Scope of Work For

Project 20-005

Using Satellite Observations to Quantify Surface $PM_{2.5}$ Impacts from Biomass Burning Smoke

Prepared for

Air Quality Research Program (AQRP)
The University of Texas at Austin

By

Matthew J. Alvarado
Atmospheric and Environmental Research, Inc.

May 11, 2020
Version 0

QA Requirements: Audits of Data Quality: 10% Required
Report of QA Findings: Required in Final Report

Approvals

This Scope of Work was approved electronically on **06/19/20** by Elena McDonald-Buller, The University of Texas at Austin

Elena McDonald-Buller
Project Manager, Texas Air Quality Research Program

This Scope of Work was approved electronically on **06/30/20** by (Fernando Mercado, Texas Commission on Environmental Quality

Fernando Mercado
Project Liaison, Texas Commission on Environmental Quality

TABLE OF CONTENTS

1 Abstract

Biomass burning smoke can have major impacts on surface $PM_{2.5}$ concentrations both near the fires and hundreds of miles downwind. These smoke impacts pose two challenges for air quality managers. First, they want to accurately report the potential smoke impacts in time for the public to take protective actions. Second, they need to estimate the recent impacts of smoke on $PM_{2.5}$ in order to determine which elevated $PM_{2.5}$ episodes may fall under the US EPA Exceptional Events Rule (EER). The EER determines the conditions under which the US EPA will forgo comparison of policy relevant air monitoring data to a relevant National Ambient Air Quality Standard (NAAQS).

NOAA and NASA satellite observations provide valuable information on the locations of fires and transport of smoke. Existing analysis products, such as the NOAA Hazard Mapping System (HMS) Fire and Smoke product, provide observed fire locations and identify regions that are being impacted by biomass burning smoke. However, there are multiple products that use different techniques to identify smoke plumes, and thus may disagree on the extent of the area covered by biomass burning smoke. In addition, as these products primarily use passive, single-angle geostationary and polar satellite observations (due to their greater spatial coverage), these products do not currently provide information on the height of the smoke plumes or estimates of the surface impacts of the observed smoke. **An analysis of existing smoke products that increases our confidence in the identification of smoke and provides an estimate of smoke height and surface $PM_{2.5}$ impact would greatly help TCEQ air quality managers protect the public and properly enforce air quality standards.**

In this project, we will evaluate the ability of these existing remote sensing smoke products to accurately and consistently identify regions impacted by smoke. We will compare and evaluate the smoke products using additional polar satellite observations that are sensitive to smoke, specifically observations of CO and NH_3 from CrIS and AIRS and aerosol absorption Angstrom exponent (a proxy for brown carbon) from OMI. We will evaluate two methods for estimating the height of the plumes detected by the HMS and other smoke products: the plume height estimates from the MODIS MAIAC algorithm and a new method based on the observed transport direction of the smoke plumes. Finally, we will test different statistical and model-based approaches to estimate the impact of the observed smoke on surface $PM_{2.5}$.

The objectives of this project are thus:

1. **To compare different methods for identifying smoke plumes from NOAA and NASA remote sensing imagery;**
2. **To investigate different remote sensing techniques to estimate the height and vertical profiles of these smoke plumes; and**
3. **To investigate new statistical and machine learning methods to relate the smoke AOD observations to surface $PM_{2.5}$ concentrations.**

This work directly responds to the AQRP priority research area ***"Estimate Impacts of Smoke from Biomass Burning"*** by investigating the question "*Is it possible to quantify ground level impacts of biomass burning ($PM_{2.5}$) using remote sensing tools, such as the NOAA Hazard Mapping System (HMS) Fire and Smoke product?*".

2 Background

Biomass burning smoke, both from local fires and transported from fires hundreds of miles away, can have a large impact on surface $PM_{2.5}$ concentrations. Air quality managers in Texas need to be able to quickly estimate these impacts of biomass burning smoke in order to warn the general public in time to take protective actions (*e.g.* staying indoors, using indoor air filters). In addition, air quality managers need to estimate the $PM_{2.5}$ impacts of biomass burning smoke in order to determine which elevated $PM_{2.5}$ episodes may fall under the US EPA Exceptional Events Rule (EER). The EER determines the conditions under which the US EPA will forgo comparison of policy relevant air monitoring data to a relevant National Ambient Air Quality Standard (NAAQS).

NOAA and NASA satellite observations provide valuable information on the locations of fires and transport of smoke, which have been compiled into several publicly available products for air quality managers (Section 1.2). However, these products can disagree on the extent of the smoke plume and generally do not provide information on either the height of the smoke plumes or the impact of the smoke on surface $PM_{2.5}$ concentrations. ***An analysis of existing smoke products that increases our confidence in the identification of smoke and provides an estimate of smoke height and surface $PM_{2.5}$ impact would greatly help TCEQ air quality managers protect the public and properly enforce air quality standards.***

In this project, we will evaluate the ability of existing near-real-time (NRT) remote sensing smoke products to identify regions impacted by smoke using additional polar satellite observations that are sensitive to smoke, specifically observations of CO and NH_3 from CrIS and AIRS and aerosol absorption Angstrom exponent (AAE) (a proxy for brown carbon) from OMI (Task 1, Section 1.3.1). We will also evaluate two methods for estimating the height of the plumes detected by the HMS and other smoke products: the plume height estimates from the MODIS MAIAC algorithm and a new method based on the observed transport direction of the smoke plumes (Task 2, Section 1.3.2). Finally, we will test different statistical and model-based approaches to estimate the impact of the observed smoke aerosol optical depth (AOD) on surface $PM_{2.5}$ (Task 3, Section 1.3.3).

Our three project tasks are designed to answer our three key science questions:

1. How consistent are the different methods for identifying the extent of smoke plumes?
2. How well can the height of the smoke plumes over Texas observed in current smoke products be constrained?
3. How well can the surface $PM_{2.5}$ impacts of smoke in Texas be constrained using current remote sensing products?

2.1 Near-Real-Time (NRT) Smoke Detection Products over Texas

2.1.1 NOAA Hazard Mapping System (HMS) Fire and Smoke Product

To make the HMS Fire and Smoke product, National Environmental Satellite, Data, and Information Service (NESDIS) satellite analysts manually generate a daily operational list of fire locations and outline areas of smoke (Figure 1). These analysts compare automated fire detections to the infrared satellite images used to produce them to ensure each fire exists (Ruminski *et al.*, 2006; Schroeder *et al.*, 2008; Brey *et al.*, 2018). Small fires are more difficult to detect and are underreported (*e.g.*, Hu *et al.*, 2016). False fire detections are removed, and fires that were not automatically detected are added manually. After identifying fire locations, HMS analysts use imagery from multiple NOAA and NASA satellites to identify the geographic extent of smoke plumes (Rolph *et al.*, 2009; Ruminski *et al.*, 2006). Smoke detection is done primarily with visible-band geostationary GOES imagery, which has high temporal coverage (typically every 15 min), occasionally assisted by GOES infrared imagery and polar orbiting satellite imagery (Ruminski *et al.*, 2006). Due to the frequent interference by cloud cover, the number and extent of smoke plumes reported in the HMS represents a conservative estimate. No information about the height or vertical profile of smoke plumes is provided.

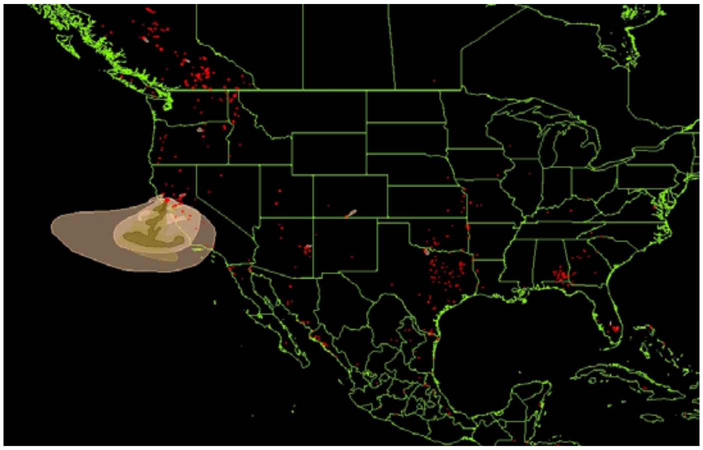

Figure 1. NOAA HMS Fire and Smoke product for October 27, 2019, during the severe fires in Southern California.

2.1.2 GOES-R Aerosol Detection (Smoke and Dust) Algorithm

The GOES-R aerosol detection algorithm detects smoke and dust contaminated pixels using images taken by the Advanced Baseline Imager (ABI) flown on the GOES-R series NOAA operational geostationary meteorological satellites (NOAA/NESDIS/STAR, 2018). The algorithm provides an initial estimate of the presence or absence of smoke or dust within each ABI pixel. The smoke and dust detection algorithm is based on the fact that smoke/dust exhibits features of spectral dependence and contrast over both the visible and infrared spectrum that are different from clouds, surface, and clear-sky atmosphere (NOAA/NESDIS/STAR, 2018). The GOES-R smoke and dust algorithm has been tested for different scenarios such as wildfires and dust storms against MODIS and CALIPSO observations.

2.1.3 NOAA Automated Smoke Detection and Tracking Algorithm (ASDTA)

The ASDTA product provides smoke-specific GOES AOD maps at a 30-minute interval to provide observational support for verification of NOAA HYSPLIT smoke ($PM_{2.5}$) forecasts. ASDTA uses a source apportionment technique to fuse GOES observations of fire hot spots and GOES AOD maps at a 30-minute interval (Zeng and Kondragunta, 2010). Plume direction and extent from all observed fire sources are first determined, then AOD values not associated with the fires are dropped. A pattern recognition technique is used for plumes transported long distances from fire sources. ASDTA provides wind speed and direction associated with the plumes; however, the vertical location of the plumes is not provided.

3 Objectives

The objectives of this project are:

1. **To compare different methods for identifying smoke plumes from NOAA and NASA remote sensing imagery;**
2. **To investigate different remote sensing techniques to estimate the height and vertical profiles of these smoke plumes; and**
3. **To investigate new statistical and machine learning methods to relate the smoke AOD observations to surface $PM_{2.5}$ concentrations.**

This work directly responds to the AQRP priority research area ***"Estimate Impacts of Smoke from Biomass Burning"*** by investigating the question "*Is it possible to quantify ground level impacts of biomass burning ($PM_{2.5}$) using remote sensing tools, such as the NOAA Hazard Mapping System (HMS) Fire and Smoke product?*". We investigate both the height of the smoke plumes and the ability to link the observed smoke plumes to surface $PM_{2.5}$ concentrations, as requested. Both local and transported smoke will be investigated. In addition, we will provide TCEQ staff with the software developed in this project, along with documentation and training, so that TCEQ can use the methods developed in this project in future Texas air quality decision making.

4 Task Descriptions

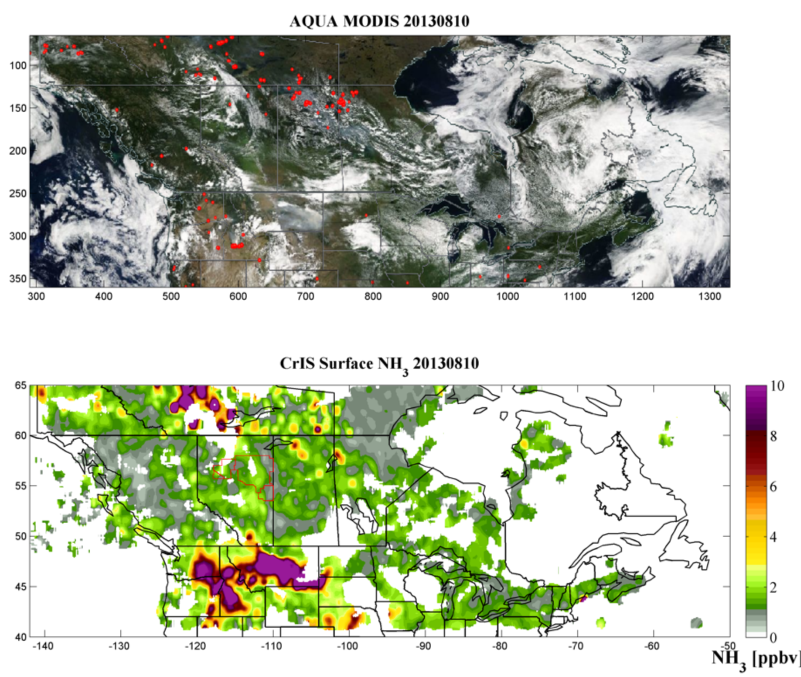

Figure 2. (top) MODIS fire hot spots on August 10, 2013 (red circles) over MODIS visible imagery. (bottom) CrIS NH_3 observations for the same day. Note the MODIS fire hot spots over northern Canada, Washington, Oregon, and Idaho are associated with plumes of elevated CrIS NH_3.

4.1 Task 1: Critical Review of Methods to Identify Smoke Plumes in NRT

In this task, we will compare and evaluate the different NRT smoke detection products described in Section 1.2. Our evaluation will focus on periods when fires were present within Texas, as well as time where smoke is known to have been transported to Texas urban areas from fires in the rest of the US and Mexico (*e.g.*, Wang and Talbot, 2017). These evaluations will use the figure of merit in space (FMS) evaluation metric, defined as the intersection over the union of the observed and calculated smoke plumes, which has been frequently used to evaluate smoke forecasts using satellite observations (*e.g.,* Rolph *et al.*, 2009; Stein *et al.*, 2009).

While simple comparisons of the three NRT products will allow us to assess their consistency, none of the products provide a "truth" dataset to use as a reference. (This also makes the training of machine learning algorithms to identify smoke difficult, as they require a truth dataset.) Thus, in this task we will use additional satellite observations to determine if the detections of smoke from the three NRT products are robust. First, we will use polar satellite observations of the trace gases CO and NH_3 from the Cross-Track Infrared Sounder (CrIS; Shephard and Cady-Pereira, 2015) as an additional indicator of the presence of smoke. Both CO and NH_3 are emitted in large quantities by biomass burning (*e.g.*, Akagi *et al.*, 2011; Alvarado *et al.*, 2011), and daily observations of NH_3 and CO from CrIS can be used to determine the extent of smoke transport (Figure 2). The FMS between the smoke extent determined by the CrIS trace gas observations and the NRT products will be calculated and examined. The PI Dr. Alvarado has extensive knowledge of the CrIS NH_3 and CO products from his work on trace gas remote sensing (*e.g.*, Alvarado *et al.*, 2011, 2013, 2015b) and his work to use the CrIS NH_3 observations to improve estimates of NH_3 emissions (Alvarado *et al.*, 2019b).

Second, we will use data from the polar-orbiting Ozone Monitoring Instrument (OMI) to identify areas that have large concentrations of brown carbon (BrC) aerosols, which are emitted by biomass burning. OMI provides absorption aerosol optical depth (AAOD) at five wavelengths between 342.5 nm and 483.5 nm once a day around 13:30 local solar time. These wavelengths can be used to calculate an AAE in the UV. High values of this UV AAE imply the presence of BrC aerosols from biomass burning smoke: for example, Wang *et al.* (2016) found that $AAE_{388/440\ nm}$ for BrC is generally ~4 worldwide, with a smaller value in Europe (< 2), compared to ~1 for black carbon aerosols from both biomass burning and anthropogenic sources.

The PI Dr. Alvarado is currently exploring the use of OMI AAE to identify brown carbon and biomass burning smoke as part of a TCEQ funded project that will be completed by the end of July 2020. These OMI identifications of BrC aerosols will then be used in this project to provide an additional, independent FMS evaluation of the NRT smoke products from Section 1.2.

Deliverables: Work Plan and Quality Assurance Project Plan.

Schedule: The schedule for Task 1 Deliverables and Milestones are shown in Section 6.

4.2 Task 2: Determine Heights of Smoke Plumes

As noted above, none of the NRT smoke plume products provide information on the height of smoke plumes or the vertical distribution of the smoke. This is because passive single-angle sensors, such as the GOES ABI, do not have enough information to calculate the height of the smoke plumes. Other satellites use multiple viewing angles (*e.g.*, MISR, Nelson *et al.*, 2013) or active lidar (*e.g.*, CALIPSO, Soja *et al.*, 2017) to determine smoke plume height, but these instruments have much less spatial and temporal coverage than the GOES imagery used in the NRT smoke products.

In this task, we will explore two different methods to provide height information for the smoke plumes identified in the NRT smoke products. First, Collection 6 of the MODIS Multi-Angle Implementation of Atmospheric Correction (MAIAC, Lyapustin *et al.*, 2011, 2019) algorithm provides an estimated injection height of smoke plumes over land under certain conditions (*i.e.*, thick smoke near clear-sky pixels). We will develop a technique that takes the twice-daily heights from the MAIAC product and extrapolates them in time to provide estimates of smoke height for the NRT products.

Second, we will take advantage of the plume wind speed and direction provided by the ASDTA product (Section 1.2.3) to estimate the height of the smoke plumes. As the wind speed and direction at any location will depend on height, the ASDTA plume wind speed and direction estimates could be matched to modeled vertical profiles of horizontal winds to provide an estimate of the height at which most of the smoke transport is occurring. We will explore two ways of performing this matching: directly comparing the wind speed and direction fields from the NOAA high resolution rapid refresh (HRRR) smoke forecasts (Ahmadov *et al.*, 2017) and performing HYSPLIT simulations at fire locations with different injection heights to determine which height is most spatially consistent with the observed transport direction and speed, using the methods used by Stein *et al.* (2009). MISR and CALIPO data will also be used to evaluate these wind direction height estimates.

Deliverables: None.

Schedule: The schedule for Task 2 Deliverables and Milestones are shown in Section 6.

4.3 Task 3: Estimating Surface $PM_{2.5}$ Impacts from Smoke AOD

In this task we will develop methods to determine the impact of the observed smoke on surface $PM_{2.5}$ by connecting the observed smoke AOD from GOES to the observed surface $PM_{2.5}$ concentrations using a variety of statistical and model-based techniques. One of the challenges of these approaches is that satellites cannot retrieve AOD over cloudy scenes, which can limit the number of $PM_{2.5}$ events that can be observed by satellite. One method for addressing this limitation is by gap-filling the AOD observations when the satellite data is missing by using an artificial AOD based on the observed seasonal mean of AOD adjusted by the daily $PM_{2.5}$ measurements at ground stations (*e.g.*, Goldberg *et al.*, 2019). Lv *et al.* (2016, 2017) applied this technique to the Beijing metropolitan area and were able to predict $PM_{2.5}$ with a correlation coefficient (r^2) of 0.78. Thus, in this task we will apply the Lv *et al.* (2016, 2017) technique to the GOES smoke AOD observations to increase the number of smoke events that can be evaluated.

We will then test two methods for relating the observed smoke AOD to the surface $PM_{2.5}$ impacts. We will start with a two-stage statistical approach (Zhang *et al.*, 2019). The first stage of the approach will use a linear mixed effect model (Lee *et al.*, 2011). In these models, the fixed-effect term explains the average effect of the relationship between the independent variables and $PM_{2.5}$ concentrations during the whole study period. The random effect explains, for each day, the variation in this relationship. Both the fixed and random effect slopes are assumed to be the same for all sites. In addition to the presence or absence of smoke and the observed GOES AOD, meteorological variables (*e.g.*, temperature, RH, PBL height), the estimated smoke plume heights from Task 2, and other variables will be tested as predictors for the smoke AOD/$PM_{2.5}$ relationship. The second stage will use geographically weighted regression (GWR, van Donkelaar *et al.*, 2015) to develop site-specific corrections for the smoke AOD/$PM_{2.5}$ relationship, using geographic variables (*e.g.*, % urban cover nearby, population density) as predictors. Zhang *et al.* (2019) used this two-stage approach to relate VIIRS-derived AOD to $PM_{2.5}$ concentrations in the Guanzhong Basin of China with a correlation coefficient (r^2) of 0.70. We will explore training two separate statistical models, one for smoke-influenced days and one for days without observed smoke and use the difference between these model predictions on smoky days to estimate the impact of smoke on surface $PM_{2.5}$.

In addition, we will test one model-based approach where output from a chemical transport model is used to estimate the relationship between AOD and surface $PM_{2.5}$ (*e.g.*, van Donkelaar *et al.*, 2015) and the modeled surface $PM_{2.5}$ estimate is scaled up to match the observed AOD. We will use the predictions from the 3-km resolution HRRR WRF-Chem smoke forecasts (Ahmadov *et al.*, 2017) to estimate the vertical profile of the smoke plumes. The AOD for these profiles will be calculated using the smoke aerosol model from the GOES AOD retrievals. Both methods will be evaluated against surface $PM_{2.5}$ observations not included in the model training dataset, and the correlation, linear regression slope, mean bias, and root-mean-square error of the $PM_{2.5}$ predictions will be quantified. The results of this evaluation will allow us to answer the AQRP priority area question "*Is it possible to quantify ground level impacts of biomass burning ($PM_{2.5}$) using remote sensing tools, such as the NOAA Hazard Mapping System (HMS) Fire and Smoke product?*". At the end of the project, we will provide the software, as well as documentation and on-line training, to TCEQ staff so that they will be able to perform these smoke impact analyses as needed in the future.

Deliverables: Provide software, documentation, and on-line training to TCEQ staff to perform these smoke impact analyses as needed in the future.

Schedule: The schedule for Task 3 Deliverables and Milestones are shown in Section 6.

4.4 Task 4. Project Reporting and Presentation

As specified in Section 7 "Deliverables" of this Scope of Work, AQRP requires the regular and timely submission of monthly technical, monthly financial status and quarterly reports as well as an abstract at project initiation and, near the end of the project, submission of the draft final and final reports. Additionally, at least one member of the project team will attend and present at the AQRP data workshop. For each reporting deliverable, one report per project will be submitted (collaborators will not submit separate reports), with the exception of the Financial

Status Reports (FSRs). The lead PI (or their designee) will electronically submit each report to both the AQRP and TCEQ liaisons and will follow the State of Texas accessibility requirements as set forth by the Texas State Department of Information Resources. The report templates and accessibility guidelines found on the AQRP website at http://aqrp.ceer.utexas.edu/ will be followed. ****Draft copies of any planned presentations (such as at technical conferences) or manuscripts to be submitted for publication resulting from this project will be provided to both the AQRP and TCEQ liaisons per the Publication/Publicity Guidelines included in Attachment G of the subaward.**** Finally, our team will prepare and submit our final project data and associated metadata to the AQRP archive.

Deliverables: Abstract, monthly technical reports, monthly financial status reports, quarterly reports, draft final report, final report, attendance and presentation at AQRP data workshop, submissions of presentations and manuscripts, project data and associated metadata

Schedule: The schedule for Task 4 Deliverables are shown in Section 7.

5 Project Participants and Responsibilities

- Matthew Alvarado of AER will be the Principal Investigator for this project. He will lead all tasks in this project and will be responsible for directing this project's day-to-day activities. He will also maintain overall responsibility for the successful completion of the project and ensure that project quality standards are met on all deliverables. Dr. Alvarado will lead all project tasks.

- Dr. Alvarado will be assisted on these tasks by a Staff Scientist from AER's Air Quality and Atmospheric Composition Section, whom he will supervise.

6 Timeline

2020	
Q2	**Deliverable 1:** Work Plan and Quality Assurance Project Plan. **Due:** 10 business days after notification of funding.
	Compare existing smoke products over Texas and nearby areas (Task 1).
Q3	Evaluate existing smoke products using OMI Brown Carbon estimates (Task 1).
	Evaluate existing smoke products using CrIS and AIRS CO and NH_3 retrievals (Task 1).
	Evaluate MAIAC smoke plume height product over Texas using MISR and CALIPSO data (Task 2).

Q4	Use MAIAC product to estimate heights for smoke plumes observed by GOES (Task 2).
	Develop HYSPLIT-based estimates of plume heights based on GOES smoke transport observations (Task 2).
	Evaluate HYSPLIT-based estimates of plume heights using MISR and CALIPSO data (Task 2).
	Gap-fill smoke AOD observations from MODIS and GOES (Task 3).
2021	
Q1	Develop and evaluate different methods for converting AOD to surface $PM_{2.5}$ concentrations (Task 3).
	Develop models separately for smoke and non-smoke days to estimate smoke impact on total $PM_{2.5}$ (Task 3).
Q2	Determine if height estimates from Task 2 improve the predictions of surface $PM_{2.5}$ impacts (Task 3).
	Deliverable 2: Provide software, documentation, and on-line training to TCEQ staff to perform these smoke impact analyses as needed in the future. **Due:** June 30, 2021
Q3	Write final report and draft presentation to AQRP workshop.

7 Deliverables

AQRP requires certain reports to be submitted on a timely basis and at regular intervals. A description of the specific reports to be submitted and their due dates are outlined below. One report per project will be submitted (collaborators will not submit separate reports), with the exception of the Financial Status Reports (FSRs). The lead PI will submit the reports, unless that responsibility is otherwise delegated with the approval of the Project Manager. All reports will be written in third person and will follow the State of Texas accessibility requirements as set forth by the Texas State Department of Information Resources. Report templates and accessibility guidelines found on the AQRP website at http://aqrp.ceer.utexas.edu/ will be followed.

Abstract: At the beginning of the project, an Abstract will be submitted to the Project Manager for use on the AQRP website. The Abstract will provide a brief description of the planned project activities, and will be written for a non-technical audience.

Abstract Due Date: Friday, July 31, 2020

Quarterly Reports: Each Quarterly Report will provide a summary of the project status for each reporting period. It will be submitted to the Project Manager as a Microsoft Word file. It will not exceed 2 pages and will be text only. No cover page is required. This document will be inserted into an AQRP compiled report to the TCEQ.

Quarterly Report Due Dates:

Report	Period Covered	Due Date
Quarterly Report #1	May, June, July 2020	Friday, July 31, 2020
Quarterly Report #2	August, September, October 2020	Friday, October 30, 2020
Quarterly Report #3	November, December 2020, January 2021	Friday, January 29, 2021
Quarterly Report #4	February, March, April 2021	Friday, April 30, 2021
Quarterly Report #5	May, June, July 2021	Friday, July 30, 2021
Quarterly Report #6	August, September, October 2021	Friday, October 29, 2021

Monthly Technical Reports (MTRs): Technical Reports will be submitted monthly to the Project Manager and TCEQ Liaison in Microsoft Word format using the AQRP FY20-21 MTR Template found on the AQRP website.

MTR Due Dates:

Report	Period Covered	Due Date
Technical Report #1	Project Start - June 30, 2020	Wednesday, June 10, 2020
Technical Report #2	July 1 - 31, 2020	Friday, July 10, 2020
Technical Report #3	August 1 - 31, 2020	Monday, August 10, 2020

Technical Report #4	September 1 - 30 2020	Thursday, September 10, 2020
Technical Report #5	October 1 - 31, 2020	Friday, October 9, 2020
Technical Report #6	November 1 - 30, 2020	Tuesday, November 10, 2020
Technical Report #7	December 1 - 31, 2020	Thursday, December 10, 2020
Technical Report #8	January 1 - 31, 2021	Friday, January 8, 2021
Technical Report #9	February 1 - 28, 2021	Wednesday, February 10, 2021
Technical Report #10	March 1 - 31, 2021	Wednesday, March 10, 2021
Technical Report #11	April 1 - 30, 2021	Friday, April 9, 2021
Technical Report #12	May 1 - 31, 2021	Monday, May 10, 2021
Technical Report #13	June 1 - 30, 2021	Thursday, June 10, 2021
Technical Report #14	July 1 - 31, 2021	Friday, July 9, 2021

DUE TO PROJECT MANAGER

Financial Status Reports (FSRs): Financial Status Reports will be submitted monthly to the AQRP Grant Manager (RoseAnna Goewey) by each institution on the project using the AQRP 20-21 FSR Template found on the AQRP website.

FSR Due Dates:

Report	Period Covered	Due Date
FSR #1	Project Start - June 30	Wednesday, July 15, 2020
FSR #2	July 1 - 31, 2020	Friday, August 14, 2020
FSR #3	August 1 - 31, 2020	Tuesday, September 15, 2020
FSR #4	September 1 - 30 2020	Thursday, October 15, 2020

FSR #5	**October 1 - 31, 2020**	**Friday, November 13, 2020**
FSR #6	**November 1 - 31, 2020**	**Tuesday, December 15, 2020**
FSR #7	**December 1 - 31, 2020**	**Friday, January 15, 2021**
FSR #8	**January 1 - 31, 2021**	**Monday, February 15, 2021**
FSR #9	**February 1 - 28, 2021**	**Monday, March 15, 2021**
FSR #10	**March 1 - 31, 2021**	**Thursday, April 15, 2021**
FSR #11	**April 1 - 30, 2021**	**Friday, May 14, 2021**
FSR #12	**May 1 - 31, 2021**	**Tuesday, June 15, 2021**
FSR #13	**June 1 - 30, 2021**	**Thursday, July 15, 2021**
FSR #14	**July 1 - 31, 2021**	**Friday, August 13, 2021**
FSR #15	**August 1 - 31, 2021**	**Wednesday, September 14, 2021**
FSR #16	**Final FSR**	**Friday, October 15, 2021**

DUE TO GRANT MANAGER

Draft Final Report: A Draft Final Report will be submitted to the Project Manager and the TCEQ Liaison. It will include an Executive Summary. It will be written in third person and will follow the State of Texas accessibility requirements as set forth by the Texas State Department of Information Resources. It will also include a report of the QA findings.

Draft Final Report Due Date: Monday, August 2, 2021

Final Report: A Final Report incorporating comments from the AQRP and TCEQ review of the Draft Final Report will be submitted to the Project Manager and the TCEQ Liaison. It will be written in third person and will follow the State of Texas accessibility requirements as set forth by the Texas State Department of Information Resources.

Final Report Due Date: Tuesday, August 31, 2021

Project Data: All project data including but not limited to QA/QC measurement data, metadata, databases, modeling inputs and outputs, etc., will be submitted to the AQRP Project Manager within 30 days of project completion (September 20, 2021). The data will be submitted in a format that will allow AQRP or TCEQ or other outside parties to utilize the information. It will also include a report of the QA findings.

AQRP Workshop: A representative from the project will present at the AQRP Workshop in the first half of August 2021.

Presentations and Publications/Posters: All data and other information developed under this project which is included in **published papers, symposia, presentations, press releases, websites and/or other publications** shall be submitted to the AQRP Project Manager and the TCEQ Liaison per the Publication/Publicity Guidelines included in Attachment G of the Subaward.

8 References

Ahmadov, R., Grell, G., James, E., Freitas, S., Pereira, G., Csiszar, I., Tsidulko, M., Pierce, B., McKeen, S., Peckham, S., Alexander, C., Saide, P., and Stan, B. (2017), A high-resolution coupled meteorology-smoke modeling system HRRR-Smoke to simulate air quality over the CONUS domain in real time. In *EGU General Assembly Conference Abstracts* (Vol. 19, p. 10841).

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O. (2011), Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos. Chem. Phys.,* 11, 4039–4072, doi:10.5194/acp-11-4039-2011.

Alvarado, M. J., and Prinn, R. G. (2009), Formation of ozone and growth of aerosols in young smoke plumes from biomass burning, Part 1: Lagrangian parcel studies, *J. Geophys. Res.*, 114, D09306, doi:10.1029/2008JD011144.

Alvarado, M. J., Logan, J. A., Mao, J., *et al.* (2010), Nitrogen oxides and PAN in plumes from boreal fires during ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite observations, *Atmos. Chem. Phys.,* 10*,* 9739–9760, doi:10.5194/acp-10-9739-2010.

Alvarado, M. J., Cady-Pereira, K. E., Xiao, Y., Millet, D. B., and Payne, V. H. (2011), Emission ratios for ammonia and formic acid and observations of peroxy acetyl nitrate (PAN) and ethylene in biomass burning smoke as seen by the tropospheric emission spectrometer (TES), *Atmosphere,* 2, 633–654, doi:10.3390/atmos2040633.

Alvarado, M. J., Payne, V. H., Mlawer, E. J., Uymin, G., Shephard, M. W., Cady-Pereira, K. E., Delamere, J., Moncet, J.-L. (2013), Performance of the line-by-line radiative transfer model (LBLRTM) for temperature, water vapor, and trace gas retrievals: Recent updates evaluated with IASI case studies, *Atmos. Chem. Phys.,* 13, 6687–6711, doi:10.5194/acp-13-6687-2013.

Alvarado, M. J., Lonsdale, C. R., Yokelson, R. J., Akagi, S. K., Coe, H., Craven, J. S., Fischer, E. V., McMeeking, G. R., Seinfeld, J. H., Soni, T., Taylor, J. W., Weise, D. R., and Wold, C. E. (2015a), Investigating the links between ozone and organic aerosol chemistry in a biomass burning plume from a prescribed fire in California chaparral, *Atmos. Chem. Phys.*, 15, 6667–6688, doi:10.5194/acp-15-6667-2015.

Alvarado, M. J., Payne, V. H., Cady-Pereira, K. E., Hegarty, J. D., Kulawik, S. S., Wecht, K. J., Worden, J. R., Pittman, J. V. and Wofsy, S. C. (2015b), Impacts of updated spectroscopy on thermal infrared retrievals of methane evaluated with HIPPO data, *Atmos. Meas. Tech.,* 8, 965–985, doi:10.5194/amt-8-965-2015.

Alvarado, M. J., Brodowski, C. M., and Lonsdale, C. R. (2016), *An Analysis of Biomass Burning Impacts on Texas*, Final Report to Texas Commission on Environmental Quality (TCEQ) for Work Order No. 582-16-62311-03 under TCEQ Contract No. 582-15-50414, June 30.

Alvarado, M. J., McVey, A., Hegarty, J., Cross, E., Hasenkopf, C., Lynch, R., Kennelly, E., Onasch, T., Awe, Y., Sanchez-Triana, E., and Kleiman, G. (2019a), Evaluating the use of satellite observations to supplement ground-level air quality data in low- and middle-income countries, *Atmos. Environ.*, 218, 117016 https://doi.org/10.1016/j.atmosenv.2019.117016.

Alvarado, M. J., Lonsdale, C. R., Mascio, J., Cady-Pereira, K., Dayalu, A., Henze, D., Capps, S., and Shephard, M. (2019b), Using CrIS Satellite Retrievals to Improve Ammonia Emissions in the CMAQ Regional Air Quality Model, presented at the 2019 AMS Joint Satellite Conference, Boston, MA, Oct. 2.

Brey, S. J., Ruminski, M., Atwood, S. A., and Fischer, E. V. (2018), Connecting smoke plumes to sources using Hazard Mapping System (HMS) smoke and fire location data over North America, *Atmos. Chem. Phys*., 18, 1745–1761, https://doi.org/10.5194/acp-18-1745-2018.

Brown-Steiner, B., Lonsdale, C., Hegarty, J., and Alvarado, M. (2018), *Assessment of the Exceptional Event Rule's 'Q/D' Guidance*, Final Report to Texas Commission on Environmental Quality (TCEQ) for Work Order No. 582-18-81899-09 under TCEQ Contract No. 582-15-50414, June 29.

Brown-Steiner, B., Dayalu, A., and Alvarado, M. (2019), *Uncertainty analysis and improvement of STILT-ASP for determining O_3 formation from biomass burning*, Final Report to Texas Commission on Environmental Quality (TCEQ) for Work Order No. 582-19-92805-03 under TCEQ Contract No. 582-19-90498, June 30.

Goldberg, D. L., Gupta, P., Wang, K., Jena, C., Zhang, Y., Lu, Z., and Streets, D. G. (2019), Using gap-filled MAIAC AOD and WRF-Chem to estimate daily $PM_{2.5}$ concentrations at 1 km resolution in the Eastern United States, *Atmospheric Environment*, 199, 443–452.

Hu, X., Yu, C., Tian, D., Ruminski, M., Robertson, K., Waller, L. A., and Liu, Y. (2016), Comparison of the Hazard Mapping System (HMS) fire product to ground-based fire records in Georgia, USA, *J. Geophys. Res.-Atmos.,* 121, 2015JD024448, https://doi.org/10.1002/2015JD024448.

Lee, H. J., Liu, Y., Coull, B. A., Schwartz, J., and Koutrakis, P. (2011), A novel calibration approach of MODIS AOD data to predict $PM_{2.5}$ concentrations, *Atmospheric Chemistry & Physics*, 11(15).

Lonsdale, C. R., Alvarado, M. J., Yokelson, R. J., Travis, K. R., and Fischer, E. V. (2014), A sub- grid scale parameterization of biomass burning plume chemistry for global and regional air quality models, presented at the 2014 Community Modeling and Analysis System (CMAS) Conference, Chapel Hill, NC, 27-29 Oct.

Lonsdale, C. R., Hegarty, J. D., Cady-Pereira, K., Alvarado, M. J., Henze, D. K., Turner, M. D., Capps, S. L., Nowak, J. B., Neuman, J. A., Middlebrook, A. M., Bahreini, R., Murphy, J. G., Markovic, M., VandenBoer, T. C., Russell, L. M., and Scarino, A. J. (2017a), Modeling the diurnal variability of agricultural ammonia in Bakersfield, California during CalNex, *Atmos. Chem. Phys*., 17, 2721–2739, doi:10.5194/acp-17-2721-2017.

Lonsdale, C. R., Brodowski, C. M., and Alvarado, M. J. (2017b), *Improving the Modeling of Wildfire Impacts on Ozone and Particulate Matter for Texas Air Quality Planning*, Final Report to Texas Air Quality Research Program (AQRP) Project 16–024, August 31.

Lv, B., Hu, Y., Chang, H. H., Russell, A. G., and Bai, Y. (2016), Improving the accuracy of daily PM2.5 distributions derived from the fusion of ground-level measurements with aerosol optical depth observations, a case study in North China, *Environmental Science & Technology*, 50(9), 4752–4759.

Lv, B., Hu, Y., Chang, H. H., Russell, A. G., Cai, J., Xu, B., and Bai, Y. (2017), Daily estimation of ground-level PM2.5 concentrations at 4 km resolution over Beijing-Tianjin-Hebei by fusing MODIS AOD and ground observations, *Science of the Total Environment*, 580, 235–244.

Lyapustin, A., Martonchik, J., Wang, Y., Laszlo, I., and Korkin, S. (2011), Multiangle implementation of atmospheric correction (MAIAC): 1. Radiative transfer basis and look-up tables, *Journal of Geophysical Research: Atmospheres*, 116(D3).

Lyapustin, A., Wang, Y., Korkin, S., Kahn, R., and Winker, D. (2019), MAIAC Thermal Technique for Smoke Injection Height from MODIS, *IEEE Geoscience and Remote Sensing Letters*, 2019 Sep 12.

McDonald-Buller, E., Y. Kimura, C. Wiedinmyer, C. Emery, Z. Liu, and G. Yarwood (2015), *Targeted Improvements in the Fire Inventory form NCAR (FINN) Model for Texas Air Quality Planning,* Final Report to Texas Air Quality Research Program (AQRP) for Project 14-011, December 2015.

Nelson, D., Garay, M., Kahn, R., and Dunst, B. (2013), Stereoscopic height and wind retrievals for aerosol plumes with the MISR INteractive eXplorer (MINX). *Remote Sensing*, 5(9), 4593–4628.

NOAA/NESDIS/STAR (2018), Algorithm theoretical basis document: ABI aerosol detection product. Available at https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Baseline/ATBD_GOES-R_Aerosol_Detection_v3.0_Jan2019.pdf (last access: 11 January 2020).

Rolph, G. D., Draxler, R. R., Stein, A. F., Taylor, A., Ruminski, M. G., Kondragunta, S., Zeng, J., Huang, H.-C., Manikin, G., McQueen, J. T., and Davidson, P. M. (2009), Description and verification of the NOAA smoke forecasting system: The 2007 fire season, *Weather Forecast.*, 24, 361–378, https://doi.org/10.1175/2008WAF2222165.1.

Ruminski, M., Kondragunta, S., Draxler, R., and Zeng, J. (2006), Recent changes to the Hazard Mapping System, 15th Int. Emiss. Inventory Conf, (Reinventing Inventories), available at: https://www.researchgate.net/publication/228625934_Recent_changes_to_the_Hazard_Mapping_System (last access: 11 January 2020).

Schroeder, W., Ruminski, M., Csiszar, I., Giglio, L., Giglio, E., Schmidt, C., and Morisette, J. (2008), Validation analyses of an operational fire monitoring product: The Hazard Mapping System, *Int. J. Remote Sens.,* 29, 6059–6066.

Shephard, M. W., and Cady-Pereira, K. E. (2015), Cross-track Infrared Sounder (CrIS) satellite observations of tropospheric ammonia, *Atmos. Meas. Tech*., 8, 132–1336, doi:10.5194/amt-8-1323-2015.

Soja, A. J., Choi, H. D., Fairlie, T. D., Pouliot, G., Baker, K. R., Winker, D. M., Trepte, C. R., and Szykman, J. (2017), CALIOP-based Biomass Burning Smoke Plume Injection Height. In *AGU Fall Meeting Abstracts*.

Stein, A. F., Rolph, G. D., Draxler, R. R., Stunder, B., and Ruminski, M. (2009), Verification of the NOAA smoke forecasting system: model sensitivity to the injection height, *Weather and Forecasting*, 24(2), 379–394.

Van Donkelaar, A., Martin, R. V., Spurr, R. J., and Burnett, R. T. (2015), High-resolution satellite-derived $PM_{2.5}$ from optimal estimation and geographically weighted regression over North America, *Environmental Science & Technology*, 49(17), 10482–10491.

Wang, X., Heald, C. L., Sedlacek, A. J., de Sá, S. S., Martin, S. T., Alexander, M. L., Watson, T. B., Aiken, A. C., Springston, S. R., and Artaxo, P. (2016), Deriving brown carbon from multiwavelength absorption measurements: method and application to AERONET and Aethalometer observations, *Atmos. Chem. Phys.,* 16, 12733–12752, https://doi.org/10.5194/acp-16-12733-2016.

Wang, Y., and Talbot, R. (2017), *High Background Ozone Events in the Houston-Galveston-Brazoria Area: Causes, Effects, and Case Studies of Central American Fires.* Final Report to Texas Air Quality Research Program (AQRP) Project 16 – 008, October.

Zeng, J., and S. Kondragunta (2010), Tracking Smoke Plumes Using GOES Imagery. In *17th Conference on Satellite Meteorology and Oceanography*. Available at https://ams.confex.com/ams/17Air17Sat9Coas/techprogram/paper_174773.htm (last access: 11 January 2020).

Zhang, K., de Leeuw, G., Yang, Z., Chen, X., Su, X., and Jiao, J. (2019), Estimating spatio-temporal variations of $PM_{2.5}$ concentrations using VIIRS-derived AOD in the Guanzhong Basin, China, *Remote Sens.,* 11, 2679.