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TEMPO Green Paper: Chemistry, physics, and meteorology experiments with the Tropospheric Emissions: Monitoring of Pollution instrument

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ABSTRACT

The NASA/Smithsonian Tropospheric Emissions: Monitoring of Pollution (TEMPO; tempo.si.edu) satellite instrument will measure atmospheric pollution and much more over Greater North America at high temporal resolution (hourly or better in daylight, with selected observations at 10 minute or better sampling) and high spatial resolution (10 km^2 at the center of the field of regard). It will measure ozone (O_3) profiles (including boundary layer O_3), and columns of nitrogen dioxide (NO_2), nitrous acid (HNO_2), sulfur dioxide (SO_2), formaldehyde (H_2CO), glyoxal ($C_2H_2O_2$), water vapor (H_2O), bromine oxide (BrO), iodine oxide (IO), chlorine dioxide (OClO), as well as clouds and aerosols, foliage properties, and ultraviolet B (UVB) radiation. The instrument has been delivered and is awaiting spacecraft integration and launch in 2022. This talk describes a selection of TEMPO applications based on the TEMPO Green Paper living document (http://tempo.si.edu/publications.html).

Applications to air quality and health will be summarized. Other applications presented include: biomass burning and O_3 production; aerosol products including synergy with GOES infrared measurements; lightning NO_x; soil NO_x and fertilizer application; crop and forest damage from O_3; chlorophyll and primary productivity; foliage studies; halogens in coastal and lake regions; ship tracks and drilling platform plumes; water vapor studies including atmospheric rivers, hurricanes, and corn sweat; volcanic emissions; air pollution and economic evolution; high-resolution pollution versus traffic patterns; tidal effects on estuarine circulation and outflow plumes; air quality response to power blackouts and other exceptional events.

Keywords: Air pollution, ozone, troposphere, fires, lightning

1. INTRODUCTION

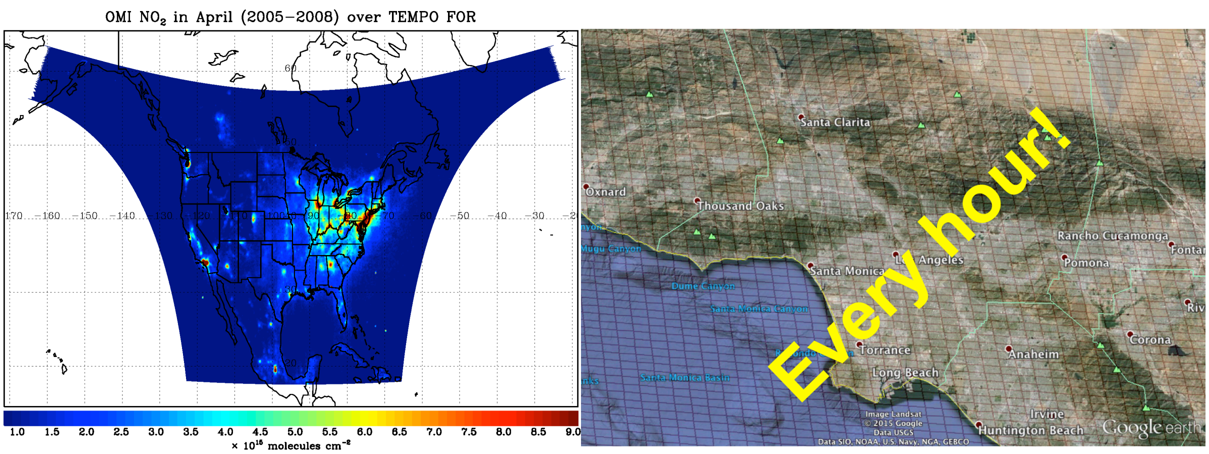

Figure 1. Left: The TEMPO field of regard (FOR), as swept hourly (illustrated using OMI NO_2 data). Right: The resulting hourly coverage over the greater Los Angeles region.

TEMPO was selected in 2012 by NASA as the first Earth Venture Instrument, and is scheduled to launch in early 2022 into a geostationary (GEO) orbit at 92.85°W. TEMPO takes advantage of a GEO host spacecraft to provide a modest cost mission that will measure pollution hourly over Greater North America. TEMPO is capable of measuring the spectra required to retrieve O_3, NO_2, HNO_2, SO_2, H_2CO, $C_2H_2O_2$, H_2O, BrO, IO, OClO, aerosols, cloud parameters, foliage properties, and UVB. TEMPO thus can measure the major elements, directly or by proxy, in the tropospheric O_3 chemistry cycle. Multi-spectral observations provide sensitivity to O_3 in the lowermost troposphere, reducing uncertainty in air quality predictions by 50%. TEMPO provides near-real-time air quality products that will be made widely and publicly available. This paper presents a selection of studies that have been suggested from the highly-anticipated TEMPO measurements.

TEMPO measures pollution over North America, from Mexico City, Cuba, Hispaniola, and Puerto Rico to the Canadian oil sands, and from the Atlantic to the Pacific, hourly during daylight and at high spatial resolution, 2.1 km N/S × 4.8 km E/W at 36.5°N, 100°W. Figure 1 illustrates the TEMPO field of regard (FOR) and the hour coverage over greater Los

Angeles. TEMPO spectroscopic measurements in the ultraviolet and visible wavelengths provide a tropospheric measurement suite that includes the key gases of tropospheric air pollution chemistry, as well as contribute to advancing our knowledge of land-atmosphere interactions, weather, and the carbon cycle. Measurements are made hourly in daylight from GEO, to capture the inherent high variability in the diurnal cycle of emissions and chemistry. A small product spatial footprint resolves pollution sources at a sub-urban scale. Together, this temporal and spatial resolution improves emission inventories, monitors population exposure, and enables effective emission-control strategies[1].

TEMPO makes the first North American tropospheric trace gas measurements from GEO, by building on the heritage of six spectrometers flown in low-earth-orbit (LEO). These LEO instruments measure spectra at similar spectral resolution to TEMPO, but at a much coarser spatiotemporal resolution, and use retrieval algorithms developed by TEMPO Science Team members which are currently running in operational environments. Figure 2 shows the TEMPO wavelength coverage illustrated with spectra from the European Space Agency's GOME-1 satellite, at characteristic earth conditions, along with some relevant molecular absorptions. This measurement strategy makes TEMPO an innovative use of well-proven techniques, able to produce a revolutionary dataset. TEMPO will be the North American component of the global geostationary constellation of pollution monitoring that also includes the European Sentinel-4 (S4) and

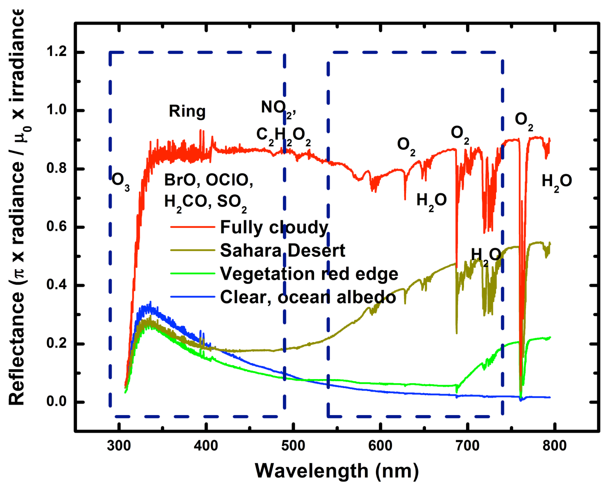

Figure 2. The TEMPO wavelength coverage (dashed rectangles), illustrated with GOME-1 spectra. The four surface types show a range of earth conditions. Some of the relevant absorptions are noted.

Korean Geostationary Environment Monitoring Spectrometer (GEMS) instruments.

TEMPO is required to spend much of its observing time scanning the full FOR each hour, for as much of the daylight portion of the diurnal cycle as we can arrange (but certainly to 70^{o} solar zenith angle). However, some observing time, perhaps up to 25%, is available for non-standard observations. Non-standard operations simply mean observing a portion of the FOR at higher temporal resolution. (An East/West slice, as North/South is nearly fixed; The latitude can be shifted by up to about ±3°, as measured at the southern end of the FOR.)

Non-standard observations may be of two types: First, events, which might include volcanic eruptions, forest fires, dust outbreaks, significant storms, or environmental emergencies. Second, "chemistry experiments" which use the world's highest chemistry set to inform atmospheric pollution science in general and satellite retrievals of pollution (especially for TEMPO) in particular. Note that:

1. Image Navigation and Registration (INR, think "pointing") is likely to be slightly worse in the first hour of daylight and also in the easternmost several hundred kilometers of the FOR.
2. Research scans may need supplemental hand registration to take full advantage of the spatial resolution.
3. It is reasonable to think that some experiments will be done in commissioning phase but they are not required to be.
4. Current mission requirements designate O_3, NO_2, H_2CO and clouds as operational products. We hope as we fully retire instrument risk to add SO_2, aerosol, $C_2H_2O_2$ as operational products and provide validation for them. However, they are always in the spectra, so they can reasonably be included in chemistry experiments.
5. If TEMPO command sequences are pre-loaded, about 1-hour notice is required to initiate a special sequence.
6. Discussion of special observations now hopefully ensures that flexibility remains when operations become more fully developed.

For purposes of discussion, it is assumed that non-standard operations have 10-minute time resolution and 1000 km E/W swath but these parameters are not fixed. For oversampling studies, for example, sampling could be quicker and narrower. Anything down to step and stare (with several km jitter) should be possible.

2. NORMAL TIME RESOLUTION STUDIES

2.1 Air quality and health

The U.S. geostationary mission TEMPO is targeted at improving monitoring, assessment, and chemical understanding of air quality over Greater North America. Current observation of air quality from space has been limited so far by the temporal sparseness of LEO satellite data, often daily sampling, and low sensitivity to near-surface ozone. TEMPO's hourly measurements allow better understanding of the complex chemistry and dynamics that drive air quality on short timescales. The time and space densities of TEMPO data are ideally suited for data assimilation into chemical models for both air quality forecasting and for better constraints on emissions that lead to air pollution exceedances. Planning is underway to combine TEMPO data with regional air quality models to improve Environmental Protection Agency (EPA) air quality indices and to directly supply the public with near real time pollution reports and forecasts through website and mobile applications. The dense spatial coverage of TEMPO will also offer valuable information for epidemiological studies to understand local health effects. Hourly temporal resolution offers benefits for cloud slicing to separate lower-mixed layer concentrations from those aloft. The ability to observe and attribute air pollution events over the entire TEMPO FOR has great policy and societal benefits. There is existing communication with air quality managers through programs such as the NASA Health and Air Quality Applied Sciences Team (HAQAST) that will assist in exploitation of TEMPO data for air quality applications.

2.2 Ultraviolet exposure

Changes in clouds, aerosols and the stratospheric ozone layer modulate biologically harmful ultraviolet (UV-B and UV-A: 290-400nm) radiation reaching the Earth's surface and penetrating to ecologically significant depths in natural waters. Current operational LEO satellite algorithms for mapping of hyperspectral UV irradiance at the Earth's surface[2-5] and at different depths underwater[6,7] assume "frozen cloud transmittance," estimated from the measured UV reflectivity at the time of LEO satellite overpass[8,9]. A spectral surface ultraviolet (UV) irradiance retrievals using TEMPO hourly O_3 amounts and cloud and surface reflectances will enable us to account for diurnal changes in cloudiness and produce hourly targeted UV indices and accurate daily exposures, employing different action spectra for erythemal exposure of skin, vitamin D synthesis, DNA damage, and plant response.

2.3 Biomass burning

Emissions from biomass burning can vary greatly both regionally and from event to event, but previous work has been unable to fully explain this variability. The unexplained variability in ozone production rate from fires is of particular interest. The primary emissions from burning and the chemistry in fire plumes evolve on hourly and daily timescales, making observations from TEMPO especially valuable for investigating these processes. The suite of NO_2, H_2CO, $C_2H_2O_2$, O_3, H_2O, and aerosol measurements from TEMPO is well suited to investigating how the chemical processing of primary fire emissions affects the secondarily formed compounds such as volatile organic compounds (VOCs), ozone and secondary organic aerosols. Ongoing efforts are working to address algorithmic complications for trace gas retrievals in forest fires from high aerosol loadings. TEMPO measurements will not only increase understanding of the chemical emissions from biomass burning, but will also be a powerful tool for monitoring and assessing its impact on human health and climate change. TEMPO observations will also help evaluate the effect of climate change on the frequency and severity of air pollution due to wildfires.

There is growing evidence on the consequences on soil, soil biota, soil chemistry, indigenous plant life, and fauna of not letting fire-adapted ecosystems burn. The accumulated dry fuels caused by suppressing wildfires can be partially moderated by prescribed fires. These controlled activities can be monitored by TEMPO to assure minimal short-term air pollution impact on humans, while being able to restore natural unperturbed ecosystem components. For particularly important fires it is possible to command special TEMPO observations as special operation, revisiting at 10-minute frequency.

2.4 Synergistic GOES-16/17 Products

As TEMPO will use NOAA GOES-16/17 advanced baseline imager (ABI) data for INR, GOES ABI products can be easily used for TEMPO applications. GOES cloud information is of particular interest for improving and using TEMPO products. A wealth of GOES cloud information such as clear sky mask (i.e., cloud classification), cloud optical depth, geometrical cloud fraction, cloud-top height, cloud-top phase, and temperature is available at TEMPO sub-pixel level. These cloud products can be mapped to TEMPO spatial pixels and can be used to improve TEMPO cloud, aerosol and trace gas retrievals, and assist in screening cloud-contaminated TEMPO data. In addition, other GOES products including radiances, aerosol detection/optical depth, fire/hot spot characterization, and snow/ice cover can also be mapped to TEMPO footprints to help improve the retrievals and analysis of TEMPO data.

2.5 Advanced aerosol products

As the first geostationary satellite to measure ultraviolet and visible spectra over North America, TEMPO provides a unique opportunity to develop new research algorithms for aerosol retrievals by taking advantage of its hourly observations and its synergy with GOES satellite measurements of radiation in the visible, shortwave infrared and thermal infrared. TEMPO may be used together with the ABI instruments on GOES-16/17 for aerosol retrievals. A combination of 3 shortwave GOES bands (470, 640, and 860 nm) and 4 bands from TEMPO (340, 380, 470, and 640 nm) can improve the retrieval of both total AOD and fine-mode AOD accuracy; compared to the retrieval from the single sensor, the joint retrieval reduces total AOD and fine model AOD uncertainties respectively from 30% to 10% and from 40% to 20%[1]. In addition, TEMPO spectra in the regions of O_2-O_2 and O_2 absorption (e.g., O_2 *B*, O_2 γ) can be used to retrieve cloud and aerosol plume heights. Multiple measurements taken for the same pixel (from same viewing angle but multiple solar zenith angles and therefore scattering angles) can provide information on aerosol particle shape. TEMPO observations of aerosol precursors (e.g., SO_2) will offer information on aerosol production processes.

2.6 Soil NO_x after fertilizer application and after rainfall

U.S. and Central American inventories of soil NO_x due to nitrogen fertilization are uncertain by more than 100%. There is an underestimate of NO release by nitrogen-fertilized croplands as well as an underestimate of rain-induced emissions from semiarid soils[10,11]. TEMPO measures Greater North America croplands hourly and so can follow the temporal evolution of NO_x emissions from croplands after fertilizer application and from rain-induced emissions from semi-arid soils. Should even higher temporal resolution over selected regions be useful, that may be accomplished by special observations.

2.7 Solar-induced fluorescence from chlorophyll

TEMPO measurements of solar-induced fluorescence from chlorophyll may be made over both land and ocean. Land measurements can be used for studies of primary productivity, the length of carbon uptake period, drought responses, and tropical dynamics. These apply both to agriculture and forests. Coastal Atlantic Ocean, Gulf of Mexico and Chesapeake Bay measurements can be used to detect red tides and to conduct studies on the physiology, phenology, and productivity of phytoplankton.

2.8 Foliage studies

TEMPO will be capable of measuring spectral indices for estimating foliage pigment contents and concentrations applied generally to leaves but not the full canopy. A single spectrally invariant parameter, the Directional Area Scattering Factor, relates canopy-measured spectral indices to pigment concentrations at the leaf scale.

2.9 Mapping NO_2 and SO_2 dry deposition at high resolution

TEMPO measurements of NO_2 and SO_2 can be used in combination with high-resolution model calculations of deposition velocity to map NO_2 and SO_2 dry deposition to soil, water and vegetation. Previous studies have used space-based observations of NO_2 and SO_2 from low Earth orbit to map regional and global deposition[12-14], but at coarser spatial resolutions than those available from TEMPO. As deposition changes greatly between surface types and with local meteorology, the high spatial resolution of TEMPO should allow improvements in our spatial quantification of dry deposition, and in the resulting nitrogen and sulfur deposition budgets. With only one or fewer observations per day, previous studies needed to make model-based assumptions of the diurnal cycles of surface NO_2 and SO_2 concentrations. The hourly TEMPO products will allow improved constraints on time-dependent deposition.

2.10 Crop and forest damage from ground-level ozone

Ozone damages vegetation by entering through the stomata and oxidizing chemicals that perform the photosynthetic process. This damage amounts to several billion dollars per year in the U.S. alone[15], and much more worldwide. Collateral effects include changes in water and carbon exchange. TEMPO will measure ozone as well as water vapor, permitting quantitative studies of the detailed correlation of vegetation damage for various crop types and cultivars at the TEMPO pixel scale or smaller by oversampling[16-17]. Such studies can contribute to optimized agricultural choices. Forest studies can contribute to improved prevention of human-induced wildfires.

2.11 Halogen oxide studies in coastal and lake regions

The atmospheric chemistry of halogen oxides (e.g., BrO and IO) over the ocean, and particularly in coastal regions, can play important roles in ozone destruction, oxidizing capacity, and dimethylsulfide oxidation to form cloud condensation nuclei. The budgets and distribution of reactive halogens along the coastal areas of North America are poorly known. Therefore, providing a measure of the budgets and diurnal evolution of coastal halogen oxides is necessary to understand their roles in atmospheric photochemistry of coastal regions. Previous ground-based observations have shown enhanced levels (at a few pptv) of halogen oxides over coastal locations with respect to their background concentrations over the remote marine boundary layer[18]. Previous global satellite instruments lacked the sensitivity and spatial resolution to detect the presence of active halogen chemistry over mid-latitude coastal areas. TEMPO observations together with atmospheric models will allow examination of the processes linking ocean halogen emissions and their potential impact on the oxidizing capacity of coastal environments of North America.

TEMPO also performs hourly measurements of one of the world’s largest salt lakes, the Great Salt Lake in Utah. Measurements over Salt Lake City show the highest concentrations of BrO over the globe. Hourly measurement at a high spatial resolution can improve understanding of BrO production in salt lakes.

TEMPO measurements of BrO over the coastal areas and salt lakes can also provide better understanding of Br contribution from short-lived species to stratospheric Br budget and their effect on ozone hole recovery.

2.12 Air pollution from oil and gas fields

TEMPO measurements of O_3, NO_2, H_2CO, $C_2H_2O_2$, SO_2, and aerosols will contribute to understanding and quantifying the emission from oil and gas fields, and to understanding the chemical evolution of air pollution (e.g., wintertime high ozone episodes) near oil and gas production regions[19].

2.13 Night light measurements resolving lighting type

TEMPO offers the possibility of collecting spectra of nighttime lights when the sun is >60° from its boresight or when the sun is fully eclipsed by the Earth. Many different types of outdoor lighting are used across the U.S., including Hg vapor, high and low-pressure Na lamps, and LEDs, which should be classifiable by virtue of their spectral signatures. With a 10 s dwell time, TEMPO can map such lights with adequate signal-to-noise ratio over Greater North America in a single scan of about 3 hours near the winter solstice[20]; the domain can be covered piecemeal in several days during other time periods. Weaker signals within a small region can be detected with even longer dwell time. While not specifically intended for nighttime collections, TEMPO provides an interesting capability for studying nightlights as markers for surface aerosol pollution, human activity, energy conservation, and compliance with outdoor lighting standards intended to reduce light pollution.

2.14 Ship tracks, drilling platform plumes, and other concentrated sources.

TEMPO will be able to monitor pollution over ship tracks and from drilling platform plumes, e.g., in the Gulf of Mexico and off the coast of California. Especially for the drilling platform plumes, higher temporal measurements may improve detection limits and measurement precisions enough to make measurements for significantly fainter platform sources than can now be done. It will likely be possible to measure NO_x emissions from highways and aircraft routes as well.

2.15 Water vapor studies

TEMPO water vapor and pollution measurements[21] will contribute to understanding the extent that corn sweat worsens heat waves and air pollution in the U.S. Midwest. There is significant short-term variability in water vapor columns due to land moisture fluxes from evapotranspiration, atmospheric turbulence and large-scale horizontal motions. The high temporal resolution of the TEMPO water vapor product will be a valuable top-down constraint on surface moisture fluxes, or the vertical mass column. GOES-16/17 provides high resolution water vapor maps based on IR bands (6.2-7.3

μm), but they are usually applicable for qualitative analyses. TEMPO will offer an hourly quantitative measurement of water vapor that can mathematically be incorporated into models. Synergistic use of GOES cloud and aerosol products will provide better scattering corrections to the TEMPO water vapor product, allowing cloudy scenes to be incorporated in to data assimilation systems. The tails of land-falling atmospheric rivers over the West Coast can be captured by TEMPO. Land-falling hurricanes from the Atlantic and the Gulf of Mexico can be monitored after they move into the FOR. A considerable number of severe rainfall incidents in southern U.S. occur during frontal passages, which are mainly a result of discontinuity and rapid changes in density and wind velocity between two different air masses (cold and dry vs. warm and moist). TEMPO provides the high temporal water vapor measurements for assimilation into weather models to bolster the capabilities of operational models to produce better forecasts before a front enters a specific region.

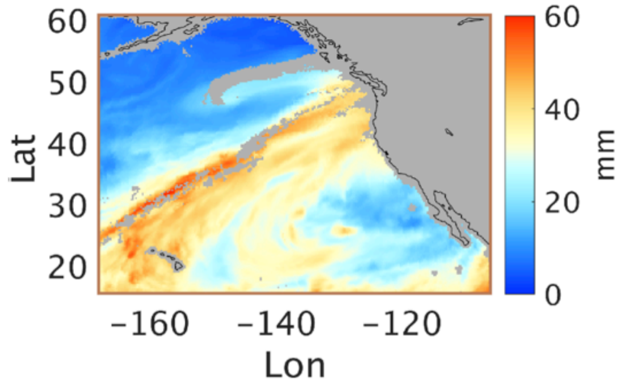

Figure 3. Total column water vapor from the Weather Research and Forecasting model v3.9.1 after assimilation with OMI water vapor from the Smithsonian Astrophysical Observatory[21].

2.16 Volcanoes

The FOR of TEMPO includes several active volcanoes including Popocatépetl and Fuego de Colima in Mexico, and the emissions from Soufrière Hills in Montserrat and the downwind area of several volcanos in Alaska. TEMPO will provide detailed understanding of the pollution produced by dispersed volcanic ash (VA), sulfur dioxide (SO_2), and sulfate (H_2SO_4) particles and how they are transformed and transported. BrO/SO_2 ratios can be calculated downwind of craters at different distances to determine their evolution and, in combination with meteorological data, estimate hourly fluxes. TEMPO also will provide information about volcanic BrO injection into the lower stratosphere.

Volcanic eruptions can inject significant amounts of SO_2, VA, and H_2SO_4 particles into the atmosphere at commercial aircraft cruising altitudes. The ash clouds, in particular, pose a substantial risk to aviation safety due to the potential ingestion of silicate ash into jet engines. Present regulations dictate a zero ash tolerance policy for jet aircraft, which in case of uncertain VA location, could lead to prolonged flight cancellations that have a ripple effect on the airline industry's economy and personal travel as happened in the aftermath of the 2010 Eyjafjallajökull (Iceland) eruption. TEMPO's frequent volcanic SO_2 and ash measurements will complement GOES-16 and -17 infrared VA observations and could be used by NOAA/NESDIS Washington VA Advisory center to issue VA advisories for North American airspace[22].

2.17 Socio-economic studies

TEMPO will perform quantitative studies of pollution that inform the state of developing economies such as Cuba, as pollution and economic activity are often highly correlated. TEMPO will be able to evaluate the horizontal inhomogeneity of pollutants in megacities such as Los Angeles and the Mexico City Metropolitan Area, illustrating not only health hazards in different neighborhoods, but linking pollution to demographics and socio-economical levels. Combining TEMPO observations with ancillary information on economic activity it will be possible to obtain information about the effect on air quality of different economic activities in urban areas.

2.18 National pollution inventories

Space- and time-resolved TEMPO measurements of NO_2 and SO_2 will provide information about point and mobile sources and significantly contribute to National Pollution Inventories. LEO satellite pollution (NO_2, SO_2) plume tracking and "top-down" point source emission estimates have been proved valuable reducing latency and improving accuracy of traditional "bottom-up" emissions inventories. TEMPO will drastically improve number of measurements over North

American point pollution sources (e.g., power plants, refineries, cities) reducing statistical uncertainties and improving time resolution of the top-down emissions estimates, which will be assimilated into the next generation of chemical weather forecast models[23-27].

2.19 Regional and local transport of pollutants

TEMPO will provide unique hourly information, never available before, to conduct research on local and regional transport of aerosols and pollutants. TEMPO can be used (coupled with meteorological datasets) to determine the impact of agricultural practices on the air quality of recipient areas (such as urban areas where biomass burning is not common). In turn, the impact of emissions from urban areas (coupled with meteorological datasets) over suburban or rural areas can be determined using a similar approach.

2.20 Sea breeze studies

TEMPO will be able to examine daytime sea breeze transport into the mainland of maritime, biomass burning, and other anthropogenic aerosols from industrial and populated cities located along the coasts. Cuba[28-35] and the Florida peninsula are two natural laboratories for studying the contribution of aerosols to cloud formation produced by the sea breezes converging from their coasts using TEMPO synergistic cloud products combined with advanced aerosol products. Since Cuba has few surface stations conducting air quality monitoring in the country, TEMPO will make an additional contribution by filling information gaps on these data. Validation of the broadband aerosol optical depth (BAOD) measurements at four Cuban stations conducting solar radiation measurements with TEMPO AOD observations will contribute to the improvement of the Cuban BAOD dataset dating back in some stations more than 30 years and extend existing comparisons performed with MODIS AOD[35].

2.21 Transboundary pollution gradients

TEMPO can explore whether there are significant gradients in the air quality of contiguous urban areas extending on both sides of national borders, the impact of different air quality regulations, and how the transport of people and goods across borders affects air quality. TEMPO will be able to measure whether there are areas where systematic transport of pollution across the border occurs. TEMPO spatial and temporal resolution will be able to address these issues in areas of the U.S./Mexico border (i.e., San Diego/Tijuana, El Paso/Juárez) and the U.S./Canada border (i.e., Detroit/Windsor).

2.22 Transatlantic dust transport

Degraded air quality in the Greater Caribbean Basin (GCB), including Small Island States, is often linked to transatlantic transport of Saharan dust[36]. TEMPO dense spatial and temporal observations are well suited to characterize these synoptic-scale events, the dispersion of dust throughout the northern part of the GCB, the uptake of tropospheric O_3 by dust particles, and the correlation between dust particles, diesel particular matter with enhanced NO_2 concentrations. Saharan air masses can also act to suppress the formation of tropical storms and hurricanes[37]. TEMPO will provide continuous measurements of aerosols and water vapor that will enhance our understanding of the microphysical processes governing storm formation/suppression.

3. HIGH TIME RESOLUTION EXPERIMENTS

3.1 Lightning NO_x

Lightning-produced NO is the major NO_x source in the upper troposphere and can lead to substantial tropospheric O_3 production. Interpretation of satellite measurements of tropospheric NO_2 and O_3, and upper tropospheric HNO_3, in association with a global chemical transport model leads to an overall estimate of 6 ± 2 Tg N y^{-1} from lightning[38]. Assimilation of satellite observations of these species into a global model[39] has yielded similar values of 6.3 ± 1.4 $TgNy^{-1}$. Direct analysis of satellite NO_2 observations in relation to observed lightning flashes has also been conducted to estimate NO_x production per flash[39-43], yielding smaller values of production per flash than implied by the global modeling approach. High time resolution TEMPO measurements, including tropospheric NO_2 and O_3, can be made for time periods and longitudinal bands selected to coincide with large thunderstorm activity, including outflow regions, with fairly short notice. These observations can be analyzed together with flash rates from the Geostationary Lightning Mappers onboard GOES-16/17 to estimate NO_x production per flash. Doing so, we may be able to significantly better quantify lightning NO_x and O_3 production over Greater North America, and determine regional variability of NO_x production per flash. Sophisticated analysis of NO_2 and lightning measurements and coincident meteorology will be necessary due to the substantial lightning NO_2 signal in cloudy scenes. High temporal resolution TEMPO NO_2 observations will allow evaluation of NO_x lifetime in the near field of deep convection. An understanding of this lifetime is critical in constraining satellite-based estimates of NO_x production per flash.

3.2 Morning and evening higher-frequency scans

TEMPO's optimized data collection scan pattern during mornings and evenings provides multiple advantages for addressing TEMPO science questions. The increased frequency of scans coincides with peaks in vehicle miles traveled on each coast, and thus is better able to capture the variability in NO_x and VOC emissions from mobile sources through measurements of NO_2, H_2CO, and $C_2H_2O_2$. The morning and evening are also of interest for better quantifying the diurnal changes in photochemistry, driven by the rapid change in photolysis rates during these times. More frequent observations of the morning atmosphere in the Eastern U.S. are of particular benefit since there is usually a concurrent rapid rise in ozone concentrations.. Morning NO_x and VOCs are often the primary drivers of peak ozone levels later in the day. More frequent observations lead not only to more accurate quantification of the early morning production of these ozone precursors, but also better characterization of the diurnal patterns of emissions, and better assessment and forecasting of peak ozone air quality levels.

TEMPO can measure pollution development during the morning and evening rush hours at urban scales over non-coastal as well as coastal cities using special observations. TEMPO will also determine how pollution varies during the week and on weekends and determine long-term seasonal and interannual variability. TEMPO will be able to monitor pollution with the resolution to quantify emissions over major highways.

3.3 Dwell-time studies and temporal selection to improve detection limits

Possible additional measurements include HNO_2 (early morning measurements are likely necessary), methyl glyoxal ($C_3H_4O_2$), and IO over coastal areas.

3.4 Exploring the value of TEMPO in assessing pollution transport during upslope flows

The Northern Colorado Front Range Metro area (NFRMA) is in non-attainment for the EPA 8-hour ozone standard (NAAQS). Characterizing and modeling air quality in the NFRMA poses large challenges due to the complex terrain and meteorology as well as the mix of diverse pollution sources including urban sources, power generation and large industrial sources, agricultural activities, oil and gas exploration, and also natural sources like wildfires or biogenic VOCs. High ozone typically occurs on days with upslope flows but the transport characteristics can vary widely and there are still open questions such as how much of the transported pollution is brought back to the NFRMA via return flows or mixed into the free tropospheric westerlies. TEMPO measurements should resolve upslope events but it is open whether the expected vertical resolution of the ozone product would be sufficient to provide information of return flows. Data might also allow for a statistical assessment of the impact of upslope pollution transport on remote mountain areas. Such studies would be also of interest for other areas in the U.S. with similar topography, e.g., Salt Lake City and a variety of areas in the Intermountain West.

3.5 Tidal effects on estuarine circulation and outflow plumes

TEMPO will resolve tidal effects on estuarine circulation and the pollution outflow plume in the Chesapeake Bay and their relationship to ecosystem variability.

3.6 Air quality responses to sudden changes in emissions

TEMPO high time resolution could enable monitoring of air quality responses to sudden changes in emissions, such as those that occur during temporary power blackouts.

3.7 Cloud field correlation with pollution

TEMPO high time resolution studies may resolve photochemical effects under moving cloud fields.

3.8 Agricultural soil NO_x emissions and air quality

A portion of the non-standard operational time of TEMPO will be used for monitoring and assessing the influence of agricultural soil conditions and associated NO_x emissions on trace gas concentrations (i.e., NO_2 and O_3) and air quality conditions over areas such as California. Although NO_x emissions from fossil fuel sources have significantly reduced due to policies instituted in California, field measurements reveal that agricultural soils are a major source of NO_x in California's Central Valley. Recent evidence has shown that these biogenic NO_x emissions likely play a much larger role in contributing to the atmospheric NO_x throughout the state. Quantifying NO_2 and O_3 production due to the various NO_x emission sources, including smoke, mobile sources, and agricultural soils in California is extremely challenging using the current fleet of polar-orbiting spectrometers with limited overpasses per day over the region. TEMPO tropospheric NO_2 and O_3 profiles will permit more detailed attribution studies of NO_x emissions over California. However, due to the highly fluctuating emissions that often occur during the daytime in the state, it will be very beneficial to monitor the region at an even higher temporal resolution, down to 10 minutes, in an effort to fully understand the evolving NO_x emissions and associated NO_2 and O_3 concentrations. This enhanced monitoring capability will allow detailed process studies of how trace gases evolve with meteorology and surface and soil conditions in the state. The high-resolution TEMPO retrievals of NO_2 and O_3 will be used alongside soil moisture retrievals from the Soil Moisture Active Passive (SMAP) satellite to assess the diurnal cycle of soil NO_x emissions, in relation to rainfall, irrigation schedule, and temperature, and impact on air quality in California. This study will utilize the California Irrigation Management Information System (CIMIS), which maintains over 145 weather stations near and within agricultural areas throughout the state for monitoring soil temperature and precipitation. Finally, this proposed region of interest also incorporates the Primary Target Area planned over Los Angeles as part of the Multi-Angle Imager for Aerosols (MAIA) satellite mission, which will promote impactful air quality and public health studies in the future.

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