NASA Resources to Monitor Offshore and Coastal Air Quality



U.S. Department of the Interior Bureau of Ocean Energy Management Sterling, VA



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DISCLAIMER

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ABSTRACT

In this report, we present the suite of National Aeronautics and Space Administration (NASA) datasets and tools, which are free and publicly available, that will enable Bureau of Ocean Energy Management (BOEM) personnel to monitor air pollution offshore and along coastal environments of the continental U.S. We provide three case studies to demonstrate the current capabilities of these resources in the Gulf of Mexico region and discuss how they may be integrated into BOEM's standard operating procedure (SOP) for assessing offshore air quality.

In addition, we make three high-level recommendations to BOEM:

- 1) We recommend that BOEM adopts an integrated approach to monitoring air quality (AQ) that combines the strengths of various monitoring technologies, including regulatory-grade AQ monitors and non-traditional sources of AQ data: satellite data, AQ models, low-cost portable sensors, in situ monitors, and other ancillary datasets. As a first step, we recommend that BOEM personnel take advantage of the NASA Applied Remote SEnsing Training (ARSET) and Health and Air Quality Applied Sciences Team (HAQAST) programs to explore NASA's free and publicly available resources, so that BOEM personnel may identify the potential of these resources for BOEM's various applications and to begin integrating them into BOEM's SOP. Most of these resources are easily accessed via webtools, though accessing, processing, and analyzing satellite data (beyond visualization with webtools) will require more effort on the part of BOEM personnel.
- 2) We recommend that BOEM personnel continue to interact with NASA personnel, and potentially personnel from the U.S. Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA), to identify mutually beneficial collaborations that will advance BOEM's goals to monitor AQ in U.S. offshore and coastal waters. Several potential examples of these collaborations are given (e.g., field campaigns to measure air pollution).
- 3) We recommend that BOEM personnel continue to work with NASA personnel to understand the relation between quantities observed from space and pollutant concentrations within the boundary layer, including offshore and along the coast. In a companion report (i.e., Thompson, 2020), we show that pollutant concentrations can have complex 3-d distributions offshore (e.g., from the vertical structure of pollutant emissions) and in coastal environments (e.g., from complex sea breezes). BOEM personnel would benefit from working with NASA personnel, who have developed the NASA data and simulated products and, therefore, know their strengths and limitations for BOEM's applications, as well as how to avoid common mistakes when analyzing them.

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List of Abbreviations and Acronyms

| Acronym/Name | Phrase/Description | | | | |
|-----------------------|--|--|--|--|--|
| Chemical Species | | | | | |
| AOD | Aerosol Optical Depth | | | | |
| CH ₄ | Methane | | | | |
| CO | Carbon Monoxide | | | | |
| НСНО | Formaldehyde, a VOC | | | | |
| NO ₂ | Nitrogen Dioxide | | | | |
| NO _x | Nitrogen Oxides ($NO_x = NO + NO_2$) | | | | |
| | Ozone | | | | |
| PM, PM _{2.5} | Particulate Matter, < 2.5 µm in size | | | | |
| SO ₂ | Sultur Dioxide | | | | |
| VOC | Volatile Organic Compound | | | | |
| Instruments | | | | | |
| MOPITT | Measurement of Pollution in the Troposphere | | | | |
| MODIS | MODerate resolution Imaging Spectrometer | | | | |
| OMI | Ozone Monitoring Instrument | | | | |
| TEMPO | Tropospheric Emissions: Monitoring of Pollution | | | | |
| | I ROPOspheric Monitoring Instrument | | | | |
| | | | | | |
| Agencies/Programs | | | | | |
| ARSEI | NASA Applied Remote SEnsing Training | | | | |
| BOEM | Bureau of Ocean Energy Management | | | | |
| | Environmental Protection Agency | | | | |
| ESA | European Space Agency | | | | |
| | Royal Dutch Meteorological Office | | | | |
| | National Aeronautics and Space Administration | | | | |
| | National Oceanic and Atmospheric Administration | | | | |
| Other | | | | | |
| | Air Quality | | | | |
| | All Quality | | | | |
| CEMS | Continuous Emission Monitoring System | | | | |
| CONUS | CONtinental United States | | | | |
| GoM | Gulf of Mexico | | | | |
| HYSPLIT | NOAA Hybrid Single Particle Lagrangian Integrated Trajectory Model | | | | |
| LOOP | Louisiana Offshore Oil Port | | | | |
| ONG | Oil and Natural Gas | | | | |
| SCOAPE | Satellite Coastal & Oceanic Atmospheric Pollution Experiment | | | | |
| SOP | Standard Operating Procedure | | | | |
| TC NO ₂ | Total Column NO_2 = atmospheric column | | | | |
| TropC NO ₂ | Tropospheric Column NO ₂ = tropospheric column | | | | |
| VCD | Vertical Column Density = the total number of molecules between the | | | | |
| | satellite and Earth's surface per unit area, such as molecules/cm ² . | | | | |

1 Introduction

The Outer Continental Shelf Lands Act (OCSLA) requires the Bureau of Ocean Energy Management (BOEM) to ensure compliance with the National Ambient Air Quality Standard (NAAQS) so that Outer Continental Shelf (OCS) oil and gas exploration, development, and production do not significantly impact the air quality (AQ) of any state. In July 2015, BOEM personnel first approached the National Aeronautics and Space Administration (NASA) to inquire if satellite data could be used to help monitor offshore AQ in BOEM's jurisdiction, that portion of the OCS west of 87°30' West longitude in the Gulf of Mexico (GoM) Region and the Chukchi and Beaufort Sea Planning Areas in the Alaska Region. An interagency agreement was signed in 2017 to begin a study, which was named the Satellite Coastal and Oceanic Atmospheric Pollution Experiment (SCOAPE).

The ultimate goal of SCOAPE is to enable BOEM personnel, through the use of a suite of NASA and non-NASA resources (e.g., satellite data, in situ observations, and AQ forecasts), to assess how pollutants from offshore oil and natural gas (ONG) exploration, development, and production activities affect AQ on land. That is, we present *a cost-effective and integrated approach to air pollution monitoring*. To this end, this document provides an overview of NASA resources and demonstrates their potential, including through case studies.

As we demonstrate in **Section 2**, NASA resources have the potential to advance BOEM's goal to monitor the impact of air pollution from offshore oil and gas sources in the GoM on onshore AQ; this is also likely the case for coastal waters in all of the continental U.S. (CONUS). However, observing air pollution with satellites in BOEM's Arctic jurisdiction is currently challenging as discussed in a recent review article led by Duncan (see Sections 5.1 and 5.2 of Duncan et al., 2020 for details). Therefore, the focus of this report is on the GoM Region.

As we demonstrate in a companion document (Thompson, 2020), satellite data of nitrogen dioxide (NO_2) , a product of fossil fuel combustion, correlate well with surface and in situ observations, including from the SCOAPE field campaign in May 2019 in the GoM, supporting that satellite data may be used to monitor offshore AQ.

We make recommendations throughout the report and provide a high-level summary of our recommendations in **Section 3**.

2 Capacity Building: Tools for BOEM's "Toolbox"

Point of Contact: Bryan Duncan (Bryan.N.Duncan@nasa.gov)

⇒ Recommendation to BOEM: In this section, we present the suite of NASA datasets and tools, which are free and publicly available, that would enable BOEM personnel to monitor offshore air pollution. Rather than relying on one monitoring technology, we recommend a cost-effective and integrated approach to air pollution monitoring, which includes satellites (Section 2.1), in situ instruments and other ancillary datasets (Section 2.2), AQ models (Section 2.3), and low-cost portable sensors (Section 2.4), and that combines the strengths of these monitoring technologies (Figure 1). In Section 2.5, we provide three case studies to demonstrate the current capabilities of these resources and discuss how they may be integrated into BOEM's standard operating procedure (SOP).



Figure 1. An integrated approach for AQ monitoring. Source: Cromar et al., 2019

2.1 Satellite Data for AQ Applications

⇒ Recommendation to BOEM: This section is meant to be a brief overview of satellite data for AQ applications. For a more in depth overview, the reader is referred to Duncan et al. (2014) and the webpage, *Air Pollution: Observations from Space* (<u>https://airquality.gsfc.nasa.gov</u>), which is maintained by Duncan. The latter source is updated regularly and will serve as a resource for BOEM of new developments in using satellite data to monitor AQ.

The major pollutants that can be measured from space are nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), formaldehyde (HCHO), and aerosol optical depth (AOD), from which surface particulate matter (PM) may be inferred. NO₂ is reliably detected from space and serves as an excellent tracer of fossil fuel combustion. With today's technology, it is not currently feasible to monitor surface levels of ozone (O₃) from space, though it is possible to observe the precursors to O₃: a component of NO_x (i.e., NO₂) and volatile organic carbons (VOCs; i.e., HCHO—an oxidation product of many VOCs). However, the HCHO data product has large uncertainties associated with it, especially over the ocean where its emission sources are low. SO₂ also has large uncertainties, especially because its concentrations are low in the GoM due to emissions controls. Large emissions of SO₂ associated with Mexican-operated ONG activities in the GoM are easily detected from space (Zhang et al., 2019).

AQ managers take advantage of the primary strength of satellite instruments over typical groundbased monitoring networks of instruments—spatial coverage (**Figure 2**). For example, the efficacy of environmental controls to improve U.S. air pollution over land is clearly demonstrated by satellite data of multiple pollutants: NO₂, SO₂, and PM. From 2005 to 2018, there has been a 20–60% decrease in NO₂ over polluted areas of the U.S. (**Figure 2**; Duncan et al., 2016). Visit <u>https://airquality.gsfc.nasa.gov</u> for images, animations, and general information of how satellite data have been used to monitor trends in major air pollutants.

Figure 3 is the same as **Figure 2**, but zooms in the GoM. \Rightarrow **Relevance to BOEM**: The top and middle panels illustrate that offshore NO₂ levels are only a fraction of the magnitude of onshore

levels. The bottom panel also shows that NO₂ levels over land (e.g., Houston, New Orleans) decreased dramatically (20–60%) between 2005 and 2019 as shown in **Figure 2**. Levels over open waters along the U.S. coast of the GoM decreased significantly as well, especially near large onshore sources, indicating that large decreases in onshore NO₂ levels likely resulted in relatively large decreases over open water from 2005 to 2019. That is, onshore sources for some pollutants likely contributed significantly to offshore levels on average, especially during meteorological conditions of offshore flow as discussed in **Section 2.5**.

The satellite data products, which are free and publicly available, are primarily collected by instruments on satellites operated by NASA, the National Oceanic and Atmospheric Administration (NOAA), the European Space Agency (ESA), and the space agencies of some individual countries (e.g., Korea, Japan). Atmospheric composition satellite data have proven valuable to the AQ community for a number of applications (Duncan et al., 2014), such as the following:

- Estimating ozone (O₃) and aerosol precursor emissions;
- Monitoring events (e.g., wildfires);
- Monitoring regional long-term trends in ozone (O₃) and PM precursors;
- Validating AQ models;
- Tracking long-range transport of pollution.

 \Rightarrow Relevance to BOEM: Although satellite data for AQ applications have been evaluated over a range of land environments (e.g., urban to rural; tropical to high latitude), *there has been little evaluation thus far over open ocean and coastal waters*.



Figure 2. Tropospheric column nitrogen dioxide (TropC NO₂) vertical column density (VCD; x10¹⁵ molecules/cm²) data from the NASA Aura Ozone Monitoring Instrument (OMI), as annual averages for (top) 2005 and (bottom) 2019. Source: NASA Science Visualization Studio (SVS).



Figure 3. OMI TropC NO₂ vertical column density (VCD; $x10^{15}$ molecules/cm²) in (top) 2005 and (middle) 2019 with the (bottom) absolute difference between 2019 and 2005. Source: Lok Lamsal (NASA).

2.1.1 How Do Satellite Data of Air Pollutants Translate to Surface Concentrations and Emissions?

Most satellite instruments that collect data relevant for AQ applications are spectrometers that detect <u>electromagnetic (EM) radiation</u> from the sun. The incoming radiation, which is absorbed, re-emitted, reflected, and scattered by the Earth and its atmosphere, is measured as a function of wavelength with the infrared (IR), visible, and ultraviolet (UV) regions of the EM spectrum containing the most useful information for observing pollutants from space. Satellite-observed pollutants, either gases or aerosols, absorb IR wavelengths (e.g., CO) or scatter visible and UV wavelengths (e.g., NO₂). Unlike remote sensing of aerosols that use the signature of aerosol scattering, remote sensing of trace gases uses the signature of gas absorb radiation at different wavelengths, we can identify a "fingerprint" for each atmospheric constituent and estimate physical measurements (such as number density, partial pressure, column amount) of the different gases (i.e., NO₂, SO₂, etc.) with limited information on the vertical structure of the pollutant in the atmosphere. The accuracy of the measurements will vary with meteorology, chemistry, polluted versus non-polluted regions, and exceptional events.

Satellite vertical column densities (VCD) can provide observations of the spatial variability of air pollutants, such as NO₂, on daily, monthly, and yearly time scales (depending on the satellite instrument and product), with the benefit of spatial coverage over most ground-based monitoring networks that measure "nose-level" surface concentrations. For example, in polluted environments, trends in the total column NO₂ can be a proxy for trends in surface NO_x as most of the column resides near the surface. **Figure 4** shows an example of the down-looking satellite instrument, the ESA TROPOspheric Ozone Monitoring Instrument (TROPOMI), and its observable, (VCD), and its relation to "nose-level" surface concentrations. (A VCD equals the total number of molecules between the satellite and Earth's surface per unit area, such as molecules/cm².)

To infer "nose-level" concentrations from satellite data, an atmospheric model can be used, which takes into account the vertical distribution of the pollutant within the total column. For a deeper discussion, the reader is referred to the overview article, which is written in plain language, of Duncan et al. (2014). The article provides an overview of how satellite data of air pollutants are being used by the AQ community, giving examples of applications, a summary of end-user resources, and answers many frequently asked questions.



Figure 4. Diagram depicting various surface AQ instruments in relation to the TROPOMI pixel size. Notes: 1. The Pandora instrument has similar capabilities as the satellite instruments, OMI and TROPOMI, which observe NO₂, HCHO, and SO₂. Therefore, Pandora instruments are deployed for satellite validation purposes. 2. The in situ instrument, such as those used by EPA, monitor surface level pollutant concentrations. 3. Tropospheric Ozone Lidar Network (TOLNET) observes the vertical structure of ozone within the troposphere. 4. The ceilometer is an instrument that measures the height of clouds and aerosol layers. 5. The TROPOMI satellite. Source: Alexander Kotsakis of the NASA Pandora effort.

2.1.2 Relevant New and Upcoming Satellite Capabilities

Several new satellite instruments, that were recently launched or are nearing launch, promise to provide much better data, including over the ocean, on air pollutants than can be obtained from current satellites.

- Higher Spatial Resolution: The ESA TROPOspheric Monitoring Instrument (<u>TROPOMI</u>; launched in 2017) collects data on NO₂, SO₂, CO, and methane (CH₄) at sub-urban spatial resolutions (e.g., a few kilometers) and at resolutions much finer than current instruments. TROPOMI has many superior capabilities to its predecessor, OMI, such as finer spatial resolution and better signal-to-noise. ⇒ Things to Know: The TROPOMI data products are still being refined. A new release is anticipated by the end of 2020, which will address several shortcomings of the current products.
- Higher Temporal Resolution: A satellite in geosynchronous orbit will appear to remain in a fixed location in the sky relative to an observer on the ground. Currently, there are several satellites (e.g., NOAA GOES-R) in geosynchronous orbits that provide information on aerosols. A satellite in geosynchronous orbit is planned to observe NO₂, SO₂, CO, and CH₄ over North America (NASA Tropospheric Emissions: Monitoring Pollution, <u>TEMPO</u>) with a planned launch date in 2022. TEMPO is an instrument that will have similar capabilities as OMI.

These new capabilities are/will improve BOEM's ability to monitor air pollution, infer surface concentrations of air pollutants, and constrain pollutant emissions from satellite data.

2.1.3 NASA Tutorials on Satellite Data

NASA's <u>Applied Sciences Program</u> (ASP) promotes innovation in public and private sector organizations to apply NASA satellite data, model products, and scientific findings in AQ management and policy activities that benefit human health and safety. To this end, ASP supports several capacity building programs, which will benefit BOEM's mission by educating BOEM personnel on what satellite data are available and how to access and process the data.

⇒ Recommendation to BOEM: We highly encourage BOEM personnel take advantage of two free NASA programs:

- NASA ARSET: The complexity of accessing, processing, and properly interpreting satellite
 products is often difficult for end-users without the technical skill required. NASA's Applied
 Remote SEnsing Training (ARSET) program (<u>https://arset.gsfc.nasa.gov</u>) offers satellite
 remote sensing training that builds the skills to integrate NASA Earth Science data into an
 agency's decision-making activities, including AQ monitoring. They provide lessons on
 pertinent basics of pollutant detection and products and give a tour of NASA's satellite
 data products and some applications (i.e., what is available/applicable for AQ studies).
- NASA HAQAST: The NASA Health and AQ Applied Sciences Team (HAQAST; <u>https://haqast.org</u>) members work directly with stakeholders to facilitate the use of NASA resources for their applications. (Duncan, a HAQAST member, leveraged his NASA HAQAST funding to work with BOEM on SCOAPE.) In addition, HAQAST members develop review articles and how-to materials for end-users. For example, Streets et al. (2013) reviewed the use of satellite data to inform about the distributions of pollutants and pollutant emissions for AQ applications. Duncan et al. (2014) described in more detail the helpful resources available for viewing satellite observations, including guidance on web tools for visualizations and sample applications.

We recommend the following HAQAST and ARSET tutorials for BOEM personnel to begin discovering NASA resources:

<u>HAQAST</u>

Points of Contact: HAQAST is currently being recompeted, though Tracey Holloway (<u>taholloway@wisc.edu</u>) is the current lead and Duncan is a current HAQAST member.

Introductory

- Upgrading the Toolbox: NASA Resources to Support Air Quality Management
- Visualizing Air Quality: How to Use NASA's Giovanni to Plot Satellite Tropospheric NO₂ Columns

<u>ARSET</u>

Point of Contact: Ana Prados (<u>aprados@umbc.edu</u>)

Introductory

- An Inside Look at how NASA Measures Air Pollution
- Introduction to Satellite Remote Sensing for Air Quality Applications
- Application of Satellite Observations for Air Quality and Health Exposure
- Satellite Remote Sensing of Dust, Fires, Smoke, and Air Quality

Advanced (TEMPO (not yet launched), TROPOMI)

- High Temporal Resolution Air Quality Observations from Space
- <u>Advanced Webinar: High Resolution NO₂ Monitoring from Space with TROPOMI</u>

⇒ Recommendation to BOEM: Assign several BOEM employees with differing skill sets to view the above webinars to gain a more comprehensive overview of NASA resources than presented in this report. These webinars would enable BOEM personnel to identify which resources may be brought to bear on particular BOEM applications.

⇒ Recommendation to BOEM: Accessing, processing, and properly interpreting satellite data require BOEM personnel to invest time in acquiring the necessary skills. Of course, the necessary skills ultimately depend on BOEM's desired applications. For instance, tracking pollution requires minimal investment as demonstrated by the illustrative case studies in **Section 2.5** and could easily be done by one person part time. However, using satellite data to infer emission source strengths (e.g., from individual platforms) requires a more sophisticated data user. Therefore, it is recommended that BOEM management clearly identifies specific desired applications and works with NASA personnel to design the best strategy for achieving these goals.

2.2 In Situ Observations and Other Ancillary Datasets

Point of Contact: Bryan Duncan (Bryan.N.Duncan@nasa.gov)

In situ instruments on board various platforms (e.g., stationary, ship, aircraft) and other ancillary datasets are necessary to independently validate and interpret satellite data, such as for understanding the correspondence of the quantity observed by a satellite and the observation at the surface (e.g., from an AQ monitor). Here are some of the techniques:

 Ground-based remote sensing instruments: As illustrated in Figure 4, column data from satellites may be compared to similar ground-based instruments. For example, the portable <u>Pandora instrument</u> (Figure 5) is used to evaluate the magnitude, variations and trends of OMI and TROPOMI data. However, there are issues of 1) "representativeness" of a small Pandora footprint to the large footprint of a satellite (e.g., Kim et al., 2016; Judd et al., 2019) and 2) comparing data from a satellite that looks down to a ground instrument that tracks the sun's movement throughout the day (**Figure 4**). Nevertheless, the satellite data generally compare well, except under polluted conditions (e.g., in urban areas), with differences of 20% or less to the Pandora data under partially cloudy to clear weather conditions.

⇒ Recommendation to BOEM: We recommend that BOEM contact Tom Hanisco (NASA; thomas.hanisco@nasa.gov), the Pandora PI, to discuss the possibility of Pandora instruments becoming part of BOEM's integrated observing strategy. For example, a Pandora instrument placed next to an in situ monitor in a coastal location would facilitate understanding of the relationship between the total column (TC) NO₂ and NO₂ surface concentration. ⇒ Things to Know: There could be potential issues of siting Pandoras in coastal environments because of high humidity and salt air.

⇒ Recommendation to BOEM: As part of a feasibility study, EPA has sited several Pandora instruments next to EPA surface AQ monitors in the northeast U.S. We recommend that BOEM personnel contact Luke Valin (EPA; <u>Valin.Lukas@epa.gov</u>) to discuss their findings, which may provide BOEM guidance on the utility of having Pandora instruments sited near in situ monitors along the coast of BOEM's GoM domain.



Figure 5. Pandora instruments on the roof of the LUMCON building in Cocodrie, LA, in May 2019. Image courtesy of Duncan.

Airborne remote sensing instruments: There are other OMI-like sensors (e.g., GEOstationary Coastal and Air Pollution Events (GEO-CAPE) Airborne Simulator (GCAS); Nowlan et al., 2018), in addition to Pandora, that NASA regularly deploys on aircraft. These sensors may be useful for BOEM, such as mapping NO₂ concentrations in the GoM.

⇒ Recommendation to BOEM: We recommend that BOEM personnel contact NASA personnel (Barry Lefer; <u>barry.lefer@nasa.gov</u>; NASA HQ) about the possibility of mutually beneficial deployments. For instance, we recommend that BOEM remain in contact with Bill Swartz (Johns Hopkins University Applied Physics Lab; <u>bill.swartz@jhuapl.edu</u>), to continue discussion (telecon on January 1, 2020) of the possible collaboration of BOEM with the NASA Compact Hyperspectral Air Pollution Sensor – Demonstrator (CHAPS-D), which derives heritage from TROPOMI. The demonstration will likely be on an aircraft over

a region yet to be determined; BOEM could potentially negotiate for the demonstration to be over the GoM in BOEM's jurisdiction. For instance, the flight pattern could help to validate NO_x emissions in BOEM's emission inventory.

- Surface Monitors: A number of studies have compared trends and surface concentrations inferred from OMI NO₂ data to those estimated from surface AQ monitors, such as those part of the EPA AQS (Lamsal et al., 2008, 2015; Duncan et al., 2016). The results indicate that satellite-observed trends complement the AQS-observed trends, and both show the decrease in NO₂ levels (on the order of 20–60%) since 2005 over U.S. cities due to a combination of environmental policies and technological changes (Figure 2).
- Continuous Emissions Monitoring System (CEMS): Several studies have compared NO_x emissions inferred from OMI NO₂ data to emissions independently reported for power plants (Duncan et al., 2013; de Foy et al., 2015; Liu et al., 2016). There is a clear response of OMI NO₂ data to NO_x emission reductions from power plants with the implementation of mandated emission control devices and generally have good agreement between the bottom-up inventory (i.e., CEMS) and the top-down emissions estimates based on the satellite data.

⇒ Recommendation to BOEM: We recommend that BOEM consider using satellite data (e.g., from TROPOMI or TEMPO) to infer NO_x emissions from offshore ONG activities in the GoM and to validate the distribution and intensity of emissions from BOEM's emission inventory. There are several techniques to infer emissions from satellite data, including ones developed at NASA.

• *Field Campaigns:* Although field campaigns are typically of short duration (e.g., 1–2 weeks), the data collected by the suite of instruments may be used to validate satellite data. In Thompson (2020), we show how data collected during the SCOAPE cruise in May 2019 validate the satellite data over the GoM.

2.3 NASA AQ Forecasts

Point of Contact at GMAO: mission-support@gmao.gsfc.nasa.gov

The NASA <u>Global Modeling and Assimilation Office (GMAO)</u> develops and maintains the <u>GEOS</u> <u>system of models</u>, which has a suite of capabilities including simulating weather, climate, chemistry-climate interactions, and now air pollution. They assimilate satellite and in situ data of some variables that affect weather and AQ into the GEOS model. The assimilation of these data improves the simulation of weather and AQ by providing the best representation of the atmosphere at the start of the forecast period.

Of relevance to BOEM, the GEOS system produces 5-day AQ forecasts of common air pollutants, such as ozone, NO_x, CO, and PM_{2.5}. The model output may be <u>accessed directly</u>, if BOEM personnel wish to perform their own analysis, or the forecasts may be easily visualized with a webtool called <u>FLUID</u>. FLUID includes <u>BOEM's GoM domain</u> (Figure 6-Figure 8).

⇒ Recommendation to BOEM: The learning curve is minimal (estimated time: < 1 day) to begin effectively using the NASA AQ forecasts to track pollution transport through the FLUID interface. Therefore, it is recommended that BOEM personnel integrate the AQ forecasts into BOEM's SOP immediately. The learning curve is steeper, though reasonable, for downloading and processing the forecast data.

 \Rightarrow Things to Know: The NASA AQ forecasts have been evaluated using numerous in situ and satellite datasets and have been found to perform well. The validation paper is in preparation.



Figure 6. The dedicated SCOAPE domain on FLUID.



Figure 7. Example of pollutants at various points that may be plotted with FLUID.

This image shows the forecasted temporal evolution of the (top) vertical distribution of PM_{2.5} over Cocodrie, LA, (middle) total aerosol speciation near the surface, and (bottom) weather variables.



Figure 8. An example of spatial maps of pollutants, including tracers of various sources.

This figure shows CO VCDs from onshore sources only (i.e., North American fossil fuel CO) that affect offshore during offshore flow. This capability allows a forecasted period to animate, which is useful for attributing the various sources of pollution that affect the GoM. \Rightarrow Things to Know: The forecast system carries tracers of CO that are "colored" or "tagged" by source as illustrated on the panel on the right of this image. This capability will allow BOEM personnel to estimate the impacts of various sources on AQ in the GoM.

 \Rightarrow Things to Know: The forecasts are <u>archived</u> since the beginning of 2018. They may be accessed and processed using commonly available software to understand past AQ events or seasonal variations, for instance.

⇒ Things to Know: The GMAO system currently does not include the BOEM emission inventory or any offshore emissions from ONG extraction activities. Nevertheless, the forecasts proved critical for interpreting satellite data and observations collected during the SCOAPE cruise, as discussed in Thompson (2020). BOEM could contact GMAO if it is desired to discuss the possible implementation of the latest BOEM emission inventory into their forecast system.

Tailored Forecasts

Point of Contact at GMAO: Christoph Keller (christoph.a.keller@nasa.gov).

The current horizontal spatial resolution of the forecast system is about 25x25 km². Although this spatial resolution is not as fine as the resolutions of current regional AQ models, the model

forecasts are for the entire globe. The near-term (< 2 year) goal is to move to about 12x12-km² resolution forecasts, which will be made possible by continuing advances in computing resources and efficiency improvements.

Christoph Keller (NASA GMAO) provides tailored local forecasts for a given location using a machine learning algorithm that he developed (Keller et al., submitted). Using local AQ monitor data in combination with co-located NASA AQ model output, the algorithm generates bias-correction factors that correct for systematic model-observation mismatches (e.g., due to uncertainties in emission estimates or sub-gridscale local influences [i.e., representational error]). Once developed, these correction factors can be applied to the AQ forecasts on an ongoing basis to generate localized forecasts that capture the observations much better (e.g., **Figure 9**).



Figure 9. Example of a tailored local forecast using machine learning (ML) applied to the NASA AQ modeled concentrations of O_3 .

The ML drastically reduces the model bias.

 \Rightarrow Recommendation to BOEM: We recommend that BOEM upload AQ monitor data (1 year minimum) from along the GoM to the <u>OpenAQ</u> platform so that Keller can add provide automated tailored forecasts, which are delivered daily.

2.4 The Potential of Low-Cost Sensors

Point of Contact: Bryan Duncan (Bryan.N.Duncan@nasa.gov)

Most satellite datasets (**Section 2.1**) of pollutants do not provide much information, if any, on the 3-d distribution of pollution. (For example, satellite data of NO₂ are given in units of the total number of molecules of NO₂ between the satellite and Earth's surface, which is referred to as an atmospheric column [molecules/cm²] or VCD—a 2-d quantity.) An AQ network (**Section 2.2**) of regulatory-grade monitors across BOEM's jurisdiction would only provide information on the distribution of air pollution at the surface and is prohibitively expensive to install and maintain. Although an AQ model (**Section 2.3**) does provide information on the 3-d distribution of pollutants, most models do not have detailed emission inventories (as input) with a realistic distribution of emissions in the vertical (e.g., ships, aircraft, platforms, flares with plume rise).

The accuracy and precision of low-cost sensors (e.g., NO₂, PM, O₃) are improving with time and have become an indispensable tool for many AQ managers and NASA scientists to, for instance, identify pollution sources and high concentrations, understand hour-to-hour variations in pollution, and map out pollution gradients. Low-cost sensors could be deployed on various platforms, such as tethered balloons and drones, to collect the vertical data necessary to determine the complex 3-D concentration structure of pollution from sources (e.g., onshore, offshore, including ships,

helicopters, rigs, flares with plume rise) and the transport of pollution onshore. For instance, a low-cost sensor could be deployed on a Department of Interior drone and flown along a coastline through the depth of the mixed layer to understand the complex transport of pollution with land-sea breezes.

During the SCOAPE campaign, a low-cost, lightweight, and portable NO_2 sensor (Sluis et al., 2010) was deployed on a mobile platform (**Figure 10–Figure 12**) as a proof-of-concept for BOEM's applications. By taking co-located observations, the sensor was calibrated with NO_2 data from a regulatory-grade monitor sited at the LUMCON facility in Cocodrie, LA, before and after deployment.

⇒ Things to Know: The low-cost NO₂ sensor was developed and deployed in the field by personnel from the Royal Dutch Meteorological Institute (KNMI). The sensor is currently undergoing commercialization for easy operation. Low-cost sensors for O₃ (e.g., ozonesondes) and PM are already commercially available.

⇒ Recommendation to BOEM: We recommend for BOEM to explore the potential of low-cost sensors for BOEM's needs. Low-cost NO₂, O₃, and PM sensors are lightweight and may be deployed on mobile, drone, and tethered balloon platforms. Their versatility could prove very useful for BOEM for many applications, especially in areas with sparse or no observations from more traditional data sources.



Figure 10. The low-cost NO₂ sensor has been deployed in numerous photochemical environments and on various platforms (e.g., mobile, tethered balloon, drone) around the world. The sensor was deployed on a mobile platform during the SCOAPE campaign to detect NO₂ from offshore sources

along the coast. The image shows data collected at an industrial facility in Port Fourchon and demonstrates the power of the sensor to collect data with fine spatial resolution. Image and analysis courtesy of Mirjam den Hoed (KNMI), who participated in the SCOAPE campaign.



Figure 11. Same as the previous figure, except this figure shows data collected along a path from Cocodrie to Burns Point State Park, LA.

Image and analysis courtesy of Mirjam den Hoed (KNMI), who participated in the SCOAPE campaign.





Image and analysis courtesy of Mirjam den Hoed (KNMI), who participated in the SCOAPE campaign.

2.5 Illustrative Case Studies

In this section, we present three illustrative case studies to demonstrate the methodology of how to use a suite of cost-effective NASA and non-NASA resources to monitor and understand variations in pollution within the GoM (and all coastal waters of the continental U.S.), and to attribute sources. Two of the case studies highlight the differences in pollution over the GoM under predominately offshore and onshore flows. Typically, air from the GoM has lower levels of NO₂ than air originating over land (**Figure 13** and **Figure 14**). The other case studies were developed by Dan Anderson (NASA; postdoctoral fellow of Duncan) and all images in this section are courtesy of him, except where noted.

 \Rightarrow Things to Know: The resources and methodology illustrated in the case studies are employed to assess the daily state of AQ during NASA field campaigns, including SCOAPE, to determine, for instance, where to send research vessels to intercept plumes or to sample concentration gradients. They have been refined over the past several decades, integrating new datasets and tools as they become available.



Figure 13. NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) back trajectories initiated every hour at Cocodrie, LA, for April and May 2019.

The colors indicate the NO₂ concentrations observed at Cocodrie, LA, when each trajectory arrived. The NO₂ data are from the Pandora instruments deployed on the roof of the LUMCON facility. (right) The average NO₂ VCD (DU) for the two flow regimes show that air masses originating deep within the GoM are typically cleaner than air originating over land. \Rightarrow Things to Know: Typically, satellite data of NO₂ are reported in units of molecules/cm² for either the total column (i.e., TC NO₂ = total atmosphere column) or tropospheric portion of the total column (i.e., TropC NO₂). The data reported from the Pandora network are total columns, but in units of DU (Dobson Unit = 2.687×10¹⁶ molecules/cm²).



Figure 14. TROPOMI TropC NO₂ (VCD) on a day (i.e., Case #1) with offshore flow near the surface from Louisiana, Mississippi, and Alabama and weak onshore flow in East Texas (left) and relatively stronger onshore flow (i.e., Case #2) for the same area (right).

The near-coastal environment of the GoM has higher VCDs during offshore flow than onshore. White areas indicate "no data", such as may result from when clouds are present.

We use the following resources in our analyses as presented in the case studies:

- NASA AQ forecasts: <u>https://fluid.nccs.nasa.gov/missions/mission_SCOAPE/</u>. Skill level* required: beginner.
- NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model: <u>https://ready.arl.noaa.gov/HYSPLIT.php</u>. Skill level required: beginner.
- NASA WorldView: https://worldview.earthdata.nasa.gov/ for visualizing NASA data. Skill level required: beginner.
- EO Browser: <u>http://apps.sentinel-hub.com/eo-browser/</u> for visualizing ESA data, including TROPOMI.

Skill level required: beginner.

 Satellite Data: The TROPOMI data were downloaded from the NASA EarthData website (<u>https://search.earthdata.nasa.gov/search?q=S5P_L2_NO2_HiR_1</u>) and plotted with MATLAB software. Other software sources may be used: <u>http://www.tropomi.eu/tools</u>; general information on accessing NO₂ data: <u>https://earthdata.nasa.gov/learn/articles/feature-articles/health-and-air-quality-articles/find-no2-data</u> *Skill level required*: intermediate-advanced.

*Skill level refers to using the tool, not necessarily accurately interpreting the data.

⇒ Things to Know: The GoM typically has some clouds (Figure 15), which reduces the spatiotemporal coverage of remote sensing instruments, whether on platforms in space (i.e., satellite) or on the surface (e.g., Pandora). Satellites with fine pixels (e.g., TROPOMI) will be able to collect more cloud-free data than those with coarser pixels (e.g., OMI). Therefore, AQ forecast output in concert with satellite data will allow BOEM personnel to better interpret the AQ state than relying on satellite data alone.





May is one of the least cloudy months on average (i.e., only ~30–40% cloud cover). Figure courtesy of Ryan Stauffer (NASA).

2.5.1 Case #1: Offshore Flow (September 5, 2019)

There was offshore flow near the surface over the Louisiana coast on September 5, 2019, as simulated by the NASA AQ forecast and NOAA HYSPLIT models (**Figure 16**). In this flow pattern, pollution from the land pushed offshore over the areas of ONG operations in the GoM as shown by multiple tracers from the AQ forecast (**Figure 17**). Clear skies extended far offshore (**Figure 18**), allowing for satellite data collection over most of the region (**Figure 19** and **Figure 20**). Interpretation and other details are given in the captions of each figure.



Figure 16. Wind speed and direction from the NASA AQ model and backward trajectories from the NOAA HYSPLIT model on September 5, 2019.

(left) The flow at 925 hPa was predominately from the continent at Cocodrie, LA. The red line indicates the location of vertical cross-sections shown in subsequent figures. The red dots represent the locations of specialized forecasts on FLUID, which correspond to cities, major ONG platforms and the Louisiana Offshore Oil Port (LOOP). (right) Backward trajectories from HYSPLIT indicate that air (from the surface to 3 km) that arrived at Cocodrie, LA, had originated inland. \Rightarrow Relevance to BOEM: Note that pollution from offshore flow over Louisiana is transported back over land in Texas. Recirculation of continental pollution in the GoM is a common feature, which highlights the need for the AQ forecasts to help identify pollution sources and source regions.



Figure 17. Simulations of concentrations for CO (top), NO₂ (middle), and O₃ (bottom) from the AQ model accessed via FLUID.

Near-surface concentrations (left). The red line indicates the location of the cross-section plots (right). The plots show onshore pollution flowing into the GoM, primarily near the surface. \Rightarrow Things to Know: Though the simulated O₃ tends to be biased high in the model, the regional transport of O₃ is simulated well.



Figure 18. NASA Terra/Aqua MODerate resolution Imaging Spectrometer (MODIS) True Color Imagery of the GoM at midday on September 5, 2019.

Shows clear skies over much of the GoM. Image processed and downloaded from Worldview.



Figure 19. TROPOMI (left) TropC NO₂ VCDs (x10¹⁵ molecules/cm²) and (right) TC CO VCDs (x10¹⁸ molecules/cm²) on September 5, 2019.

Given its short lifetime (~hours), the highest NO₂ VCDs are near emissions sources. NO₂ levels are relatively high near the shore, which is likely associated with onshore pollution that was transported offshore, mixing with offshore pollution, such as from shipping and offshore ONG activities. High NO₂ concentrations from large offshore sources, such as the LOOP, are visible. There is less of a gradient in CO, which has a longer lifetime (~month). However, the data indicate rather widespread levels of pollution in the GoM, which is consistent with offshore flow. The white areas indicate where TROPOMI data are missing due to clouds. \Rightarrow Things to Know: The various data products from the same instrument may be processed differently, so that their spatial coverages can differ as in this example.



Figure 20. NASA Terra Measurement of Pollution in the Troposphere (MOPITT).

TC CO and OMI TropC NO₂ VCDs do not indicate enhanced pollution levels over the GoM for this day despite offshore flow. The datasets have gaps over most of the region of interest on September 5, 2019. These instruments are on an older generation of satellites (Aqua, launched 2002, and Aura, launched 2004) relative to TROPOMI (launched 2017). \Rightarrow Things to Know: OMI has part of its field of view blocked, which results in areas of no data in clear skies.

2.5.2 Case #2: Onshore Flow (September 11, 2019)

There was onshore flow near the surface over the Louisiana coast on September 11, 2019, as simulated by the NASA AQ forecast and NOAA HYSPLIT models (**Figure 21**). In this flow pattern, pollution from offshore sources in the GoM pushes onshore as shown by multiple tracers from the AQ forecast (**Figure 22**). Partly to mostly sunny skies extended over the GoM (**Figure 23**), allowing for satellite data collection over most of the region (**Figure 14** and **Figure 24**). Interestingly, a flare was detected at about 1:30 am using NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) thermal imagery, but neither TROPOMI nor OMI (not shown) detected elevated levels of NO₂ 12 hours later at their 1:30 pm overpasses (**Figure 25**). Interpretation and other details are given in the captions of each figure.



Figure 21. Onshore flow near the surface over the Louisiana coast on September 11, 2019. (left) Wind speed and direction at 925 hPa from the NASA AQ forecast on September 11, 2019. The red line indicates the location of vertical cross-sections shown in subsequent figures. (right) Backward trajectories from HYSPLIT indicate air (from the surface to 3 km) arrived at the Brutus platform from the east.



Figure 22. Simulated concentrations of CO (top), NO₂ (middle), and O₃ (bottom) accessed via FLUID. Near-surface concentrations (left). The red line indicates the location of the cross-section plots (right). The plots show tropical air flowing into the GoM in the western part of the domain and continental polluted air in the eastern part, which originated from the southeast U.S., particularly Florida.



Figure 23. MODIS True Color Imagery of the GoM at midday on September 11, 2019. Shows partly to mostly sunny skies extended over the GoM. Image processed and downloaded from WorldView.



Figure 24. Though much of the western part of the GoM has missing TROPOMI data because of clouds (**Figure 23**), there are generally higher CO VCDs in the eastern part of the GoM than the western part.





The VIIRS instrument that detects nighttime lights captured a flare (circled) at 1:30 am, its overpass time, (top). Image produced with WorldView. (bottom left) The HYSPLIT model indicates that the plume was transported slowly to the northwest (bottom right). However, elevated NO₂ concentrations are not evident in TROPOMI data 12 hours later. Some of the NO₂ in the plume may have been dispersed and/or converted to NO at the 1:30 pm TROPOMI overpass time. The plume is not evident in OMI NO₂ either (not shown).

2.5.3 Case #3: Pollution from Outside GoM (May 13, 2019)

During the SCOAPE field campaign, pollution from widespread agricultural fires in Mexico polluted the GoM, significantly elevating pollutants, such as aerosol and CO (**Figure 26–Figure 29**). The AQ forecasts indicate that Cocodrie, LA, was less impacted than farther offshore, such as the Atlantis platform (**Figure 30–Figure 32**). Interpretation and other details are given in the captions of each figure.



Figure 26. MODIS True Color Imagery illustrates the widespread smoke from agricultural fires (red dots indicate detected fires) that polluted the GoM.



Figure 27. Aerosol optical depth (AOD) is an indicator of the concentration of the smoke with the warmest colors being the highest concentrations.

Interestingly in this example, much of the smoke was so thick that some of the data are marked as "missing" because they were likely flagged as clouds.



Figure 28. TROPOMI shows that high levels of CO were transported from Mexico into the GoM.



Figure 29. The AQ forecast simulates the northeastward transport of smoke from Mexican agricultural fires. Black carbon (BC) is used as an indicator of the smoke.



Figure 30. The AQ forecast predicts high levels of organic carbon (OC) and BC associated with the fires early in the forecast period over Cocodrie, LA, but a cold front moved south off the coast clearing out the smoke.



Figure 31. The smoke was predicted to impact offshore for a longer period, such as at the Atlantis platform.



Figure 32. A clear increase in elevated O_3 and BC concentrations from trajectories originating over the Yucatan peninsula, where agricultural burning was occurring. 24-hour HYSPLIT back trajectories were initiated every hour along the SCOAPE ship track for May 12, 2019. The trajectories are colored by the concentration of O_3 (top) and BC (bottom) observed on the SCOAPE ship.

3 Summary and High-level Recommendations to BOEM

In this report, we show that satellite data and other NASA resources may be used to monitor AQ in the GoM, including the coastal environments. Here we provide a high-level summary of our recommendations that are given throughout the report.

⇒ High-level Recommendation #1: We recommend that BOEM adopts an integrated approach to monitoring AQ in the GoM, which consists of regulatory-grade AQ monitors and non-traditional sources of AQ data, including satellite data, AQ models, and in situ monitors (Section 2). As a first step, we recommend that BOEM personnel take advantage of the NASA ARSET and HAQAST programs to explore NASA's free and publicly available resources, so that BOEM personnel may identify the potential of these resources for BOEM's various applications and to begin integrating them into BOEM's SOP. Most of these resources are easily accessed via webtools, though accessing, processing, and analyzing satellite data (beyond visualization with webtools) will require more effort on the part of BOEM personnel.

 \Rightarrow High-level Recommendation #2: We recommend that BOEM personnel continue to interact with NASA personnel, and potentially personnel from EPA and NOAA, to identify mutually beneficial collaborations that will advance BOEM's goals to monitor AQ in the GoM. Several potential examples of these collaborations are given in **Section 2.2**.

 \Rightarrow High-level Recommendation #3: We recommend that BOEM personnel continue to work with NASA personnel to understand the relation between quantities (e.g., VCDs) observed from space and pollutant concentrations within the boundary layer, including offshore and along the coast. In Thompson (2020), we show that pollutant concentrations can have complex 3-d distributions

offshore (e.g., from the vertical structure of pollutant emissions) and in coastal environments (e.g., from complex sea breezes). BOEM personnel would benefit from working with NASA personnel, who have developed the NASA data and simulated products and, therefore, know their strengths and limitations for BOEM's applications, as well as, how to avoid common mistakes when analyzing them.

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The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

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