A climatology of visible surface reflectance spectra

Peter Zoogman*, Xiong Liu, Kelly Chance, Qingsong Sun, Crystal Schaaf, Tobias Mahr, Thomas Wagner

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, United States
University of Massachusetts Boston, Boston, MA, United States
Max Planck Institute for Chemistry, Mainz, Germany

A R T I C L E   I N F O

Article history:
Received 26 January 2016
Received in revised form 4 April 2016
Accepted 4 April 2016
Available online 13 April 2016

Keywords:
Surface reflectance
Ozone
Satellite
Retrieval
Trace gas
Albedo

A B S T R A C T

We present a high spectral resolution climatology of visible surface reflectance as a function of wavelength for use in satellite measurements of ozone and other atmospheric species. The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument is planned to measure backscattered solar radiation in the 290–740 nm range, including the ultraviolet and visible Chappuis ozone bands. Observation in the weak Chappuis band takes advantage of the relative transparency of the atmosphere in the visible to achieve sensitivity to near-surface ozone. However, due to the weakness of the ozone absorption features this measurement is more sensitive to errors in visible surface reflectance, which is highly variable. We utilize reflectance measurements of individual plant, man-made, and other surface types to calculate the primary modes of variability of visible surface reflectance at a high spectral resolution, comparable to that of TEMPO (0.6 nm). Using the Moderate-resolution Imaging Spectroradiometer (MODIS) Bidirection Reflectance Distribution Function (BRDF)/albedo product and our derived primary modes we construct a high spatial resolution climatology of wavelength-dependent surface reflectance over all viewing scenes and geometries. The Global Ozone Monitoring Experiment–2 (GOME-2) Lambertian Equivalent Reflectance (LER) product provides complementary information over water and snow scenes. Preliminary results using this approach in multispectral ultraviolet + visible ozone retrievals from the GOME-2 instrument show significant improvement to the fitting residuals over vegetated scenes.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Tropospheric ozone is a principal component of urban smog and a major contributor to anthropogenic global warming. Ozone over the current Environmental Protection Agency (EPA) air quality standard of 75 ppbv affects 53 million people in the United States [33], more than any other air pollutant. Tropospheric ozone has the third-largest short-term radiative forcing among anthropogenic greenhouse gases [14]. Tropospheric ozone is formed by the reaction of nitrogen oxide radicals ($$\text{NO} + \text{NO}_2 = \text{NO}_3$$) and volatile organic compounds (VOCs) in the presence of sunlight. However, no current measurements of ozone and its precursors combine the spatial density, temporal frequency, and vertical resolution to observe and attribute harmful air quality. Surface and ozonesonde measurements are too spatially sparse to capture ozone distributions [10]. Satellite measurements of ozone and related atmospheric gases have become an increasingly powerful tool over the past two decades [22], but are limited by poor sensitivity to near-surface ozone and return times of at best one day [9].
The Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument holds much promise in addressing the current shortcomings in the air quality observing system [5]. TEMPO will be launched in 2018–2020 and will be stationed in geostationary orbit, providing hourly measurements at $4 \times 8$ km$^2$ spatial resolution over the US, southern Canada, and northern Mexico. This mission is a member of a global geostationary constellation of air quality focused satellites, which also includes Sentinel-4 over Europe [13] and GEMS over East Asia [1,15]. TEMPO will observe in ultraviolet (UV) and visible spectral regions (290–490 nm and 540–740 nm) to measure ozone and ozone precursors including NO$_2$, HCHO, and glyoxal. Observation in the weak Chappuis band takes advantage of the relative transparency of the atmosphere in the visible to achieve sensitivity to near-surface ozone [25,30,6]. It has been shown that combining the UV and visible spectral regions at a high temporal resolution is necessary for TEMPO to achieve its air quality mission objectives [39].

Due to the weakness of ozone absorption features in the visible [3] the combined UV+visible measurement is sensitive to the visible surface reflectance, which is highly variable not only spatially and temporally but also as a function of wavelength. The surface reflectance spectrum describes the ratio of reflected radiation to incident solar radiation at every wavelength. The reflectance and its spectral dependence vary based on the physical and biological properties as well as the solar illumination and viewing geometry for each satellite measurement. The spatial variation of surface reflectance at discrete wavelength bands has been characterized by many land imaging satellite instruments, including Moderate-resolution Imaging Spectroradiometer [MODIS, [28]], Multi-angle Imaging SpectroRadiometer [MISR, [23]], and Polarization and Directionality of the Earth’s Reflectances [POLDER, [16]]. In addition, the capability of these instruments to observe the same surface scene from many angles has allowed surface anisotropy to be calculated. These studies represent a valuable resource to inform current and future multispectral ozone retrievals.

Current operational satellite retrievals of atmospheric trace gases in the UV and visible spectral regions do not account for the variability of surface reflectance spectrum and its anisotropy. This can lead to large errors in measured trace gas amounts [26,38]. Russell et al. [27] utilized the MODIS albedo product to develop a new NO$_2$ retrieval from the OMI satellite instrument that showed better agreement with aircraft measurements than the operational OMI retrieval, which uses a much more spatially coarse albedo. Similarly, McLinden et al. [24] used the MODIS albedo product for improved OMI retrievals of NO$_2$ and SO$_2$ over Canadian oil sands. However, due to the narrow bands used in the retrievals of these gases a full surface reflectance spectrum was not needed. Conversely, multispectral ozone retrievals require continuous surface reflectance spectra. A key advancement of this study is the development of surface reflectance spectra as a function of wavelength targeted at the visible region by combining the spatially dense (but spectrally discrete) information from satellites with continuous surface spectra that capture the potential variability of surface reflectance.

To calculate the primary modes of variability of visible surface reflectance at a spectral resolution comparable to that of TEMPO (0.6 nm) we utilize reflectance measurements of individual plant, man-made, and other surface types. Using the MODIS Bidirectional Reflectance Distribution Function (BRDF)/albedo gap-filled product and our derived primary modes we construct a high spatial resolution climatology of wavelength-dependent surface reflectance over all viewing scenes and geometries. We incorporate the Global Ozone Monitoring Experiment-2 (GOME-2) Lambertian Equivalent Reflectance (LER) product [32] to extend coverage to snow/ice and water scenes. We implement the use of surface albedo EOFs in combination with the MODIS BRDF climatology for fitting GOME-2 visible radiances in our GOME-2 ozone profile retrieval algorithm to test the efficacy of our approach.

**Fig. 1.** Land reflectance spectra and EOFs used in this study. The left panel shows the individual surface reflectance spectra for the land cover types that compose our land cover database. Vegetation spectra (green) share a peak in the green (500–600 nm) and high reflectance in the near-infrared (NIR). The right panel shows the mean and four leading EOFs of the set land cover spectra. The inset numbers are the amount of variance explained by each EOF. We find that the first four EOFs capture over 99% of the spectral variation of the land surface reflectance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
2. Visible surface reflectance variability

To capture the range of different surface reflectance spectra we use spectra from three different reflectance databases: University of Heidelberg and Max Planck Institute for Chemistry (UH/MPIC) vegetation, Jet Propulsion Laboratory, Advanced Spaceborne Thermal Emission Reflection Radiometer (JPL ASTER), and United States Geological Survey (USGS). The land surface in the conterminous US is primarily covered in crops and natural vegetation (approximately 83%, NLCD 2011) and thus having a state-of-the-science database for vegetation reflectance is of particular importance. We use a new high spectral resolution database of vegetation reflectance spectra taken at UH/MPIC by Mahr et al. [21] that covers the visible to NIR (360–900 nm). They used a spectrometer with a CCD detector to measure reflectance of samples taken from 93 plants and trees. A unique feature of this dataset is its spectral resolution of 0.3 nm, which is finer than that of TEMPO (0.6 nm). Mahr et al. investigated the variation in surface reflectance from three different databases we include the range of vegetation (approximately 83%, NLCD 2011) and thus a state-of-the-science database for vegetation reflectance is of particular importance. We use spectra from these databases that describe surface types expected in the TEMPO field of regard: soils, vegetation, and man-made materials. By combining spectra from three different databases we include the range of variation in surface reflectance in our spectra.

Fig. 1 (left panel) shows the reflectance spectra from the UC/MPIC, ASTER, and USGS databases used in this work. There are spectral patterns that stand out among different surface types. Vegetation spectra (green lines) have a peak in the green (500–600 nm) and a strong peak in the NIR, called the red edge. Soil spectra (blue lines) have increasing reflectance with wavelength; man-made materials (red lines) also have increasing reflectance with wavelength and can be brighter. The category of man-made materials includes 37 samples, such as concretes and roofing types, which are the dominant contributors to urban land cover. The spectral databases we use cover the variability from all the land cover types expected for the future geostationary satellites.

To capture the variability of surface reflectance contained in our composite dataset we perform an Empirical Orthogonal Function (EOF) decomposition, also known as a Principal Component Analysis. Each EOF represents a distinct mode of variability as a function of wavelength found in the dataset. Fig. 1 (right panel) shows the mean spectrum and the four leading EOFs for our spectral dataset as well as the percent of the spectral variation described by each EOF. While the enforced orthogonality of the EOFs precludes straightforward interpretation, we see features that conform to expectations. The 1st EOF (red line) has the features of a vegetation spectrum while the 2nd (green line) has characteristics from soils and man-made spectra along with a negative component of vegetation (due to orthogonality). The first 4 EOFs are the primary modes of variability and capture over 99% of the spectral variation of the land surface reflectance. The relative number of the different spectra types influence the ordering and magnitude of variability captured by EOF but should not significantly affect the shape of the EOFs we find. As the EOFs describe the variability about the mean spectrum, we can describe the reflectance spectra of any land satellite footprint as a linear combination of these 4 EOFs and the mean spectrum.

3. Surface reflectance from satellites

The surface reflectance spectrum in a given scene observed by a satellite instrument will be a mixture of the surface types described. To capture the spatial variability of surface types and their effect on surface reflectance we utilize the MODIS BRDF gap-filled product [28,29]. MODIS provides surface reflectance and its dependence on viewing geometry at four wavelength bands relevant to visible ozone retrievals, centered on: 469, 555, 645, and 859 nm. Observed reflectances are corrected for atmospheric and aerosol effects [35]. The MODIS product uses a RossThick-LiSparse Reciprocal model for the anisotropy of the surface reflectance [19], where the total reflectance is parameterized as a linear combination of three components: isotropic (Lambertian); volumetric reflectance (leaf/vegetation scattering); and gap-driven geometric reflectance (characteristic of terrain with shadows, e.g. forest or buildings). MODIS provides parameters $f_{iso}$, $f_{vol}$, $f_{geo}$ to compute the reflectance $R$ for a given wavelength $\lambda$ and viewing geometry:

$$R(\lambda, \theta, \phi) = f_{iso}(\lambda) + f_{vol}(\lambda)K_{vol}(\theta, \phi) + f_{geo}(\lambda)K_{geo}(\theta, \phi)$$

(1)

where the viewing geometry is described by the solar zenith angle (SZA, $\theta$), viewing zenith angle (VZA, $\theta$), and relative solar azimuth angle (SAA, $\phi$). $K_{vol}$, $K_{geo}$ are the contribution from the reflectance parameters given by the RossThick-LiSparse model based on the viewing geometry. The V005 BRDF parameters are provided at 30° (~1 km) horizontal resolution at an 8-day temporal frequency by inverting cloud-free and atmospherically corrected surface reflectance observations within a grid cell acquired by MODIS on board the Terra and Aqua satellites. Each 8-day product is computed based on daily sampling over a 16-day period. We calculated a climatology (2002–2011) of these 8-day periods in order to best capture the average seasonal variation. The ability to compute the reflectance at each viewing geometry is critically important to finding the correct shape of the surface reflectance spectrum, as the geometrical dependence of the reflectance can vary with wavelength [12]. Due to the occurrence of multiple scattering in typical atmospheric observations, surface reflection includes contributions from all directions rather than only from the observation geometry. The BRDF model is often integrated with the radiative transfer model to calculate the overall surface reflectance. MODIS also provides black-sky albedo (BSA) and white-sky albedo (WSA), which are respectively the direct and diffuse components of the total albedo. The overall albedo for a given scene can be approximated as the weighted average of these two
values, called the blue-sky albedo. The weighting is determined by the fraction of diffuse downwelling irradiance, which we calculate using the VLIDORT radiative transfer model [31]. Either the BRDF or the blue-sky albedo can be used to describe the reflectance properties of land surfaces using MODIS.

To extend surface reflectance to snow and water scenes, which are not included in the gap-filled MODIS product, we use GOME-2 Lambertian Equivalent Reflectance (LER). This provides global reflectance over all surfaces but at coarser temporal and spatial resolutions (0.5° × 0.5° monthly) and without any dependence on viewing geometry. GOME-2 LER has higher spectral resolution than MODIS reflectance products (9 channels instead of 4 channels in the 400–900 nm range). The monthly values are averaged from observations over the 2007–2013 period. Similar to the MODIS algorithm, the GOME-2 product removes the modeled atmospheric contribution from the observed top of the atmosphere radiance, but here the surface is assumed to have uniform reflectance in all directions (Lambertian). Snow and water scenes are more spatially uniform than land scenes, so coarse resolution of the GOME-2 LER introduces less error. MODIS observations include coastal regions and are used to distinguish the boundaries between and land and water scenes that may not be resolved by the coarser resolution GOME-2. Snow scenes act as Lambertian reflectors over the range of viewing geometries planned for TEMPO (< 70° SZA; [20,8]). While ocean scenes can have a strong anisotropic reflectance effect (glint), this anisotropy is similar over the visible range [11]. This means that there is no significant spectral dependence on viewing geometry in visible wavelengths, i.e. glint affects all visible wavelengths equally. Thus, ocean glint should not affect the shape of the reflectance spectrum and so using a Lambertian satellite product over the open ocean will not negatively affect the ozone profile retrieval. This exploits the fact that for trace gas retrievals the shape of the reflectance spectrum, not the magnitude, is the relevant information.

4. Land surface reflectance

To construct the surface reflectance spectrum of a given land scene we combine the satellite-derived reflectance at discrete wavelengths with the EOFs capturing the variation in land reflectance. A continuous spectrum is needed for the multispectral ozone retrievals but the satellite data are only for discrete wavelength bands; hence the EOFs are needed. To determine the contribution of each EOF to the surface spectrum we perform a linear fit of the EOFs to the satellite-derived surface reflectances. This is done by solving for \( x \), the vector of relative contributions of each EOF in the equation

\[
Ax = b
\]  

where the columns of \( A \) are the values of each EOF at the satellite measurement wavelengths and \( b \) contains the satellite-derived reflectances at those wavelengths with the mean land surface reflectance removed. In the case of using MODIS and the four leading EOFs (Fig. 1b) \( A \) is a square matrix and Eq. (2) can be solved exactly. If the number of satellite wavelengths and EOFs does not match (e.g. using GOME-2 LER or changing the number of EOFs fitted) the equation does not have an exact solution. We then solve for \( x \) that minimizes the sum-of-squares error

\[
x = (A^T A)^{-1} A^T b
\]  

In either case we reconstruct our best estimate of the surface reflectance spectrum as a linear combination of the mean surface reflectance and the EOFs fitted, with the coefficients given by the corresponding values of \( x \). The calculation of \( x \) is fast since \((A^T A)^{-1} A^T \) can be pre-calculated once the discrete wavelengths are selected. This algorithm has been implemented both for BRDF and albedo products.

This method is similar to that employed by Vidot and Borbas [36] to construct the Radiative Transfer for the Television infrared observation satellite Operational Vertical sounder (RTTOV) reflectance database. However, our product differs by: (a) limiting the wavelength window for the EOF calculation and fitting to 400–900 nm compared to 400 nm to 2.5 \( \mu \)m and (b) inclusion of a high-resolution vegetation spectra database. This leads to EOFs and land

**Fig. 2.** Continuous land surface reflectance spectra from fitting land Empirical Orthogonal Functions (EOFs) to MODIS reflectances (x’s) for a proposed TEMPO viewing geometry. The seasonal variability of the reflectance spectra is shown over a forested scene in New York (75°W, 41°N) and over an urban scene (Boston, MA; 71°W, 42°N).
spectra that are more accurate for the visible spectral range relevant for TEMPO ozone and other trace gas retrievals; RTTOV was developed principally for NIR applications. The wavelength window is limited on the UV side of the domain to 400 nm due to limitation of both the spectral databases and satellite BRDF data. EOF decomposition is found to perform better at capturing the variability of surface reflectances than using average spectra for each land cover classification.

Fig. 2 shows examples of fitting the EOFs to MODIS BRDF data for two scenes for dates spanning a seasonal cycle. The MODIS reflectances ($x'$s) are calculated using the BRDF kernels using a proposed TEMPO viewing geometry (geostationary orbit over 100°W). The left panel shows reflectance spectra for a forested scene in New York State (75°W, 41°N), where the surface reflectance strongly resembles the vegetation reflectances from Fig. 1a. There is seasonal variation, but the vegetation signal is dominant throughout the year; the scene is a combination of ever-green and deciduous vegetation. The right panel shows reflectance spectra for the city Boston, where the surface reflectance spectra is a combination of vegetation and man-made materials. Boston is shown for comparable viewing geometry between the two scenes. The seasonal variation for Boston is damped compared to the forested scene due to the lower vegetation fraction. These examples demonstrate how the combination of satellite reflectances and land reflectance EOFs can be used to account for the temporal and spatial variability of the surface reflectance spectrum. These examples also highlight the usefulness of the MODIS channel centered at 859 nm for the shape of the visible surface reflectance, even though it is not in the visible itself: this channel helps constrain the vegetation fraction of the scene and thus the contribution to the overall spectrum of the vegetation reflectance.

Although TEMPO will be observing from a fixed point relative to the surface of the Earth, the anisotropy of the surface reflectance (or BRDF) must be accounted for due to the differences in viewing angle from scene-to-scene, the changing position of the incident solar radiation relative to both the surface and TEMPO, and the various degrees of multiple scattering. Fig. 3 shows the effect of the sun’s position on surface reflectance at 600 nm, the peak of ozone absorption in the Chappuis band, for three scenes. The VZA for each pixel is fixed (geostationary orbit over 100°W) but the circles show the surface reflectance for the full range of SZAs and SAAs. The SZA is given by the radial distance and the SAA is given by the angle from the bottom of each plot. The reflectance at 600 nm is computed by finding the MODIS reflectances for the given geometry and fitting the land reflectance EOFs. We compare two scenes at similar viewing angles with different surface types (left and center panels) and two urban scenes at greatly different viewing angles (center and right panels). Generally, scenes are brighter in a back-scattered viewing geometry, when the sun is on the same side of a scene as the satellite (bottom half of panels) than in a forward-scattered viewing geometry. We see that the dependence on the solar position of the reflectance is significantly different for different land types and viewing angles.

5. Snow and ocean reflectance spectra using GOME-2

To generate surface reflectance spectra for scenes not captured by the MODIS BRDF product we use the GOME-2 LER product at seven visible reflectance channels. The limitations of GOME-2 LER (coarse spatial resolution, does not account for anisotropy) are minimized for snow and ocean scenes, as discussed in Section 3. As the spectral variability over these scenes is less well characterized in the reflectance databases, the additional channels provided by GOME-2 over MODIS are beneficial. Further investigation of MODIS snow albedo products [37] could be beneficial for future TEMPO retrievals over snow. Over land scenes, we can also use the discrete GOME-2 LERs to generate LER spectrum. Fig. 4 shows the comparison of land surface reflectance spectra computed by fitting the calculated land EOFs to MODIS blue-sky albedo or GOME-2 LER. The black line is the mean difference over the TEMPO field of regard over the year for snow-free land scenes and the red lines denote the middle 68% (2σ) of the differences at each wavelength. The fitted spectra show very good agreement for wavelengths shorter than 700 nm. This agreement holds particularly true between 500 nm and 700 nm where the ozone absorption in the Chappuis band is strongest. This gives confidence that using MODIS and GOME-2 reflectances to retrieve ozone profiles over different scenes will not introduce significant errors. The positive MODIS bias relative to GOME-2 for wavelengths

![Fig. 3. Surface reflectance at 600 nm (the peak of visible ozone absorption) as a function of solar position for 3 scenes viewed from TEMPO geostationary orbit (100°W). The radial distance is the solar zenith angle (0° at the center to 90° at the edge) and the angular distance from the bottom of the plot is the relative solar azimuth angle between the sun and the satellite.](image-url)
longer than 700 nm is likely due to the GOME-2 LER product not extending into the red edge at as long a wavelength as the MODIS blue-sky albedo (772 nm vs. 859 nm).

We generate continuous spectra for snow/ice and ocean scenes by adding a mean snow/ice spectrum and a mean ocean spectrum from the USGS database to our suite of land EOFs. We then fit this extended set of primary modes of variability to the GOME-2 LER product over snow/ice and ocean scenes. Fig. 5 shows an example of this algorithm for a scene in Canada (110°W, 60°N) that transitions from snow-covered to vegetated during late winter to early spring. In February the scene is snow-covered: the reflectance is close to unity and mostly constant with wavelength, apart from the decrease starting at 750 nm. These features agree with snow scenes measured from aircraft [20]. Over the following two months the snow fraction of the scene decreases: the reflectance becomes much lower and by April the spectrum primarily resembles vegetation. Fig. 6 shows the mean ocean spectra and its variation (red lines denote 95% of the spectra) globally over the yearly cycle. We show the aggregated statistics in this case since the variability of the ocean spectrum is much smaller than that of snow or land scenes. The magnitude and shape of this spectrum agrees well with airborne measurements of water reflectances by Varotsos et al. [34]. There may be additional variation in coastal waters; the significance of this variation on trace gas retrievals is still to be studied.

6. Improvements on GOME-2 visible spectral fitting

We have implemented the use of surface albedo EOFs in combination with the MODIS BRDF climatology for fitting GOME-2 visible radiances in our GOME-2 ozone profile retrieval algorithm. The GOME-2 algorithm was adapted from our GOME and OMI ozone profile algorithms [17,18] and was first described in Cai et al. [4] for ozone profile retrievals from UV radiances. It has been modified to perform ozone profile retrievals from joint UV (289–307 nm in band 1, 315–340 nm in band 2) and visible spectra. For visible, we use radiances in band 3 (540–595 nm) and band 4 (602–646 nm, excluding the overlapping region which has degraded quality), which contains most of the visible spectral region that contributes to ozone sensitivity. Prior to the use of surface EOFs, the surface albedo spectrum is fitted as polynomials for both UV and visible regions; this has been shown to perform well for UV retrievals and is still used for fitting the UV part. To take advantage of the visible surface reflectance spectrum developed in this study, we use MODIS BRDF parameters averaged over the GOME-2 footprint to derive the blue-sky albedo at the four MODIS wavelengths for the given observation geometry. The four EOFs in Fig. 1 and the derived MODIS albedos are combined to initialize the surface albedo spectrum based on Eq. (2). The three leading EOFs matching MODIS values are currently further fitted in the retrievals.

To show the improvements of GOME-2 visible spectral fitting with the use of surface EOFs, we compare with retrievals that fit visible surface albedo as a second-order polynomial (also with 4 parameters). Fig. 7 shows such an example for a GOME-2 pixel over the South-eastern United States, which is mostly covered with forest and agricultural vegetation. We find that the fitting residuals are significantly reduced from 0.83% to 0.14% with the use of four surface EOFs. Generally, we found significant improvement over vegetation scenes, but insignificant difference for soil and desert scenes that do not have much surface spectral structure in the selected spectral region. The use of four EOFs for visible surface reflectance in conjunction with high-resolution MODIS BRDF climatology is an important step toward using visible to improve retrieval sensitivity in the lower troposphere. Testing is ongoing on how to best use the combination of surface EOFs and satellite BRDF information. However, the above fitting still requires further optimization to reduce the systematic calibration differences among bands 2–4 as the visible fitting residual of 0.14% is still much larger than the random-noise of the spectra (~0.05%).

7. Summary

We developed a global climatology of surface reflectance spectra at high spectral resolution in the visible. Our goal was to produce this climatology for use in satellite retrievals of ozone and other atmospheric constituents. To accomplish this we used spectra from three different reflectance databases to capture the range of different surface reflectance spectra through an EOF analysis. We then utilized the MODIS BRDF and GOME-2 LER satellite products which inform the surface reflectance at discrete wavelengths for each given scene. By fitting our high spectral resolutions EOFs to the satellite-derived reflectances we generated a climatology of geometry dependent surface reflectance spectra for all locations and days of the year. We implemented the use of surface albedo EOFs in
combination with the MODIS BRDF climatology for fitting GOME-2 visible radiances in our GOME-2 ozone profile retrieval algorithm. This algorithm is the forerunner of future ozone profile retrievals from the TEMPO mission, which has measurement of near-surface ozone as a primary mission objective. The surface reflectance information can be provided to the retrieval algorithm either as one surface spectrum or as BRDF parameters and surface EOFs; testing is currently ongoing as to the best method for multispectral ozone retrievals. These data are provided for each MODIS 8-day period and adjusted for the solar geometry for each retrieval.

An important component of this work is the inclusion of a high-resolution vegetation spectra database. This, along with limiting the wavelength window for the EOF calculation and fitting to 400–900 nm leads to land spectra that are as accurate as possible for the visible spectral range relevant for TEMPO ozone and other trace gas retrievals. The improvement shown over vegetated scenes for GOME-2 spectral fitting over vegetation is promising as the land surface in the conterminous US is primarily covered in crops and natural vegetation. The use of a surface albedo climatology is intended to support the near-real-time processing planned for TEMPO operational products. However, we can also exploit high time resolution satellite reflectance data for specific time periods (as becomes available) for TEMPO research products that are processed on a less time-sensitive basis. Also, further optimization of the ozone profile algorithm is needed since the fitting residuals remain above acceptable limits even after this quantification of the surface reflectance spectrum.

The TEMPO geostationary satellite mission represents a transformative development for remote sensing of ozone air pollution and related atmospheric species. Measuring near-surface ozone has presented a significant technical challenge but will yield great benefits in our understanding of tropospheric chemistry as well as our assessment and attribution of pollution events. The precise quantification of the visible surface reflectance spectra that we have performed has proved necessary to enable these ozone measurements.

Acknowledgments

This work was supported by NASA Grant NNX13AR40G.

References


