TEMPO Early Adopters Workshop

Meeting Summary

Elizabeth Hotel, Fort Collins, CO

Hosted by: Western States Air Resources Council (WESTAR) and Western Regional Air Partnership (WRAP)

April 10-11, 2018

Workshop Purpose and Objectives

In April 2018, the Western States Air Resources Council (WESTAR) and Western Regional Air Partnership (WRAP) held the Tropospheric Emissions: Monitoring of Pollution (TEMPO) Early Adopters Workshop to demonstrate the myriad of capabilities and applications of TEMPO with the end user communities in the West, to identify specific needs of end users, and to plan how these needs can be met using TEMPO data. The TEMPO Early Adopters Workshop focused on the following specific objectives:

- Identify and plan applications of TEMPO data by gathering technical staff from state, tribal, local, and federal air quality management agencies in the West to interact with remote sensing experts from academia and federal agencies.
- Review and discuss TEMPO capabilities for western air quality assessment, analysis, and planning needs
  - What does TEMPO have to offer, how does TEMPO fit with other platforms?
  - What are possibilities and needs for integration of data results and tools for user applications?
- Discuss and specify attributes of "TEMPO-like" synthetic data needed for testing prior to launch.
- Discuss processing and delivery needs from NASA for operational forecasting, episode analysis, and trends evaluation by western air quality agencies.

Fulfilling these specific objectives well ahead of the expected launch date of the instrument will allow for a smooth transition of TEMPO data to the end user communities once data becomes available.

Workshop Organization

The organizing process of the Western U.S. TEMPO Early Adopters Workshop was facilitated through a broad representation from the applications and end-user community. Members of the organizing committee included:

Participants	**Affiliation**
Tom Moore (lead)	WESTAR and WRAP
Mike Newchurch	University of Alabama in Huntsville / Department of Atmospheric Science
Kelly Chance	Smithsonian Astrophysical Observatory
John Haynes	NASA Headquarters
Barry Lefer	NASA Headquarters
Brad Pierce	NOAA / NESDIS / Center for Satellite Applications and Research (STAR)
Aaron Naeger	University of Alabama in Huntsville / Earth System Science Center (ESSC)
Emily Berndt	Marshall Space Flight Center (MSFC)

The very comprehensive two-day agenda assembled by the organizing committee primarily focused on identifying the most suitable delivery and display platforms of TEMPO data through short-format talks and discussion sessions between data producers and end user communities. On day two of the workshop, end user communities highlighted data needs and potential applications from TEMPO data for mitigating local and regional air quality monitoring and forecast problems. Discussions and breakout group sessions during day two allowed for feedback from data producers on the local and regional capabilities of TEMPO data. Informal networking breaks after each session allowed time for further discussion and brainstorming among the attendees and program managers. The workshop agenda is provided in the appendix.

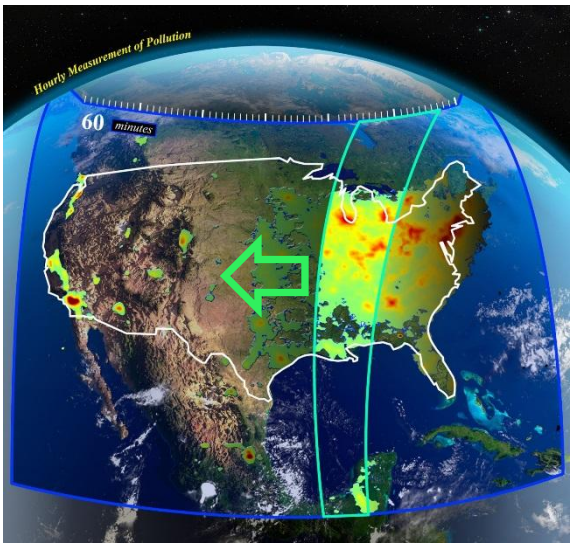


Figure. 1*. TEMPO Field of Regard (FOR) over the greater North America (blue box). Scanning pattern of TEMPO spectrometer highlighted by green box and arrow indicating scan direction.*

Workshop Summary

The primary objectives of the workshop were centered on building a plan to successfully prepare and deliver essential TEMPO data products to the end user communities. These early pre-launch interactions between remote sensing experts on the TEMPO science team and the end users will ensure that TEMPO data will fulfill application needs. Remote sensing experts highlighted the capabilities, expected products, and data delivery mechanisms of TEMPO, while also discussing the potential limitations of the instrument during the first day of the workshop.

End users from state, local, and federal air quality management agencies in the West were the focus for day two of the workshop, where they discussed limitations of the current fleet of satellite sensors and their application needs from the unique TEMPO measurements. This face-to-face engagement between remote sensing experts and end user communities in the West throughout the workshop will help scope out a detailed plan for TEMPO during the early pre-launch period, which will ultimately lead to a smooth transition of the data once the instrument is in orbit.

1. TEMPO capabilities and applications

The TEMPO mission is currently on-schedule and on-budget for an expected launch date in 2020 or 2021, and will be hosted on a commercial geostationary communications satellite with a Field of Regard (FOR) over North America for allowing hourly daytime monitoring capabilities (Fig. 1). For each geospatial scene in the FOR, the TEMPO grating spectrometer instrument will measure the solar backscattered radiance in the ultraviolet (290-490 nm) and visible (540-740 nm) with a spectral resolution and sampling of 0.6 and 0.2 nm, respectively, for retrieving aerosol and cloud parameters, along with the major elements in tropospheric ozone (O_3) chemistry cycle consisting of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (H_2CO), glyoxal ($C_2H_2O_2$), water vapor (H_2O), and UVB radiation. The high spatial resolution of 2.1 km x 4.7 km at the center of the FOR will allow for air-quality monitoring at sub-urban scales.

Altogether, the unprecedented daylight observations from TEMPO will enhance current observational capabilities of effectively monitoring the rapidly varying emissions and chemistry that governs our air-quality conditions. Current satellite instruments designed for measuring chemical species in the ultraviolet and visible spectrum, including the Ozone Monitoring Instrument (OMI) and Ozone Mapping Profiler Suite (OMPS), are incapable of resolving the diurnal cycle of the major O_3 elements due to their limited morning and afternoon overpass times. Also, their spatial resolution is too coarse for adequately monitoring air quality conditions at the urban scale (Fig. 2). Conversely, the high spatial and temporal resolution of TEMPO will allow for the effective monitoring of pollution emissions throughout the diurnal cycle, while also tracking the transport from the source region at sub-urban scales. This information can be used in conjunction with chemical weather forecasts to enhance our understanding of air quality processes. Furthermore, the unique combination of hyperspectral measurements from TEMPO with different absorption and scattering properties in the ultraviolet and visible spectrums will help distinguish between

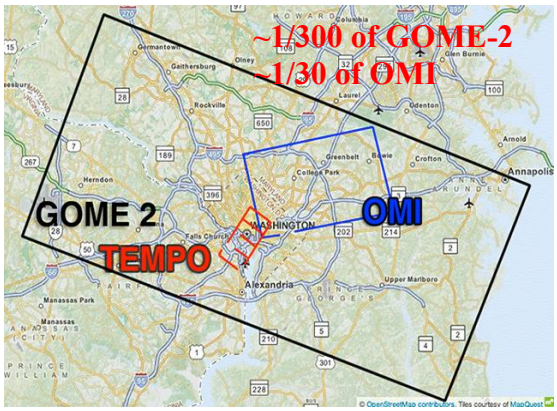


Figure 2. *Spatial resolution comparison between the Global Ozone Monitoring Experiment GOME-2 (black), OMI (blue), and TEMPO (red).*

boundary layer and free tropospheric O_3. Additional information on the potential capabilities of TEMPO will be gathered after launch of the Geostationary Environmental Monitoring Spectrometer (GEMS) satellite in 2019 with a FOR over Asia, which is part of the three-satellite constellation carrying very similar instruments in geostationary orbit. Overall, the unique characteristics of TEMPO will allow for the quantification of the diurnal variability of the major elements contributing to degradation in air quality, which has yet to be realized through current satellite instrumentation. Although potential applications of TEMPO were discussed in detail during the First TEMPO Applications Workshop at the University of Alabama in Huntsville in July 2016 (https://www.nsstc.uah.edu/tempo/).

TEMPO is required to spend 75% of its observing time scanning the complete field of regard (FOR) for measuring required pollutants throughout the daylight portion of the diurnal cycle. The other 25% of observing time is available for non-standard operations, which means observing a portion of the FOR at higher temporal resolution. Non-standard operations may include high resolution monitoring of volcanic eruptions, forest fires, dust outbreaks, and significant storms, in addition to chemistry experiments to inform atmospheric pollution science and associated satellite retrievals. Research investigators can propose innovative ideas for using the non-standard observing time of TEMPO.

2. TEMPO Data Products and Delivery Mechanisms

The following data products will be available from TEMPO: 1) Level 0 (L0) product of reconstructed, unprocessed data; 2) Level 1b (L1b) product of calibrated, geolocated radiances; 3) Level 2 (L2) geophysical baseline and research data products; 4) Level 3 (L3) daily and monthly gridded geophysical data product; and 5) Level 4 (L4) product derived from multiple Level 2 and 3 products (e.g., AQ and UV index). Baseline L2 data products derived from TEMPO radiances are shown in Table 1. Cloud products used in trace gas retrievals will include cloud fraction and pressure. All TEMPO data products are expected to be delivered no later than 6 months after on-orbit checkout, with a data latency of 3 hours for the L1b and L2 products, except for 0-2 km O_3. Data format will be netCDF-4/Hierarchical Data Format Version 5 (HDF5), and NASA Langley's Atmospheric Sciences Data Center (ASDC) will represent the official archive for the TEMPO mission. The L2 data files will consist of individual 6-min granules for a total of 10 granules covering the FOR.

Table 1. *TEMPO baseline L2 data products.*

Species/Products	Required Precision	Temporal Revisit
0-2 km O_3	10 ppbv	2 hr
Tropospheric O_3	10 ppbv	1 hr
Total O_3	3%	1 hr
Tropospheric NO_2	$1x10^{15}$ molecules cm^{-2}	1 hr
Tropospheric H_2CO	$1x10^{16}$ molecules cm^{-2}	3 hr
Tropospheric SO_2	$1x10^{16}$ molecules cm^{-2}	3 hr
Tropospheric $C_2H_2O_2$	$4x10^{14}$ molecules cm^{-2}	3 hr
Aerosol Optical Depth	0.1	1 hr

Several data delivery and display mechanisms are anticipated for TEMPO, including the DAAC at NASA Langley's ASDC and NASA Worldview. The primary function of the DAAC is to ingest data from numerous data providers to archive and support science driven requirements, and the system currently supports over 44 science projects, with CALIPSO, CATS, CERES, DSCOVR, MISR, MOPITT, SAGEIII-ISS, and TES, representing the primary projects. The DAAC provides customer support and outreach to the science community to support science teams and facilitate use of data products and associated technologies by current and emerging users. As mentioned earlier, the DAAC represents the official long-term data archive for processed TEMPO data products (Level 1b and above), but has no direct requirements for delivering real-time data from TEMPO. However, the DAAC has linkages to the NASA Land, Atmosphere Near real-time Capability for EOS (LANCE) system, which is built for real-time access to satellite data products. Furthermore, the linkages between the data delivery LANCE system and Worldview display platform will allow for effective delivery and display of TEMPO data products for use in rapid response applications and meeting end user community needs.

The EPA's Remote Sensing Information Gateway (RSIG) application represents the official display platform for TEMPO data products, which has linkages to the NASA Langley's DAAC. The RSIG currently includes direct access to MODIS, VIIRS, CALIPSO, OMI, NOAA GOES GASP AOD (GOES-16 will be added in the future), and AIRNow and Air Quality System (AQS) data, along with Community Multiscale Air Quality (CMAQ) model output. Key features of RSIG include regridding of datasets, 3-D visualization of CALIPSO and CMAQ data, overlaying of multiple data sets at once, and an offline mode for large data requests for viewing later (Fig. 3). The RSIG is primary used for model evaluation, blending of model, satellite, and surface air quality data, and exceptional event case study analyses. Recently, the system was upgraded to include display capabilities for Weather Research and Forecasting (WRF) – CMAQ model based estimates of tropospheric columns of TEMPO relevant species. Since 2011, the EPA has used RSIG metrics to report

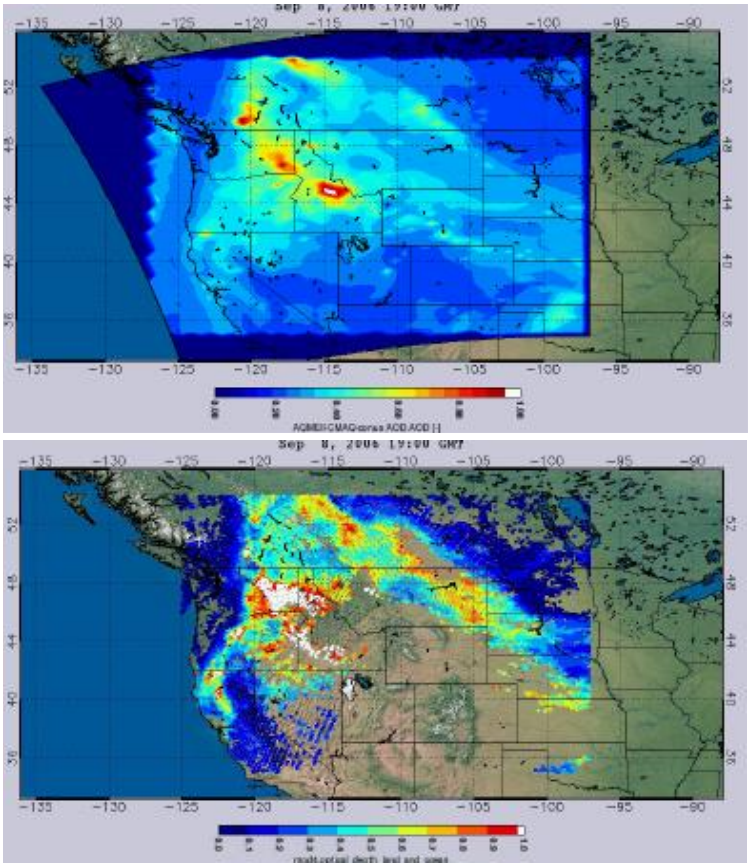


Figure 3. *RSIG Example of (top) AOD from a 12 km CMAQ model simulation and (bottom) Aqua MODIS AOD regridded onto the CMAQ model grid.*

use of NASA satellite data products for air quality related National Interests to the NASA Earth Science Senior Mission Review. In addition to EPA's RSIG, the Intermountain West Data Warehouse – Western Air Quality Study (IWDW-WAQS) manages a data display platform suited for TEMPO applications. The IWDW-WAQS platform allows access to air quality monitoring data over the CONUS, online visualization, and evaluation tools. The wealth of monitoring data will benefit retrieval development and validation work for TEMPO data products. Additionally, the platform shows county level emissions by chemical species and source sector, which includes area and point sources, with displays for gridded model-ready emissions also available. Thus, the incorporation of TEMPO data into the IWDW-WAQS platform can also help address discrepancies between top-down and bottom-up emissions inventories.

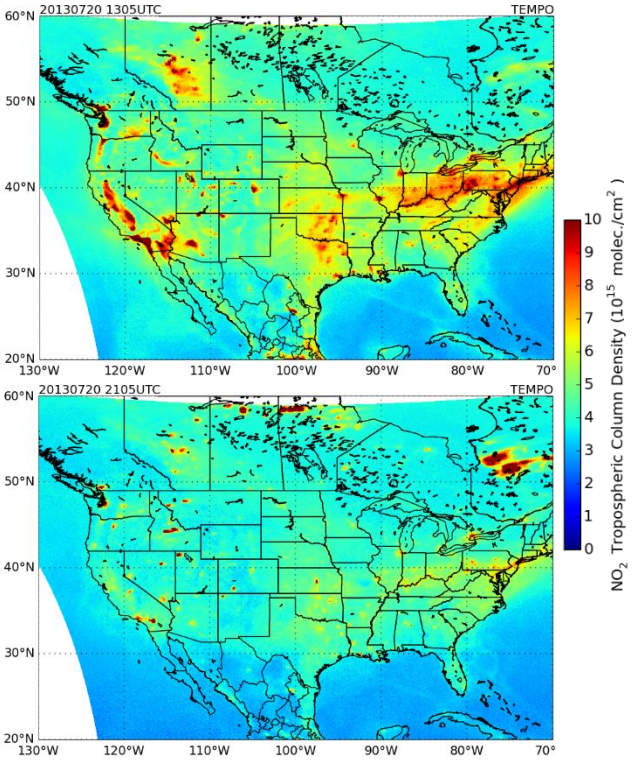


Figure 4*. Morning (1300 UTC) and afternoon (2100 UTC) TEMPO scans over the FOR on 20 July 2013 showing synthetic NO_2 column retrievals.*

The NASA Short-term Prediction Research and Transition (SPoRT) Center also maintains multiple platforms for displaying TEMPO imagery. The highly successful Research-to-Operations/Operations-to-Research (R2O/O2R) paradigm developed by the SPoRT Center over the past 15 years will be utilized for transitioning real-time TEMPO data products to end user communities to assess impact on operations and develop end-user tailored products. Currently, the SPoRT Center hosts satellite imagery via a Web Map Service (WMS), with more robust web viewers currently in development, such as the Esri ArcGIS Enterprise, which will support the real-time display of TEMPO data products. Prior to launch, the SPoRT Center aims to ingest synthetic TEMPO L2 products (Fig. 4) into their current display platforms, while also working closely with the TEMPO Science Team and end user communities for realizing the future regional specific application needs of TEMPO.

3. TEMPO Data User Perspectives and Applications

Operational and research forecast modeling systems are maintained at NOAA, which could greatly benefit from the assimilation of TEMPO data. In particular, NOAA maintains the National Center for Environmental Prediction (NCEP) Climate Prediction Center (CPC) Global Forecast System (GFS) provides 5-day operational forecasts of ozone at 0.25x0.25° resolution, which assimilates OMI total column O_3 retrievals for improving model forecasts. NOAA also

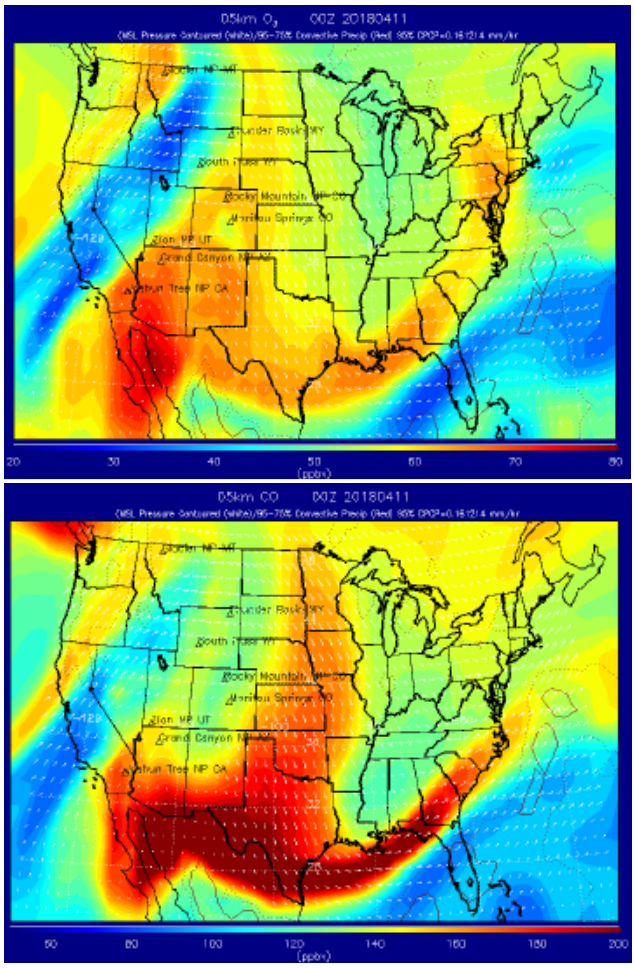


Figure 5*. RAQMS 60-hr forecast valid at 00 UTC 11 April 2018 for (top) total column O_3 and (bottom) CO over the CONUS.*

supports a research model called the Rapid Refresh with Chemistry (RAP-Chem) providing 48-h chemistry forecasts at 13-km resolution. RAP-Chem forecasts are aided by a robust assimilation procedure conducted through the Real-time Air Quality Modeling System (RAQMS; Fig. 5), which assimilates MLS stratospheric ozone profiles, OMI cloud cleared total column O_3, MODIS Terra and Aqua AOD, and fire detection. RAQMS real-time forecasts are used for lateral boundary conditions into the RAP-Chem system. Preliminary work focused on assimilating synthetic TEMPO data into this robust modeling framework showed a significant error reduction in O_3 forecasts due to the assimilation of hourly data, which highlights the tremendous potential of TEMPO for improving air quality forecasts. The UV-Visible ozone retrievals from TEMPO should also lead to an improvement in constraining lower tropospheric ozone in models.

The public health community expects to greatly benefit from the advanced TEMPO measurements. TEMPO monitoring efforts will create a body of data describing surface-level characteristics and diurnal variations of criteria air pollutants (AP), gases and aerosols that contribute to ozone formation, and UVB rays (associated with malignancies of the skin). Ultimately, TEMPO data is capable of improving the quality of research on the public health impact of AP by better addressing existing spatiotemporal confounders, and reducing the gaps in our comprehension of AP and health relationships (Sorek-Hamer et al., 2017). Special observations conducted at higher temporal resolutions over selected areas using the non-standard operation time of TEMPO will level the balance of health and air quality data in models used in epidemiological studies, which can improve research designs and increase our understanding of the relationships between surface-level exposures and public health indicators (Hodges and Reich, 2010; Paiorek, 2010; Sheppard, 2012, Domenici, 2013). Baseline data products from TEMPO will address questions that arise in caring for patients who may be especially susceptible to health changes associated with increased AP.

The EPA expects tremendous benefits of incorporating TEMPO data products into their air quality activities. Potential applications of TEMPO data include improved evaluation of

meteorological and photochemical models, development of top-down constraints on emission inventories, model assimilation for improving air quality forecasts, quantifying precursor concentrations of species for better identification of exceptional events, and quantifying O_3 in the free troposphere and stratosphere. In particular, the EPA stressed the potential for TEMPO data to help define a clear causal relationship between a specific event and a monitored concentration due to the high temporal frequency and multi-layer O_3 retrievals, which can better identify exceptional events. For example, stratospheric and 0-2 km O_3 retrievals from TEMPO have the potential to better define linkages between stratospheric intrusions and high levels of O_3 in the boundary layer, which could help exclude these types of episodes from being classified as exceptional events. Furthermore, stratospheric intrusions can also be associated with very low concentrations of other oxidants, especially for international transport events, so the additional species (NO_2, H_2CO) concentrations available in the baseline TEMPO L2 product could help better define contributions from source regions. TEMPO data will also greatly benefit air quality monitoring and model validation activities in data sparse rural areas, where the CMAQ model has shown substantial biases in O_3 concentrations. Overall, the high temporal resolution and unique data products from TEMPO will be valuable for episodic and day specific analyses, which should greatly benefit EPA activities.

State and local air quality agencies addressed how TEMPO observations could help meet their specific state and local needs. With only three ozone monitors in Idaho, the Idaho Department of Environmental Quality (DEQ) relies substantially on model forecasts, so TEMPO data will provide more spatial and temporal information for aiding the model forecasts. Early morning measurements from TEMPO would be particularly beneficial at the Idaho DEQ due to the lack of monitoring sites across the state. Additionally, the Idaho DEQ discussed the capability of TEMPO data for improving the understanding of the O_3 cycle, while also providing CH_2O and NO_2 retrievals within smoke plumes for better characterization of these events. Near real-time TEMPO data is a strong need at Idaho, since they actively use real-time data for addressing their current air quality monitoring needs. The Colorado Air Pollution Control Division (APCD) and Denver/Northern Front Range Regional Air Quality Council (RAQC) highlighted the potential for TEMPO to better define NO_x emissions from the oil/gas industry in their region, which will aid in creating regulatory control strategies. These Colorado agencies also noted the substantial emissions transporting into their state, and that improved TEMPO data will provide a cost-effective solution by quantifying the transported emissions.

State air quality agencies from Wyoming and New Mexico highlighted specific needs from TEMPO for their regions. Due to the snow/ice cover that can hamper Wyoming during the cold season, Wyoming DEQ addressed the need for quality TEMPO data products over snow/ice areas in order to effectively use the data for industry applications throughout the year. Similar to Colorado, the Wyoming DEQ highlighted the ability of the high-resolution TEMPO data for constructing a robust emission inventory for the myriad of oil and gas source regions across the state. Furthermore, they noted the importance of TEMPO for better characterizing shallow, wintertime O_3 events and regional haze planning, along with validating and improving air

quality models. The New Mexico Air Quality Bureau (AQB) stressed the potential use of TEMPO for exceptional event analysis for high wind dust storms, as dust accounts for most of the exceptional events across the state and uncertainties with categorizing these storms are a major concern with current satellite data. With most O_3 over New Mexico originating from source regions in Texas, TEMPO data will also be useful for quantifying the transported concentrations. Finally, TEMPO data could help define preferred locations of future air quality monitoring sites, which will be beneficial to all air quality agencies.

4. End User Data/Training Needs

The general tone from all air quality agencies is the need for translators between the science and end user communities, since explaining the technical TEMPO data to the public will be a major challenge. Training activities consisting of workshops and face-to-face interactions with the science community, along with clear, concise training materials will greatly benefit the end users. These training activities could be facilitated by defining a satellite liaison for TEMPO for distributing and communicating TEMPO data products to the end users for their specific applications. Synthetic data products from TEMPO would also help better prepare the air quality agencies for the large amount of post-launch data, while also realizing the regional and local applications of the data, such as applying TEMPO over snow/ice areas. Furthermore, the air quality agencies stressed the need for having readily available open data formats due to the different resources available to the individual agencies. The ability to analyze TEMPO data in near real-time through multiple visualization platforms was also important to the agencies. Multiple visualization platforms are needed for fully addressing the wide range of end user needs. Lastly, easily searchable data archives are needed for effectively providing TEMPO data to the end user community.

5. Summary and Outcomes of Workshop

Science and end user communities discussed the myriad of TEMPO applications throughout the workshop. The huge potential for improving the ground truth emission inventories within the TEMPO FOR was noted by both science and end user communities. Our current emission inventories, particularly with NO_x and mobile sources, are highly uncertain, and the high spatial and temporal resolution of TEMPO data is expected to drastically reduce these uncertainties. A significant improvement in air quality forecasts is expected due to the assimilation of future TEMPO data, which will benefit all end user communities. Air quality agencies noted numerous regional and local applications of TEMPO data that will help better characterize exceptional events and air quality exceedances, which will ultimately permit an interface for effective interaction between the agencies and planning and regulations development communities. Overall, the unprecedented TEMPO data will improve our ability to track, monitor, and predict pollutant concentrations over the FOR, which will tremendously advance our knowledge of air quality.

This workshop prompted the creation of a data distribution and training roadmap. A public health workshop on TEMPO data was also strongly encouraged during the workshop, which is expected to take place in Huntsville, AL in fall 2019. The need for tribe organization involvement was also stressed at the workshop, especially since tribe member attendance was nonexistent. A defined liaison for TEMPO would be beneficial for tribe communication.