BAMS
Meeting Summary

Revolutionary Air-Pollution Applications from Future Tropospheric Emissions: Monitoring of Pollution (TEMPO) Observations

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2020 NASA TEMPO Early Adopters Workshop

What: Stakeholders and end users with diverse backgrounds in the fundamental and applied research communities gathered to learn and discuss the game-changing capabilities of the TEMPO instrument for enhancing health and air quality applications after launch in 2022. A planning strategy to optimize the scientific and societal benefits of future TEMPO data products was introduced to the participants.

When: 18 November 2020

Where: Virtual

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Satellite imaging spectrometers dedicated to observing trace-gas pollution have been orbiting Earth since the late 1970s. Initial efforts were focused on understanding the global distribution of Earth's atmospheric ozone (O_3) with the launches of the National Aeronautics and Space Administration (NASA) Total Ozone Mapping System (TOMS) followed by the European Space Agency's (ESA) Global Ozone Monitoring Experiment (GOME) in the mid-1990s. Follow-on NASA and ESA satellite missions in the early 2000s, consisting of the Ozone Monitoring Instrument (OMI; Levelt et al. 2006), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY; Bovensmann et al. 1999) and GOME-2 series (Munro et al. 2016), significantly improved upon the heritage of TOMS and GOME by providing observations of more trace gases, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and formaldehyde (HCHO), at higher column spatial resolution (13×24 km^2 for OMI vs 40×320 km^2 for GOME). ESA's Tropospheric Monitoring Instrument (TROPOMI), launched on board the *Sentinel-5 precursor* (*Sentinel-5P*) satellite in October 2017, further advanced capabilities to observe pollution from space due to its increased sensitivity to trace gases and unprecedented column spatial resolution of 7×3.5 km^2 that improved to 5.5×3.5 km^2 since August 2019 (Veefkind et al. 2012). Although the new-generation of spectrometers enable daily global mapping of trace gas pollutants at enhanced resolution, their low-Earth orbits provide observations only once per day and, as a result, are unable to monitor pollution throughout the daytime.

Geostationary air quality constellation

A new era of satellite imaging spectrometers in geostationary orbit is already upon us. The National Institute of Environmental Research (NIER) of the Ministry of Environment, South Korea, recently launched the Geostationary Environment Monitoring Spectrometer (GEMS; Kim et al. 2020) in February 2020 with a field of regard (FoR) encompassing Asia. GEMS is the first satellite mission to provide hourly observations of pollutants, including O_3, NO_2, SO_2, HCHO, and glyoxal (CHOCHO), throughout the daytime. The combination of high temporal and column spatial resolution (7×8 km^2 at Seoul, South Korea) from GEMS will permit detailed observations of the diurnal variability of pollutants across Asia, where large populations are often exposed to hazardous air quality (Baklanov et al. 2016). GEMS will be joined in the next few years by the NASA Tropospheric Emissions: Monitoring of Pollution (TEMPO) and ESA Sentinel-4 missions to form a geostationary constellation of air quality observations.

NASA'S TEMPO mission is the next to launch, planned for November 2022, on board the Intelsat 40e satellite on a Falcon 9 booster, providing similar observational capabilities as GEMS across a FoR covering greater North America. A unique advantage of the geostationary TEMPO spectrometer will be the use of two detectors that operate from UV (290–490 nm) to visible (540–740 nm) wavelengths compared to the single detector (300–500 nm) on GEMS. The extension into the visible spectrum will provide enhanced sensitivity to O_3 in the lowest 2 km of the troposphere; therefore, an O_3 profile product with information in the 0-2 km layer is a key data product planned for the mission (Zoogman et al. 2017). The ability to monitor the daytime evolution of O_3, along with the suite of other trace gases [NO_2, SO_2, HCHO, CHOCHO, BrO (bromine), H_2O] and aerosols [aerosol optical depth (AOD), absorbing aerosol index (AAI), single scattering albedo (SSA)] from TEMPO, will lead to a new understanding of the rapidly varying emissions and chemical processes that govern our air quality over greater North America. TEMPO will also have higher column spatial resolution of $2.0 \times 4.75\ km^2$ ($8.0 \times 4.75\ km^2$ for 0–2-km O_3) compared to GEMS, which can offer even more detailed information on fine-scale emission sources and strong pollution gradients, especially over urban areas.

An important feature of the TEMPO mission is the commitment to use as much as 25% of the observing time for nonstandard (hereafter high-time) observations with temporal resolution down to 10 min or less over selected portions of the FoR. Natural and man-made disasters, including volcanic eruptions, wildfires, dust storms, chemical explosions, and extreme weather events (e.g., atmospheric rivers, hurricanes), are one focus area of the high-time observations. The second focus area represents chemistry experiments aimed at further enhancing our understanding of rapidly varying pollution in complicated scenes, such as upslope flows, rush hour traffic, lightning storms, and agricultural regions. Detailed descriptions of different disaster events and chemistry experiments can be found in the TEMPO Green Paper (Chance et al. 2019). To properly manage the high-time observations of TEMPO with the standard hourly scans, planning has been initiated during the prelaunch era of the mission. Altogether, the TEMPO mission will revolutionize our capabilities to monitor, assess, and understand air pollution in the troposphere, which will provide tremendous value to the fundamental and applied science communities.

TEMPO Early Adopters program

The TEMPO Early Adopters (EA) program, formally established in 2019, aims to broaden the fundamental research facet and enhance air quality and health applications of future operational TEMPO data, with special attention on applications that directly benefit society. The three main objectives of the EA Program are as follows:

1) Engage new and existing stakeholders and end users in the applied air quality and health communities along with the fundamental research community
2) Demonstrate and enhance TEMPO applications through use of prelaunch proxy data and relevant observations from currently available sensors
3) Tailor TEMPO observing time, products, and data interfaces to end-user needs

The overarching goal of the program is to accelerate and maximize the use of TEMPO data for societal benefit. As a user-centric program, participation from early adopters during workshops, meetings, and tutorials, is key to achieving the defined objectives and goals. In addition to providing important prelaunch input on TEMPO data products, early adopters can govern use of the high-time operations of TEMPO by contributing experiment ideas to the Green Paper, receive access to proxy data along with detailed product information and support tools, and develop new collaborations within the applied science community. Overall, the TEMPO EA Program strives to successfully prepare a diversity of end users in the fundamental research, air quality, and health communities for the large volume of scientific data that will be disseminated from the TEMPO mission.

In 2020, the EA Program hosted two virtual workshops (fourth and fifth in the EA series) that provided an effective interface between TEMPO science and technical teams and end-user communities. A joint workshop with NASA's Multi-Angle Imager for Aerosols (MAIA) mission from 18 to 19 May 2020 was attended by over 170 people, including air quality managers, environmental-health researchers, environmental advocates, and epidemiologists. Workshop participants shared their perspectives on the anticipated benefits of TEMPO for air quality and health applications, reviewed in-development versions of proxy data products, and discussed data latency, format, and resolution needs from TEMPO data. A TEMPO EA workshop, held later in the year on 18 November 2020, was attended by about 160 people with diverse backgrounds in the research and applied science communities spanning the TEMPO FoR, including international organizations. A high-level overview and outcomes from the successful TEMPO EA workshop will be provided here. The workshop description, agenda, and presentations can be found on the TEMPO EA website (https://weather.msfc.nasa.gov/tempo/).

Workshop structure and high-level overview

The half-day workshop fostered interactions between new and experienced members of the TEMPO EA team, as early registration responses indicated that more than half of the 160 expected participants were attending their first TEMPO EA workshop. Approximately 65 of the participants were from federal, state, local, and nonprofit environmental organizations, about 85 were air quality and health researchers from universities, the federal government, and nonprofit organizations, while the remainder of participants were from health and private organizations. To inform and engage participants with novice to expert levels of experience using satellite data, presentations covered introductory and advanced topics on the TEMPO mission and applications. End users from scientific and applied-research backgrounds provided their input and feedback on TEMPO capabilities, applications, and data products during discussion sessions. Specific workshop objectives were to build on the unprecedented applications of TEMPO using proxy data products, identify user needs for prelaunch proxy products and operational TEMPO data, and commence preparations for the applied and fundamental TEMPO Green Paper experiments.

The workshop commenced with an introduction from the NASA Applied Sciences Program, followed by an overview and status update on the TEMPO mission and EA Program. This short session educated new early adopters on the TEMPO mission and applications, while informing all participants on recent developments in the EA Program. Participants received details on the high spatial resolution of TEMPO across the entire FoR, along with coverage of TEMPO footprints over southern and northern sections of the FoR such as Mexico City and the Canadian Tar Sands. New early adopters were especially impressed by the unprecedented hourly daytime coverage of TEMPO across greater North America (Fig. 1). The high-time

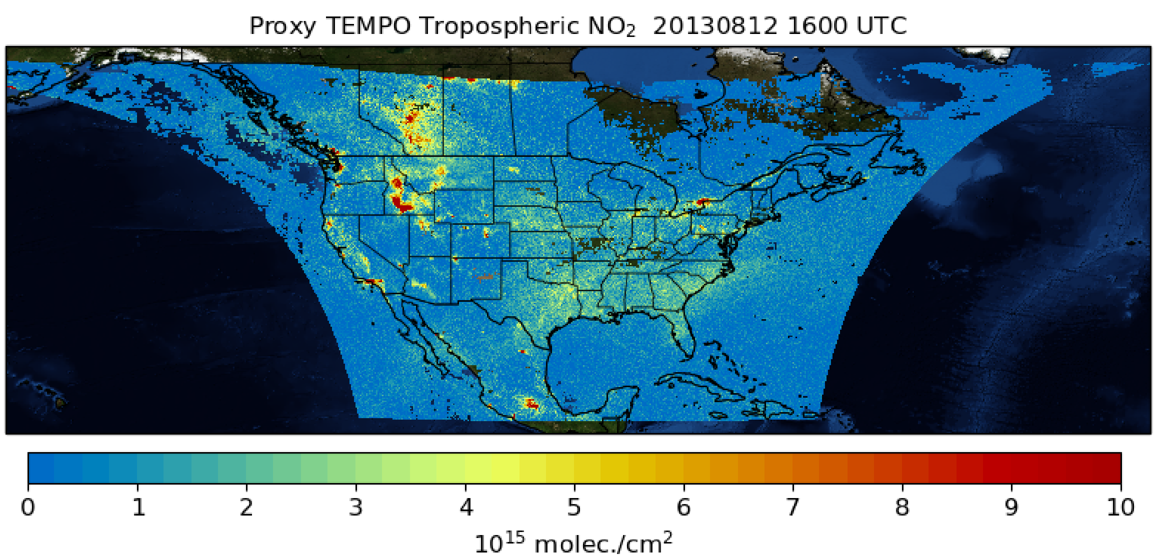

Fig. 1. TEMPO proxy tropospheric NO_2 product showing vertical column density (VCD) for a hypothetical hourly scan at 16 UTC across the FoR on 12 August 2013. Wildfire smoke plumes led to the enhanced NO_2 columns over remote areas of the western U.S. and near the northern boundary of the FoR in Canada. Gaps in spatial coverage of NO_2 are due to removal of TEMPO pixels associated with cloud fraction > 30%.

observations of TEMPO were also stressed in this session, as the rapid scans will further enhance applications of TEMPO data, especially in the context of disasters such as wildfire smoke events.

A session following the introductory and overview session focused on proxy TEMPO products. Methods for producing the current proxy NO_2 and HCHO products along with updates on future proxy products, including the O_3 profile and aerosol products, were presented. Animations of the proxy NO_2 product highlighted the daily operational timeline and scanning pattern of TEMPO from morning to evening. Use of the proxy NO_2 and HCHO products during wildfire events demonstrated the game-changing capability of TEMPO to monitor the rapidly evolving chemical composition in wildfire smoke plumes and impacts on air quality. Proxy products also showed how TEMPO data will better characterize sharp gradients in pollutants from different emission sectors throughout the day. The potential of generating additional TEMPO proxy data from aircraft measurements of NO_2, HCHO, and O_3 during the NASA Tracking Aerosol Convection Experiment–Air Quality (TRACER-AQ) in the summer 2021 was also discussed.

During the next session, end users with backgrounds in air quality forecasting, management, and pollution and human health shared their perspectives on how future TEMPO data could help fill regulatory and applied-science gaps in current Earth observations. Users noted the potential application of TEMPO data for implementing near-real-time emission updates to improve air quality forecasts in modeling systems such as the experimental Rapid Refresh with Chemistry (RAP-Chem) model. Forecasts of secondary air pollutants from wildfire emissions and smoke transport could also be improved through the combined use of TEMPO NO_2 and HCHO products for model evaluation. Users also discussed key advantages of TEMPO data for supporting air quality management including better characterizing the spatiotemporal patterns and source attribution of different emission sectors, in addition to the diurnal pattern of O_3 sensitivity to variations in precursor gases. The importance of TEMPO data for filling the gaps in coverage of ground-based monitor networks for exceptional-event analyses in nonattainment areas was also noted. Last, end users discussed the potential of integrating TEMPO data and patient-generated health data in an app that can track the air quality effects on human health.

The user-focused session concluded with presentations on the application of TEMPO data for monitoring smoke from fires across the western United States where the number of fires has been increasing in the recent decade (Jaffe et al. 2020). Presenters noted the possibility of quantifying emission factors for individual fires, such as wildfires and prescribed burns, by integrating information from the hourly TEMPO AOD and NO_2 products. The HCHO product will add another layer of information for better understanding of fire emissions and NO_x sensitivity downwind of source locations. Furthermore, the O_3 profile product will be especially valuable for characterizing the space–time evolution of O_3 production within smoke plumes in the free troposphere and boundary layer, which can lead to O_3 exceedances at the surface. Overall, the suite of TEMPO products is expected to improve our understanding of photochemistry and background O_3 contributions to air quality conditions across the TEMPO FoR. Presenters also discussed the tremendous benefits of integrating near-real-time TEMPO trace gas and aerosol products into decision support systems for advancing operational forecasting capabilities at end-user organizations.

The final session of the workshop provided an overview of the current applied and fundamental experiments outlined in the TEMPO Green Paper, and unveiled a planning strategy for the standard and high-time operations of TEMPO during the prelaunch era of the mission. The importance of preparing for the high-time observations of TEMPO was stressed, as the unique scans will further advance the science and applications value of TEMPO observations while introducing an added level of complexity to the operational mission. Participants were encouraged to submit a TEMPO Green Paper experiment request to diversify and optimize the Green Paper for scientific and societal benefits from TEMPO observations. Presenters highlighted experiments that could benefit from the high-time observations, including dust storms and soil and lightning NO_x experiments.

Workshop takeaways and outcomes

New and experienced early adopters gained further insight into how the game-changing capabilities of TEMPO observations can lead to tremendous societal benefits through enabling exciting new air quality and health applications. Participants stressed the importance of near-real-time TEMPO data for air quality monitoring and forecasting applications. For example, high spatiotemporal monitoring of smoke plumes from TEMPO will likely support more accurate air quality alerts for informing decisions on canceling outdoor activities and protecting public health. For the health community, guidance on preferred methods to fill gaps in satellite data would shorten the time between adoption of operational TEMPO data for epidemiology studies and exposure models. A postworkshop survey revealed that about 70% of participants are interested in using the TEMPO proxy data, including the field-campaign-like data, to prepare for applications of TEMPO during the prelaunch era of the mission. The potential of using the proxy data to help build assimilation capabilities for TEMPO in air quality forecasting models was explicitly mentioned during the workshop. To enable effective use of the proxy and eventual operational data, participants promoted the development of user-friendly codes, notebooks, and tutorials within the TEMPO EA Program. There was also a high level of interest in forming working groups focused on core applications of the TEMPO mission.

Several key outcomes resulted from the workshop discussions. The TEMPO EA Program plans to organize working groups to enable comprehensive dialogue on planning and implementation of TEMPO applications and Green Paper experiments. Working groups will be arranged according to the core application areas of TEMPO, including air quality, health, agriculture, and weather applications. Development of TEMPO proxy data in an operational framework will be a top priority of the TEMPO EA Program, as emulating the distribution of operational data will promote the prelaunch development of tools for smoothly transitioning from the proxy to real data after launch. Working-group engagements will emphasize the use of TEMPO proxy data to help users learn the data and system requirements for integrating operational data, while also executing specific Green Paper experiments to highlight applications of TEMPO observations. Last, the TEMPO EA Program will also develop user-friendly codes for processing and analyzing TEMPO data and provide user guides and tutorials to ensure effective use of proxy data in the early adopters community.

Final remarks

The revolutionary applications offered by TEMPO observations are now well recognized by the current early adopters community. There are plenty of opportunities to further expand the user base in the TEMPO EA Program prior to the expected launch in November 2022, especially in private sector and nonprofit organizations. The TEMPO EA Program seeks to engage new end users during the pre-launch era and into the post-launch era of the mission, while enhancing interactions and building knowledge within the early adopters team as new proxy products and Green Paper experiment ideas are conceived. End users interested in joining the early adopters team can find a registration link on the TEMPO EA website. By engaging a broad spectrum of potential end users across the core application areas of TEMPO, users will be prepared for immediate adoption of operational data once available after launch and, as a result, maximize the value of TEMPO data for societal benefit.

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