TEMPO Aerosols and Clouds

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Outline

• Introduction: aerosols/clouds in TEMPO STM

• Aerosol data/science uniquely enabled by TEMPO
  1) hourly retrieval of aerosol absorption
  2) hourly retrieval of spectral AOD and surface reflectance
  3) hourly retrieval of aerosol centroid layer height

• Cloud data/science uniquely enabled by TEMPO
  – hourly retrieval of cloud optical centroid pressure from O2-O2 band

• TEMPO applications and synergy with other sensors
  1) surface networks, AOD-PM2.5 relationship
  2) with GOES-16 and GOES-17
  3) with TROPOMI, GMES, Sentinel-4 (S4), Sentinel-5 (S5), …
  4) with MODIS, MISR, VIIRS, MAIA
Importance of aerosols and clouds

**Aerosols are omnipresent,**
- affect retrieval of gases
- partially and collectively reflect emissions of various gases
- Integrated part of TEMPO objectives for AQ forecast & process studies
- Integrated part of TEMPO objectives for climate forcing studies

**Clouds are present 60%-70% of time,**
- Affect life cycle of gases and aerosols
- Key source of uncertainty for aerosol retrievals
- Integrated part of TEMPO objectives for climate forcing studies

<table>
<thead>
<tr>
<th>TEMPO Science Goals</th>
<th>TEMPO Objectives</th>
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<tr>
<td>Characterize the temporal and spatial variations of emissions important for AQ and climate; observe continental inflow and outflow of pollution. 1,2,5,6,7,8,9</td>
<td>Collect simultaneous high temporal and spatial resolution measurements of pollutants over Greater North America.</td>
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<tr>
<td>Understand how processes determine AQ over range of time and space scales. 1,2,5,6,7,8</td>
<td>Measure the major elements in tropospheric O\textsubscript{3} chemistry &amp; aerosol cycles.</td>
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<tr>
<td>Characterize the effect of episodic events, e.g. volcanic eruptions, wild fires and dust outbreaks, on AQ. 1,2,6,8</td>
<td>Observe aerosols &amp; gases for quantifying and tracking evolution of pollution.</td>
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<td>Determine how observations from space can improve AQ forecasts and assessments for societal benefit. 3,4,5,8,9</td>
<td>Integrate observations from TEMPO and other platforms into models to improve representation of processes.</td>
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<tr>
<td>Understand how air pollution drives climate forcing and how climate change affects AQ on a continental scale. 1,5,6,8</td>
<td>Determine the instantaneous radiative forcings associated with O\textsubscript{3}, aerosols &amp; clouds on the continental scale.</td>
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Table D.1-1 in TEMPO proposal
Aerosol data/science uniquely enabled by TEMPO
(1) hourly retrieval of aerosol absorption

Operational product led by O. Torres
- UV Aerosol Index,
- AOD and SSA (388 nm) using 354 and 388 nm measurements
- Heritage Algorithms : OMAERUV (Aura-OMI) & TropOMAER (S5P-TROPOMI)
- Status: ready at launch

Sciences
- Tracking smoke/dust plumes including in cloudy conditions
- Process understanding of aerosol particle evolution in the atmosphere
- Aerosol radiative absorption

For a given aerosol type and layer height, satellite measured radiances at 354 and 388 nm are associated with a set of AOD and SSA values.
From OMI (13x24 km at nadir) ..... August 18, 2018 wildfires

To TROPOMI (7x3.5km nadir) and TEMPO (~ 2x5 km)
Aerosol data/science uniquely enabled by TEMPO
(2) hourly retrieval of spectral AOD and surface reflectance

Research algorithm led by U. Iowa
– Simultaneous retrieval of spectral AOD, AOD fine-mode fraction, and surface reflectance
– New algorithm developed under support of GEO-CAPE, GEO-TASO, and TEMPO
– Status: prototype tested with KORUS-AQ data; continuing with GCAS data;

Sciences
– Hourly analysis of aerosol size
– Process understanding of aerosol particle evolution in the atmosphere
– Improve estimates of aerosol radiative forcing

An algorithm for hyperspectral remote sensing of aerosols
2. Information content analysis for aerosol parameters and principal components of surface spectra, JQSRT. 2017.
Results in KORUS-AQ

In collaboration with Scott Janz @ GSFC NASA James Leitch @ Ball

Hou et al., *JQSRT*, 2020.
Aerosol data/science uniquely enabled by TEMPO
(3) hourly retrieval of aerosol centroid layer height

Research algorithm, U. Iowa & GSFC
– Retrieval of aerosol layer height (ALH) using O2 B-band.
– Heritage: EPIC/DSCOVR
– Status: prototype tested with TROPOMI data.

Sciences
– Mesoscale 3D view of aerosol movement
  Process understanding of aerosol injection and vertical transport in the atmosphere
– Improved estimate of surface PM2.5

Simultaneous Retrieval of ALH and AOD from O2B bands (680 vs. 688 nm)

S-NPP/VIIRS July 31, 2018

Retrieved Aerosol Layer Height

532 nm Backscatter

Comparison to CALIOP and KNMI O2A Retrieval

Tropomi 680 nm AOD vs MODIS 660 nm AOD

Courtesy: O. Torres
Retrieval of ACH and AOD from blue & O$_2$ B bands over land

for details, see Xi Chen’s poster

\[
ACH_{\text{CALIOP}} = \frac{\sum_{i=1}^{n} \beta_{\text{ext},i} z_i}{\sum_{i=1}^{n} \beta_{\text{ext},i}}
\]

- TROPOMI operational retrieval of ALH with O$_2$ A band has a negative bias of 1-2 km, and this bias increases with surface albedo (Nanda et al., 2020, AMT).

- Land surface reflectance at O$_2$ B band and blue band are much lower than in that in O$_2$ A band, which favor the retrieval of ALH.
Cloud data/science uniquely enabled by TEMPO
cloud optical centroid pressure retrieval from $O_2$-$O_2$ band

Courtesy: Alexander (Sasha) Vasilko & Joanna Joiner

• An advanced spectral fitting algorithm for retrieving $O_2$-$O_2$ slant column densities (Vasilkov et al., 2018)
  – Use of the temperature-dependent $O_2$-$O_2$ cross sections
  – Removal of $O_3$, NO$_2$, and H$_2$O absorption based on estimates of their slant column densities (SCDs) from independent algorithms
  – Account for specifics of surface reflectivity

• Hourly cloud optical centroid pressure (OCP) retrieved from the $O_2$-$O_2$ SCD (using LUTs with the DOAS-type approach); cloud fraction, etc.

• Status: adaptation for TEMPO geometry may need additional nodes of the LUTs
TEMPO applications and synergy with other sensors

1) importance of surface networks, AOD-PM$_{2.5}$ relationship,

PM$_{2.5}$ spatial auto-correlation in U.S.


Huanxin (Jessie) Zhang

Zhang et al., 2020, JGR
Diurnal variations of AOD and PM2.5 – what should we expect from geostationary satellite observations for air quality

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¹NASA Goddard Space Flight Center ²Bay Area Environmental Research Institute ³Now at Cornell University ⁴University of Maryland Baltimore County
Background

• Monitoring air quality from space has played a key role in our understanding of the status and trends of air pollution. The geostationary satellite data bring the possibility of getting hourly air quality

• Challenges: the AOD-PM$_{2.5}$ relationship is not constant but depends on many factors including
  • aerosol vertical profile (e.g., aerosol fraction in the PBL) – affecting PM$_{2.5}$ levels
  • chemical composition, size distribution – affecting PM$_{2.5}$ and AOD
  • relative humidity or water vapor amount – affecting AOD
  • Mesoscale and synoptic scale meteorology
Fresno 2013 as an example: Collocated AERONET AOD and EPA PM$_{2.5}$

19% of the days in 2013 the hourly AOD and PM$_{2.5}$ are correlated at $R \geq 0.7$ and 31% of the days they are negatively correlated.

- **a)** Examples of daytime hourly variations of AOD and PM$_{2.5}$ in four different days in May 2013
- **b)** Daily mean AOD and PM$_{2.5}$ in May 2013
- **c)** Monthly mean AOD and PM$_{2.5}$ in 2013

- AOD-PM$_{2.5}$ often have different variability on diurnal timescale
- AOD-PM$_{2.5}$ are better correlated on daily scale in the sub-seasonal time domain
- AOD-PM$_{2.5}$ ratios change significantly with seasons
Beijing 2015 as an example: Collocated AERONET AOD and surface PM$_{2.5}$

36% of the days in 2013 the hourly AOD and PM$_{2.5}$ are correlated at $R \geq 0.7$ and 25% of the days they are negatively correlated.

**a)** Examples of daytime hourly variations of AOD and PM$_{2.5}$ in four different days in September 2015

**b)** Daily mean AOD and PM$_{2.5}$ in September 2015

**c)** Monthly mean AOD and PM$_{2.5}$ in 2015

**Recommendations:**
1) Including diurnal variations of PBL height, RH or column water vapor, and effective aerosol layer height (can be obtained from satellite and ground stations) in deriving PM2.5 from TEMPO or GOES AOD data
2) Including aerosol composition and/or particle size and aerosol vertical profiles (can be estimated from limited observations, or from credible models or reanalysis)
Using a physically-based machine learning model to retrieve PM$_{2.5}$ from AOD:

Preliminary experiment with GEOS simulation as a test

- GEOS/GOCART output at 3-hourly, 0.5° horizontal resolution over the globe for the entire year of 2012
- Randomly select $2 \times 10^7$ data points as training dataset including variables of AOD, PM$_{2.5}$, PBL height, column water vapor, and aerosol vertical extinction profiles (surface to tropopause), and $6 \times 10^6$ independent data points to retrieve PM$_{2.5}$ from AOD

ML overestimates PM$_{2.5}$ in polluted areas but underestimates that in dust dominated areas, mostly likely due to no consideration of aerosol composition and/or size distribution in training.

Using the above ML to retrieve PM$_{2.5}$ from AERONET AOD and compared to EPA observations shows an overestimation.

(Preliminary study by Tianle Yuan, NASA GSFC)
TEMPO applications and synergy with other sensors (2) with GOES-16, GOES-17, and AQ applications

Synergy between GOES and TEMPO algorithms

- Cloud screening and sub-pixel cloud
- Spectral properties of aerosols and surfaces
- Multiple angle characterization of aerosol properties

- Retrieval of aerosol layer height, enabling OMI+MODIS type of algorithm for air quality applications

DFS for AOD are increased by TEMPO+GOES, especially near the exact backscattering angle. Wang et al., JQSRT, 2014.
To estimate PM2.5 concentrations of the air we breathe, we need temporally resolved AOD measurements.

Courtesy: S. Kondragunta
Suite of Aerosol Products from Imager/Spectrometer Synergy

Imager Pixel Resolution
- 2.2 um reflectance
- 4-level cloud mask
- Visible AOD

Spectrometer Pixel Resolution
- 2.2 um reflectance
- 4-level cloud mask
- UV AOD

NASA UV Aerosol Algorithm

Aerosol Optical Depth
Single Scattering Albedo
Aerosol type
Aerosol layer height

Courtesy: S. Kondragunta
Requirements for Synergy

- Orbital location of satellites carrying the imagers and spectrometers important
  - Longitudinal separation of 30° or less is desired
  - GOES-R (16) at 75.2°W and TEMPO at 100°W
  - Two to six 500m ABI pixels fall into each TEMPO pixel depending on whether the region of interest in near-nadir or off-nadir

Courtesy: S. Kondragunta
• GOES-R/TEMPO Synergy tested with S5P TROPOMI/SNPP VIIRS
• G2A AMI/G2B GEMS gives an opportunity to test the synergy from a geostationary orbit

\[
AAI = -100 \left[ \log_{10} \left( \frac{R_{0.41}}{R_{0.44}} \right) - \log_{10} \left( \frac{R'_{0.41}}{R'_{0.44}} \right) \right]
\]

\[
DSDI = -10 \log_{10} \left( \frac{R_{0.41}}{R_{2.2}} \right)
\]

Courtesy: S. Kondragunta
TEMPO applications and synergy with other sensors (3) with TROPOMI, GEMS, Sentinel-4 (S4), Sentinel-5 (S5), …

Use TROPOMI as a ‘bridge’ to bring together intercomparisons of aerosols/clouds products among different algorithms/sensors

- Aerosol centroid layer heights
  - GEMS O4 technique
  - TROPOMI/S5 O2 A-band *spectral fitting* technique
  - TEMPO O2 B-band *band-intensity* fitting technique
- Cloud centroid pressure
  - TROPOMI O4 technique
  - TEMPO O4 technique
  - GEMS O4 technique
  - Cloud fraction
- UV aerosol product
- AOD product

…
TEMPO applications and synergy with other sensors
(4) with MODIS, MISR, VIIRS, MAIA, …

TMEPO intercomaprsion with
– MISR aerosol/cloud stereo height
– MODIS/VIIRS cloud top height, cloud fraction, ….
– MISR/MAIA AOD, fine-mode AOD, …
– Surface reflectance

Synergy with VIIRS for nighttime AOD and nighttime light pollution studies
– VIIRS + TEMPO have the potential to characterize the surface light bulb type and spectral intensity
– VIIRS + TEMPO may lead to improved retrieval of nighttime AOD and fire confusion efficiency

Carr et al., JRSL, 2017.
Nighttime AOD and PM$_{2.5}$ mapping
for details, see Meng Zhou’s poster

Needs:
• NAAQS requires 24-hr averages.
• Nighttime AOD data enriches model evaluation and data assimilation & forecast

TEMPO + VIIRS
• TEMPO: derive urban light spectra
• VIIRS: retrieve AOD and derive surface PM$_{2.5}$

PM$_{2.5}$: 5 ug/m$^3$

7 Sep. 2012
8 Sep. 2012

Atlanta

Wang et al., AE, 2016
TMEPO+VIIRS have the potential to advance surveillance of light pollution and studies of light pollution on public health

- 99% U.S. population live with light-polluted activities skies (Falchi et al., Sci. Adv., 2016)
- Light pollution leads to circadian disruption & sleep deficiencies, affecting human health.
- Photoreceptor cells critical to circadian regulation in human eyes peaks at blue wavelength

ISS nighttime image over Houston on 9 Aug. 2014
Summary

• Daytime hourly retrieval of aerosol absorption, spectral AOD and surface reflectance, as well as aerosol centroid layer height, which can advance AQ forecast and climate forcing studies (a key component of TEMPO STM).

• Daytime hourly retrieval of cloud centroid pressure and cloud fraction.

• Strong synergy with other sensors and surface networks to characterize AOD, fine-mode AOD, aerosol/cloud layer height.

• New nighttime observations to explore surface light pollution, AOD and surface PM$_{2.5}$ air quality, fires, ....

• Many exciting products can be on the way provided there are resources support.

• An emergent era for aerosol layer height retrieval also calls for validation planning with surface networks of ceilometer/lidar and space-borne lidar (especially after CALIOP).
Ceilometer Network

- Research Collaboration between EPA, University of Maryland, Baltimore County (UMBC), Maryland Department of the Environment (MDE), and NASA - https://alg.umbc.edu/ceilometer-network/

- Objectives:
  - Maximize the science and applications value of ceilometer measurements at EPA Photochemical Assessment Monitoring Station Network
  - Allow for ceilometers at non-PAMS sites to become part of a larger network
  - Development and application of standardized retrieval algorithms for heterogeneous network
  - Development of data archive for ceilometer backscatter profiles and associated geophysical data products – mixing layer heights/aerosol layers heights/cloud based heights
  - PAMS/Ncore sites contains a suite of trace gases and aerosols, subset of sites with Pandoras
  - Used to support model development and evaluation and EPA exceptional events analysis
  - Collaboration with MPLNet to extend use of data through WMO
  - Operational by June 2021

PAMS sites with requirement for hourly MLH

Courtesy: James Szykman
Vanessa Caicedo
Ruben Delgado
Thank you!

TEMPO, GEO-CAPE, ACMAP, KORUS-AQ, Applied sciences
Backup slides
Large uncertainty in aerosol vertical profile

Sulfate  Sea Salt  Black Carbon
Organic  Mineral dust

Annual- and zonal-mean mass-weighted mean pressure level (vertical center of mass in pressure coordinates)

Kipling et al., 2016; ACP. AeroCOM-II
Large uncertainty in our modeling of aerosol vertical profile highly relevant to climate and air quality prediction

Uncertainty in free troposphere and UTLS is the very large; but this part of the atmosphere is also where lidar is best at for observing.

Annual and global mean normalized shape of aerosol vertical profile

Kipling et al., 2016; ACP. AeroCOM-II
$h = \frac{d}{\tan \theta_F + \tan \theta_A}$

Forward view

Afterward view

Aerosol plume
TEMPO, GEO-TASO, and GCAS

TEMPO
290–490 nm  540–740 nm
λ sampling: 0.2 nm
Resolution/FWHM: 0.57 nm

GEO-TASO
290-400 nm  415-695 nm
λ sampling: 0.14/0.28 nm
Resolution/FWHM: ~0.4 nm/ 0.8 nm

GCAS
300–490 nm  480–900 nm
λ sampling: 0.2/0.8 nm
Resolution/FWHM: 0.6/2.8 nm

Kelly Chance (Harvard – Smithsonian)