-Katrina level. By Katrina's landfall, 75% of the 819 manned platforms and 72% of the 137 rigs were evacuated for safety reasons, reducing daily oil and gas production by 92% and 83%, respectively (MMS, 2005a). Oil production was stopped completely during Rita (MMS, 2005b). Between the two storms, 116 platforms were destroyed, and another 163 platforms suffered extensive damage (MMS, 2007); Fig. 1 shows the locations of destroyed platforms (http://www.cccarto.com/gulf_platforms.html). Emissions from oil platforms and drilling rigs in October were more than 80% lower along the hurricane tracks and 37% lower in the GOM OCS than in July (Wilson et al., 2007); platform and rig emissions contribute 21% and 9%, respectively, to total emissions in the GOM OCS. By the end of October, more than 25% of the 819 platforms in the GOM OCS were still evacuated and oil and gas production was lower than the pre-Katrina level by more than 65% and 50%, respectively (Fig. 4) (MMS, 2005c). About two-thirds of the 53 000 km of offshore pipelines were in the paths of the two hurricanes, resulting in 542 damage reports (DNV, 2007). Due to Katrina, there was a significant reduction in the production of oil (95%) and gas (88%). After Rita, the reductions were 100% (oil) and 81% (gas) (Fig. 4). From September 2005 to June 2006, the decreases were 30% (oil) and 22% (gas) in the GOM OCS (MMS, 2005c). Though there were minor evacuations (~30% of platforms and ~20% of rigs), no major damage in the GOM OCS was reported from Hurricane Wilma (MMS, 2005c), which made landfall in Mexico.

The largest source of NO_x emissions in the GOM OCS is ships such as support ships for oil/natural gas extraction activities and commercial marine vessels, which account for 38% and 24% of all emissions, respectively (Wilson et al., 2007). While emissions from platforms decreased by about 37% in October as compared to July 2005, emissions from support vessels may have been higher than normal due to evacuation and repair activities. On the other hand, emissions from commercial vessels were certainly lower because of damage to ports, which disrupted cargo shipping (http://www.ocean.udel.edu/news/article.aspx?336). For Gulfport, one of the most severely damaged ports, the tonnage moved through the port was only 65% of its pre-Katrina volume in mid-2006 (GAO, 2007; Scott, 2007).

Fig. 5 shows the column amounts in the pre-Katrina and post-Rita periods for 2005 with the mean of the same periods in 2006 and 2007 removed. The column amounts over the ocean (box 4 in Fig. 2c) in 2006 and 2007 were ~40% lower than in 2005 in the pre-Katrina period. Total, annual oil production in the GOM OCS was similar in 2005, 2006, and 2007 and natural gas production was lower in 2006 and 2007 than in 2005 [MMS, 2009], reflecting the long-term impact on pollution sources in the GOM OCS, particularly near eastern Louisiana and Mississippi. In the post-Rita period, the column amounts in the Port Arthur/Lake Charles area (box 1) were ~14% higher in 2006/2007 than 2005, which is consistent with the relatively rapid return to normal operations for refineries in that area (Fig. 4), and the New Orleans and Mississippi coast areas (boxes 2–3) showed higher, albeit relatively weak, column amounts, indicating some recovery. However, these signals in the post-Rita period are somewhat muddled by the interannual variability in the columns which are evident in Fig. 2c; we address this issue in the next section.

3.5. Seasonal transition

The changes in the column amounts in 2005 (Fig. 2) consist of changes in emissions associated with damage from the hurricanes and the seasonal transition that occurs each year from summer to fall. The lifetime of NO_2 typically increases from August to October

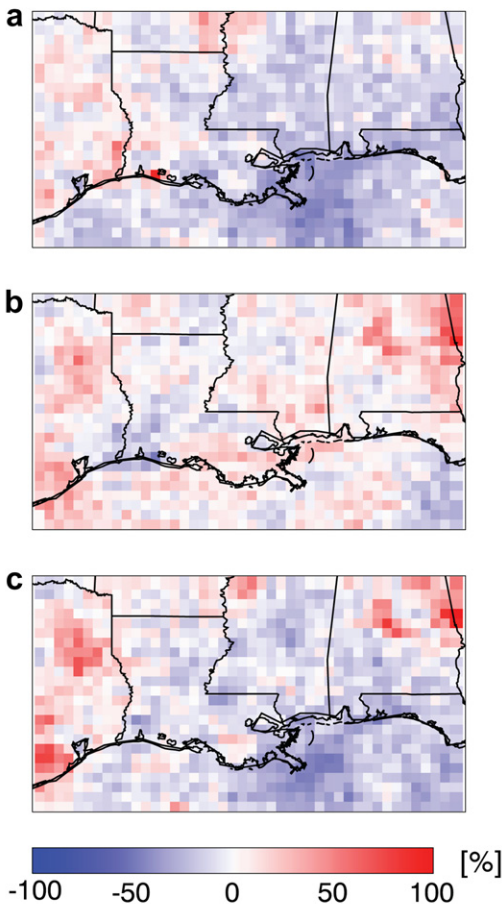

Fig. 3. a) The difference of the OMI tropospheric column amounts of NO_2 (%) between the pre-Katrina and post-Katrina/pre-Rita periods (September 1 to 21, 2005), calculated as the post-Katrina/pre-Rita minus pre-Katrina periods divided by pre-Katrina period. b) The same as a), but for the difference between the post-Katrina/pre-Rita and post-Rita periods. c) The same as a), but for the difference between the pre-Katrina and post-Rita periods.

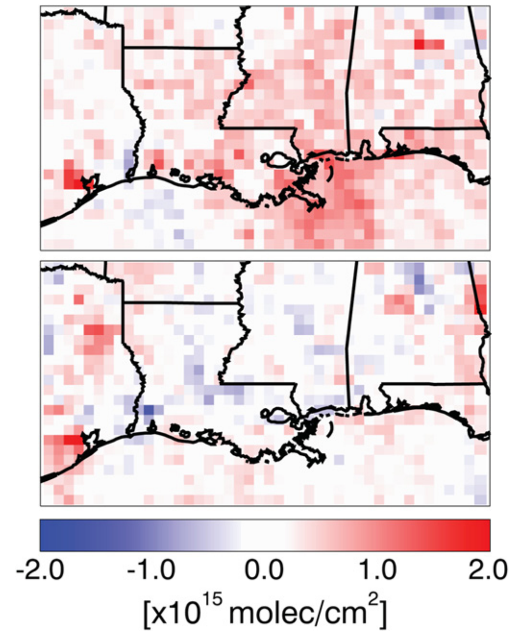

Fig. 5. (top) The OMI tropospheric column amounts of NO_2 ($\times 10^{15}$ molec cm^{-2}) in the pre-Katrina period for 2005 with the mean of the same period in 2006 and 2007 removed. (bottom) The column amounts in the post-Rita period for 2005 with the mean of the same period in 2006 and 2007 removed.

because of decreases in sunlight intensity and temperature, for instance. This seasonal growth in NO_2 is important as it damps our estimate of the overall impact of the hurricanes on emission sources. Therefore, the percent changes in inferred emissions discussed above should be seen as lower limits of the impact of the hurricanes.

There are two ways to account for this seasonal change. First, we could subtract the mean of the post-Rita periods (Fig. 2b) in 2006 and 2007 from 2005, which assumes that the mean represents a normal year. The column amounts in 2006 and 2007 indicate that the largest seasonal increases (>30%) occurred in cities, which is also apparent in 2005 in areas not impacted by the hurricanes (e.g., Dallas, Birmingham) (Fig. 2c). Smaller magnitude increases or decreases occurred in less polluted areas. The problem with this method is that 1) the impact of the hurricanes in the GOM OCS lingered into 2006 and 2007 as discussed above, and 2) the column amounts for 2006 and 2007 indicate interannual variations in the timing and magnitude of the seasonal transition, which is associated with variations in weather. For instance, the seasonal transition in 2006 in rural areas was generally less than in 2007. However, the transition in urban areas (e.g., Birmingham) was similar for the two years. One final consideration is that the impact of the seasonal transition on the column amounts in 2005 would be less than in a normal year as the magnitude of the emissions was lower in the post-Rita than the pre-Katrina period.

Second, we could use a model of chemistry and transport to estimate the magnitude of this seasonal transition and then remove it. We used the Global Modeling Initiative's chemistry and transport model (GMI CTM) (Duncan et al., 2007) to understand the influence

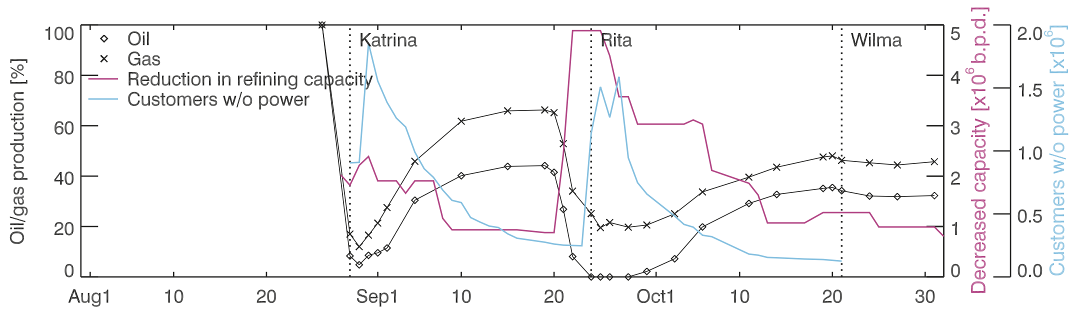

Fig. 4. Reduction in oil (diamond symbol) and natural gas (x symbol) production in the GOM OCS relative to the value on August 26, 2005. The magenta line represents the total capacity of shut down refineries (million barrels/day) and turquoise represents the number of customers without power (millions). The vertical dotted lines indicate the dates of hurricane landfalls.

of the seasonal transition for our study period. We did not change surface sources of NO_x that were impacted by the hurricanes, as we have no emission estimates (e.g., for ships, rigs, etc.) other than that for oil platforms from Wilson et al. (2007). The simulation indicates that the column amounts increased along the Louisiana and Mississippi coasts by 30–50% from the pre-Katrina to the post-Rita period. When put onto the same horizontal resolution (2° latitude by 2.5° longitude) of the GMI CTM, the seasonal change in the observed column amounts in 2006 and 2007 was considerably lower, ranging from -7 to $+11\%$.

Possible reasons for the model/data discrepancy may be associated with the emissions estimate and/or chemistry of the biogenic hydrocarbon, isoprene, both of which are highly uncertain (Guenther et al., 2006; Pacifico et al., 2009). First, the magnitude and timing of the seasonal transition in emissions may not be accurately represented by the MEGAN inventory, whether due to deficiencies in the inventory or the meteorological variables used as input by the inventory (e.g., temperature, sunlight). Guenther et al. (2006) reported that there are a number of differences between the magnitude and distribution of isoprene emissions as estimated by MEGAN and from GOME data. Second, from the pre-Katrina to the post-Rita period, isoprene emissions, as estimated from the MEGAN inventory (Guenther et al., 2006), decreased by ~60%, repartitioning NO_y in favor of NO_2; organic nitrate concentrations decreased substantially (e.g., PAN by ~40–60%). Consequently, this seasonal decrease in isoprene emissions ultimately enhances the increase in NO_2 caused by the summer to fall transition in the NO_2 lifetime. As future work, we will use the OMI HCHO column amounts in an attempt to help constrain and understand the impact of the seasonal change in isoprene emissions on NO_x. This is important as there is considerable uncertainty in the isoprene oxidation mechanism, particularly the yield and fate of organic nitrates (Fiore et al., 2005).

4. Summary

We present the first comprehensive space-based assessment of the impact of Hurricanes Katrina and Rita on pollution emissions associated with power generation, shipping, and oil/natural gas production activities in the GOM region. We inferred changes in pollution emissions using the OMI tropospheric column amounts of NO_2, though our estimates should be seen as lower limits of the total impact of the hurricanes because of issues associated with the seasonal transition in the lifetime of NO_2. The OMI data indicate that anthropogenic emissions were lower in nearly all of Louisiana, the southern half of Mississippi, and southwestern Alabama in the month after Rita made landfall as compared to the month before Katrina made landfall. Areas hard hit by the hurricanes included the Port Arthur/Lake Charles and New Orleans/Gulfport regions, where column amounts were 14% and 25% lower, respectively, in the post-Rita period as compared to the pre-Katrina period. Emissions associated with intensive oil and natural gas production over a broad area of the GOM OCS, stretching from Port Arthur, Texas to Mobile, Alabama, and 150 km out to sea, were 43% lower.

There are a number of uncertainties associated with the estimation of the OMI tropospheric column amounts of NO_2 (e.g., Lamsal et al. (2008)) and as discussed in Sections 2 and 3 (e.g., isoprene chemistry, lightning emissions). Nevertheless, we conclude that the changes in the distribution of pollution emissions as inferred from the column amounts are consistent with the locations of NO_x sources damaged by the hurricanes. Therefore, these products can be used to assess the impact of natural disasters and monitor the progress of recovery.

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