TEMPO Applications Plan

Aaron R. Naeger[1], Kelly Chance[2], Xiong Liu[2], John Haynes[3]

[1] Earth System Science Center, University of Alabama in Huntsville
[2] Harvard-Smithsonian Center for Astrophysics
[3] NASA Headquarters

December 2019

TEMPO Smithsonian

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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1. Purpose

The main purpose of this document is to define the guidelines of the applications program for the NASA Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission. This document will provide guidance on existing and potential future activities in the TEMPO applications program, which is focused on building an expansive user community and enhancing applications of TEMPO data, with a particular focus on applications that directly benefit society.

2. Mission Description

Air pollution refers to the mixture of gases and solid particulates in the atmosphere, which can pose a serious environmental threat to public health, the ecosystem, and climate. The amount of air pollution that we breathe at the ground level is governed by a myriad of emission sources (e.g., vehicles, industry, power generation, agriculture, wind-blown dust, wildfires), transport and chemical reactions in the atmosphere, and meteorological conditions. To date, space-based observations of criteria air pollutants of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3), which are regulated by the U.S. Environmental Protection Agency (EPA) and can lead to chronic respiratory diseases and premature death, have been limited by the mid-day overpass times from low-earth orbiting (LEO) satellite instruments. The TEMPO instrument will be launched into geostationary earth orbit (GEO) about 22,000 miles above the Earth's equator, enabling hourly and sub-hourly observations of major air pollutants, including NO_2, SO_2, and O_3, across North America throughout the day. TEMPO will also resolve pollutant levels to regions of several square miles, better than any current instrument in space. Altogether, TEMPO will revolutionize our capabilities to monitor and characterize the evolution of major air pollutants from the complexity of emission sources in the troposphere and, as a result, advance our understanding of how different pollutants govern our air quality.

Key objectives of the TEMPO mission include:

- Diagnose how the spatial and temporal variations of emissions of gases and aerosols influence air quality and climate.
- Examine the processes that transform tropospheric composition and air quality over scales ranging from urban to continental and diurnally to seasonally.
- Understand how air pollution drives climate forcing and how climate change affects air quality on a continental scale.
- Determine how observations from space can improve air quality forecasts and assessments.
- Characterize the impact of episodic events (e.g., wildfires, dust outbreaks, volcanic eruptions) on atmospheric composition and air quality.
- Examine the contributions of intercontinental transport on air quality.

TEMPO is an Earth Venture Instrument (EVI) managed by NASA's Earth Science Systems Pathfinder (ESSP) program. The TEMPO instrument is developed at Ball Aerospace and will hitch a ride on a geostationary communications satellite after launch in the 2022 timeframe (to be confirmed). The baseline mission length of TEMPO is 20 months. The early formation of the

TEMPO Science Team included members from the Smithsonian Astrophysical Observatory (SAO; Principal Investigator Kelly Chance), NASA, National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), universities, and industry partners. The diversity of experts on the science team will ensure that high-quality TEMPO data products are disseminated to the user community to enable advancements in fundamental and applied science research. The TEMPO Applications Program will play the critical role of engaging new and existing users and stakeholders in the applied science community to broaden and enhance applications of TEMPO data.

2.1 Instrument and Observation Strategy

The TEMPO instrument is a spectrometer that uses two detectors to measure solar backscattered radiances in the ultraviolet (293-494 nm) and visible (538-741 nm) wavelength spectrums, permitting sensitivity to major elements in the tropospheric O_3 chemistry cycle consisting of NO_2, SO_2, formaldehyde (H_2CO), glyoxal ($C_2H_2O_2$), water vapor (H_2O), and UVB radiation. With its multi-spectral capabilities, TEMPO will be able to distinguish between boundary layer, free tropospheric, and stratospheric O_3. From its GEO position, TEMPO will perform East-West sweeps every daylight hour over a Field of Regard (FoR) covering much of North America (Fig. 1). TEMPO will also commit up to 25% of its observing time for non-standard (hereafter, high-time) operations over selected slices of the FoR at higher frequency (e.g., <= 10 minutes). Additionally, air pollution monitoring from TEMPO will be accomplished at sub-urban scales due to its high spatial resolution of 2.0 km in the north-south direction and 4.75 km in the east-west direction at the center of the FoR. The combination of unprecedented spatial and temporal observations from TEMPO will provide new insight on air pollutant emissions and transport processes in the troposphere.

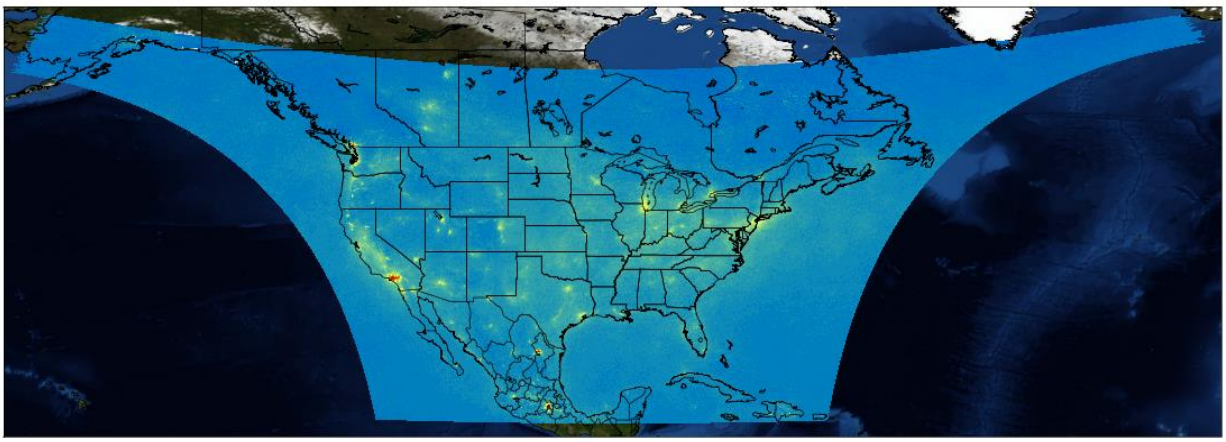

***Figure 1**. Tropospheric NO_2 vertical column density (VCD) from the TROPOspheric Monitoring Instrument (TROPOMI) remapped to the TEMPO FoR, with values ranging from 0 to 6 x 10^{15} molec./cm^2 (blue to red).*

TEMPO will be one component of an international GEO constellation for air pollution monitoring, which will consist of the Geostationary Environment Monitoring Spectrometer (GEMS) with a FoR over Asia and the Sentinel-4 mission focused over Europe and North Africa.

2.2 Data Products and Challenges

The baseline data products of the TEMPO mission are shown in Table 1. TEMPO's unique instrument design in GEO position will enable a suite of revolutionary products including tropospheric NO_2, H_2CO, and O_3. An O_3 profile product will provide O_3 columns in the troposphere and 0-2 km layer. No previous space-based instrument has provided this level of detail on O_3 in the atmosphere. The 0-2 km layer information on O_3 will be particularly important for monitoring O_3 in the layer of air where people live and breathe. TEMPO will also provide trace gas products with better precision and detail than ever seen before from space. The temporal revisit times are baseline requirements. We expect to deliver the full list of products in Table 1 for every daylight hour (e.g., 1 hour frequency) when solar zenith angle ≤ 70°. TEMPO anticipates additional products beyond the baseline list including SO_2, $C_2H_2O_2$, and aerosol optical depth (AOD).

Species/Products	Required Precision	Temporal Revisit
0-2 km O_3 (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour

Table 1. *Threshold science requirements of TEMPO.*

Table 2 shows the standard data products that will be produced by the TEMPO mission, which will be in NetCDF format and metadata following NASA Observation System Data and Information System (EOSDIS) standards. Level 2 and 3 data products of the derived geophysical products listed in Table 1 will be delivered 6 months after completion of the on-orbit checkout. The SAO-led Instrument Operations Center and Science Data Processing Center will generate the TEMPO science and data products. Data latency of level 2 products (after production of level 1 data) will

Data Product	Description	Time beyond On-Orbit Checkout to deliver initial data	Maximum data latency after first release for ≥ 80% of products
Level 0	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
Level 1b	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
Level 2	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO
Level 3	Derived Gridded Geophysical Data Product	6 months	1 month after completion of data accumulation required for individual geophysical products

Table 2*. Standard data products produced by the TEMPO mission.*

not exceed 24 hours. Browse imagery and other ancillary products will also be produced. TEMPO data will be open access and publicly available.

Although TEMPO data will be well suited for advancing science applications after launch, particularly health and air quality, the data will present challenges to the user community, including users in air quality management, environmental public health, agriculture, and air quality modeling as discussed below.

- Satellite data have been underutilized in air quality management applications, even though the current fleet of satellite instruments can aid in these activities. Air quality management agencies generally lack the expertise and knowledge to effectively apply satellite data.
- TEMPO will offer the environmental public health community, largely a community of potential (i.e., infrequent users of satellite data), a robust suite of trace gas and aerosol products to supplement surface monitor data in their human health research studies.
- TEMPO data will provide the agricultural community, a community of potential, valuable information on air pollutant concentrations in the troposphere and measurements of solar-induced florescence (SIF) to improve crop health monitoring and management applications.
- Assimilation of TEMPO data will improve air quality forecasts but assimilating the large volume of TEMPO data will present some new challenges to the air quality modeling community.

The TEMPO Applications Program will actively engage the community of practice (i.e., regular users of satellite data) and potential to characterize user and stakeholder needs and broaden and enhance the applications of operational TEMPO data. The Applications Program will also be committed to generating pre-launch proxy data products for the baseline list in Table 1, which will enable TEMPO Early Adopters to develop a detailed understanding of the products during the pre-launch era of the mission. These pre-launch products will be extremely valuable for the community of potential.

2.3 Atmospheric Science Data Center

The Atmospheric Science Data Center (ASDC), one of NASA's Distributed Active Archive Centers, processes, archives, and distributes thousands of data products to the global user community from NASA's past and current Earth-observing satellites. TEMPO data products generated at SAO will be transferred to the ASDC for storing the products and providing public access. The TEMPO Applications Program will closely coordinate with ASDC to ensure that user needs in terms of data file formats, tools, and visualizations for TEMPO data are well documented. ASDC will participate in TEMPO Early Adopter workshops and tutorials to gather direct feedback from the user community. Distribution of TEMPO proxy products to Early Adopters could be achieved through ASDC services.

2.4 Synergy with other projects and missions

The NASA Multi-Angle Imager for Aerosols (MAIA) mission

The TEMPO Applications Program will collaborate with the NASA MAIA mission and applications program. Similar to TEMPO, the MAIA mission will observe air pollution, but is specifically designed to measure particulates in the atmosphere, providing information on different sizes and compositions of particulate matter (PM) for a handful of target areas across the TEMPO FoR. With the similar launch dates of TEMO and MAIA, we can expect to have operational data available from these missions around the same time. The complementary information on gaseous and particulate pollutants provided by the TEMPO and MAIA products will further enhance health and air quality applications of the new missions, especially over the MAIA Primary Target Areas (PTAs) of Los Angeles, Boston, and Atlanta, where daily PM products will be produced. The TEMPO and MAIA Application Programs will coordinate joint Early Adopter workshops and meetings to identify and characterize user needs from mutual communities, such as the environmental health community. ASDC is the designated DAAC for both the TEMPO and MAIA missions.

The NOAA Geostationary Operational Environmental Satellites (GOES)

The GOES-16 and -17 have strong linkages to the TEMPO mission and will be a synergistic focus area of the Applications Program. TEMPO will derive its pointing from one of the GOES satellites and is thus automatically co-registered. The GOES platforms carry the Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM), which can both provide value added information for synergistic product development and enhanced application opportunities (e.g., lightning NOx). The TEMPO Science Team at SAO has plans to utilize some of the bands from ABI to create a synergistic TEMPO-ABI aerosol product that aims to improve the AOD product. Synergistic TEMPO-GOES workshop sessions will be hosted by the TEMPO Applications Program to engage a broader user and stakeholder base, understand user needs for TEMPO-GOES products, and characterize additional synergistic opportunities. Generation of synergistic TEMPO-GOES proxy products for the TEMPO Early Adopters is also possible.

The NASA Short-term Prediction Research and Transition (SPoRT) Center

The SPoRT Center will partner with the TEMPO Applications Program to facilitate broader engagement with users and stakeholders of TEMPO data. The research-to-operations/operations-to-research (R2O/O2R) paradigm employed by the SPoRT Center will be valuable in transitioning the TEMPO data products into the operational environment after launch. This R2O/O2R framework will help ensure the products being developed by the TEMPO science and algorithm team will meet user needs. SPoRT will aid in the TEMPO applications effort through: (1) Broadening relationships with user communities; (2) providing computational resources to deliver TEMPO proxy products to the Early Adopters; and (3) gathering pre-launch feedback from users through product assessments and trainings. SPoRT Center maintains numerous partnerships in the weather community, which will also benefit from the application of TEMPO data.

3. Objectives and Application Activities

The NASA Applied Sciences Program (ASP) works with a diverse group of partner organizations to uncover innovate and practical uses of data from NASA's Earth-observing satellites. A Deputy Program Applications (DPA) Lead for the TEMPO mission is funded by NASA ASP (Lawrence Friedl, the NASA ASP Director, and John Haynes, ASP Health and Air Quality Program Manager) to manage the TEMPO application activities.

The TEMPO DPA Lead will build a comprehensive community of users and stakeholders of TEMPO data while identifying new and existing health and air quality applications, with special attention on applications that directly benefit society. Workshops, tutorials, and focus sessions will be hosted by the DPA Lead to engage the user community on TEMPO data. The DPA Lead will also work closely with the TEMPO science and technical teams to ensure the most updated information on the science data products and observing capabilities are presented to the Early Adopters community.

The activities of the TEMPO DPA Lead will address the Strategic Goal 4 of Optimizing Capabilities and Operations within the NASA Strategic Plan 2018, with an emphasis on Strategic Objectives 4.1 and 4.6 that aim to (1) engage in partnership strategies and (2) sustain infrastructure capabilities and operations. Addressing these NASA Strategic Objectives during the early phase of the TEMPO mission is critical to effectively prepare the health and air quality communities for the wealth of unprecedented measurements and data products from TEMPO after launch.

3.1 Objective 1: Generation and Application of Pre-Launch Proxy TEMPO Data

The DPA Lead will generate proxy TEMPO level 2 products for demonstrating applications of TEMPO data during workshops and meetings. Proxy TEMPO data will also be distributed to the Early Adopters community to enable the development of codes, tools, and procedures to integrate TEMPO data into their workflow during the pre-launch era. Early Adopters will also be able to better realize TEMPO applications through analyzing proxy data. The overarching goal of the proxy TEMPO data is to promote immediate and effective use of operational TEMPO data after launch.

Proxy TEMPO data will be generated from July 2013 – June 2014 using the global high-resolution Goddard Earth Observing System-5 (GEOS-5) Nature Run with full chemistry (GEOS-5 NR-Chem) operated by the NASA Global Modeling Assimilation Office (GMAO). GEOS-Chem has been extensively validated over the TEMPO FoR, most recently during the NOAA Southeast Nexus (SENEX) and NASA Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) aircraft campaigns, which includes the relevant species for TEMPO. The proxy products accounting for instrument and algorithm effects will be packaged into NetCDF file specification format for TEMPO to facilitate immediate use of operational data when it becomes available. Proxy data will be initially archived and accessible on a NASA SPoRT server. There is the potential of generating additional proxy TEMPO data for more recent periods using other chemical transport model data, such as the GEOS Composition Forecasting (GEOS-CF) system.

3.2 Objective 2: Expand the TEMPO User and Stakeholder Communities

The TEMPO DPA Lead will engage a diversity of users and stakeholders, with special attention on the health and air quality communities. Preliminary TEMPO application workshops have identified a small but dedicated network of users and stakeholders of TEMPO data, including the Department of Environmental Quality (DEQ) in Idaho and Colorado and Western States Air Resources Council (WESTAR) and Western Regional Air Partnership (WRAP). To expand outreach and engagement to a much broader community, the DPA Lead will be pro-active in advertising the capabilities and applications of TEMPO through conferences, workshops, publications/reports, and social media. The DPA Lead will seek organizations that have a clear need for the hourly air pollution data from TEMPO, but have limited experience working with satellite data (i.e., community of potential). Engagement activities will include the use of proxy TEMPO data to demonstrate pertinent applications of TEMPO. A major outcome of these engagement activities is to maximize the utility and usability of TEMPO data products by the broader user community, especially the community of potential. In particular, actively engaging the TEMPO user community can support future decision-making activities that use air quality data for protecting public health.

TEMPO Early Adopter workshops, tutorials, and focus sessions will be organized and hosted by the TEMPO DPA Lead. The DPA Lead will also coordinate with other missions (as noted in Section 2.4) to co-host workshops and sessions on synergistic opportunities and applications of TEMPO data. Workshop reports will be generated to present outcomes and user feedback, which will be shared with the TEMPO Early Adopters and Science Team.

3.3 Mission Phases and Applications

The TEMPO Applications Program will evolve throughout the different phases of the TEMPO mission.

Gap between Phase C and D (Phase C ended with instrument delivery in Nov. 2018)

- Actively engage users and stakeholders in the health and air quality communities and expand the TEMPO Early Adopters Program
- Specify the core application areas of TEMPO via input from Early Adopters
- Characterize synergistic applications of TEMPO data with other missions
- Develop proxy TEMPO data products and distribute preliminary products to subset of Early Adopters via NASA SPoRT server

Phase D (System Integration, Test, and Launch)

- Continue building the TEMPO Early Adopters Program and expand engagement in new application areas
- Identify new synergistic applications of TEMPO data with other missions
- Finalize version 1 release of proxy TEMPO products and distribution via ASDC services
- Implement refinements to the TEMPO data products based on feedback from the Early Adopters
- Develop the TEMPO Green Paper based on application ideas from Early Adopters

Phase E (Operations and Sustainment)

- Promote the application of TEMPO operational data products
- Manage the TEMPO Green Paper experiments and coordinate the TEMPO high-time scan operations with the TEMPO team at SAO
- Facilitate distribution of high-time TEMPO data to Green Paper Investigators
- Work with established partners to transition TEMPO data
- Continue to build the TEMPO community of practice and identify new applications of TEMPO data

Appendix A: List of Partners

TEMPO has developed early partnerships with some organizations focused on key applications of TEMPO data. The following organizations have been engaged to date:

- U.S. Environmental Protection Agency
- Western States Air Resources Council (WESTAR) and Western Regional Air Partnership (WRAP)
- Idaho Department of Environmental Quality
- Colorado Department of Public Health and Environment (CDPHE)
- Arizona Department of Environmental Quality
- Wyoming Department of Environmental Quality, Air Quality Division
- New Mexico Environment Department – Air Quality Bureau
- California Air Resources Board
- Georgia Department of Natural Resources
- Texas Commission on Environmental Quality
- U.S. Forest Service
- The University of Alabama in Huntsville
- National Center for Atmospheric Research
- NOAA / NESDIS / Center for Satellite Applications and Research (STAR)
- Marshall Space Flight Center (MSFC)

The TEMPO Applications Program aims to build a comprehensive Early Adopters Program consisting of a large number of important organizations within and outside the TEMPO FoR.