NASA Ups the TEMPO on Monitoring Air Pollution

Ernest Hilsenrath, University of Maryland Baltimore County, ADNET Systems, hilsenrath@umbc.edu
Kelly Chance, Smithsonian Astrophysical Observatory, kchance@cfa.harvard.edu

If the projected 2018-2019 launch timeframe holds for TEMPO, its observations should coincide with measurements from Europe's Sentinel-4 spacecraft, planned for launch in 2019, and Korea's Multi-Purpose Geostationary Satellite (MP-GEOSAT), planned for launch in 2018. All three missions will have similar geostationary orbits and similar air quality observation objectives.

Introduction

The National Research Council (NRC) 2007 Decadal Assessment for Earth Science (Decadal Survey[1]) called for Venture class missions that are "...stand-alone using simple, small instruments/spacecraft/launch vehicles." The Assessment further stated that maintaining a steady stream of opportunities for the Earth science community to participate in innovative mission development and implementation is a key to the success of the program. One element of NASA's Venture Class program is the development of principal investigator (PI)-led spaceflight instruments, to be deployed on NASA-selected satellites to address high-value Earth science questions.

The goal for innovation is now being realized as result of the first Earth Venture Class selected Instrument (EVI-1[2]). The instrument is called the Tropospheric Emissions: Monitoring of Pollution (TEMPO), led by **Kelly Chance** [Smithsonian Astrophysical Observatory]. As PI, Chance is responsible for developing an instrument that will measure major air pollutants over Greater North America, from Mexico City to the Canadian tar sands, and from the Atlantic to the Pacific, every daylight hour. The measurements will be taken from geostationary orbit, which will enable continuous data collection over this region. A unique aspect of this mission is that the instrument will be "hosted" by a non-NASA satellite and placed into orbit on a non-NASA launch, most likely co-manifested with a commercial geostationary satellite.

The TEMPO mission builds on the science team's experience with the European Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric CHartography (SCIAMACHY) missions and with the Ozone Monitoring Instrument (OMI) flying on NASA's Aura spacecraft. All of these missions measure atmospheric pollution from Sun-synchronous, polar orbit. If the projected 2018-2019 launch timeframe holds for TEMPO, its observations should coincide with measurements from Europe's Sentinel-4, planned for launch in 2019, and Korea's Multi-Purpose Geostationary Satellite (MP-GEOSAT[3]), planned for launch in 2018. All three missions will have similar geostationary orbits and similar air quality observation objectives. The three satellites will comprise a constellation for observing continental air quality and estimating transcontinental transport of pollution across the Atlantic and Pacific oceans.

TEMPO provides part of the urgently needed GEOstationary Coastal and Air Pollution Events (GEO-CAPE) atmospheric measurement[4]. In addition, TEMPO will demonstrate the use of commercially hosted payloads (described in more detail below) to accomplish NASA Earth science objectives to enable affordable earlier implementation of components of the full GEO-CAPE mission. TEMPO thus fulfills the NRC's 2012 Midterm Assessment of NASA's Implementation of the Decadal Survey, which

[1] NRC, 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* The National Academies Press.
[2] Venture Class missions were defined in the 2007 Decadal Survey. EVI is one of three different categories of Venture Class proposals. The program was detailed in the September–October 2010 issue of *The Earth Observer* [**Volume 22**, **Issue 5**, pp. 13-18].
[3] MP-GEOSAT will involve three Korean agencies: the Korean Aerospace Research Institute (KARI,) the Korean Ocean Research and Development Institute (KORDI,) and the National Institute of Environmental Research (NIER.)
[4] The Decadal Survey proposes the Geo-CAPE mission as *Tier II* (lower) priority. This mission would provide measurements of key components of air quality and their short-term evolution, along with climate-forcing gases. In addition, it would obtain simultaneous measurements of key water quality, ocean chemistry, and ecological indicators in coastal waters, including their response to environmental change. The recommendation was to make these measurements from a dedicated platform in geostationary orbit. The launch would not occur until after 2020.

states that "The Earth Venture-class program has the added value of enabling individual university principal investigator-type missions to pursue specific science questions," and that overall, "...the program is being well implemented and is a crucial component of the Decadal Survey's objectives[5]."

The Principal Investigator is responsible for the instrument development and end-to-end data processing after Level 0 data are delivered to the Smithsonian Astrophysical Observatory. This responsibility includes data calibration, validation, and archiving at NASA. The TEMPO Science Team includes members from NASA's Langley Research Center (LaRC) and Goddard Space Flight Center (GSFC), National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), National Center for Atmospheric Research (NCAR), and a number of universities. LaRC manages the TEMPO Project. Ball Aerospace & Technologies Corporation will build, test, and calibrate the spaceborne ultraviolet (UV)/visible (VIS) spectrometer that operates in wavelengths sensitive to various atmospheric pollutants.

TEMPO thus fulfills the NRC's 2012 Midterm Assessment of NASA's Implementation of the Decadal Survey, which states that "The Earth Venture-class program has the added value of enabling individual university principal investigator-type missions to pursue specific science questions," and that overall, "...the program is being well implemented and is a crucial component of the Decadal Survey's objectives."

Science Objectives

The TEMPO science objectives result from many years of experience with requirements developed by the air quality community, using observations of pollution from Sun-synchronous, polar orbits. TEMPO's advanced capabilities over heritage instruments are designed to answer the following science questions:

- What are the temporal and spatial variations of emissions of gases and aerosols important for air quality and climate?
- How do physical, chemical, and dynamical processes determine tropospheric composition and air quality over spatial scales ranging from urban to continental, and temporally from diurnal to seasonal?
- How does air pollution drive climate forcing, and how does climate change affect air quality on a continental scale?
- How can observations from space improve air quality forecasts and assessments for societal benefit?
- How does intercontinental pollution transport affect air quality?
- How do *episodic events* (e.g., wild fires, dust outbreaks, and volcanic eruptions) affect atmospheric composition and air quality?

Each of these questions has been explored from polar orbit using data from OMI onboard Aura, SCIAMACHY on the European Space Agency's (ESA) Envisat, and the GOME instruments flown on ESA and European Organization for the Exploitation of Meteorological Satellites (Eumetsat) missions. These instruments have surveyed key atmospheric constituents that relate to air pollution and quality and include tropospheric and stratospheric ozone (O_3), which in the troposphere is a pollutant and a greenhouse gas; sulfur dioxide (SO_2); formaldehyde (H_2CO); nitrogen dioxide (NO_2); glyoxal ($C_2H_2O_2$); water vapor; cloud properties; aerosol characteristics, including aerosol optical depth (AOD); and UV-B radiation. TEMPO will also measure the same atmospheric constituents, but from geostationary orbit, thereby allowing better spatial and temporal resolutions.

The heritage satellite data have revealed how air quality changes from day-to-day and year-to-year. They have shown improvements in air quality over North America because of regulation of power plant and automobile emissions, and also have tracked recent severe pollution events originating over urban locations from Asia to North America. These observations have more recently shown the degradation of air quality with high amounts of pollution over the Canadian tar-sand oil excavation fields. An example of

[5] NRC, 2012, *www.nap.edu/catalog.php?record_id=13405*.

NO_2 data collected from OMI over the course of a year is shown in **Figure 1**. These data show urban and industrial *hot spots* that typically result from auto emissions and power plants.

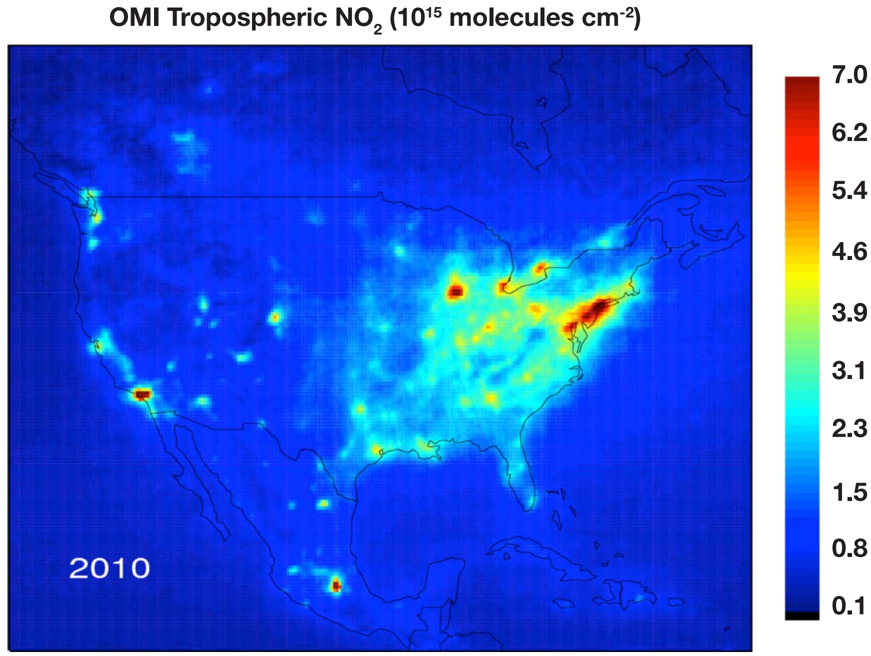

Figure 1. The OMI instrument—flown in a polar Sunsynchronous orbit—accumulated data over one year to produce the cloud-free map shown here. TEMPO's geostationary orbit will provide similar maps but at higher spatial resolution in considerably less time. OMI's spatial resolution is between 13×24 and 40×150 km^2 (~ 5×9 and 15×58 mi^2) ,while TEMPO's will be 2.5×4.0 km^2 (~1.0×1.5 mi^2) at the center of the field of regard (FoR), varying with measurement geometry for other locations. **Image credit: Lok Nath Lamsal**, [GSFC/Universities Space Research Association].

Instruments flying on polar Sun-synchronous satellites observe a given location about twice per day. Instruments that observe in the UV/VIS wavelengths provide coverage only in daylight hours. On the other hand, the geostationary location of TEMPO will provide the first-of-kind capability to observe chemically active atmospheric constituents nearly continuously in daylight for given locations. Emissions that result in pollution vary strongly with weather and sunlight; therefore, pollution events occur over a broad range of temporal and spatial scales, from the rapidly varying (e.g., hourly variations in the local planetary boundary layer) to daily and longer (e.g., continental-scale transport events). Quantifying these processes requires continuous, high-spatial and -temporal-resolution measurements possible only from geosynchronous orbit. Such observations will provide crucial data to separate and quantify the effects of chemical and dynamical processes, which will enable more-accurate forecasts of pollution events.

With both high temporal and spatial resolution, TEMPO data will improve emission inventories, monitor population exposure to pollution, and make possible effective emission control strategies by regulatory agencies.

Instrument and Mission Capabilities

Instrument

TEMPO's spectrometer design will incorporate many of the features and lessons learned from heritage spectrometers flown by Europe and the U.S. The key instrument characteristics and capabilities are:

- *Spectral range*: 290–690 nm; *Spectral sampling*: 0.2 nm; *Spectral resolution*: 0.6 nm.
- *Spatial resolution:* 2 km per pixel in the north-south direction, 4.5 km per pixel in the east-west direction at the center of the field of regard (FoR)—36.5° N, 100° W.
- *Hourly measurements* stepping east to west of the entire FoR (2.5 ×10^6 spectra per hour).
- *Signal/noise requirements* met at solar zenith angles less than 50° for all products—and at angles up to 70° for NO_2, clouds, and aerosols.
- *Ozone profile products* include 0–2 km O_3, free tropospheric O_3, and the stratospheric O_3 column.

TEMPO measurements will capture the high variability in the diurnal cycle of emissions and their evolving chemistry, which occurs mostly during the day. TEMPO's footprint—smaller than for previous missions measuring air quality—will resolve pollution sources at suburban scales. With both high temporal and spatial resolution, TEMPO data will improve emission inventories, monitor population exposure to pollution, and make possible effective emission control strategies by regulatory agencies.

An example of the TEMPO temporal capability is shown in **Figure 2**. The figure depicts a model calculation of column amounts of NO_2 over the course of two days based on emissions, photochemistry, and the local meteorology. Two observations from OMI over the same location are also indicated, illustrating the limitations of a polar-orbiting satellite for observing evolving time-of-day processes. The TEMPO observational period shown will be similar to the model calculations, but limited to daytime and cloud-free scenes. TEMPO's near-continuous observations will be superior to polar orbiting satellite data for verifying model predictions and likely observe features not seen in the model. It is also anticipated that data in the boundary layer will be significantly improved with TEMPO's higher spatial resolution, which is made possible by longer integration times from geostationary orbit.

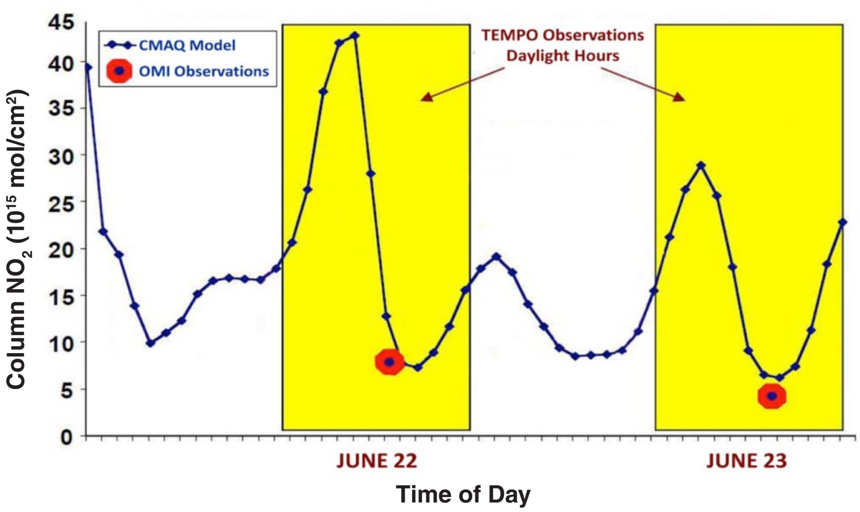

Figure 2. This graphic shows diurnal variation of NO_2 over Houston, TX, calculated from the Community Multi-scale Air Quality (CMAQ) model. The daily OMI observations, taken about 1:15 PM local time, are also shown. For this location, maximum NO_2 appears in the morning (responding to traffic congestion) with a second peak in the (evening rush-hour period). OMI data, which agree reasonably well with CMAQ output, are limited to the time period during the lull between the two rush hours. Continuous sampling by TEMPO during the daylight hours will completely overcome this sampling limitation. **Image Credit:** J. Fishman

Mission

The mission's key capabilities are listed here:

- *Geostationary location* at 100° W longitude—proposed to cover Greater North America.
- Planned *data latency* is two hours (near real-time) for air quality products developed with the EPA and NOAA.
- A *two-year operations (Phase-E) period*, driven by the cost cap. Instrument lifetime—allowing extended operations—is much greater.

TEMPO will observe the components of pollution and their source gases over all major cities and industrial areas in Greater North America (i.e., coverage similar to Figure 1). EPA has designated O_3, SO_2, NO_2, and aerosols as *criteria pollutants,* and are recognized to be harmful to health and the environment and cause property damage. Major *proxies* for air pollution include formaldehyde and glyoxal in the atmosphere, indicating the presence of non-methane volatile organic compounds (NMVOC) emissions. The short lifetime of NMVOCs make them ideal for locating the source of emissions from natural and anthropogenic processes, including biomass burning. **Figure 3** illustrates the TEMPO instrument's FoR for a one-hour measurement cycle.

Figure 3. TEMPO's FoR is outlined in green. The spread with increasing latitude is due to the projection of the FoR as seen from geostationary orbit where the satellite is over the Equator. The narrow white band is an exaggeration of TEMPO's field of view [nominally 4.5 km (~2.8 mi)], which scans from east to west over the course of an hour. The coverage from south to north will include the range from Mexico City to the Canadian tar sands. **Image Credit:** Ball Aerospace & Technology Corp.

Selecting a Host for TEMPO

By fall 2017 the TEMPO PI and science team will deliver the instrument for integration into an appropriate, yet to be determined, *host* commercial geostationary satellite. The "hosted payload" concept, under development for years by NASA as an alternative access to space, has now come to fruition with the EVI-1 solicitation issued by the Earth Science Division of NASA's Science Mission Directorate. "Commercial satellite and launch suppliers have for a long time held excess capacity, which they would like to see exploited, while NASA continued to search for low-cost opportunities for access to space to implement its Venture Class missions—and now these two needs seem to be coming together," said **Sanghamitra Dutta** [NASA Headquarters, Earth Science Division—*TEMPO Program Executive*]. While this is an unprecedented approach for access to space for NASA, it has been successfully implemented with a U.S. Department of Defense (DoD) space mission.

Fortunately, Korea and Europe plan to develop and launch their own geostationary satellites.... [with] measurement capabilities and science objectives similar to TEMPO. Therefore it will be possible, with a minimum of three geostationary satellites positioned to view Europe, East Asia, and North America, to collectively provide near-global coverage (in the Northern hemisphere).

To implement the TEMPO mission, the PI, science team, and the Earth System Science Pathfinder Program Office will generate a set of instrument accommodation and observational requirements during Phase A (ending late summer 2013), including mass; power; electrical and mechanical interfaces; and spacecraft services, including geolocation, pointing stability, contamination control, and data rate. Once the TEMPO instrument requirements are well established, NASA will release a request for proposal to select the appropriate commercial host provider. To further facilitate the hosting process, NASA is planning to participate in the Air Force's Indefinite Delivery/Indefinite Quantity (ID/IQ) Hosted Payload Solution program for a study contract to establish necessary interfaces with possible TEMPO payload hosts.

The PI-led TEMPO mission costs—capped at $90 million—must result in the delivery of an instrument, data acquisition and processing at the PI institution (i.e., Smithsonian Astrophysical Observatory), and data delivery to the NASA archive for two years of operations (Phase A through Phase D and Phase E Mission Operations and Data Analysis). The cost of integration and test of the instrument with the host platform and the cost of launch are outside of the cap. Launch vehicles for several commercial communication satellites are expected to be suitable for hosting TEMPO in the 2018-2019 launch timeframe. However, a specific launch date is not on the critical path, so NASA can opt for the best value.

International Collaboration

A single geostationary satellite views only one sector of the globe, limiting the capability to observe sources of pollution outside the instrument FoR. Fortunately, Both Korea and Europe [the European Space Agency (ESA) and Eumetsat] plan to develop and launch their own instruments to fly on geostationary satellites to measure air composition and quality in the 2017-2022 timeframe. These missions will have measurement capabilities and science objectives similar to TEMPO. Therefore, it will be possible, with a minimum of three geostationary satellites positioned to view Europe, East Asia, and North America, to collectively provide near-global coverage in the Northern Hemisphere. The synergy of contemporaneous satellite missions having similar observing capabilities and data distribution protocols will provide unique opportunities to advance understanding of the interactions between regional and global atmospheric composition in the troposphere. This would include assessments—not possible before—of emission sources, intercontinental pollution transport, and regional interactions between air quality and climate. These activities would address several *societal benefit areas* of the Global Earth Observation System of Systems (GEOSS), listed online at *www.earthobservations.org/geoss.shtml*.

In addition to TEMPO, the European Sentinel-4[6] and the Korean MP-GEOSAT[7] missions have been approved. By harmonizing these missions it is possible to improve the scientific return and societal benefit of each of the individual missions while beginning a global observing system that will be impossible for any one country to implement alone. Best efforts to cooperate on defining common requirements and data products can enable improved designs for all instruments and allow cost savings by minimizing duplication of effort. While recognizing that unique requirements likely exist for individual missions, this approach defines common objectives that build a foundation for a future integrated observing system for atmospheric composition, as envisioned in 2004 by the Integrated Global Observing System[8].

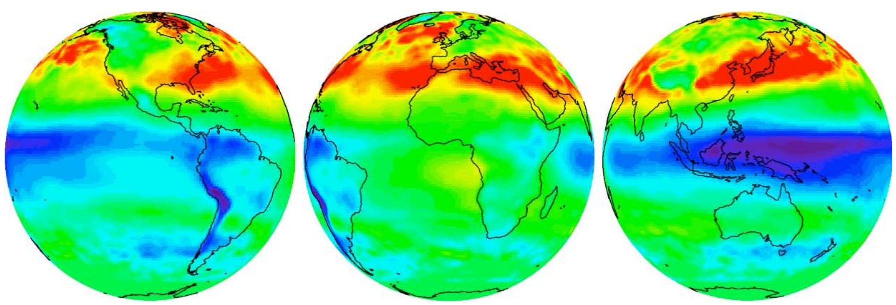

Figure 4. These images show simulation of average tropospheric ozone—an indicator of poor air quality—using data from Aura's OMI and Microwave Limb Sounder (MLS) when viewed from three geostationary positions over major continents for May-July 2008. The three geostationary missions (i.e., originated by NASA, ESA, and Korea) however, will focus on the Northern Hemisphere only. Shades of purple and blue correspond to 10-20 Dobson Units (DU) representing low ozone amounts while lighter shades correspond to 35-50 DU. Green, yellow, and red indicate high-pollution areas. **Image credit: J. Ziemke,** GSFC, and the OMI and MLS instrument and algorithm teams.

The simultaneous development of these individual missions to acquire data over Earth's major industrialized regions presents a real opportunity for international collaboration to improve the preparation for these missions and their combined capabilities within a global system. Best efforts are all ready underway to cooperate on defining common measurement requirements, retrieval algorithms, validation, data quality, and access to achieve the above goals. Consistency of data products will result in better understanding of the science, improved application capabilities, and subsequent use by regulatory agencies. The potential global coverage of the three geostationary missions, separated by roughly 120° in longitude, is depicted in **Figure 4**. Demonstrating this synergy is an ongoing effort by the Committee on Earth Observing Systems and has been described in, *A Geostationary Satellite Constellation for Observing Global Air Quality: An International Path Forward,* which can be found online at *www.ceos.org/images/ACC/AC_Geo_Position_Paper_v4.pdf*.

continued on page 35

[6] Sentinel-4 (anticipated 2019 launch) will carry the Ultraviolet-Visible-Near infrared imaging spectrometer (UVN).

[7] MP-GEOSAT (anticipated 2018 launch) will carry the Geostationary Environment Monitoring Spectrometer (GEMS).

[8] For more information, visit: *ftp.wmo.int/Documents/PublicWeb/arep/gaw/gaw159.pdf*.

Ecosystem/Oceanography

K. Iwao [GSJ/AIST] began by offering a summary of ASTER-related ecology research activities in Japan. He then discussed the current status of the ASTER/AIST Global Urban Area Map (AGURAM). Employing an automated method for integrating ASTER images and GIS data, AGURAM covers 3500 cities at 15-m resolution.

J. Kargel introduced a proposal requesting ASTER inputs to contribute to an in-depth biophysical survey of the Upper Seti Basin, Nepal. Year-round ASTER imaging would help improve understanding of the mass movement environment and processes, including snow avalanches, rockfalls, and debris flows.

L. Prashad [Arizona State University (ASU)] discussed ASU's 100 Cities Project and Java Mission-planning and Analysis for Remote Sensing (JMARS) for the Earth [J-Earth] activities. J-Earth updates include code integration with all JMARS products and the incorporation of *OpenStreetMap*[8] data. While the capability for users to directly import ASTER data is still under development, import is possible by processing ASTER data with *daVinci*[9] and using J-Earth as a display tool. The 100 Cities Project increased their global urban imagery holdings by obtaining all ASTER L1B, surface emissivity (AST05), and surface kinetic temperature (AST08) data for cities with populations over 500,000. The project is working with the LP DAAC to distribute these products as "Urban Bundles" with select urban-relevant datasets. Prashad concluded with examples of humanitarian remote sensing applications.

[8] Founded in the U.K. in 2004, *OpenStreetMap* is a GPS-based community project to generate editable global maps.
[9] *daVinci* is an interpreted language with vector-oriented features that works well as an image-processing tool.

G. Geller [JPL] discussed *TerraLook*[10] activities, including plans for an upcoming "TerraLook-inspired" version of Google Earth Engine.

STAR Committee

The committee heard, reviewed, and approved a new STAR proposal to support the HyspIRI preparatory aircraft campaign. Updates to the GLIMS and Volcano STARs will be forthcoming. **R. Crippen** reported that his GDEM/SRTM void-fill STAR proposal would be finalized by the end of January 2013. The STAR Committee will meet with the TES WG to discuss TGM modifications that will be required following the cessation of the SWIR data stream. The session concluded with the introduction of an action item to promote ASTER DAR and STAR capabilities.

Closing Plenary Session

All attendees reconvened to hear summaries from each WG session and to discuss issues proposed at the opening plenary. A short presentation by the instrument calibration team described their recommended actions to address VNIR response degradation, including fixing the RCC at present values so that RCC values do not deviate further from cross- and vicarious-calibration values. Attendees also discussed TGM data acquisition monitoring following SWIR data-off. Resource allocations will likely be rebalanced between day and night collections.

The meeting concluded with an announcement that the forty-third ASTER Science Team Meeting has been scheduled for June 10-12, 2013, in Tokyo, Japan. ■

[10] The *TerraLook* program provides no-cost access to ASTER and historical Landsat georeferenced *jpeg* images, along with a suite of simple visualization and analysis tools.

NASA Ups the TEMPO on Monitoring Air Pollution

continued from page 15

For More Information

On degradation of air quality over the Canadian tar-sand oil excavation fields

- McLinden, C. A., V. Fioletov, K. F. Boersma, N. Krotkov, C. E. Sioris, J. P. Veefkind, and K. Yang, Air quality over the Canadian oil sands: A first assessment using satellite observations, *Geophys. Res. Lett*., **39**, L04804, doi:10.1029/2011GL050273, 2012.

On the potential of observing air quality from geostationary orbit

- Fishman, J., et al., Remote sensing of tropospheric pollution from space. *Bull. Amer. Meteor. Soc.*, **89**, 805–821, 2008.

- Fishman, J., *et al.*, The United States' Next Generation of Atmospheric Composition and Coastal Ecosystem Measurements: NASA's Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission, *Bull. Amer. Meteor. Soc.*, **93**, 1547-1566, doi:10.1175/BAMS-D-11-00201.1, 2012. ■