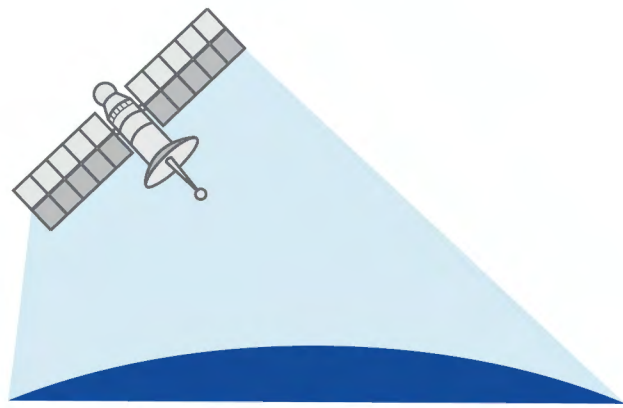
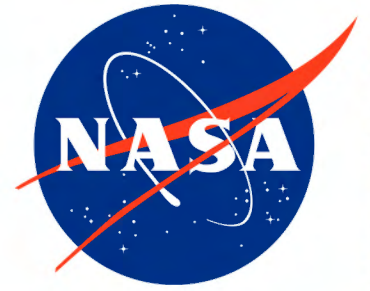




HAQAST

NASA Health and Air Quality Applied Sciences Team FINAL REPORT

2016-2020

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HAQAST Final Report

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Executive Summary

Over the past four years, the Health and Air Quality Applied Sciences Team (HAQAST) has worked to connect NASA satellite data and products with public health experts and air quality managers. With 13 members, and over 70 co-investigators, HAQAST has been supported with NASA funding through the Applied Sciences Program. The mission and structure of HAQAST has yielded a wide range of tangible deliverables and social benefits for specific organizations, while advancing cutting-edge science published in over 220 peer-reviewed articles.

From the beginning, HAQAST conceived of itself as a “front door” to connect NASA resources and expertise with stakeholders in the air quality and public health communities. This mission could only be realized by developing effective communications vehicles to meet the needs of various constituencies. HAQAST leadership at the University of Wisconsin--Madison led the organization of twice-yearly HAQAST meetings, developed HAQAST-wide communication activities, managed the selection process for Tiger Teams, and represented HAQAST to various audiences. Our twice-yearly meetings have emerged as a venue that gathers diverse experts together with the goal of solving new applied-research challenges.

Two broad categories of work represent HAQAST applied research: investigator-led projects and Tiger Teams. Investigator-led projects were defined in the peer-reviewed proposals used to determine the HAQAST membership. Tiger Teams are sub-teams formed from among funded HAQAST participants, designed to tackle short-term needs from stakeholder organizations. HAQAST included 13 individual projects and 8 competitively selected Tiger Teams.

Together, this portfolio of applied research yielded a wide range of outcomes. Seven areas were identified where 2016 – 2020 HAQAST efforts highlight the value of a collaborative team: 1) Growing the Air Quality and Public Health User Community; 2) Satellite-Derived Surface PM_{2.5} for Health Applications; 3) Characterizing Global Background Ozone Affecting the U.S.; 4) Advancing Global Health Challenges with NASA Data; 5) Evaluating Community Scale Health Impacts; 6) Quantifying Uncertain Emissions Sources; and 7) Improving Tools for Real-Time and Retrospective Fire Analysis.

Through HAQAST, we have tested a range of strategies to enhance collaboration, responsiveness, and engagement with new communities. These include the Tiger Team selection and funding process, the design of meetings, and the use of digital technology. These experiences tested new frameworks to promote applied science activities, and identified challenges associated with the unique HAQAST mission. Overall, the HAQAST enterprise has helped to move NASA satellite data towards the center of the national and international efforts to monitor and maintain air quality and public health.

1. HAQAST Team Overview

Over the course of the past four years, the Health and Air Quality Applied Sciences Team (HAQAST) has worked to connect NASA satellite data and products with public health experts and air quality managers. Our team of 13 PIs and 70+ total collaborating investigators has grown to support and serve hundreds of stakeholders across the US and throughout the world. These partnerships have grown through two-way dialogue in which stakeholders share their research needs and priorities, and scientists share their resources, insights, and new discoveries.

HAQAST is unique in its interdisciplinary, applied research focus. Our PIs come from a wide range of academic departments: from mechanical engineering, earth science, and public health, and many more. With the expertise of the wider team of investigators, HAQAST includes modelers, measurement experts, and data scientists with interests in epidemiology, science communications, agricultural emissions, and sustainable international development. This HAQAST community has helped to move NASA satellite data towards the center of the national and international efforts to monitor and maintain air quality and public health.



Figure 1: The HAQAST Team at HAQAST6, Pasadena CA, 2019.

In 2015, the NASA Applied Sciences Program solicited proposals to form a three-year Health and Air Quality Applied Sciences Team (originally referred to as H-AQAST, henceforth HAQAST) through the Research Opportunities in Space and Earth Sciences (ROSES) omnibus solicitation. HAQAST was to “apply Earth observations to improve and develop decision-making activities and enable transition and adoption by public- and/or private-sector organization(s) for sustained use in decision making and services to end users in the areas of public health and air quality.” The ROSES solicitation specified that HAQAST would additionally be tasked with building bridges between the public health and air quality communities, while also addressing issues unique to each community.

HAQAST was designed to build upon and extend the lessons and successes of the 2010 – 2015 Air Quality Applied Science Team (AQAST). The 13-member HAQAST was launched in 2016 and scheduled to conclude in the summer of 2019. Based on the successes of the team in advancing its mission, NASA announced in 2018 that they would extend the HAQAST mission by one year, to conclude in the summer of 2020.

The collective, interdisciplinary power of HAQAST is a valuable asset in meeting our stakeholders’ “real world” information needs. HAQAST has become a hub to connect stakeholder information needs with a diverse range of expertise. Our twice-yearly meetings have emerged as a venue that gathers diverse experts together with the goal of solving a new applied-research challenges. The HAQAST approach to applied science has yielded a wide range of tangible deliverable and social benefits for specific organizations, while advancing cutting-edge science published in over 220 peer-reviewed articles (See Appendix D for a full list of publications as of late 2020).

This report reviews the structure, activities, and outcome of the 2016 – 2020 HAQAST Team. More information on HAQAST may be found at haqast.org, including our online summary of the Showcase Meeting in July 2020.

1.1 Team Leadership

Cultivating the team structure of HAQAST has been the primary objective of the Team Leader, Dr. Tracey Holloway from the University of Wisconsin-Madison. The role of a Team Leader was defined in the original HAQAST solicitation, wherein potential members could propose a leadership plan in addition to the applied research of their individual project (discussed below). Additional funding was available to support leadership initiatives, to be used for coordination, promotion, reporting and outreach on team activities.

Holloway developed a leadership team including HAQAST Communications Coordinator Dr. Daegan Miller, a HAQAST Digital Media manager, and coordination with other UW-Madison staff and students to support meeting planning, website development, utilization of digital resources, and video creation.

This leadership team led the organization of twice-yearly HAQAST meetings, developed HAQAST-wide communication activities, managed the selection process for Tiger Teams (discussed below), and represented of HAQAST at various professional conferences. Dr. Miller

met regularly with NASA Office of Communications and monthly meetings of the Health and Air Quality Applied Sciences Program (HAQ). All of these activities were designed to cultivate a team culture, promote networking between HAQAST PIs and members of the public health and air quality stakeholder communities, and expanding the audience for NASA data and products.

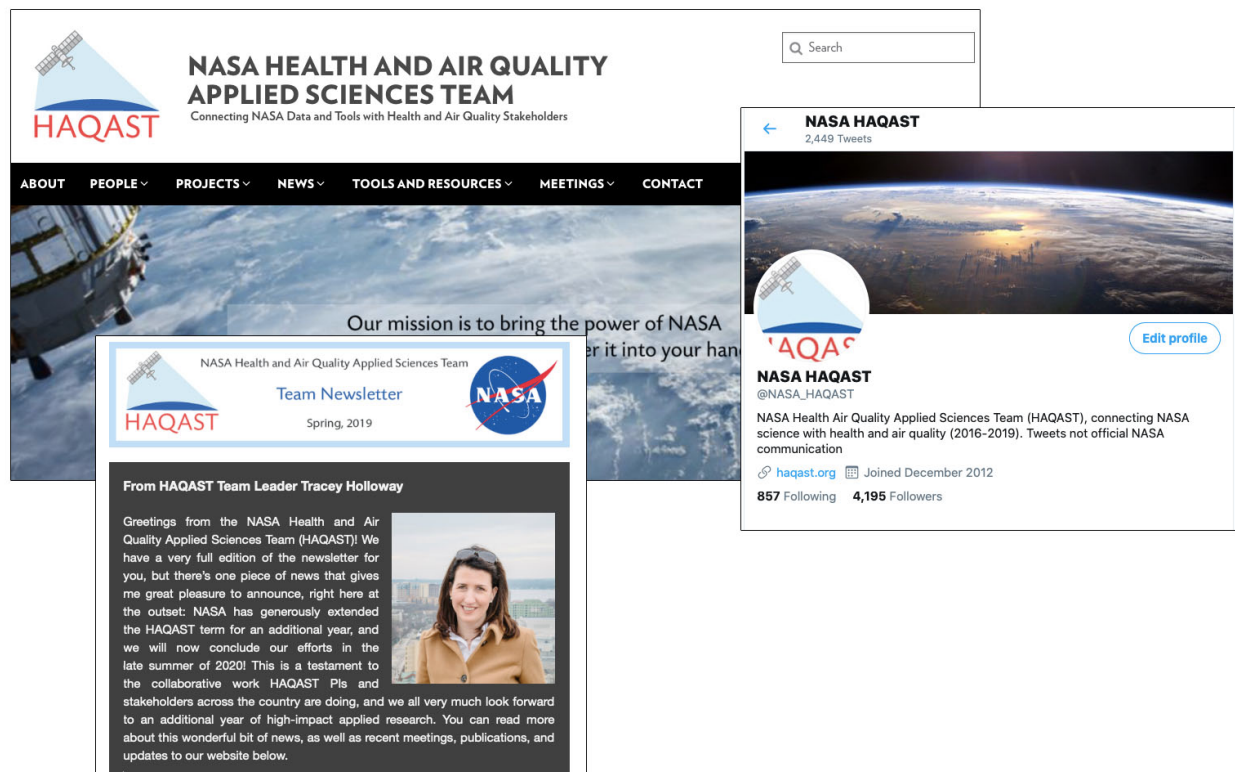


Figure 2: HAQAST digital communications vehicles, including the website (www.haqast.org), Twitter feed (@NASA_HAQAST), and newsletter.

From the beginning, HAQAST conceived of itself as a “front door” connecting NASA resources and expertise with stakeholders in the air quality and public health communities. This mission could only be realized by developing effective communications vehicles to meet the needs of various constituencies. HAQAST communications included the design, implementation, and regular updating of the HAQAST website (haqast.org); production of a quarterly newsletter (600+ subscribers as of summer 2020); active HAQAST Twitter feed, @NASA_HAQAST; and supporting HAQAST PIs in the development of press releases and media outreach efforts. The leadership team also formed a communication nexus between stakeholders, HAQAST investigators, and NASA HAQ. Regular communication involved reporting back on conference attendees and survey responses, publications, outreach, and other issues raised by community members.

Significant time and management were required to ensure the success of the biannual HAQAST conferences (HAQAST1 – HAQAST6), and two online webinar series (HAQAST2020 and the HAQAST Final Showcase). Planning activities were shared with local hosts for most meetings, but other times led by the UW-Madison team (e.g. HAQAST5 in Phoenix, selected for

coordination with the 2019 American Meteorological Society Meeting, but with no local, HAQAST-funded host). Depending on the venue, the UW-Madison team designed the agenda, coordinated with all presenters, reserved hotels, managed a remote connection option, implemented post-conference surveys and analysis, and updated meeting design based on surveys. For HAQAST4, HAQAST5, and HAQAST6 the UW-Madison team managed a grant supplement to support the travel of stakeholders to attend these meetings, supporting the travel of 63 people and leading to a steady increase in stakeholder attendance and stakeholder presentations as HAQAST evolved. To quote one anonymous survey response:

“Thanks for an excellent meeting again this year. Clearly a lot of time is spent in planning it and making sure it's useful to everyone and it's much appreciated.”

All leadership activities were aimed at supporting and promoting the excellent work of HAQAST Members and collaborators, discussed below.

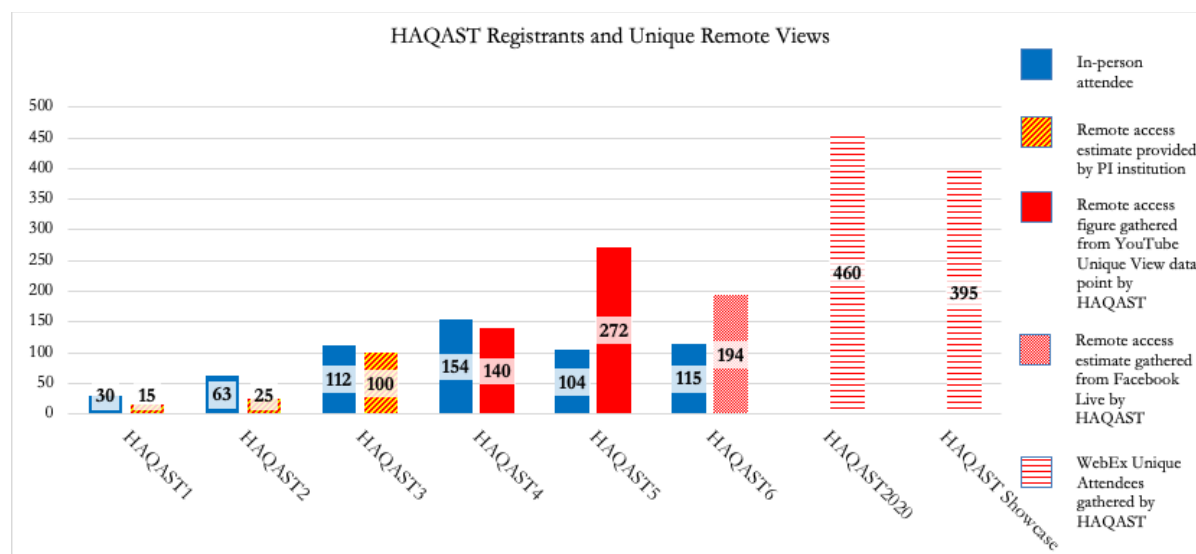


Figure 3: Attendance at HAQAST meetings, including in-person and online. All in-person meetings included a remote access option, although the platform affected the manner in which attendees were counted. HAQAST2020 and the HAQAST Showcase were conducted entirely online.

1.2 HAQAST projects

Two broad categories of work represent HAQAST applied research: investigator-led projects (IPs) and Tiger Teams (TTs). Investigator-led projects are those defined in the peer-reviewed proposals used to determine HAQAST membership. Tiger Teams are sub-teams formed from among funded HAQAST participants, designed to tackle short-term needs from stakeholder organizations.

HAQAST includes 13 IPs, led by PIs from a wide range of institutions: 10 PIs come from academic institutions geographically spread throughout the US, and 3 PIs come from federal agencies. This geographically diverse mixture of academic and public ensured a vibrant mix of expertise that

could speak to air quality and public health concerns from all corners of the country. The selection of the members for HAQAST, and the associated investigator projects, was conducted prior to the formation of HAQAST through a standard NASA peer-review process.

Tiger Teams are high impact, short turnaround projects of one year or less in which stakeholders, in collaboration with HAQAST PIs, identified pressing air quality and public health issues that could be addressed with additional funding. Two rounds of Tiger Team funding were available—the first (TT1, awarded in summer 2017 and running through summer 2018), for \$1.5 million, and the second (TT2, awarded in summer 2018 and concluding in summer 2019) for \$1.6 million. With the extension of HAQAST for a fourth year (through summer 2020), NASA allocated additional funds to maximize the impact of existing teams.

To select the HAQAST Tiger Teams, Dr. Holloway worked closely with NASA program managers to balance competition and peer-review of ideas, with incentives for collaboration and team-wide engagement. The process followed that which developed in the later years of the 2011 – 2016 AQAST Tiger Team selection, wherein each of the 13 members were assumed to participate in Tiger Teams at an equal level of funding on competitively selected research plans. So, instead of competing for funds, HAQAST members competed to propose ideas that would benefit from the expertise of participating investigators. In practice Tiger Teams emerged through brainstorming during the HAQAST-only sessions of our biannual meetings, based on requests and needs presented by stakeholders. The brainstorming typically resulted in 20+ rough ideas for possible Tiger Teams, which was then narrowed down to ~10 submitted short proposals for review. The 2-page proposals named stakeholder partners and participating HAQAST investigators. All proposals were reviewed by ~8 external reviewers, representing various stakeholder organizations in air quality and public health. Projects were ranked based on 1) usefulness to stakeholders; 2) addressing a high-priority information need; 3) appropriate scientific methodology; 4) communication plan with stakeholders; and 5) promoting wider use of NASA data and tools. The projects that ranked “Very Good” or higher were considered for funding by the HAQAST Leader and HAQ program managers, and final approval by the NASA Earth Science Steering Committee. After team selection, each HAQAST member submitted a budget plan to clarify how they or their named co-investigators would participate in one or more of the selected Tiger Teams. Each Tiger Team also had a budget dedicated to team-wide communications activities (including communication within the team, with stakeholders, and with the public).

Each round of Tiger Teams selected four projects:

- **Demonstration of the Efficacy of Environmental Regulations in the Eastern U.S.**, led by HAQAST Members Bryan Duncan and Jason West (2017-2018)
<https://airquality.gsfc.nasa.gov/us-air-quality-trends>. (continually updated)
- **Supporting the Use of Satellite Data in State Implementation Plans (SIPs)** led by HAQAST Member Arlene Fiore (2017-2018)
<https://atmoschem.ideo.columbia.edu/haqast-tt-satellite-sips/> (archived)
<https://airquality.gsfc.nasa.gov/state-implementation-plans>. (continually updated)

- **High Resolution Particulate Matter Data for Improved Satellite-Based Assessments of Community Health,**
led by HAQAST Co-I Patrick Kinney (2017-2018)
<http://sites.bu.edu/haqast-highrestt/webinar/> (archived)
- **Improved National Emissions Inventory NO_x emissions using OMI Tropospheric NO₂ Retrievals and Potential Impacts on Air Quality Strategy Development,**
led by HAQAST Member Daniel Tong and HAQAST Co-I Brad Pierce (2017-2018)
<http://cimss.ssec.wisc.edu/education/gl/ttnox.html> (archived)
- **Using Satellite Remote Sensing to Derive Global Climate and Air Pollution Indicators,**
led by HAQAST Co-I Susan Anenberg (2018-2019)
<https://haqastindicators.org> (archived)
- **Supporting the Use of Satellite Data in Regional Haze Planning,**
led by HAQAST Member Arlene Fiore (2018-2019)
<https://atmoschem.ldeo.columbia.edu/haqast-tt-haze/> (archived)
<https://airquality.gsfc.nasa.gov/hazevisibility-planning> (continually updated)
- **Satellite-Evaluated and Satellite-Informed Ozone Distributions for Estimating U.S. Background Ozone,**
led by HAQAST Member Jessica Neu (2018-2019)
- **Air Quality and Health Burden of 2017 California Wildfires,**
Co-led by HAQAST Members Susan O'Neill and Minghui Diao (2018-2019)
<https://sites.google.com/firenet.gov/wfaqrp-airfire/projects/haqast/2017NorthernCAWildfiresTT?authuser=0> (continually updated)

The Tiger Team process was highly effective at engaging the public health and air quality communities in the design of potential proposals, directly responding to requests, the review of proposals by stakeholders, and the implementation of applied research in collaboration with partners. Because air quality and public health are multidisciplinary issues, the collaborative design of each Tiger Team made for more responsive, comprehensive applied research.

2. Major HAQAST Successes

Drawing from the individual projects, Tiger Teams, and broader engagement of HAQAST, we have identified seven areas where the 2016 – 2020 HAQAST had an impact well beyond what could have been accomplished by a single research team. All along, the goal of HAQAST was to make the “whole greater than the sum of its parts.”

These outcomes highlight the collaborative strength of HAQAST and served as the structure for the HAQAST Showcase meeting in July 2020. These successes are discussed in detail below:

- Success #1: Growing the Air Quality and Public Health User Community
- Success #2: Improving Satellite-Derived Surface PM_{2.5} for Health Applications
- Success #3: Characterizing Global Background Ozone Affecting the U.S.
- Success #4: Advancing Global Health Challenges with NASA Data
- Success #5: Evaluating Community Scale Health Impacts
- Success #6: Quantifying Uncertain Emissions Sources
- Success #7: Improving Tools for Real-Time and Retrospective Fire Analysis

The full work of the team includes these successes, as well as other outcomes associated with independent projects and Tiger Teams beyond these cross-cutting successes.

Success #1: Growing the Air Quality and Public Health User Community

ROSES-15 tasked HAQAST with “execut[ing] projects on specific applied topics and demonstrations required to advance the health and air quality management communities’ sustained use and application of Earth science observations and models in decision making.” To accomplish this task, we have grown the community of users over the past four years.

Evidence of success:

- ***Many new collaborations were established.*** A few examples:
 - HAQAST Member Yang Liu began working with the New York City Department of Health and Mental Hygiene to develop PM_{2.5} models for New York City based on GOES-16 satellite data (this collaboration emerged from Dr. Liu’s participation in a HAQAST Tiger Team).
 - Satellite retrievals of formaldehyde from the OMI instrument are being used to support the National Air Toxics Assessment of the EPA (Dr. Holloway).
 - HAQAST Member Bryan Duncan spearheaded a collaboration with the Bureau of Ocean and Energy Management (BOEM) to monitor offshore emissions of oil platforms in the Gulf of Mexico using NASA satellite data.
 - The Wisconsin Department of Natural Resources included trends in OMI NO₂ in its 2018 public air trends report for the first time (Dr. Holloway).
 - Training on NASA data is now required for Air Resource Advisors working on wildfire and smoke (Dr. O’Neill, as shown in Figure 4).

- Health impact assessment tools are used by the US Department of State and Climate and Clean Air Coalition in Nigeria, Cote d'Ivoire, Maldives, Mexico, and Bangladesh (Dr. Henze).
- HAQAST Co-I Susan Anenberg and her Tiger Team worked with the Lancet Commission on Pollution and Health, Lancet Countdown, and Health Effects Institute/State of Global Air to include OMI NO₂ and satellite-based PM_{2.5} estimates as global health indicators.

Part 1: The Basics of Satellite Data for Smoke and Fire



View video [here](#) (6 min)

Part 2: The Basics of Satellite Data for Smoke and Fire



View video [here](#) (10 min)

NASA Worldview for Fire



View video [here](#) (18 min)

Figure 4: As part of PI O'Neill's 2018 TT on the California Wildfires, O'Neill and Communications Coordinator Miller created a series of training videos, highlighting NASA data and visualization products, that is now part of the required training for Air Resources Advisors working on wildfire and smoke. All videos can be found at <https://sites.google.com/firenet.gov/wfaqrp-airfire/projects/haqast/2017NorthernCAWildfiresTT/training>

- **Existing collaborations grew stronger.** A few examples:
 - HAQAST Member Bryan Duncan worked with EPA to provide NO₂ and SO₂ from the OMI instrument to the EPA's 2016, 2017, 2018, and 2019 Air Trends Report.
 - Connecticut's Department of Energy and Environmental Protection (CTDEEP) included both satellite HCHO and NO₂ as an indicator for ozone sensitivity to NO_x vs VOC emissions in their ozone State Implementation Plans (Dr. Fiore).
 - HAQAST Member Daven Henze, in collaboration with co-Is Susan Anenberg and Patrick Kinney worked with the International Council on Clean Transportation (ICCT) to evaluate health and climate impacts of fugitive diesel emissions world-wide using satellite-based PM_{2.5}.
 - HAQAST Members Bryan Duncan and Jason West and colleagues provided data to regional air quality managers in the US on how US air pollutant concentrations have generally improved in recent decades, and quantified the premature deaths avoided in the US by reductions in PM_{2.5} and O₃ since 1990, using multiple concentration datasets (see Figure 5).

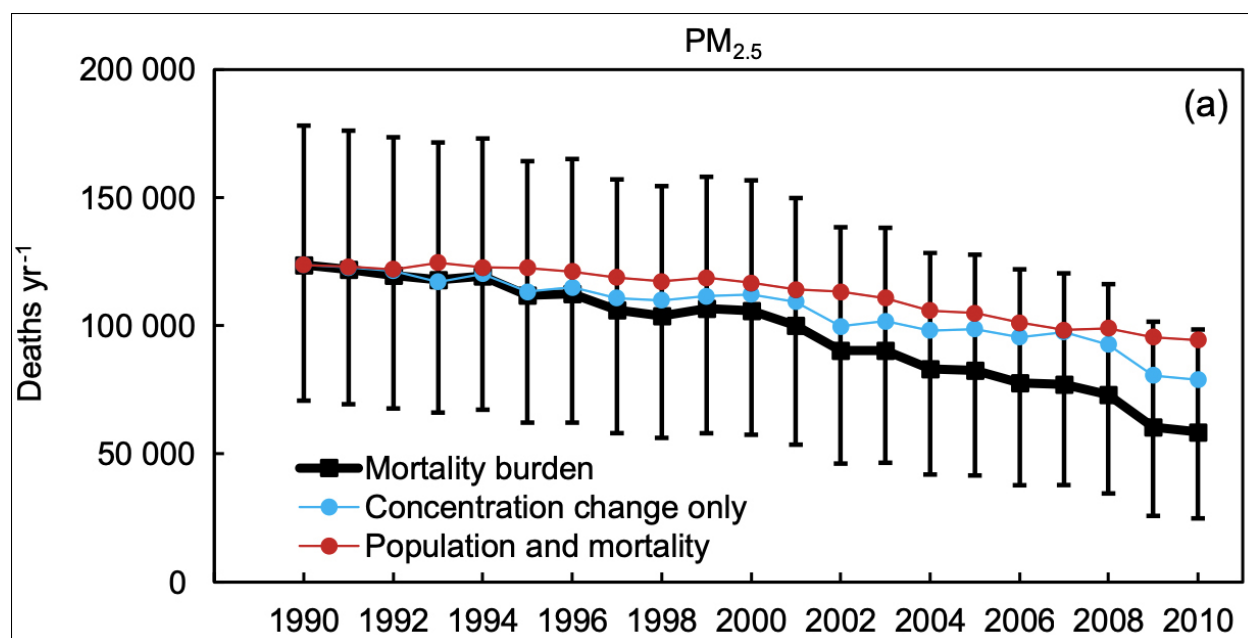


Figure 5: Trends in annual US premature deaths related to PM_{2.5} exposure, showing a 54% decrease from 1990 to 2010 (black curve), during which time air quality improved dramatically. Also shown are deaths if only PM_{2.5} had changed over this period (blue) and if only population and health status (baseline mortality rates) had changed (red). Consequently, about 35,800 avoided deaths in 2010 are attributed to the reduction in PM_{2.5} since 1990 (Zhang et al., 2018).

- **Attendance grew consistently at HAQAST meetings.** Our initial meeting attracted 30 people, whereas the final three in-person meeting averaged 121 attendees. Online attendance increased from 15 at HAQAST1 to 460 for HAQAST2020. One of the most frequent pieces of feedback

we heard was that HAQAST meetings were a place to forge new collaborative partnerships in applied research: one anonymous respondent to our HAQAST6 survey wrote:

All talks, sessions, and workshops are directly useful and relevant for my work as an exposure and health scientist.... I always come out learning a lot both on the science side but also finding out about extremely useful data resources for my own work in exposure and epidemiological health studies that I go back and apply directly to what I'm doing. Plus, it's a great venue to connect with this great community and build collaborations.

- **The proportion of stakeholder attendees at HAQAST meetings increased.** By HAQAST6, our attendees were almost evenly split between scientists and stakeholders from the air quality and public health fields, as shown in Figure 6. We evolved our format to meet stakeholder requests, including an interest in the addition of tutorials and workshops at our meetings. In response, at HAQAST6 we dedicated a half day to six, well-attended workshops (including a live how-to for NASA Giovanni, which was standing-room only). Of the tutorial “Data for Exceptional Events” led by Connecticut Department of Energy and Environmental Protection stakeholder Michael Geigert, one post-conference response said:

This workshop was the highlight of the event for me because it pertains directly to my duties at a local air district.

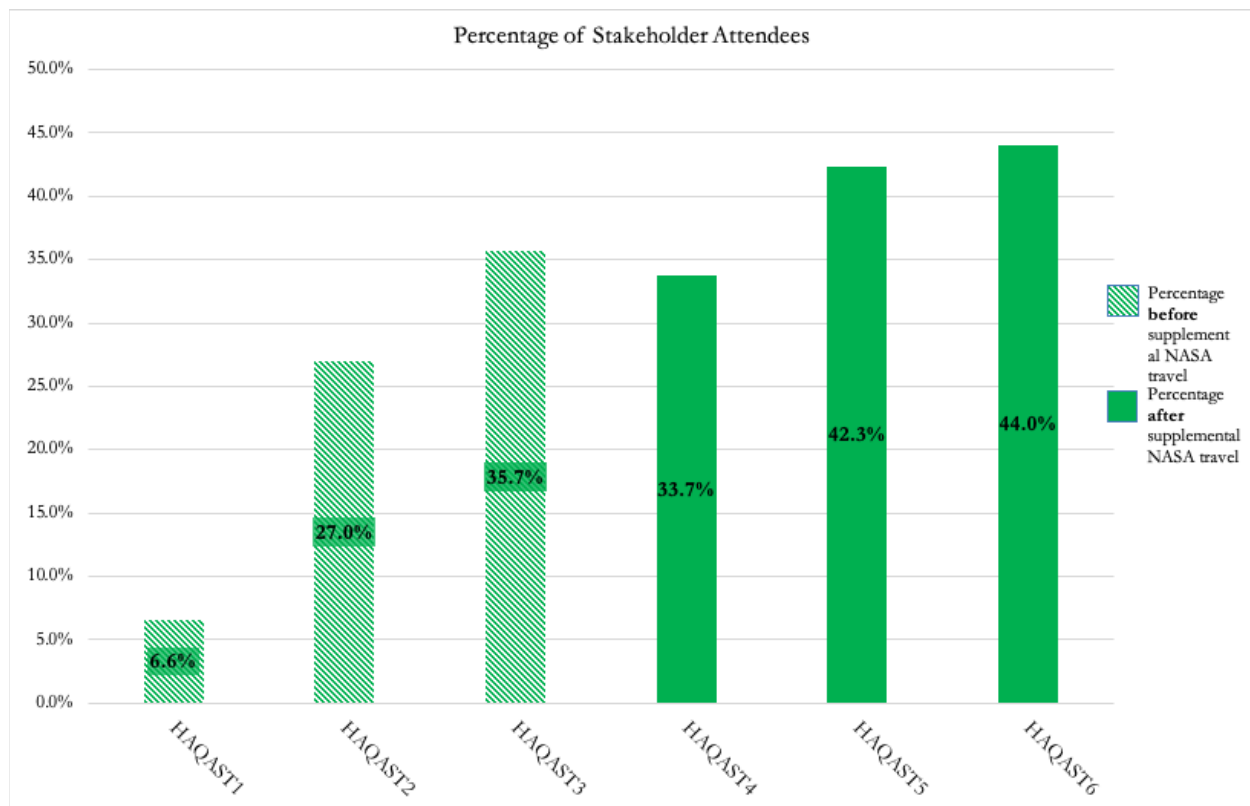


Figure 6: Percentage of stakeholder attendees at in-person HAQAST meetings.

- ***Webinars were highly attended.*** Our final regular meeting, which we called HAQAST2020, was held as month-long series of 14 webinars/workshops every Tuesday and Thursday from February 18 – March 12, 2020. The meeting hosted 460 unique attendees (for mean of 9.1 webinars-per-attendee). 99 out of 105 (94.3%) post-conference survey respondents said HAQAST should continue to offer a webinar series in the future, and, with the exception of networking, survey respondents ranked the webinar series as comparable in value to our in-person meetings.
- ***HAQAST created professional credentials for stakeholders, at their request.*** An air quality manager in West Virginia requested that we offer certificates of attendance at HAQAST2020, noting that such certificates are important in documenting professional development. We took this suggestion and offered these certificates as an option for attendees. The credential proved popular and was well received, with 87 certificates mailed to air quality and public health stakeholders throughout the US (an example shown in Figure 7).



Figure 7: A stakeholder requested that we provide certificates of attendance to the HAQAST2020 webinar participants. We mailed 87 of these certificates.

Success #2: Improving Satellite-Derived Surface PM_{2.5} for Health Applications

Through discussions with health stakeholders early in HAQAST, PM_{2.5} was identified as the most pressing concern due to its leading role in mortality and morbidity around the world. Through our collaborative problems solving, HAQAST was able to make significant progress in developing and applying satellite derived data for public health.

Evidence of success:

- ***The number of health organizations engaged with HAQAST grew***

Over the course of the past four years, we have seen a growth in the number of health organizations sending representatives to HAQAST meetings. These stakeholder organizations include the Louisiana Department of Health, Utah Moms for Clean Air, Colorado Department of Public Health and Environment, California Department of Public Health, the Health Effects Institute, the Institute for Health Metrics and Evaluation, the National Jewish Health organization, Arizona Department of Health Services, the National Institute of Health, the American Lung Association, Lehi Moms & Allies for Clean Air, the Clean Air Institute, American Cancer Society, the Icahn School of Medicine at Mount Sinai, and others.

A few examples:

- PI O'Neill's Tiger Team, "Air Quality and Health Burden of 2017 California Wildfires" engaged more than 75 individuals at over 30 different stakeholder agencies, including the California Department of Public Health, American Cancer Society, and California Office of Environmental Health Hazard Assessment.
- PI Liu connected with Dr. Laticia Nogueira, senior principal scientist at the American Cancer Society, who is interested in studying the association between cancer-patient survival and satellite-based air pollution estimates.
- Dr. Katy Walker, of the Health Effects Institute was an active member of Dr. Anenberg's climate and air-pollution indicators Tiger Team and participated as a panelist in the HAQAST Final Showcase.
- Various HAQAST PIs and members have been regular contributors to the American Thoracic Society conference.
- Dr. Michael Brauer of the Institute for Health Metrics and Evaluation joined PI West's IP, presented at both HAQAST2020 and the Final Showcase, and was a key member of contributor Anenberg's 2018 TT.

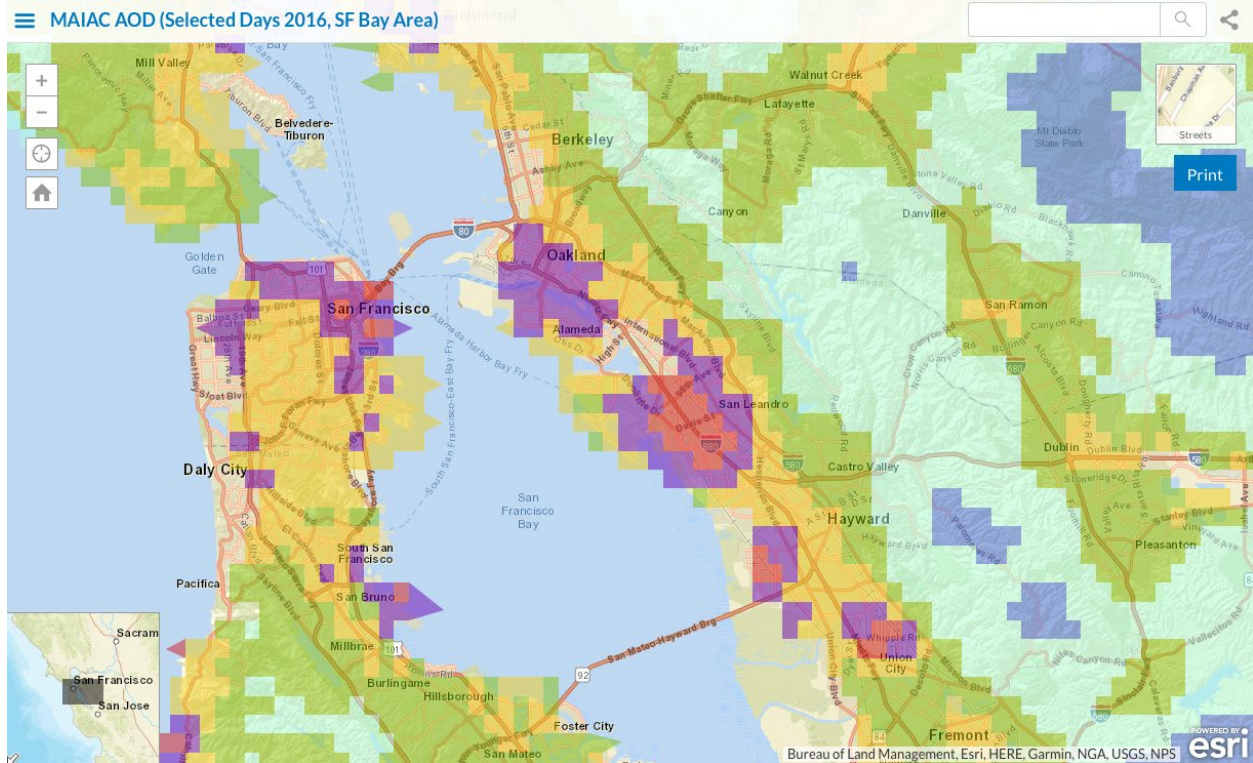


Figure 8: PI Diao's visualization of $PM_{2.5}$ in California at the 3km scale can be found at <http://www.met.sjsu.edu/weather/HAQAST/home.html>.

- **State and local health agencies used high-resolution $PM_{2.5}$ surface concentrations.** A few examples:
 - PI Diao's IP team worked with Rupa Basu and Keita Ebisu from the Office of Environmental Health Hazard Assessment (OEHHA) for California EPA as well as Sumi Hoshiko from California Department of Public Health to use $PM_{2.5}$ concentrations calculated from combined monitor and satellite data (provided by SJSU/USRA team, Al-Hamdan et al. 2019) to quantify $PM_{2.5}$ concentrations contributed by wildfires.
 - PI Diao's team also created visualization maps of $PM_{2.5}$ at a 3-km scale for the entire state of California and these maps are distributed on the SJSU HAQAST website in near real-time. This type of visualization tool has been used by Saffet Tanrikulu from BAAQMD and Cynthia Garcia from CARB to identify vulnerable communities that are most impacted by high $PM_{2.5}$ concentrations in California, directly supporting the new AB617 regulation in California, as shown in Figure 8.
 - Tiger team PI and HAQAST contributor Kinney worked with health and environmental agencies in NYC, Boston, and the SF Bay area to incorporate satellite-based high-resolution $PM_{2.5}$ into local health and air quality decision making.
 - PIs Fiore and Liu worked with Tabassum Insaf at New York State Department of Health to evaluate long-term high-resolution $PM_{2.5}$ exposure datasets and identify one, for 2002 – 2015, that is now supporting in-house epidemiological research for New York State.

- PIs Diao and Liu, along with contributor Kinney worked with the California Department of Health to examine PM exposure as an aspect of environmental justice in California's Imperial Valley.
- PI West worked with California epidemiologists studying the effects of wildfire smoke on pregnant women and their babies. The epidemiologists used PM_{2.5} wildfire smoke estimates for California, and other local agencies in California used PM_{2.5} concentrations from the 2017 California wildfire to calculate health impacts.
- ***We advanced the discussion on uses and limits of satellite-derived PM_{2.5}.*** A few examples:
 - Multiple HAQAST publications on new methods for calculating surface PM_{2.5} and developing new approaches to evaluate existing methods with observations that are being adopted by EPA for model evaluation.
 - The use of satellite-derived PM_{2.5} was a frequent, lively topic of discussion at HAQAST meetings
 - In the fall of 2019, PI Diao led a review article published in *Journal of Air & Waste Management Association*. The review paper involves a total of 17 HAQAST members and collaborators, and it serves the purpose of providing a guideline for stakeholders in public health sectors who plan to use PM_{2.5} datasets for health exposure.
- ***New estimates were provided on global health impacts from air pollution.*** A few examples:
 - PI Henze, along with contributors Anenberg and Kinney worked closely with the Stockholm Environment Institute on incorporating satellite-based PM_{2.5} and NASA model simulations used for first estimate of impacts of PM_{2.5} on premature births world-wide.
 - Contributor Anenberg, along with PI Henze and contributor Kinney, worked closely with the Institute for Health Metrics and Evaluation (IHME) to incorporate satellite-based PM_{2.5}, OMI NO₂, and NASA model simulations into the first estimates of impacts of PM_{2.5}, O₃ and NO₂ on asthma world-wide. These contributions are being evaluated for inclusion in the IHME's Global Burden of Disease 2020 report and the Health Effects Institute's State of Global Air report. This collaborative team also helped incorporate satellite-based PM_{2.5} into the first-ever study of the global health impact of PM_{2.5} in hundreds of cities worldwide, as shown in Figure 9, which have been used to support mitigation actions led by C40 Cities.

“[I’m] really pleased to be working with HAQAST... it’s really critical to the work that we do to use satellite-based information and remote-sensing information.”

- Dr. Michael Brauer, IHME affiliate

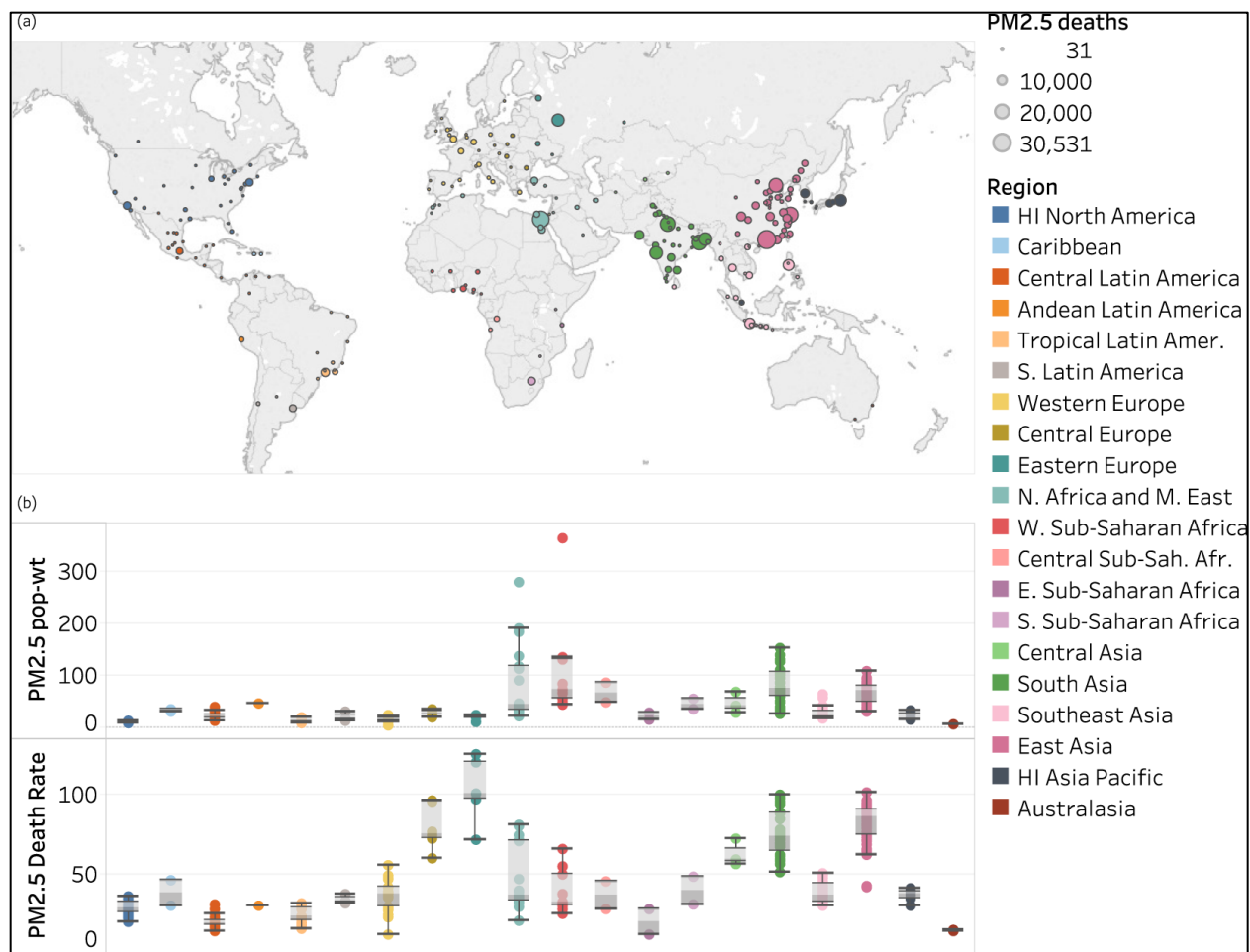


Figure 9: PM_{2.5}-attributable premature deaths in 2016 in 250 cities worldwide, from Anenberg et al. (2019).

Success #3: Improved Characterization of Global Background Ozone and Haze Affecting the U.S.

Background ozone has emerged as a pressing concern, especially in the western US, where background O₃ levels might be quite high due to stratospheric intrusions and international/intercontinental transport. A number of HAQAST PIs have worked closely with stakeholders throughout the US to better characterize background O₃ levels, and one of the most focused efforts was the 2018 Tiger Team “Satellite-Evaluated and Satellite-Informed O₃ Distributions for Estimating U.S. Background O₃,” led by PI Neu.

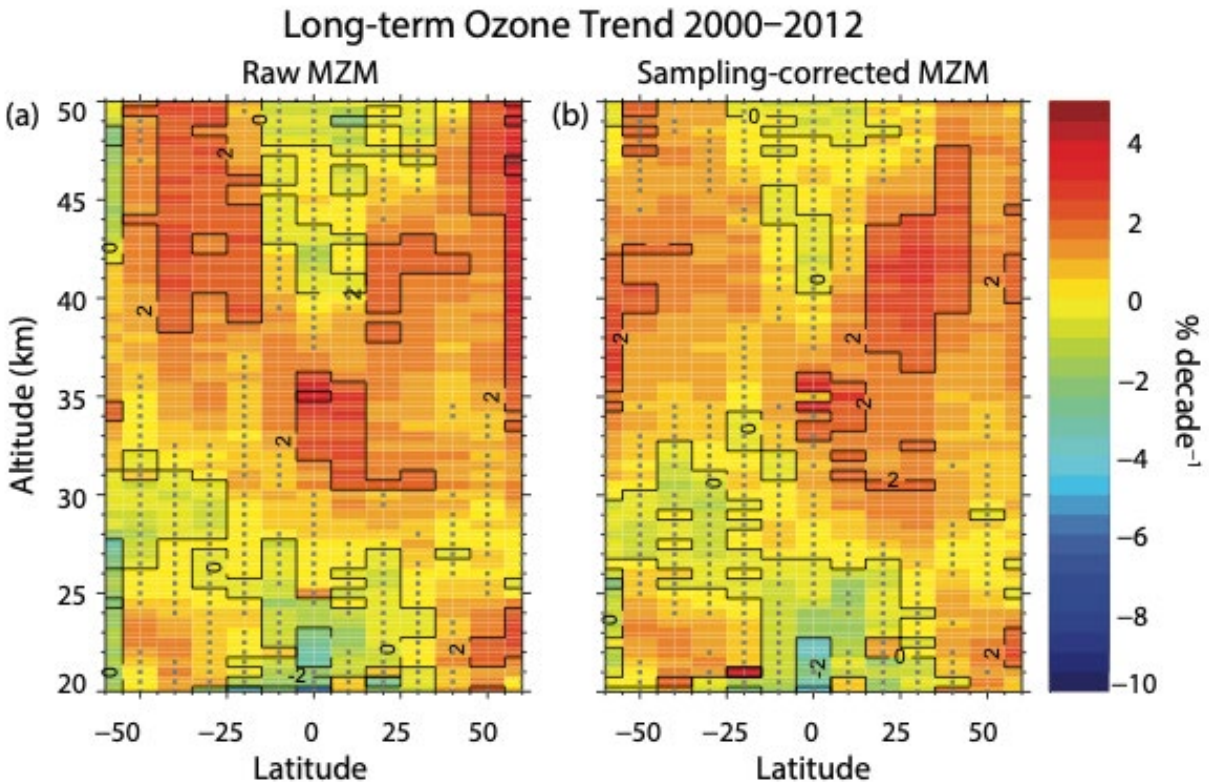


Figure 10: Long-term ozone trends in % decade⁻¹ for the period 2000–2012 derived from both (a) a regression of monthly zonal mean data (MZM) and (b) monthly zonal mean data corrected for sampling biases due to the diurnal and seasonal cycle. The diurnal correction has the greatest influence on the upper stratosphere, while the seasonal correction has the greatest influence at higher latitudes. Stippling denotes areas where the trend results are not significant at the 2 σ level. Contour lines are plotted at 2% decade⁻¹ intervals. Adapted from Damadeo et al. (2018). Image from Peter Braesicke, Jessica L. Neu, V. E. Fioletov, Sophie Godin-Beekmann, Dan Hubert, et al. Update on Global ozone: past, present, and Future. Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, chapter 3, World Meteorological Organization, 74 p., 2019, 978-1-7329317-1-8. insu-02361554

Evidence of Success

- **Western US States have a clearer understanding of background contributions to regional ozone and haze concentrations.** A few examples:
 - As part of her IP, PI Neu is providing the South Coast Air Quality Management District with a satellite-based assessment of how Chinese NO_x emissions have modulated ozone abundances in the LA basin over the past decade and a half. Furthermore, the Neu IP will provide the Western States Air Resources Council (WESTAR) with a satellite-based assessment of the contribution of stratosphere-troposphere exchange to ozone concentrations and their variations with time throughout the western-states region.

I...want to emphasize how beneficial I found the HAQAST process, in terms of interacting with the researchers. You are really studying these issues, and I look forward to the next generation of work products and routine data deliverables from these fine remote sensing platforms that are more usable by state and local EPA air quality agencies.

- Tom Moore, WESTAR/WRAP Air Quality Program Manager

- PI Henze has identified and provided the Arizona Department of Environmental Quality with the international sources that contribute to O₃ exceedances in Yuma, Arizona.
 - PI Fiore has provided estimates of different background ozone components to several air agencies and HAQAST work is featured in the most recent U.S. EPA Integrated Science Assessment.
 - Several HAQAST PIs contributed to a review paper on background ozone that include stakeholder coauthors from U.S. EPA and WESTAR/WRAP.
 - PI Fiore's 2017 TT produced a guidance document, aimed at public air-quality managers, with examples for using a range of satellite products to track long-range pollution transport from fires.
 - PI Fiore's group is also transferring model simulations (2004 – 2012) into a web-based platform housed by WESTAR/WRAP so that these can continue to be used for haze applications (which require consideration of long-term trends) in the future.
- ***EPA and state and local air agencies are being provided with satellite-informed global model simulations, including simulations of background ozone, as boundary conditions for regional models.*** An example:
 - PI Neu will provide a host of stakeholders, including EPA and WESTAR/WRAP with tailored boundary conditions for improved representation of international and stratospheric ozone in SIP modeling using 2016 as the base year, as shown in Figure 10.

The techniques that the HAQAST researchers are developing... are going to be useful for our future modeling efforts.

-Gail Tonnesen, Environmental Protection Agency

Success #4: Advancing Global Health Challenges with NASA Data

One of HAQAST's brightest points has been its global reach. From the very start many of the PIs were interested, and brought with them, an expertise in and experience working with global health. Perhaps nowhere was this more evident than in the overlap between global health and PM_{2.5}.

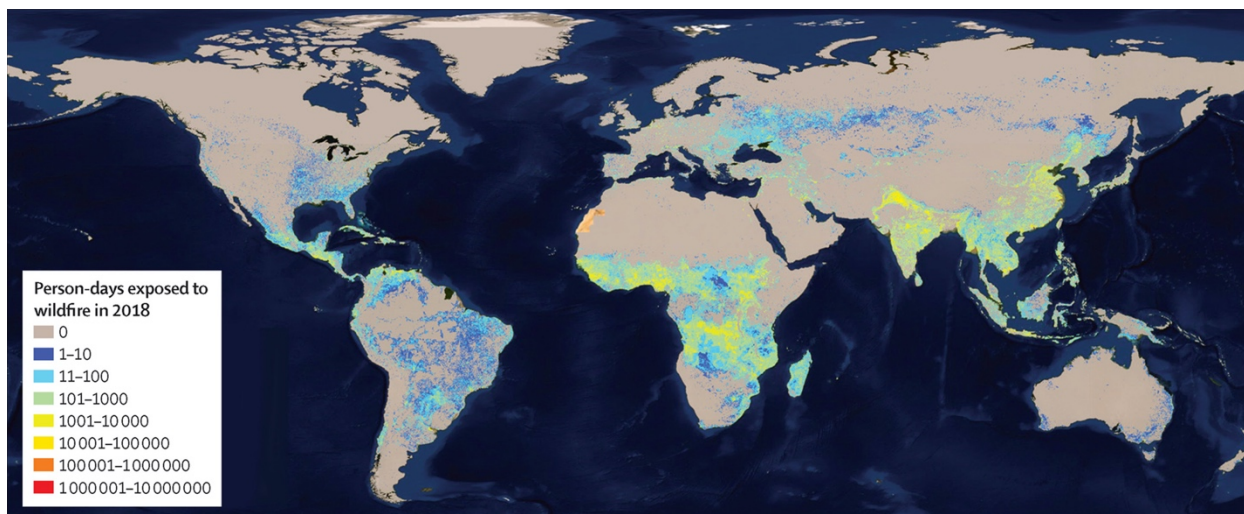


Figure 11: Indicator map of global wildfire exposure that PIs Liu and Hess generated for the 2019 Lancet report on Health and Climate Change.

Evidence of Success

- ***We worked with leading health organizations to devise new metrics for global health.*** A few examples:
 - Both the IHME and the Health Effects Institute (HEI) are very likely to include NO₂ and pediatric asthma incidence as a new risk-outcome pair in each organization's respective Global Burden of Disease 2020 study and State of Global Air project. Contributor Anenberg worked closely with both organizations to bring them NASA satellite data and products.
 - Contributor Anenberg, along with HAQAST member Henze and collaborator Kinney, also worked with C40 Cities on using urban PM_{2.5} disease burdens as part of a tool to enable cities to estimate air quality and public health benefits of climate action planning, as well as to estimate the benefits of meeting World Health Organization Air Quality Guidelines across many cities.
 - Tiger team PI Anenberg, along with collaborator Kinney worked with the Lancet Countdown on Climate Change and Health to incorporate a new greenspace exposure indicator for the 2020 report.
 - PI Duncan worked with both UNICEF and the World Resources Institute to develop a global Health and Air Quality Index.

The kinds of tools that HAQAST has been developing can provide an enhanced product so that we actually have better information.

-Michael Brauer, University of British Columbia, Institute for Health Metrics and Evaluation

- ***HAQAST improved estimates of fire exposure to support global health initiatives.*** An example:
 - PI's Liu and Hess worked closely with the Lancet Countdown Project on a global population exposure to fires dataset. This project involved Terra and Aqua MODIS

active fire data and SEDAC's GPW population data. The analysis was included in the report for the first time in 2019 and will be updated and included annually going forward. This report is widely publicized and used to drive home the importance of climate change impacts on health at the annual Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC), as shown in Figure 11.

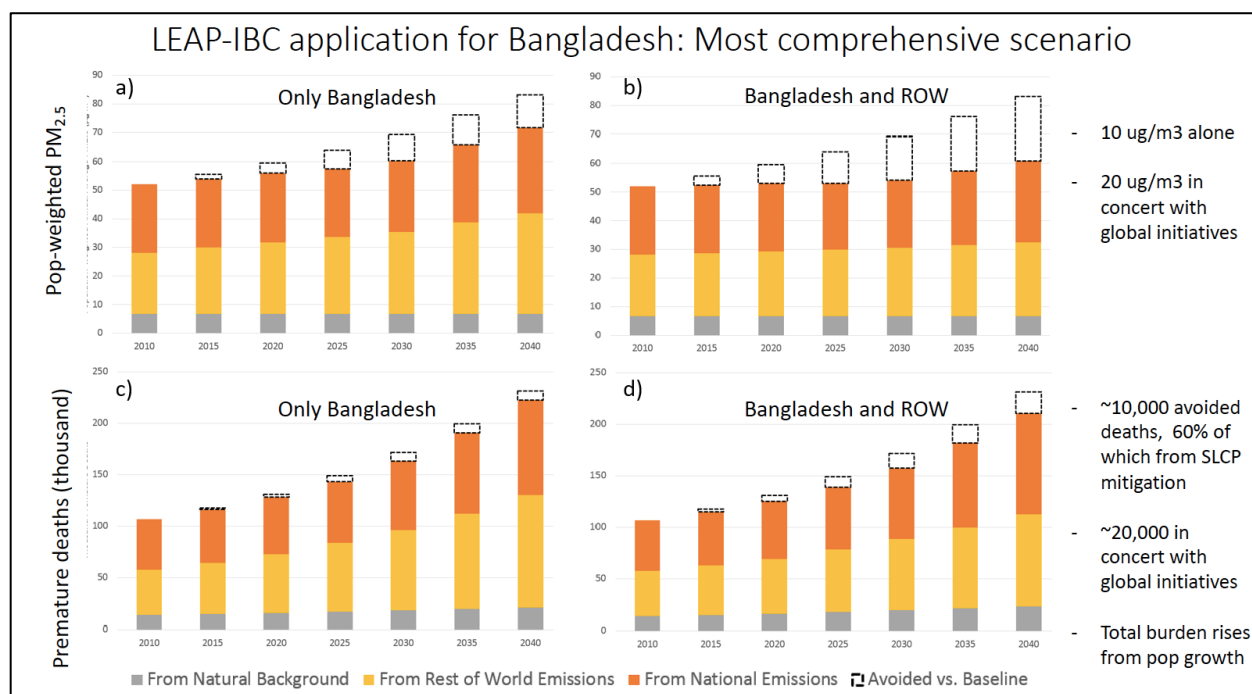


Figure 12: PI Henze worked extensively with a variety of stakeholder around the world, including Nigeria, Cote d' Ivoire, Maldives, Mexico, and, as shown here, Bangladesh, on using and incorporating air quality data into the Long range Energy Alternatives Planning System – Integrated Benefits Calculator (LEAP-IBC) tool.

- **We developed new tools and data to support decision-making.** A few examples:
 - As a result of PI Henze's collaborative work, Nigeria, Cote d'Ivoire, Maldives, Mexico, and Bangladesh use LEAP-IBC for CCAC National Actions Plans, an example of model results shown in Figure 12.

Without the input from the HAQAST researchers, we would not have been able to provide planners with this method.

-Elsa Lefèvre, Initiative Coordinator for Climate & Clean Air Coalition, Supporting National Action & Planning on Short-lived climate pollutants (SNAP) program.

- PI Henze, along with contributors Anenberg and Kinney, worked with the International Council on Clean Transportation to integrate PM_{2.5} into their evaluations of air quality impacts on vehicle emissions regulations.

- PI West worked with the IHME to create a new global ozone concentration dataset, which was incorporated into the IHME's 2017 Global Burden of Disease report (and will be incorporated into the 2019 report, as well) to estimate global premature deaths from ozone exposure. The study involved a data fusion of global ozone observations from the Tropospheric Ozone Assessment Report (TOAR) and multiple global atmospheric models, and estimates ozone concentrations at fine resolution (0.1°) for each year from 1990 to 2017. These data are also made publicly accessible through the stateofglobalair.org website created by the Health Effects Institute.

Success #5: Community Scale Health Impacts

One of the most-frequently made comments at HAQAST meetings was that many health practitioners needed fine-grained data, on the community, neighborhood, or even city-block scale—if not finer. A number of our PIs and contributors partnered with public health professionals in different cities throughout the US to get them the fine-scale data they needed.

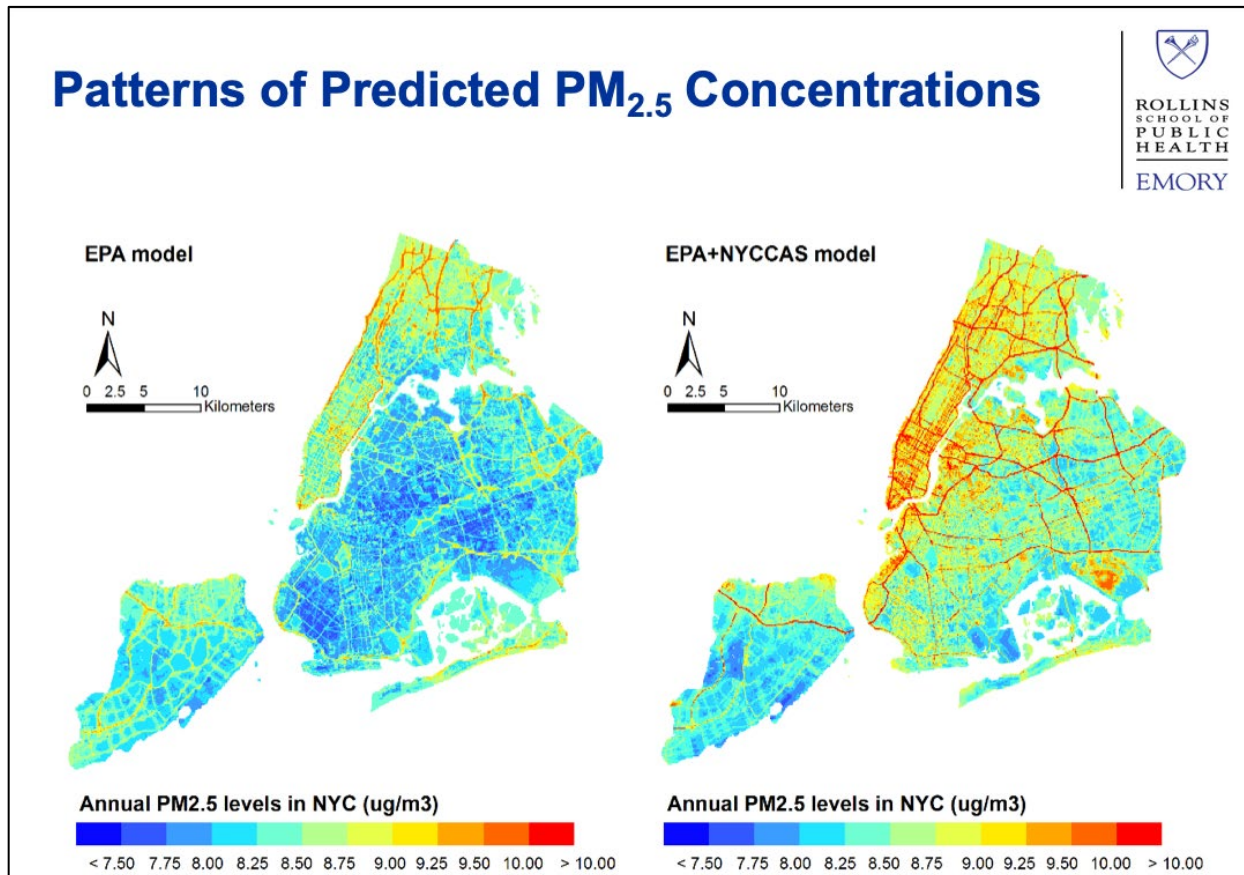


Figure 13: Patterns of predicted PM_{2.5} concentration. This slide is from PI Liu's talk in the final webinar presented to the stakeholder of contributor Kinney's 2017 TT, High Resolution Particulate Matter Data for Improved Satellite-Based Assessments of Community Health, 9/28/2018. The webinar is archived at:

<https://www.youtube.com/watch?v=2q9hBjmA3Cs&feature=youtu.be>

Evidence of Success

- ***We supported health and air agencies in using fused data products.*** A few examples:
 - Contributor Kinney worked with New York City's Department of Health and Mental Hygiene and the New York Community Air Survey to combine low-cost sensors, satellite AOD, and land-use data, in order to enhance PM_{2.5} health impact assessments.
 - Dr. Kinney also worked with the Massachusetts Department of Environmental Protection collaborated to generate new data on PM_{2.5} and ultrafine particle concentrations using a novel, low-cost sensor.
 - Dr. Kinney worked with the California Department of Public Health on particle speciation analyses to identify impacts of wildfires and diesel emissions on air quality in the San Francisco Bay Area.
 - Liu and contributor Kinney worked with New York City Department of Health and Mental Hygiene on incorporating 100-meter PM_{2.5} surfaces to examine fine scale risk patterns, as shown in Figure 13.
 - PI Diao worked with the South Coast Air Quality Management District (SCAQMD) for obtaining community-scale, high-resolution surface PM_{2.5} concentrations at the Imperial Valley, CA, the SJSU team collaborated with co-I Akula Venkatram from UC Riverside to conduct downscale modeling of PM_{2.5}, where a dispersion model and community-scale PM_{2.5} measurements from 40 low-cost monitors calculated 100-m resolution PM_{2.5} estimates for community health analysis. The results were shared and distributed to SCAQMD through quarterly Tiger Team telecons and published (Ahanger et al., 2019).
 - PI Diao also worked extensively with Jason Vargo at the California Department of Public Health's Climate Change & Health Equity Program on daily high-resolution PM_{2.5} surface concentrations to analyze the statistical distributions of PM_{2.5} on 3-km scale in the entire state of California over the past three years. The 3-km, daily, near real-time PM_{2.5} data are publicly available on the SJSU HAQAST website (<http://www.met.sjsu.edu/weather/HAQAST/home.html>).
- ***States and counties benefited from improved characterization of dust and smoke.*** A few examples:
 - PI Russell provided Georgia's Department of Natural Resources and the Georgia Forestry Commissioner with PM_{2.5} estimates from prescribed burns both to forecast air quality and to manage prescribed burn permits. Utilizing information from the Georgia Tech Hi-Res system, Georgia DNR is issuing daily forecasts of PM_{2.5} levels for Atlanta and Columbus, which are often affected by prescribed fire smoke and Georgia FC is issuing daily burn permits in consideration of the potential fire impacts.

- PI Diao worked with the California Department of Public Health to calculate windblown dust in the Imperial Valley by combining MAIAC AOD retrievals alongside low-cost monitors and routine state-agency ground PM measurements demonstrated. The results were published in Freedman et al. (2020).

The questions and products that are coming out of HAQAST improve the relevance to policy-makers and then stimulate policy action based on the science.

-Jason Vargo, California Department of Public Health

Success #6: Quantifying Uncertain Emissions Sources

Some of the most innovative HAQAST work has involved tracking and characterizing hitherto poorly understood emissions sources. We have had particular success in applying research on ammonia, dust, NO_x, and pollen.

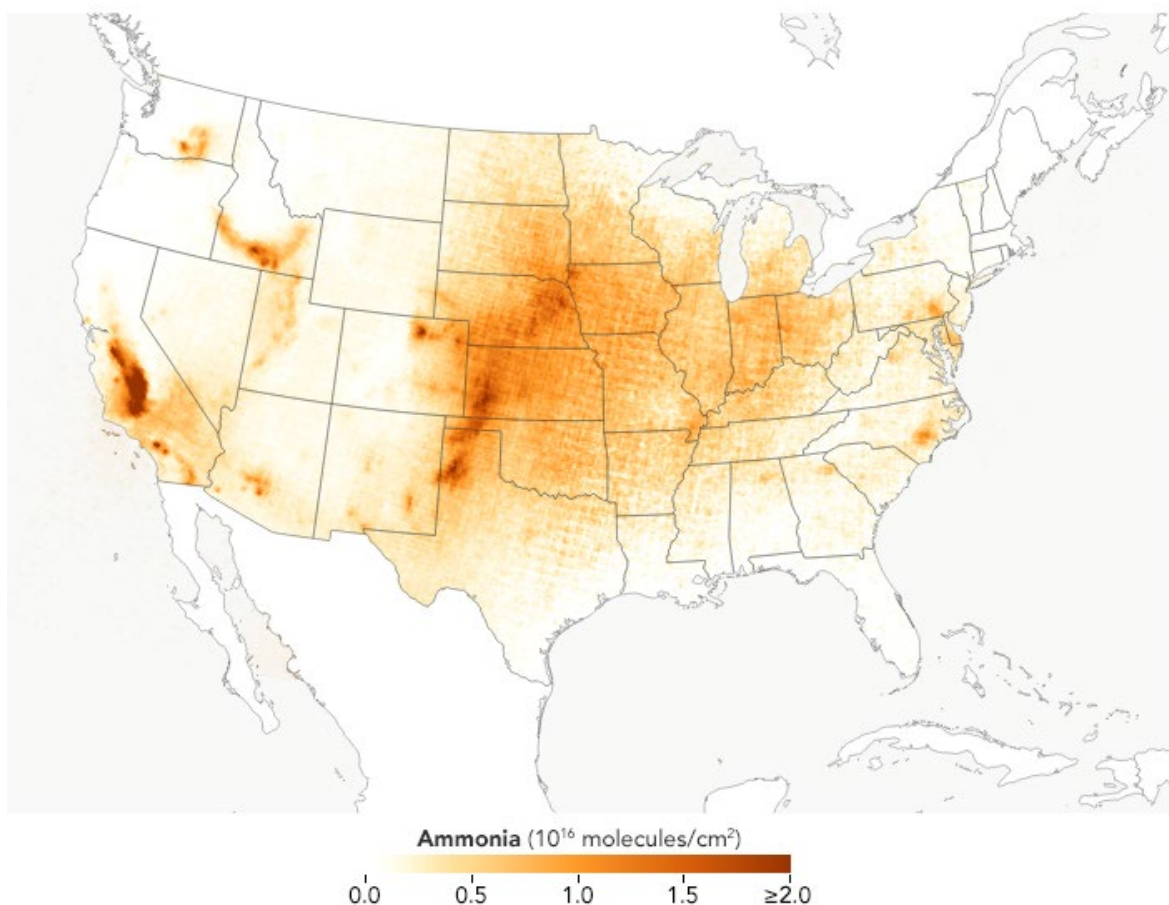


Figure 14: PI Zondlo has created a series of NH₃ maps using IASI and CrIS that show us the seasonal variations in ammonia emissions. This image was Earth Observatory's Image of the Day 12/10/2018, and is available at <https://earthobservatory.nasa.gov/images/144351/the-seasonal-rhythms-of-ammonia>.

Evidence of success

- ***We have improved ammonia emissions estimates.*** A few examples:
 - PI Zondlo developed a series of high-resolution, spatiotemporal NH₃ maps, which are currently being used by NOAA to improve spatiotemporal parameterizations of MASAGE NH₃ inventory; by EPA both to compare CMAQ-derived columns to satellite maps to help improve CMAQ/NEI representation and to help guide the placement of future Ammonia Monitoring Network sites; and the World Resources Institute is using Zondlo's maps to help constrain agricultural emission inventories in India and their impacts on air quality, as shown in Figure 14.
 - PI Henze worked with the USDA to incorporate NH₃ concentrations from CrIS to help interpret in situ NH₃ measurements in the Snake River Valley.
 - PIs Russell and Henze used data from the Infrared Atmospheric Sounding Interferometer (IASI) NH₃ column density measurements (IASI-NH₃) to provide high resolution, optimized NH₃ emission estimates by doing an adjoint analysis using CMAQ. This work is now being compared to the work of other HAQAST investigators. Using the updated emissions improves the model performance in simulating PM_{2.5} concentrations. The model results suggest that the estimated contribution of ammonium nitrate would be biased high in NEI-based assessments. The higher emission estimates in this study also imply a higher ecological impact of nitrogen deposition originating from NH₃ emissions. (Chen et al., 2020.)
- ***We have improved NO_x emissions estimates.*** A few examples:
 - HAQAST Co-I Pierce delivered capabilities to U.S. EPA Office of Research And Development (ORD) to use assimilation of OMI tropospheric NO₂ retrievals to provide off-line adjustments of CMAQ NO_x emission inventories.
 - HAQAST Co-I Pierce was awarded FY18 funding from the NOAA/NESDIS Office of Projects, Planning and Analysis (OPPA) Technology Maturation (TMP) Program to demonstrate the impact of assimilation of TROPOMI NO₂ on the National Air Quality Forecasting Capability (NAQFC) during the NASA Long Island Sound Tropospheric Ozone Study (LISTOS). Results were presented at the FY18 OPPA/TMP Annual Review.
 - HAQAST Co-I Pierce was awarded FY19 funding from OPPA to demonstrate the impact of assimilation of TROPOMI NO₂ and CO retrievals on the NOAA Unified Forecasting System (UFS) chemical forecast system during the Joint NASA/NOAA FIREX-AQ field campaign. Results will be presented at the FY19 OPPA/TMP Annual Review.
 - PI Henze used OMI to evaluate NO_x emission trends from the US EPA and NOAA, and assisted the Arizona Department of Environmental Quality with O₃ source attribution in Yuma.
 - PI Tong used satellite observations (OMI NO₂), ground monitoring (AQS NO_x) and national emission inventories to examine the impact of the 2008 Great Recession on air quality over large US cities. Results showed that satellite and

ground observations captured the gradual progression of distinct emission reduction before, during, and after the recession (Tong et al., 2015);

- PI Tong developed an emission data assimilation (EDA) technique that combined observed NO_x trends and a regional chemical transport model to quantify the impact of the recession on surface ozone (O₃) levels over the continental United States (Tong et al., 2016). This NO_x EDA package is currently used by NOAA and other stakeholders to provide rapid emission refresh to support air quality forecasts during the COVID-19 pandemic.

- ***We have improved dust emissions estimates.***

- PI Tong has developed a simple indicator, dust storm frequency, to describe the changes in the locations and numbers of dust storms in the U.S. Long-term records of dust storms were reconstructed using a new dust detection algorithm trained with the Moderate resolution Imaging Spectroradiometer (MODIS) true color dust observations. It was found that the frequency of locally originated windblown dust storms has increased 240% in 1990-2011 in the Southwest U.S., the same region in which the majority of the Valley fever cases were reported (Tong et al. 2017). The dust data are now being used by the Centers for Disease Control and Prevention (CDC) and southwestern states as part of their surveillance of Valley fever.

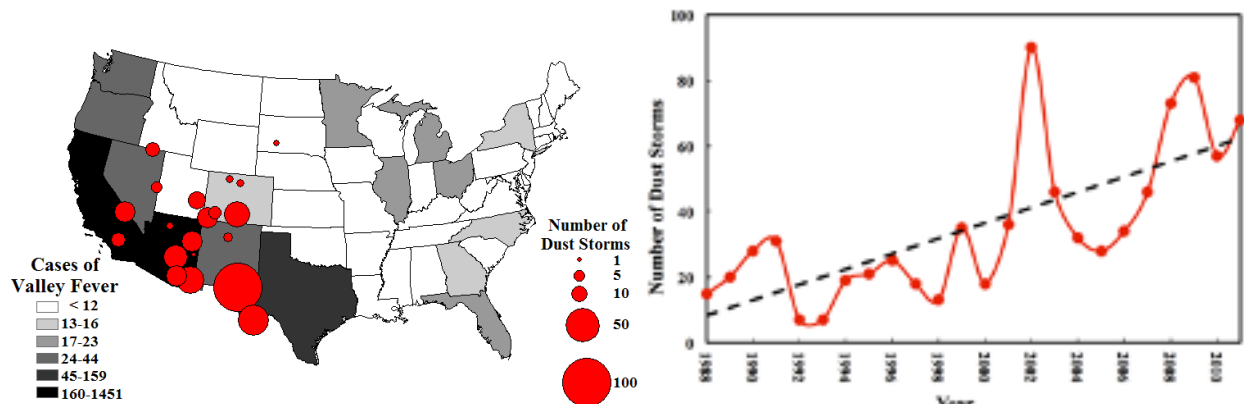


Figure 15: Dust storms (red circles) and Valley fever incidence (background color) in the United States (Source: Tong et al 2017).

- PI Tong and team have developed novel emission data assimilation techniques to use satellite observations, including aerosol optical depth (AOD), normalized difference vegetation index (NDVI), and black-sky albedo, to improve windblown dust emissions. These data assimilation packages are shown to improve dust emission prediction and are being evaluated for transitioning to the National Air Quality Forecast Capability (NAQFC) operated by the National Weather Service.

- ***We have improved pollen emissions estimates.***

- P.I. Hess developed pollen calendars, which are being distributed to individual allergy clinics and practices that lent their data to the National Allergy Bureau for use in HAQAST research. These clinics will display these calendars in their offices

and on their websites to help practitioners and patients identify the pollens that are prevalent in their areas and to identify relevant exposure patterns for allergy sufferers.

- Maps of historical pollen counts are being prepared for distribution to researchers and practitioners across the contiguous United States to link with other data like records of visits for health care and medication use, data on phenological observations in plants around the country, and data on web searches for words such as allergy and pollen. These maps will be distributed to important stakeholder groups like the Council of State and Territorial Epidemiologists, the CDC National Center for Environmental Health, and the National Phenology Network, among others.
- ***We have improved volcanic emissions estimates.***
 - PIs Zondlo and Tong compared satellite SO₂ emissions with surface network data to show how satellites present a more unified view of the 2018 Kilauea eruption than any combination of surface monitoring sites; used SO₂ emissions with STILT model to develop SO₂ and PM_{2.5} concentrations across Hawaii; found downwind coastal areas located in excess of 100 km from the source exceeded the SO₂ NAAQS up to 13% of the time during the eruption.
 - PI Tong and team have used the SO₂ column density observed by Ozone Mapping and Profiling Suite (OMPS) Nadir-Mapper (NM) aboard the Suomi-NPP satellite and the NAQFC model with an inverse emission modeling approach to quantify the impacts of the 2018 Kilauea Volcano eruption on air quality over Hawaii. While the impacts on surface PM_{2.5} and NMHCs were found mostly over the southern Big Island, near or in close proximity to major volcanic sources, the effects on surface O₃ and NO_x were much weaker but extended to a long distance (Tang et al., 2020).
- ***We have applied satellite HCHO to air quality model evaluation.***
 - Team Lead Holloway worked with the EPA to evaluate National Air Toxics Assessment model simulations against OMI HCHO from both the U.S. and European retrievals to evaluate primary and secondary HCHO production. Model simulations were found to generally agree with OMI HCHO, though models tended to underestimate background column HCHO. Two tested model configurations both show the highest level of agreement in daily HCHO variability with the OMI-QA4ECV product.
 - Team Lead Holloway also compared satellite HCHO data with ground monitoring, an idea first suggested by the Maricopa County Air Quality Department. This work found that the OMI-QA4ECV product is most appropriate for interannual trend analysis, as the retrieval has already been corrected for instrument drift. This work finds that HCHO in both surface measurements and the QA4ECV product exhibits 5 – 20% increases from 2006 – 2015 across the U.S., except the Southeast. Increasing U.S. temperatures from 2006 – 2015 partially explain HCHO trends, especially in the satellite data. Satellite data shows more pronounced seasonality than do ground-based monitors, especially at higher latitudes.

Success #7: Improved Tools for Real-Time and Retrospective Fire Analysis

Approximately half-way through HAQAST, wildfires exploded throughout California. Smoke from fire—both wildfire and prescribed fire burns—has been an important facet of HAQAST work from the very beginning, but it took on increasing importance throughout the life of the team. Much of the team has been engaged, in various degrees, in tracking the air quality and health impacts of fire and smoke.

Evidence of success:

- **State air agencies are using new tools to quantify fire impacts on air quality.** A few examples:
 - PI Russell and his team have been developing a high-resolution decision-support system (Hi-Res) that has combined air quality modeling and satellite-derived observations to predict where and when prescribed fires will occur, and the potential air quality and health impacts of those fires. Past Hi-Res predictions are achieved together with relevant prescribed fire information in the Southern Integrated Prescribed Fire Information System (SIPFIS). The Georgia Department of Natural Resources (DNR) and the Georgia Forestry Commission are using SIPFIS and NASA satellite products to investigate the role of fires in exceedance events, as shown in Figure 16.
 - PI O'Neill, leader of the 2018 TT “Air Quality and Health Burden of 2017 California Wildfires” helped create a fire emission inventory (EI) for 2018 for the Bay Area Air Quality Management District. This fire EI used the GOES-16 diurnal profile approach for wildfires greater than 12K acres, and a new methodology combining MODIS and VIIRS fire detections for all other fires.

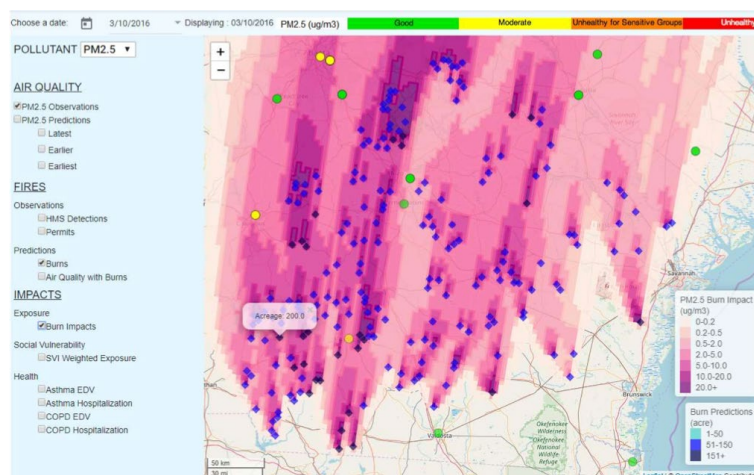


Figure 16: Image of predicted impacts of predicted burns on PM2.5 levels in southern Georgia from Southern Integrated Prescribed Fire Information System (SIPFIS). From the webinar conducted 10/15/18 by Talat Odman, a member of PI Russell's team, on using SIPFIS. Video available at https://www.youtube.com/watch?v=Q7XVO_8Pleg&feature=emb_logo.

- ***Health agencies are using new data to quantify fire impacts on health.*** A few examples:
 - PI Russell's team has included the ability to estimate health impacts from exposure to smoke in their prescribed burning forecasting and air quality impact assessment. These data were shared with the USFS for environmental justice analysis, researchers at the University of New Mexico for health economic assessments, and the American Cancer Society for studying lung cancer survival. The CDC uses the Georgia Tech health impact forecasts for prescribed burns in their National Environmental Public Health Tracking Network (Hu, et al. 2019).

The data sources that they [Russell's group] have and the tools and techniques are really a great asset. It's very helpful to me as a social scientist to be able to work with physical scientists.

- Cassandra Johnson Gaither, US Forest Service

- PI Liu worked with Colorado's Department of Public Health and Environment to provide a high-resolution wildfire smoke PM_{2.5} exposure dataset (2011 – 2014) for Colorado, and results on enhanced toxicity of wildfire smoke as compared to ambient PM_{2.5}.
- PI O'Neill provided the California Department of Health with fire PM_{2.5} exposure maps for their epidemiology studies.
- ***Fire response stakeholders benefitted from rapid implementation of new satellite products for emissions calculation.*** A few examples:
 - PI O'Neill and contributor Sean Raffuse (UC-Davis) developed an approach for large wildfires using GOES-16 fire detections to create a diurnal profile of fire emissions has been tested with Air Resources Advisors deployed with wildfire Incident Management Teams as part of the Interagency Wildland Fire Air Quality Response Program.
 - PI O'Neill and contributor Raffuse developed an interactive web viewer of GOES-16 satellite fire detections to track fire activity and calculate fire emissions in real-time via the NASA Fire Energetics and Emissions Research Algorithm.
 - PI O'Neill's 2018 California fire EI has also been used in smoke-apportionment work by the USDA Forest Service (publication in review as part of an atmosphere special issue from the third International Smoke Symposium).

Some of the information in which Susan [O'Neill]'s bringing to light and the HAQAST team members, it is ground-breaking.

-Mark Fitch, National Park Service, National Wildfire Coordinating Group

- Finally, PI O'Neill developed a statistical method based on surface observational data and remotely-sensed data, which is used to initialize the smoke forecast for "today" in the Outlook Editor tool used by Air Resource Advisors doing smoke forecasting, as shown in Figure 17.

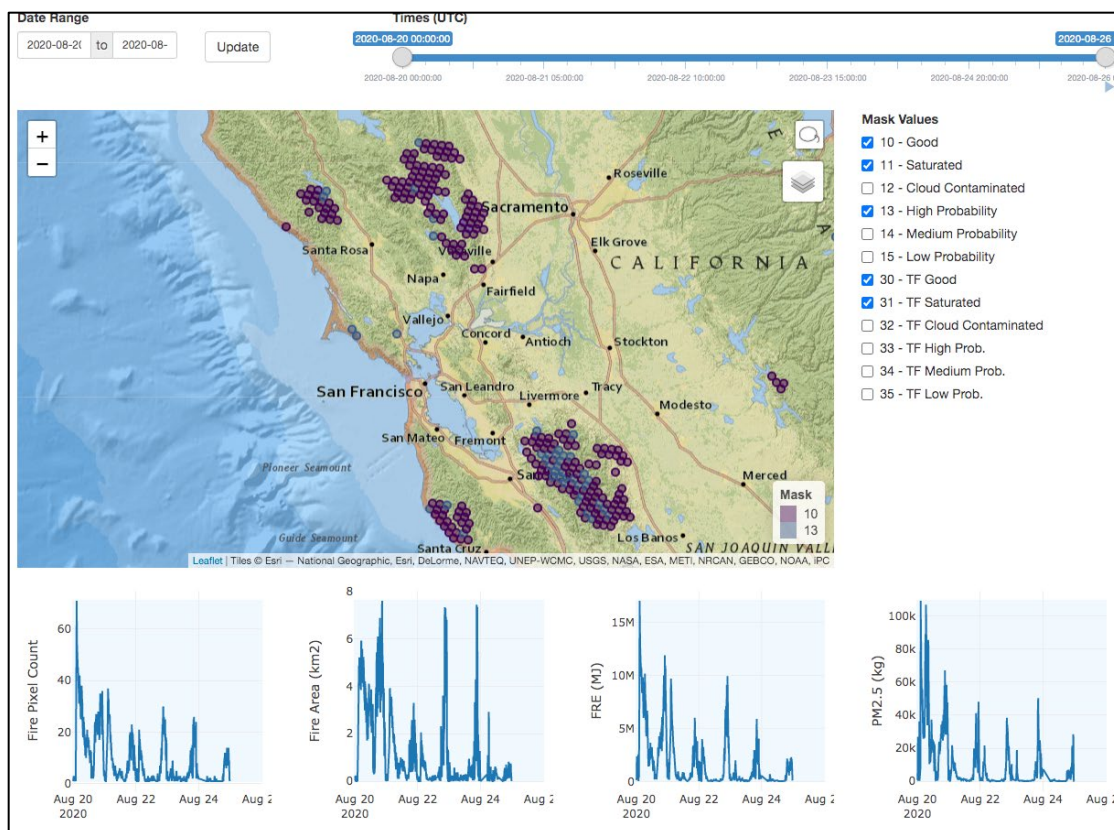


Figure 17: As part of her 2018 TT on the 2017 California Wildfires, PI O'Neill developed a wide array of data visualization deliverables, including these plots of GOES-based fire detections of the August, 2020 California wildfires. The visualizations and data outputs are all available at O'Neill's TT website, <https://sites.google.com/firenet.gov/wfaqrp-airfire/projects/haqast/2017NorthernCAWildfiresTT/data-outputs-tt>.

3. Lessons from the HAQAST Experience and Recommendations

Based on its success in expanding the Earth Observations user community and advancing applied research in air quality and health, the HAQAST leadership team views HAQAST as a major success. This success emerged in large part from the lessons learned by the HAQAST predecessor team, ACAST (2011 – 2016). Following the example of ACAST, we conclude this report with lessons and recommendations from the 2016 – 2020 HAQAST experience. We hope it will likewise prove useful to the success of future Health and Air Quality efforts.

We structure this discussion by first following-up on issues raised in the ACAST final report. Then we detail how they have affected the evolution of HAQAST. Finally, we conclude each section with the lessons that emerged from HAQAST.

3.1 Comparison with ACAST

Whereas ACAST was designed to focus on U.S. air quality issues, HAQAST had a broader mission to serve both air quality and health communities interested in air quality issues, in the U.S. and around the world. This broader mission supported global stakeholders (e.g. UNICEF), airborne

species that are not regulated by the Clean Air Act (e.g. pollen), and stakeholders who approach pollution from a health perspective (e.g. city and state health agencies). Whereas AQUEST had 19 members and a 5-year duration, HAQUEST was slated to have 13 members and a 3-year duration. In 2018 NASA extended HAQUEST's grant period and budgets to 4 years based on the success of the team.

The AQUEST final report addressed a few areas where future teams could improve, including team size and composition, grant duration, and the prior experience of the team's members. The final report is available at (http://acmg.seas.harvard.edu/aquest/pdf/aquest_retrospective_text_20160216.pdf)

With respect to team size, the AQUEST final report noted that having 19 members was too large and suggested that NASA "consider smaller Applied Sciences teams in the future." The AQUEST final report notes that:

The expertise of the 19 AQUEST PIs did not fully cover the scope of the team as sought in the original AQUEST solicitation, and there was some replication of expertise between the PIs.... In addition, some members had very little prior experience in either working with AQ agencies or working with Earth science products, and it was often a challenge for them to design appropriate AQUEST projects at the interface.

The design of HAQUEST addressed these concerns in many respects. As recommended, HAQUEST had a smaller size at 13 members. This size seemed well suited to support early collaborations among the team, such as brainstorming on Tiger Team ideas at our in-person team meetings. Most of the HAQUEST members had experience working with health or air quality agencies, as well as working with NASA data products. As a result, the skills and experience of the members fit the HAQUEST mission. HAQUEST benefitted greatly from the fact that 7 of its 13 members had previously been AQUEST members. These members brought with them the experience of working in a collaborative team and helped ensure the entire team understood the expectations in working with public stakeholders.

Though the team was smaller, it still cast a very wide net, geographically, intellectually, and in terms of the stakeholders represented. Additionally, HAQUEST benefitted tremendously from the input of co-investigators. Indeed, three of the eight TTs were led or co-led by HAQUEST co-Is. Where AQUEST included some federal employees without dedicated funding from AQUEST, all HAQUEST members received relatively equal funding for their individual projects. This decision in the structure of HAQUEST helped build camaraderie and "buy in" to the team mission. HAQUEST had a recognizable, collegial, and friendly *esprit de corps*, and this was due in part to the size and composition of the team.

HAQUEST was conceived as a 3-year program, responding to the perception that the 5-year AQUEST was too long and lost momentum at the end of the project. Two years into HAQUEST, however, it was clear that three years was too short. Second round Tiger Teams were just beginning, and publications from HAQUEST work were ramping up. It was hard to envision the ramp-down beginning just as HAQUEST was gaining momentum. In response to HAQUEST successes, as presented to a meeting of the NASA Applied Sciences Advisory Committee and other groups, NASA announced that it would be extending HAQUEST's mandate and funding by 1

year. As a result, all 13 PIs received an extra year of funding to ensure applied research outcomes were achieved and communicated to stakeholders.

Through the experiences of AQUEST, we were also able to launch HAQUEST with a set of “best practices” for stakeholder engagement. In particular, there was emphasis from stakeholders and AQUEST “alumni” on HAQUEST that regular communication was essential between HAQUEST researchers and collaborating stakeholders. This communication included phone conferences, in-person meetings, and regular email updates, as well as being available to present to audiences recommended by the stakeholders. These practices were successful in building HAQUEST collaborations and outreach, and improved outcomes of the project.

However, these communication activities significantly increase the time required by each HAQUEST member and senior funded staff. Time was required to prepare communications, engage in communication activities, and modify applied research plans based on stakeholder input. Furthermore, the success of HAQUEST collaborations and outreach led to new requests for engagement, advice, and technical support. Nearly every HAQUEST member expressed that their applied research required far more resources than were budgeted for HAQUEST.

Recommendation for future solicitations

- With 13 – 15 members, the HAQUEST size balanced team cohesion and coverage of expertise.
- A 4-year team duration works well to balance relationship-building with energy and innovation.
- All PIs should have equal funding from HAQUEST. It works well for individual project budgets, as well as Tiger Team participation budgets, to be equal among team members.
- A higher funding level should be considered to cover the required time commitment of each PI.
- HAQUEST members should already have demonstrated familiarity with NASA data products relevant for atmospheric composition (health exposure and/or air quality management), as well as expertise in working with stakeholders on applied research. Successful proposals should have specific application objectives connecting Earth Observations with stakeholder information needs.

3.2 Lessons from HAQUEST

Through HAQUEST, we have tested a range of strategies to enhance collaboration, responsiveness, and engagement with new communities. These include the Tiger Team selection and funding process, the design of meetings, and the use of digital technology. Across these HAQUEST activities, communication emerged as a significant theme. Beyond Dr. Holloway’s role as the Team Leader, for which she directed communications activities, HAQUEST’s communication staffing included senior Communications Coordinator Dr. Daegan Miller, an intern-level digital media expert (Caitlin Iverson 2016 – 2017; Rhianna Miles 2017 – 2018; Sara Grange 2018-2019; Page Bazan 2019 – 2020; Alex Pavelic 2020-2021), and additional video-editing assistance.

Emphasizing communications improved the outcomes and culture of HAQAST, and directly responded to the comment in the AQUEST Final Report recommended that “Applied Sciences teams should ensure proper communication of project results to their stakeholder community, beginning with their project partners and extending to the broader community.”

The time demands associated with enhanced communication within the team, with stakeholders, and with the public, added to an already time-intensive set of HAQAST expectations. Most HAQAST investigators have expressed concerns about the time commitment. Many commented that they were subsidizing their HAQAST activities by leveraging other projects and/or 9-month faculty appointment to cover unfunded HAQAST time. Members with limited potential to leverage activities expressed particular frustration at the time expectations of HAQAST. The problem of expectations and time commitment versus funding is not easily solved. Still, it is worth noting that this emerged as a consistent concern from the HAQAST members.

Communications were connected to the Tiger Team process in a variety of ways. Each TT proposal included a communications plan, which was one criterion used in the proposal review. Although this was only one aspect of the review, the highest ranked TT proposals consistently had the highest-ranked communications plans as well. Once TTs were selected, the TT leaders received an additional \$50K grant to be used explicitly on communications, broadly defined. Unlike the last round of AQUEST TT, the TT leaders under HAQAST did not get larger budgets for applied research. However, the communication supplement to the TT lead could be used to cover staff or PI time for communication activities (e.g. monthly telecons, preparing of deliverables, etc.). This funding helped ensure that team collaboration and stakeholder engagement would be supported, without requiring any member of the team to sacrifice funds that would otherwise go toward applied research. This additional funding was intended to partially address the concern about the large HAQAST time commitment note above, by hiring staff to support team communication and outreach and/or funding the additional time of HAQAST investigators to support communication. The additional funding helped to ensure that each TT had the resources needed to transmit final deliverables, typically in formats requested by the stakeholders.

Communication also served as the motivating force in the design of our meetings. Meetings were designed to promote two-way dialogue, especially between HAQAST investigators and stakeholder attendees. Key features included grouping speakers in panel-format presentations (short, 5-minute talks followed by extended discussion time) which included a mix of HAQAST and NASA experts, as well as stakeholders from user communities (rather than a group of science talks followed by a group of stakeholder talks); working to maximize the number of stakeholder speakers; ensuring time and events for extended networking; and surveying attendees after each meeting. These measures worked well, such that HAQAST meetings grew in size and in the satisfaction of attendees. Feedback from surveys suggested an overwhelming positive reception of the HAQAST in-person and online meeting. However, some HAQAST members expressed the concern that by serving stakeholder audience needs, it was sometimes difficult to have discussions on more advanced topics. There was always the challenge in serving a diverse audience, without creating a superficial experience for attendees with higher levels of technical expertise.

The diversity of attendees at HAQAST meetings grew through travel grants provided by NASA to UW-Madison to support stakeholder travel for our meetings in Madison, Phoenix, and Pasadena

(HAQAST4, 5, and 6). This additional funding addressed the need noted in the AQAST Final Report that “lack of travel resources [for stakeholders] at AQ agencies was often a limiting factor in their ability to attend AQAST meetings.” To incentivize applications for travel funding, we kept the application very short and prioritized funding applicants from new-to-HAQAST stakeholder organizations. When we received applications from multiple individuals within the same stakeholder application, we tended to award one grant to the organization which the organization could distribute among its employees as it saw fit. Academic researchers were rarely funded, but occasionally represented a stakeholder organization or priority application area. Travel grantees were invited to give a talk at HAQAST, but it was not a requirement of funding.

At first, UW-Madison travel staff worked with stakeholders to book and plan travel in accordance with Wisconsin state travel policies (as required for any grant administered by UW-Madison). This approach was time-consuming for the staff, and at times frustrating for the traveler, especially for individual requests, such as coordinating with a spouse’s travel, or staying at a specific hotel. To avoid these issues, travelers supported by these NASA funds were offered a fixed dollar travel stipend to book their own airfare and hotels. The travel voucher reduced the time required to manage the grant supplement, and increased traveler autonomy. We heard regular feedback from stakeholders who deeply appreciated NASA’s travel stipends. Indeed, the support engendered a great deal of goodwill in the stakeholder community toward NASA.

The in-person meetings were essential for networking within the team, and with stakeholder attendees. Coffee breaks, lunch, and a poster session with food and drink were all successful networking formats. Although the cost of coffee and other refreshments was modest, NASA funds could not be used to cover these expenses. A disproportionate amount of time was spent trying to engage sponsors or local university funds for these minor expenses. Guidance from NASA to allow these basic expenditures would have saved resources, as the time spent to figure out a way to pay for coffee cost much more than if we had been able to pay for coffee directly. (In the instances we were unable to provide complimentary coffee, meeting attendees often noted this as a particular complaint about the meeting overall).

Communication also motivated our use of digital technology throughout HAQAST. All in-person meetings were accompanied by an option for remote streaming, and two HAQAST meetings were conducted exclusively online: HAQAST2020 and the HAQAST Final Showcase. For both of the online meetings, structure and content were designed to engage audiences and meeting goals. The structure of HAQAST2020 mirrored the stakeholder-requested tutorials following HAQAST6 in Pasadena. Each webinar emphasized skill-building and applications rather than the dissemination of research results, and users could select webinars of interest (each webinar participant attended an average of 9 out of 14 webinars). The structure of the HAQAST Final Showcase mirrored the panel-format of our meetings, with 2 – 3 HAQAST speakers and 1 – 2 stakeholders discussing a common theme. In addition, the Final Showcase included 2 – 4 minute “trailer videos” summarizing the big ideas of the panel, based on pre-recorded interviews with all speakers (e.g. Figure 18).

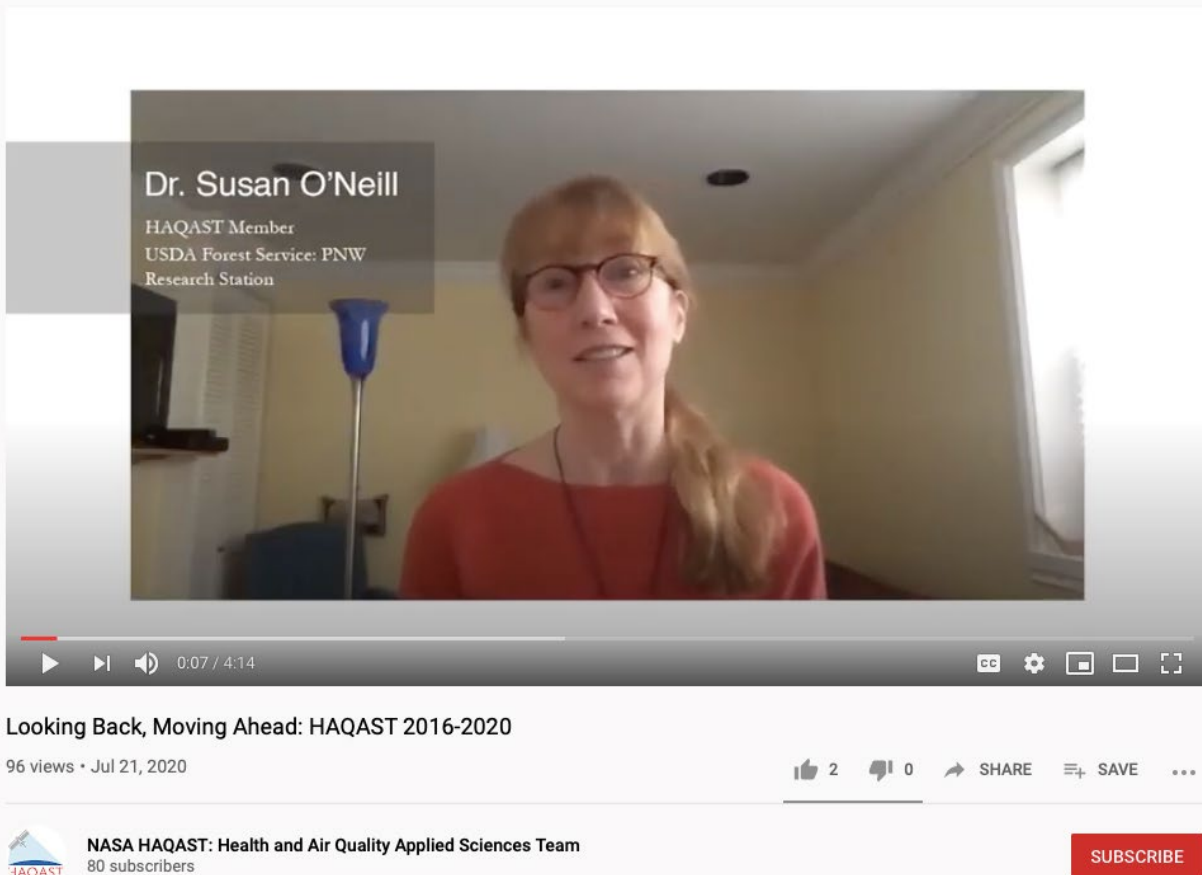


Figure 18: As part of the HAQAST Final Showcase, we created a series of 8 short highlight films that quickly summarized some of the brightest HAQAST moments over the past 4 years, as in the still from this film, "Looking Back, Moving Ahead: HAQAST 2016 – 2020," available on YouTube at https://www.youtube.com/watch?v=K2WWoPBca0k&feature=emb_logo.

Our use of digital technology significantly increased the reach of HAQAST. Most of our experience preceded the novel coronavirus, which required a digital format for the HAQAST Final Showcase. To maximize the success of digital engagement, HAQAST benefited from three digital media interns. These interns traveled to the HAQAST meetings to manage remote access. Page Bazan played a critical role in two online HAQAST meetings in 2020, including setting up meeting websites, recording speaker presentations, providing technical support before/during/after meetings, and serving as emcee for both online meetings. Creating the trailer videos for the HAQAST Final Showcase required a very large investment of time by the entire UW-Madison team (and an additional video editing intern). This level of staffing is considered a minimum to support all-online meetings. Staffing for online streaming of in-person meetings depends on the set-up and technical support provided by the host institution.

One challenge in online meetings is the ability to quantify attendees. Different platforms provide different statistics, and it can be difficult to compare an in-person attendee with an online attendee who logs in and out throughout a meeting. Differences in reporting by Facebook, YouTube,

WebEx etc. create challenges in capturing meaningful measures of digital audience engagement reliably and consistently from one meeting to the next.

Recommendation for future team implementation

- A focus on communications is essential to connect with new user communities. These communication efforts require dedicated time and expertise beyond that of the HAQAST Members and researchers.
- Meeting design should focus on engagement of new user communities, even if that requires less time for technical scientific talks. Significant time and resources are needed to create successful meetings, both in-person and on-line. HAQAST communications staff play an essential role in the organization of these meetings, and may need meeting-specific support to ensure time is covered.
- Funding to support stakeholder travel is a key ingredient in connecting with new audiences. Fixed travel awards are easier to implement than individual travel booking.
- NASA guidance to allow coffee and other meeting food and drink would be very helpful to support networking opportunities.
- Increasing the PI budgets so that they are consistent with the increased demands placed upon PIs, especially in regard to communicating their research results.
- The next iteration of HAQAST should invest in the expertise and equipment to prepare, capture, broadcast, record, and edit high-quality audio and visual content reliably.
- One HAQAST idea that was often discussed, but not implemented, was the idea of engaging all team members in a day-long communications training. Done correctly, this could help the team members get to know each other, while building a shared set of skills and methods to support a successful team-wide communication effort.

4. Appendices

Appendix A: Overview of HAQAST Tiger Teams

Description of 2017 Tiger Teams

- **Demonstration of the Efficacy of Environmental Regulations in the Eastern U.S.**, led by PIs Bryan Duncan and Jason West.

Partners: Mid-Atlantic Regional Air Quality Management Association, the Maryland Department of the Environment, the EPA, the Centers for Disease Control/National Center for Environmental Health, the Northeast States for Coordinated Air Use Management, and the Connecticut Department of Energy & Environmental Protection

HAQAST Members and Collaborators: Mark Zondlo, Ted Russell, Yang Liu, Arlene Fiore, Lok Lamsal, Daniel Tong, and Daven Henze also contribute to this team.

Description: Between 1990 and 2015, the U.S. average concentration of PM_{2.5} decreased by 37%, while O₃ decreased by 22%. Many observers expect such reductions to have brought substantial benefits for public health in the U.S., but assessing the health benefit requires an understanding of where air quality has improved relative to where people live. This team will demonstrate the efficacy of air quality regulations by analyzing the time trends for levels of ozone (O₃), nitrogen dioxide (NO₂—an O₃ precursor), particulate matter (PM), and PM precursors, including NO₂, sulfur dioxide (SO₂), and ammonia (NH₃) in the northeastern U.S., to determine how they affect population health during the same period.

- **Supporting the Use of Satellite Data in State Implementation Plans (SIPs)**, led by PI Arlene Fiore.

Partners: California's South Coast Air Quality Management District, the Connecticut Department of Energy & Environmental Protection, the Mid-Atlantic Regional Air Quality Management Association, Northeast States for Coordinated Air Use Management, Georgia Environmental Protection Division, the Texas Commission on Environmental Quality, the Bay Area Air Quality Management District, and the EPA

HAQAST Members and Collaborators: Bryan Duncan, Jessica Neu, Daven Henze, Talat Odman, Ted Russell, Patrick Kinney, Daniel Tong, Mark Zondlo, Jonathan Patz, and Tracey Holloway also contribute to this team

Description: Under the U.S. National Ambient Air Quality Standards (NAAQS), states in non-attainment of criteria pollutants, such as ozone and PM_{2.5}, must submit State Implementation Plans (SIPs) to demonstrate their approach to achieving NAAQS compliance. Satellite data may be included in SIPs as part of a weight-of-evidence

approach to show that a particular strategy is anticipated to succeed in attainment, or to show that transported pollution is confounding attainment efforts. Yet, questions often arise as to the accuracy of satellite data, the specific meteorological conditions and spatial or temporal averaging scales over which the product is most reliable, and whether a particular satellite product can be used for a desired application.

This team will work closely with at least three air agencies that are already incorporating satellite data into the SIP process and identify at least three different applications of satellite data to be showcased in a user-friendly, technical-guidance document. Each document will include frequently asked questions (FAQs) and will be “beta-tested” by at least one other air agency. The team will disseminate these case studies widely, including via the NASA Air Quality from Space website, with the goal of enabling other current and future users of satellite data in the SIP process to learn from “early-adopter” air quality managers.

- **High Resolution Particulate Matter Data for Improved Satellite-Based Assessments of Community Health**, led by HAQAST contributor Patrick Kinney.

Partners: New York City Department of Health and Mental Hygiene, the California Department of Public Health, the City of Boston Environment Department, the South Coast Air Quality Management District, and the California Air Resources Board.

HAQAST Members and Collaborators: Frank Freedman, Yang Liu, Matt Strickland, Daven Henze, Arlene Fiore, Susan Anenberg, Mohammed Al-Hamda, Akula Venkatram, Mark Zondlo, Susan O'Neill, and Daniel Tong are also members of this team

Description: Health departments and urban planners have growing needs for high-resolution data on urban-air-pollution concentrations to quantify existing health burdens at the neighborhood scale, to identify and prioritize exposure-reduction strategies for pollution hot spots, to track progress in achieving air-quality-related health-improvement goals, and to assess health co-benefits of longer-term carbon-mitigation strategies. To date, however, few data exist to inform these high-priority urban-health objectives. Newly available 1x1 km aerosol optical depth retrievals from NASA MODIS remote sensing provide opportunities to construct higher-resolution PM_{2.5} spatial fields for intra-urban public-health assessments. The retrievals also can serve as a launching pad for further downscaling using emerging low-cost sensors in conjunction with land use regression and dispersion models.

The overall objective of this Tiger Team project is to construct gridded PM_{2.5} spatial fields on 1-km MAIAC satellite-based aerosol optical depth retrievals, and to explore methods by which these can be downscaled using hi-density urban networks of low-cost sensors and dispersion modeling. The goal is to provide new tools for assessing air-pollution-related health burdens and mitigation strategies in community settings. This work will be carried out across four communities: New York City, Boston, Los Angeles, and California's Imperial Valley.

- **Improved National Emissions Inventory NO_x emissions using OMI Tropospheric NO₂ retrievals and Potential Impacts on Air Quality Strategy Development**, led by PI Daniel Tong and contributor Brad Pierce.

Partners: NOAA/Air Resources laboratory, NOAA/National Weather Service, EPA/Office of Air Quality Planning and Standards, the Centers for Disease Control, Lake Michigan Air Directors Consortium, and NOAA/Earth System Research Laboratory.

HAQAST Members and Collaborators: Ted Russell, Tracey Holloway, Susan O'Neill, and Daven Henze are also members of this team.

Description: The overall goal of this HAQAST Tiger Team effort is to improve estimates of National Emissions Inventory (NEI) area and point source NO_x emissions using NO₂ retrievals from the NASA Ozone Monitoring Instrument (OMI) and the NASA Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO).

Recent studies suggest that NO_x emissions are overestimated in the NEI. These overestimates can affect model predictions of ozone and nitrate aerosol concentrations, leading to systematic biases in forecasts of surface ozone and nitrate aerosols. Improving constraints on anthropogenic area and non-EGU point source emissions (including wild and prescribed fires) within NEI can lead to improved forecasts thereby improving NWS air quality forecasting, EPA/CDC exposure assessments, and state SIP modeling.

Description of 2018 Tiger Teams

- **Using Satellite Remote Sensing to Derive Global Climate and Air Pollution Indicators**, led by contributor Susan Anenberg

Partners: Lancet Commission on Pollution and Health, University College London/Lancet Countdown, and the Health Effects Institute/State of Global Air

HAQAST Members and Collaborators: Jeremy Hess, Bryan Duncan, Arlene Fiore, Daven Henze, Patrick Kinney, Lok Lamsal, Yang Liu, Daniel Tong, and Jason West also contribute to this team

Description: This project initiates a new collaboration between HAQAST members and LCPH, Lancet Countdown, and SoGA projects with the aim of developing satellite-derived air pollution and climate indicators at the global scale. Specifically, this team will use satellite remote sensing to:

1. Transfer knowledge and global-scale datasets tracking indicators for ozone and NO₂ concentration, PM_{2.5} and ozone disease burden in cities, and wildfire occurrence
2. Scope the potential for using satellite remote sensing to track global airborne dust storms and pollen season start date and duration. The project draws from a variety of satellite remote sensing products. HAQAST team members will work collaboratively

across indicators to share information and work towards achieving consistency among years, metrics, and outputs.

This project will provide quantitative estimates of ozone and NO₂ concentrations, ozone and PM_{2.5} disease burdens in megacities, and wildfire occurrence globally. This team will develop a methods scoping document for using satellite remote sensing to track dust storms and pollen season start date globally. In addition, they will also help develop a comprehensive set of global pollution and climate indicators for a Global Pollution Observatory that will collect and periodically report on pollution-related data, expected to be established in the near future by the LCPH. Over the long term, results may also be used to generate estimates of the global burden of disease from wildfires, dust, and pollen, and to examine historical trends as well as future climate impacts.

- **Supporting the Use of Satellite Data in Regional Haze Planning**, led by PI Arlene Fiore

Partners: U.S. EPA OAQPS, MARAMA, NESCAUM, TCEQ, ME DEP, and CT DEEP

HAQAST Members and Collaborators: Bryan Duncan, Daven Henze, Patrick Kinney, Talat Odman, Ted Russell, Daniel Tong, Jason West and Mark Zondlo also contribute to this team.

Description: This team proposes to work with stakeholders to address three applications of satellite data of direct relevance to regional haze SIPs. The team will develop technical guidance documents that describe their approaches to using satellite data for regional haze applications. They anticipate that the guidance developed under this project will also be relevant to health agencies seeking to assess health burdens due to natural events (e.g., dust, wildfires) associated with severe health effects. In addition, they'll aid air quality managers in the use of satellite data in the Regional Haze SIP process, provide tangible examples of the value of satellite data for addressing air quality and related health applications, to aid stakeholders who wish to conduct their own analyses, and lower the barrier for new health and air quality stakeholder agencies to apply satellite data.

- **Satellite-Evaluated and Satellite-Informed Ozone Distributions for Estimating U.S. Background Ozone**, led by Jessica Neu.

Partners: BAAQMD, the South Coast Air Quality Management District, the California Air Resources Board, CT DEEP, New Hampshire Air Resources Division, New York State Department of Air Quality, the Texas Commission on Environmental Quality, WESTAR & WRAP, US EPA, and OAQPS.

HAQAST Members and Collaborators: Arlene Fiore, Daven Henze, Brad Pierce, Ted Russell, Jason West, and Anne Thompson also contribute to this team.

Description: This team will provide a coordinated set of boundary conditions for O₃, background O₃ (no U.S. anthropogenic emissions), and natural O₃ (no global anthropogenic emissions) for 2016 from multiple global models, many of which are

informed by satellite data (e.g., assimilating satellite products). Their goal is to improve the quantification of background O₃ in SIPs, a critical component of the development of our stakeholders' attainment plans. This team will also establish 'best practices' for evaluating models with satellite O₃ measurements, and for evaluating satellite-informed simulations with independent datasets such as those from surface stations and ozonesondes (lightweight, balloon-borne instruments that are paired with conventional meteorological radiosonde).

- **Air Quality and Health Burden of 2017 California Wildfires**, led by Susan O'Neill

Partners: BAAQMD, NOAA, the USFS Fire & Aviation Management Program, EPA, Sonoma Technology Inc., the National Park Service, Princeton University, the University of Washington, and the University of California, Davis.

HAQAST Members and Collaborators: Daniel Tong, Talat Odman, Minghui Diao, Jason West, Pat Kinney, Brad Pierce, Jessica Neu, and Sim Larkin also contribute to this team.

Description: On October 8-9, 2017, a series of wildfires started in the northern San Francisco Bay Area, spread quickly over nine counties and became major fires in the region. Because of the smoke and prevailing weather conditions, PM_{2.5} concentrations reached the highest levels ever recorded in the region. All 13 air monitoring stations in the Bay Area captured at least one exceedance of the US EPA's 24-hr average PM_{2.5} standard. Thus, virtually all of the 7.2 million people living in the Bay Area were exposed to unhealthy air during the wildfire period.

This team will assess the effects of wildfire smoke on the air quality and human health burden resulting from October 2017 California wildfires using a combination of satellite data, air quality modeling, health risk information and hospital incidence rates. They will prepare a detailed wildfire emissions inventory, estimate the air quality impacts of wildfire emissions, use satellite and ground-based observations to evaluate model results and iteratively refine wildfire emission estimates to improve the CMAQ model predictions, and utilize short-term exposure-response relationships already established between PM_{2.5} and public health to assess health impacts of wildfire-induced pollutant exposure.

Wildfire smoke impacts will recur in the future in California and elsewhere, and having a system that can accurately estimate those impacts, not only in terms of PM_{2.5}, but in terms of short-term exposure-response relationships is critical to future planning of emergency responders to protect public health. End users such as the BAAQMD envision using this project information as a basis for an emergency response manual to help inform emergency responders regarding expected levels of ambient PM based on the nature of wildfire and the number of people who may need medical attention.

Appendix B: HAQAST Meetings

HAQAST drew on AQAST’s legacy of success by scheduling biannual meetings (approximately every 6 months)—such a schedule balanced effective and frequent outreach against the very real possibility of “meeting fatigue.” The central objectives of HAQAST meetings were to engage the public health and air quality communities in:

1. Learning about HAQAST activities and accomplishments.
2. Building bridges between NASA, public health, and air quality stakeholders
3. Educating HAQAST members as to the major challenges and priorities of various public health and air quality stakeholders.
4. Building relationships between HAQAST members and members of the public health and air quality communities.
5. Forging the bonds for new applied research projects—especially for TTs—with the input of the air quality and public health communities.

Each HAQAST meeting was located in a different part of the US (Atlanta, Seattle, the greater NYC area, Madison, Phoenix, Pasadena). We chose to move the site of our meetings to:

1. Maximize stakeholder diversity. Many local stakeholder agencies have limited funds for travel. We found that if HAQAST went to the stakeholders, rather than forcing them to come to us, we could bring in a greater number, and wider diversity of participating agencies. This was also a way to build goodwill.
2. Respond to differing regional needs. Different geographical regions of the US have widely differing public health and air quality needs. Moving the location of our biannual meeting allowed HAQAST members to gain a greater insight into how air quality needs differ by region. Each meeting also took on somewhat of a different “flavor,” as the varying composition of the audience inevitably tilted conversation one direction or another.
3. Capitalize on the audiences, institutional relationships, and professional networks of our PIs. Each HAQAST meeting was hosted by a PI, except for the meeting in Phoenix, which was hosted by the Maricopa County Air Quality Department at the Arizona State University Downtown Campus.



Figure 19: HAQAST made it a priority to go to our stakeholders, and we held our biannual meetings all across the country.

HAQAST leadership initially expected the hosting HAQAST PI would do the majority of the conference-organizing work, while the HAQAST communications team would play a supporting,

amplifying role. We expected that PIs would welcome the opportunity to put their own stamp on each HAQAST meeting. However, this proved untenable, for a number of reasons including:

- The administrative load of finding hotels, negotiating rates, planning group activities, seeking sponsorship, scheduling, digital promotion, archiving the talks, running the streaming/remote connection technology, finding the materials for a poster session, and reporting out on the conference was far beyond the scope of our PIs due to the resources and person-hours required.
- Multiple organizers made it impossible to deliver a standardized conference experience for our attendees.
- Different methods for tracking attendance—both in-person and virtual—made it very difficult to get a precise overview of audience attendance and engagement, and hence made it more difficult to measure the impact of our outreach efforts.

Because it quickly became clear that in-person meeting attendance was the most effective way that we could bring the research and applied communities together. We implemented a survey at the end of each meeting, with mean 28% response rate to our survey, with a high of 48% (HAQAST6) and low of 14% (HAQAST4). We applied the lessons learned from each previous meeting to the newest one in a cycle of continuous improvement. The HAQAST Communications Coordinator Daegan Miller played a central role in meeting planning, providing a clear point person for stakeholders to provide direct feedback and influence the course of future meetings.

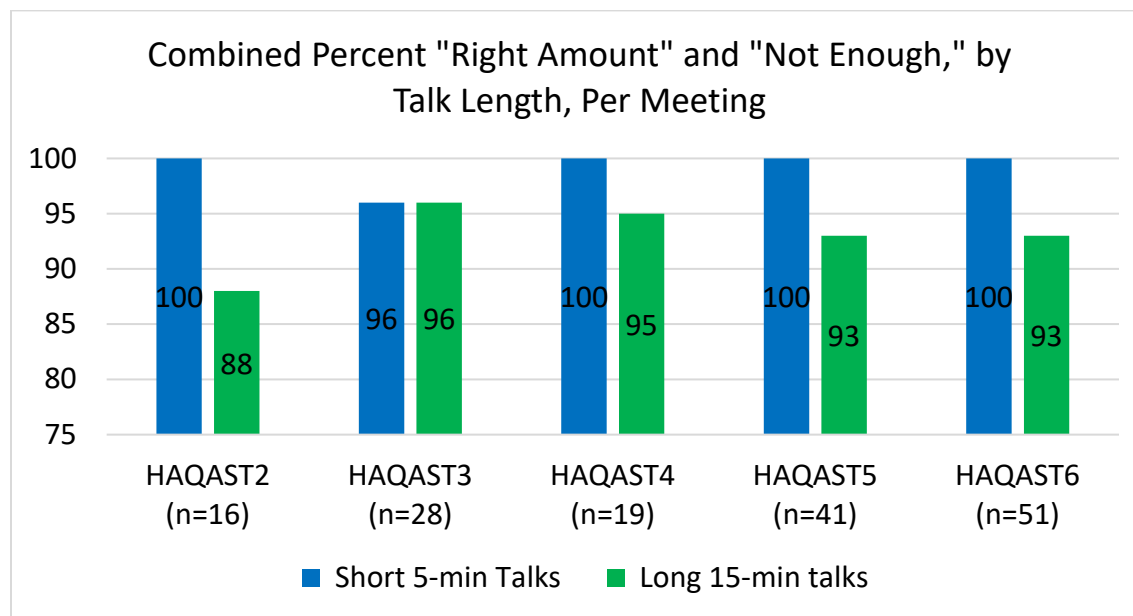


Figure 20: Aggregate HAQAST meeting audience satisfaction with length of talks.

We developed an innovative in-person meeting structure, one which prioritized networking and actively encouraged stakeholders to share their insights and needs with the research community. Each conference was broken into approximately ten ~45-minute panels. Each panel featured ~4 speakers. One speaker per panel was given a 15-minute slot, while the other three were given 5-minute slots. This format allocated ~75% of talks to the 5-minute format, and ~25% of talks to the 15-minute format for HAQAST3-HAQAST6. Based on survey results, shown in Figure 20, this

format was well received by attendees. When asked whether meetings including “too much,” “the right amount” or “not enough” of various activities, the 5-minute talk format was a consistent success. The vast majority of respondents (100% at 5 of the 6 meetings) expressed that we had the right amount, or not enough, 5-minute talks. Only one respondent from one meeting expressed that there were too many 5-minute talks. Satisfaction with the number of longer talks was also very high, with 88-96% of respondents viewing the HAQAST meetings as providing the right amount or not enough 15-minute talks (i.e. 4-12% felt there were too many longer talks). The 5-minute talks were well received by attendees, and they allowed more time for Q&A and discussion after each panel, usually 15 minutes per panel. Networking breaks were scheduled regularly (typically every 90 minutes), as well as a long break for lunch (1.5 – 2 hours). A highlight of every meeting was an extended poster session and reception, typically two hours on the evening of the first day.

Most meetings followed a two-part structure, with a public meeting followed by a HAQAST-only team meeting. For HAQAST3 – 5, the public meeting lasted 1.5 days followed by a .5 day HAQAST-only meeting. We increased the public portion of HAQST6 to two full days, to accommodate audience interest.

One of the most frequent pieces of feedback we heard was that HAQAST meetings were a place to forge new collaborative partnerships in applied research. Comments from anonymous survey responses include:

“The combination of talks and discussion helped to get folks on the same page,”

“It always feels like an extremely great use of time, every minute of every day (not always the case at most meetings). All talks, sessions, and workshops are directly useful and relevant for my work as an exposure and health scientist.”

Another marker of success is the growth in meeting attendance, as shown in Figure 3, above. From an initial meeting which attracted 30 people, we grew in size to a final meeting of 115, averaging 121 attendees for HAQAST3 – 6. We also saw an explosion in the number of attendees utilizing our option for a remote connection, from 15 at HAQAST1 to 194 at HAQAST6.

Beginning with HAQAST4 (Madison, WI) NASA began offering a supplementary stipend for stakeholder travel. For HAQAST4, 5, and 6 we were able to bring a mean of 21 stakeholders to the HAQAST meeting. These stakeholders ranged from the Federal (EPA) to the tribal (Nisqually Nation), from the regional (WESTAR/WRAP) to the ultra-local (Utah Moms for Clean Air). We saw an immediate increase in the number of stakeholder attendees, as well as the stakeholder:researcher ratio, which, by HAQAST6, nearly reached 1:1 parity, as shown in Figure 20.

Stakeholders expressed a request for workshops in our biannual meetings, so we tried this out at our final in-person meeting, HAQAST6. The final half day of the meeting hosted six workshops (two sessions of three workshops-per-session). These workshops were extremely well attended (we hosted a live how-to of Giovanni, which was standing-room only), and the post-conference response was overwhelmingly favorable. “This workshop,” wrote one attendee of the NASA Data

for Exceptional Events workshop led by CTDEEP stakeholder Michael Geigert, “was the highlight of the event for me because it pertains directly to my duties at a local air district.”

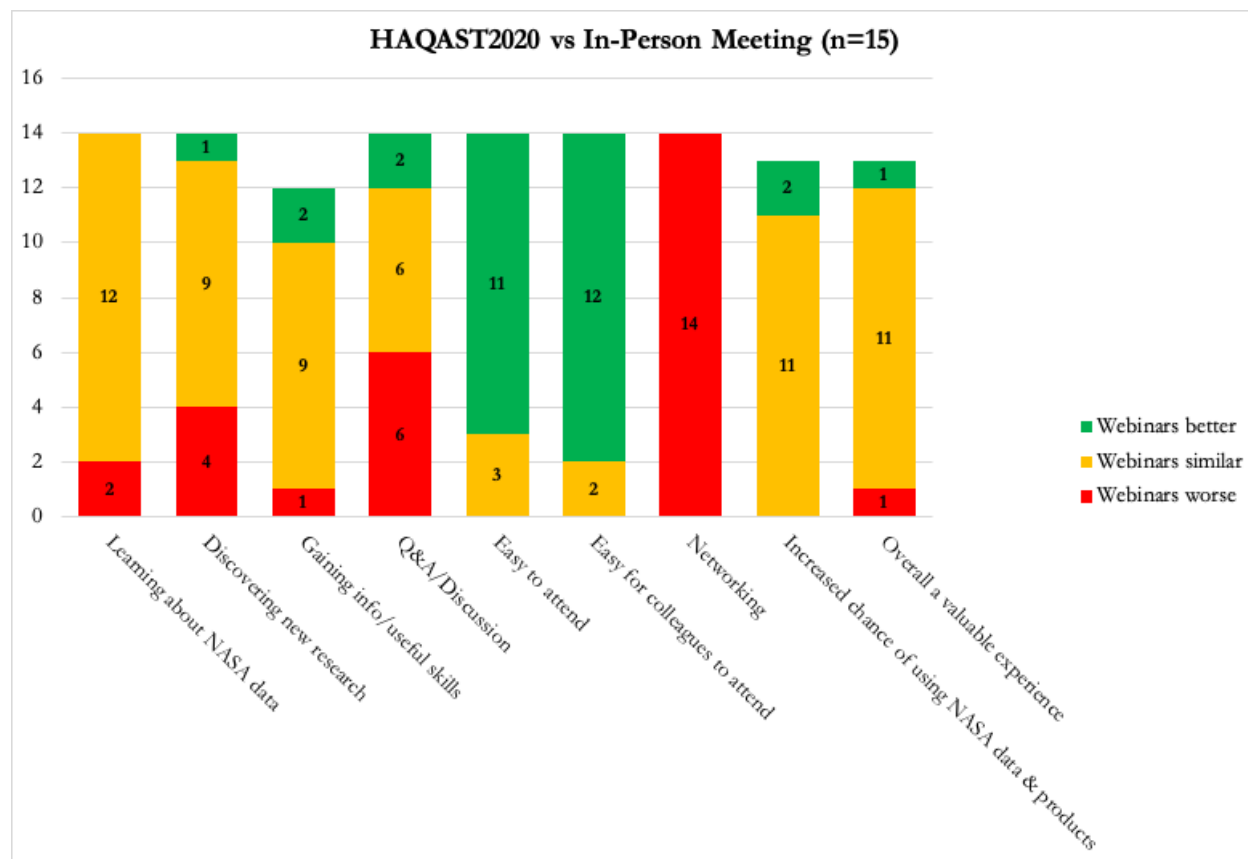


Figure 21: Comparison between in-person HAQAST meetings and webinars, as reported by respondents to the post-HAQAST2020 webinars survey

Due in part to the positive feedback we received on the HAQAST6 workshops, and in part on the growth in our online meeting attendance, we decided that our final regular meeting, which we called HAQAST2020, would be a month-long series of 14 webinars/workshops every Tuesday and Thursday from February 18 – March 12, 2020. All 14 webinars were designed either as hands-on workshops (as in the case of “Visualizing Air Quality: How to Use NASA’s Giovanni to Plot Satellite Tropospheric NO₂ Columns,” given by Lamont-Doherty Earth Observatory’s Xiaomeng Jin, a member of PI Arlene Fiore’s team) or interactive panel discussions (as in the case of PI Daven Henze’s “Tracking PM_{2.5}: How Models and Remote Sensing can be Used to Estimate Global Health Impacts of Ambient Fine Particulate Matter”). Of particular note is the webinar we co-hosted on 2/24/2020 with the American Lung Association, titled “Tracking Pollution to Help You Breathe: Data and Best Practices for Tracing the Health Impacts of Smoke for the Public Health Community.”

The webinar series was a great success: we logged 4048 registrations by 460 unique attendees (for mean of 9.1 webinars-per-attendee). Attendees tuned in from across the US, from Alaska to New York, and throughout the world: India, Vietnam, China, England, Turkey, and many other

countries were represented by our attendees. 99 out of 105 (94.3%) post-conference survey respondents said HAQAST should continue to offer a webinar series in the future, and, with the exception of networking, survey respondents ranked the webinar series as comparable in value to our in-person meetings for all outcome except networking, as shown in Figure 21.

Appendix C: Digital Communication Platforms

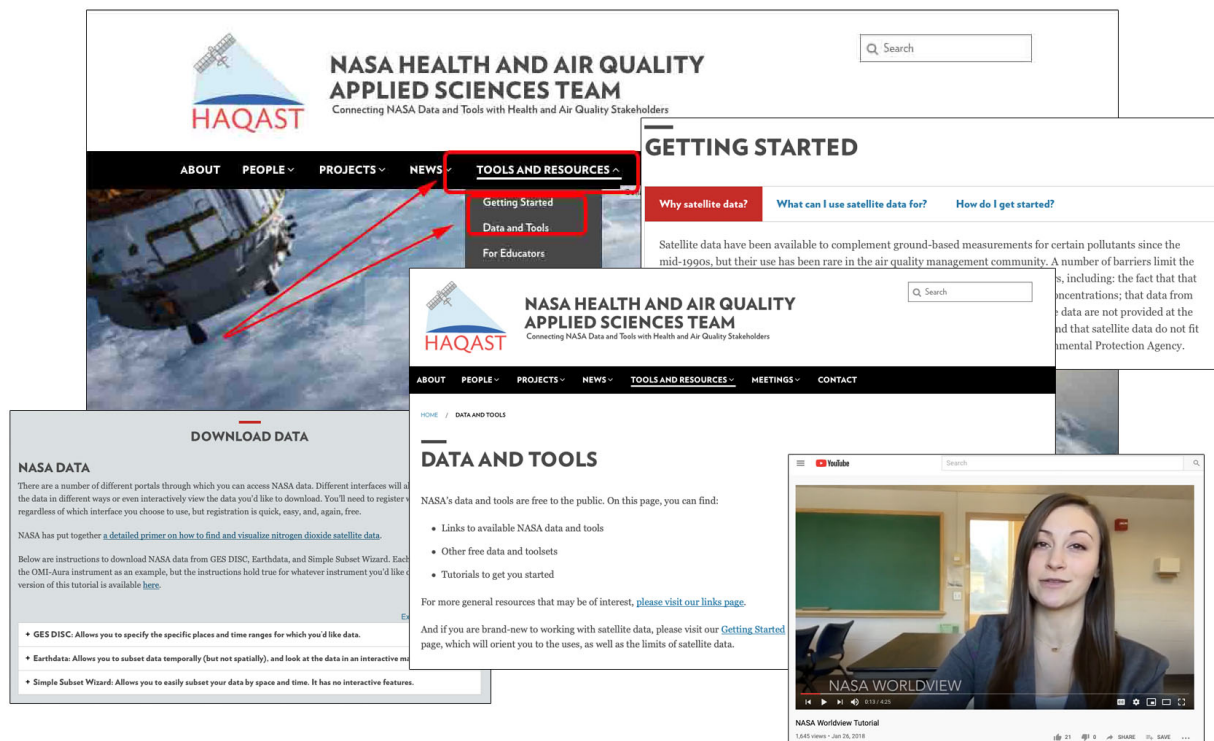


Figure 22: HAQAST has created a series of webpages that document exactly how to get started with NASA data, download it, and begin using various NASA visualization products. We've also developed text and video tutorials for both World View and Giovanni.

Team Website (www.haqast.org)

The HAQAST communication team's first task was to design a robust, intuitive, and professional-looking website as a way to broadcast, archive, and amplify the team's efforts. We decided to host haqast.org on the University of Wisconsin-Madison's servers, rather than a commercial platform like Squarespace or Wix, so that the website would remain live in perpetuity. The communications team has continually streamlined, improved, and adapted haqast.org to the needs of the air quality and public health communities. The site has seven main nodes:

- A general "About" section, for the new-to-HAQAST casual audience. This includes members of the media, school teachers, etc.
- A "People" section, which is further broken down into "HAQAST Members," which gathers detailed descriptions of each HAQAST member's research interest (including links to papers, presentations, Tiger Team Involvements, and contact information); "HAQAST Contributors," a list of the members' main colleagues; "HAQAST Leadership Team," which gives an overview of team structure and contact information; and "Stakeholder Partners," which lists stakeholders that contribute to each PI's core project.

- A “Projects” section, which is composed of separate pages for the Tiger Teams and a continually updated list of publications, sorted by year.
- A “News” section, which includes separate pages for “Recent News” (media appearances”, “HAQAST Flash” (very short, 100-word updates that don’t quite rise to the importance of a major news item), “Newsletters,” (where we archive each newsletter), and “Twitter,” (which posts the team’s Twitter feed).
- “Tools and Resources.” Two of the pages in this group, “Getting Started” and “Data and Tools,” were major, year-long communications projects that were developed in conjunction with NASA ARSET and which have proven to be one of the most popular features of the website, with over 6,570 visits since the website was launched. “Tools and Resources” includes:
 - “Getting Started,” a detailed, yet accessible description of the both the possibilities and limits of satellite data for air quality and public health.
 - “Data and Tools,” which is itself composed of sections including:
 - “NASA Health and Air Quality Tools,” which gathered 11 of the most popular online tools for displaying and working with NASA satellite data, ranked according to flexibility.
 - “Download Data,” a step-by-step online guide that walks the audiences through the various ways to download NASA satellite data.
 - “Tutorials”, which includes both text and video tutorials for Worldview and Giovanni, as well as a series of videos that the Communications Coordinator, Dr. Miller, made for PI O’Neill’s California Wildfires TT
 - “Education,” which gathered NASA air quality and public health resources suitable for a wide range of educators, from the elementary level to the undergraduate.
 - “NASA ARSET Training,” which described, and linked to, ARSET.
 - “AQAST 2011 – 2016,” which linked to the archived AQAST resources.
 - “Links to Health and Air Quality Community,” which provide links of general interest.
 - “Glossary,” intended to orient the newest users to the basic vocabulary found when working with satellite data.
- “Meetings” which includes two separate pages
 - “Current meeting,” which includes all the details (lodging and dining information, maps, the agenda, remote connect information) for whatever meeting is about to happen.
 - “Past Meetings,” which has a separate page for each HAQAST meeting, in which every talk, poster, and workshop is archived as a .pdf.
- “Contact,” which has links to our newsletter, Twitter page, Members page, and the contact information of the outreach and communications manager.

NASA Air Quality Website (<https://airquality.gsfc.nasa.gov>)

Funding by AQAST and HAQAST, PI Bryan Duncan created a NASA hosted website entitled, “Air Quality, Observations from Space.” As linked in the report, this site has become a major repository for resources developed through HAQAST. The site has six main nodes:

- A general “Home” section, highlighting air quality issues of interest to the public and professionals. The content on the home section changes to reflect new material and newsworthy resources (e.g. “NASA Air Quality Analysis of the COVID-19 Pandemic”).
- A “Pollutants” section, which is further broken down into “Nitrogen Dioxide,” “Ozone,” and “Particulate Matter.” By focusing on the atmospheric pollutants with the most direct relevance to air quality and public health, the website helps users understand the current capabilities of satellite data.
- A “Impacts” section, which is composed of separate pages for Health and Food Security. Each of these two areas includes examples and references, with a detailed timeline discussing the relevance of satellite data for public health.
- A “News” section, which provides a summary of recently developed resources and publications, accompanied by an image of the satellite data used for the application.
- The “Resources,” section, which includes:
 - “Webtools and Data,” a brief description of satellite data for air quality
 - “Factsheets,” including key data and infographics on food security and public health using satellite data
 - “AQ websites,” which includes a list of relevant websites from related organizations.
 - “Outreach,” linking to videos and outreach material.
 - “References,” with lists of publications useful to the target audience (e.g. review articles, articles on COVID-related economic changes observed from space).
- “Managers” which serves as an archive of material developed through HAQAST Tiger Team activities engaging air quality managers. For example, “Easy-to-follow technical guidance documents to support state and local air quality agencies that want to bring the power of NASA’s satellites to bear on the documentation of exceptional events,” developed through Arlene Fiore’s Tiger Team on the potential to use satellite data for State Implementation Plans.

Newsletters

Following on the successful example of ACAST, we released a newsletter approximately each quarter. We initially debated whether to have a monthly, or even twice-monthly newsletter, but were concerned about watering down the newsletter’s impact. We wanted to newsletter to gain a reputation for being informative and value-packed, rather than “fluffy” and superficial. Quarterly was the right interval to allow for PI publication, media appearance, and promotion of HAQAST meetings. At the time of this writing, we have 600+ subscribers to our newsletter, and each newsletter is archived on www.haqast.org.

Twitter (@NASA_HAQAST)

HAQAST adopted the ACAST Twitter handle, which has grown 40% from 3,000 to 4,195 followers (as of 8/2020) over the course of HAQAST’s run. We’ve found that journals, academics, air quality and public health professionals, and government agencies are all increasingly online, and though Twitter can’t replace our other outreach vehicles, it is a valuable addition which acts as an accelerant, diving more traffic to our website. It has also long been one of the ways that science journalists learn about and share breaking news. Due to its brief, ephemeral nature (posts can only be 250 characters, and are only effectively “live” for a few hours), it is ideal for quickly featuring HAQAST work, and for quickly building

community. We considered joining other social media platforms (Facebook, Instagram, etc.), but none of them seemed to quite fit the HAQAST community's needs (Facebook has turned into a platform more for long-form opining—we have a newsletter and journal articles for the long form, and opining isn't part of our mission; Instagram prizes flashy photos and is targeted more at a 20-something audience (or younger)).

Appendix D: HAQAST Publications

In accordance with the NASA HAQ program manager, we define a HAQAST publication as a peer-reviewed paper, that appears in a recognized academic or professional journal or book, and that meets one of the following criteria:

- The publication acknowledges HAQAST funding.
- A paper in which a HAQAST PI or team member uses satellite data and which the author identifies as benefitting from or contributing to HAQAST applied research.
- A paper resulting from a HAQAST collaboration and which the author identifies as benefitting from or contributing to HAQAST applied research.

What follows is a chronological list of HAQAST publications.

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