Multisensor Data Product Fusion for Aerosol Research

Pawan Gupta, Falguni Patadia, and Sundar A. Christopher

Abstract—Combining data sets from multiple satellite sensors is a powerful method for studying Earth–atmosphere problems. By fusing data, we can utilize the strengths of the individual sensors that may not be otherwise possible. In this paper, we provide the framework for combining level 2 data products, using data from three sensors aboard the National Aeronautics and Space Administration (NASA)'s Terra satellite. These data include top-of-the-atmosphere (TOA) radiative energy fluxes obtained from the Clouds and the Earth's Radiant Energy System (CERES), aerosol optical thickness from the multispectral Moderate Resolution Imaging Spectroradiometer (MODIS), and aerosol properties from the Multi-angle Imaging SpectroRadiometer (MISR). The CERES Single Scanner Footprint (SSF) contains the pixel level CERES TOA fluxes and the level 2 MODIS aerosol data. We specifically focus upon fusing the CERES SSF with the MISR aerosol products. Although this project was undertaken specifically to address aerosol research, the methods employed for fusing data products can be used for other problems requiring synergistic data sets. We present selected case studies over different aerosol regimes and indicate that multisensor information provides value-added information for aerosol research that is not available from a single sensor.

Index Terms—Aerosol forcing, aerosols, climate, Clouds and the Earth's Radiant Energy System (CERES), data fusion, Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR).

I. INTRODUCTION

ONE OF the major goals of the National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS) program is to study the Earth–atmosphere system in an integrated fashion [1]. As part of this vision, a series of individual and multisensor satellites was launched. The first EOS satellite, Terra, launched in December 1999, carried five sensors, including the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Measurement of Pollution in the Troposphere (MOPPIT) instrument, and the Clouds and the Earth’s Radiant Energy System (CERES). Since then, other satellites have been added, including: Aqua (in May 2002), which was dedicated to studying the Earth’s water cycle; the Aura (in July 2004), for studying air quality and stratospheric ozone; the Polarization and Anisotropy of Reflectances for 46 Atmospheric Science coupled with Observations from a Lidar (PARASOL), for studying clouds and aerosols; and the upcoming Orbiting Carbon Observatory (OCO) mission, for studying 49 atmospheric carbon dioxide. In April 2006, the Cloud–Aerosol 50 Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) 51 and CloudSat were also launched, and this combination of 52 Aqua, Aura, PARASOL, OCO, CALIPSO, and CloudSat flying 53 in formation within approximately 15 min of each other in a 54 low orbit is called the A-Train, which will further enhance our 55 research capabilities.

There is an increasing need to address scientific questions 57 with combinations of data sets, utilizing the strengths of indi- 58 vidual sensors and constraining weaknesses of others. These 59 combined data sets can provide value-added information that 60 would not be possible from one sensor only. In this paper, we 61 discuss the concept of combining CERES, MODIS, and MISR 62 (all aboard Terra) in the context of aerosol research.

CERES is a coarse spatial resolution (20 km² at nadir) broad- 64 band sensor that was designed to study top-of-the-atmosphere 65 (TOA) fluxes. MODIS and MISR have higher resolutions 66 (<1 km), enabling better study of clouds and aerosols. MODIS 67 has a larger horizontal swath, but MISR can address angular 68 information [2]. MODIS and MISR data, averaged to CERES 69 resolution, can help interpret CERES data as a function of 70 clouds and aerosols. In fact, the CERES team has done merging 71 of MODIS onto the CERES footprint, and this data set is 72 called the CERES Single Scanner Footprint (SSF) product [3]. 73 Level 1B MISR data have also been merged onto CERES SSF 74 [4] but is not fully operational. In this paper, we combine both 75 MODIS and MISR level 2 with CERES SSF data.

There are several data streams and products that are useful 77 for atmospheric aerosol, cloud, and radiation budget research. In this paper, we focus primarily on examples related to the study of aerosols. The fundamental data product from satellite sensors are geo-referenced calibrated radiances at the sensors’ original resolution. These data are known as level 1B. Retrieved 82 geophysical parameters are known as level 2 and are usually de- 83 rived at predefined spatial resolutions (e.g., 10 km² for MODIS 84 aerosol retrieval). Level 3 data are products provided on a reg- 85 ular latitude/longitude grid (e.g., 1 × 1° for MODIS aerosols). 86 Each of these data is suited for different applications, ranging 87 from image-based classification to validation/intercomparisons, 88 to scientific applications such as the study of aerosol radiative 89 forcing and assimilation into global climate models.

Several scientific questions related to air quality and radiative 91 effects of aerosols, can be addressed using merged aerosol and 92
radiation level 2 data products. Specifically, the combination of MODIS, MISR, and CERES can help estimate aerosol radiative effects. Until recently, MODIS aerosol products were not delivered over bright targets such as deserts. While the MODIS deep blue algorithm [19], [20] now provides aerosol retrievals over bright surfaces, it is not yet fully evaluated and has not yet been fully processed for all Terra-MODIS data. MISR data, on the other hand, have been validated over bright surfaces [5]. Since MISR is limited in horizontal swath, as compared to MODIS, but provides better retrievals in bright areas, it is desirable to merge the two. While cross-sensor MODIS/MISR validation [5] is not the focus of this paper, we use the MODIS and MISR products together to estimate the aerosol properties for specific cases (presented in Section IV).

It is generally believed that aerosols affect the climate system significantly [6]. Since the launch of Terra and other satellites, there is a shift from modeling-based assessments to increasingly observational based approaches [7] for estimating climate effects of aerosols. Another aspect of moving toward an observational approach for studying aerosol radiative effects is the integration of energy budget (CERES) and imager (MODIS/MISR) data sets from Terra [2], [8]. This method provides an independent assessment of aerosol radiative effects, which can be compared against modeling-based approaches. While the CERES provides broadband TOA fluxes, multispectral and multangle measurements from MODIS and MISR are needed to detect clouds and aerosols within the CERES footprint and provide geophysical quantities such as aerosol optical thickness (AOT) and particle size. Thus, combinations of sensors can then be used to answer questions such as “What is the radiative forcing of aerosols?” and “What is the radiative forcing efficiency (aerosol forcing per unit optical depth), and how does radiative forcing vary as a function of aerosol properties?” The goal of this paper is to raise awareness of multisensor data fusion to provide a framework for merging level 2 aerosol data products at different spatial resolutions and to finally provide some examples related to estimation of aerosol radiative effects.

Data fusion can be defined as the merging of data from multiple sensors and related information from different databases to achieve improved accuracy and more specific inferences [9]. Merging multiple satellite data sets utilizes the strengths of individual sensors, while constraining weaknesses of others. Past research studies have successfully utilized merged satellite data sets to assess landslide hazards using supervised classification [12]. In the context of aerosol research, data fusion can be done on different levels of data, such as radiance level 1B data [4], geophysical parameters level 2 data (this paper), and gridded level 3 data sets [10].

There are various issues related to data fusion, including (but not limited to) data versions, error analysis of the individual and the merged data products, and validation of these products. For example, the CERES algorithm is processed at NASA Langley with its own set of cloud and aerosol clearing algorithms. MODIS aerosol product (MOD04) is generated at the NASA Goddard Space Flight Center and then merged at NASA Langley by the CERES science team called the CERES SSF product. While the MODIS aerosol algorithm goes through changes, and while newer versions are available (currently collection 5), the CERES SSF product may not reflect the MODIS product changes immediately due to data processing timelines. The MISR level 2 data products that are developed at the Jet Propulsion Laboratory are run routinely at NASA Langley, although these products are not merged within the MISR product routinely. Therefore, the best possible scenario is only for independent users interested in data fusion is to obtain the CERES SSF and merge the MISR aerosol products into the CERES footprint, which is the focus of this paper.

II. Data

In this section, we briefly describe the satellite sensors and the data sets that are relevant to this paper. All of the data sets are in hierarchical data format (hdf) and were obtained through the NASA Langley Distributed Active Archive Center (http://eosweb.larc.nasa.gov). The MODIS, MISR, and CERES on Terra are in a polar-orbiting Sun-synchronous orbit at 705 km, with a descending equatorial crossing time of 10:30 A.M. The Terra satellite began collecting data in February 1999. Nearly 1 TB of global CERES, MODIS, and MISR data were collected and processed for this research.

MODIS is a multispectral imaging radiometer that provide measurements of the Earth’s land, ocean, and atmosphere with 36 spectral bands, covering the wavelength range from 0.405 to 14.385 µm with a swath width of 2330 km and providing global coverage in 1–2 days [11]. The applicable MODIS data set in this paper is the aerosol level 2 (collection 4) MOD04 products 177 at a 10-km2 resolution, containing, among other parameters, the AOT, the fine mode fraction, and the cloud fraction. A description of the MODIS aerosol retrieval algorithm and validation strategies is fully explained in [12]. Table I shows some commonly used MODIS level 2 (MOD04) parameters for aerosol research that are already merged within the CERES SSF files.

The MISR on Terra images the Earth in four spectral bands (0.446, 0.557, 0.671, and 0.866 µm) and has nine push broom cameras operating at nine different angles with a swath width of about 360 km [13]. Due to the narrow swath width, near 18 global coverage is obtained only over 9 days at the equator and 18 days near the poles. There are 233 distinct repeating orbits 189 called paths, which are repeated every 16 days and are labeled according to the Landsat Worldwide Reference System. To simplify the processing and storing of these data over a large geographical area, each MISR path is divided into a series of predefined uniform-sized boxes along the ground track. Each path is divided into 180 blocks, measuring 563.2 km (cross-track) by 140.8 km (along-track). For a given path, a numbered block always contains the same geographic location.

The relevant MISR data set for this paper is the level 2 aerosol data (MIL2ASAE), containing AOT at four spectral channels, AOT values for three different size ranges of particles, 200 single-scattering albedo, and other related parameters (Table I). These level 2 geophysical parameters are provided in a 17.6-km2 spatial resolution. A detailed description of the aerosol algorithm is given in [14]. Geographical information on a Space Oblique Mercator (SOM) grid is given in the MISR Ancillary Geographic Product (AGP). Geographical positions are...
of MISR pixels in terms of latitude and longitude are provided in a 1.1-km² grid resolution and stored in separate files for each fixed MISR orbit. These 233 files corresponding to 233 distinct MISR orbits provided as separate parameters can be used to geolocate the level 2 data products (Table I).

The CERES provides broadband radiative energy measurements at the TOA, both in the long and short waves [15]. Each CERES instrument has three channels: 1) a short-wave channel for measuring reflected sunlight (0.3–5 µm); 2) a long-wave channel for measuring Earth-emitted thermal radiation in the 8–12-µm “window” region; and 3) a total channel for radiation between 0.3 and 200 µm. The Terra carries two identical CERES instruments: one operates in a cross-track scan mode (FM-1) and the other in a biaxial scan mode (FM-2) for developing angular models to convert the measured broadband radiances to fluxes. On Terra, the CERES has a spatial resolution of approximately 20 km² (equivalent diameter) at nadir.

For each CERES footprint, the MODIS AOT and other relevant aerosol information from MODIS are convolved using point spread functions (PSFs) and matched in space and time to the CERES measurement [16] and are available as the CERES SSF product. Therefore, for each CERES footprint, the PSF-weighted cloud fraction and aerosol properties such as optical depth are provided only from the MODIS data. The CERES SSF data can be ordered online for user-selected regions and parameters of interest. There are 160 parameters for each pixel, ranging from geolocation information, Sun–satellite geometry, cloud and aerosol information, and CERES radiative energy fluxes (Table I).

For illustrative purposes, Fig. 1 shows an example of an aerosol event observed by the three different sensors from Terra on October 26, 2003. Fig. 1(a) shows a true-color composite of channel 0.67 µm in red, channel 0.55 µm in green, and channel 0.47 µm in blue around the west coast of the U.S., from the MODIS level 1B data. Fig. 1(b) shows the MISR (version F09, V002 data) data for the same day using similar bands as MODIS. Both MODIS and MISR clearly show the large smoke plumes from the west coast of California. The CERES short-wave flux is shown in Fig. 1(c) from this period, and the image appears blocky when compared to the MODIS and MISR imagery due to the large pixel size of the CERES scanner. Note the large swath width of the MODIS and CERES when compared to the MISR. Dark areas correspond to ocean background, whereas smoke plumes from the fires and the clouds appear brighter due to higher reflectivity when compared to the background. This difference in contrast between the background and aerosols is used to separate aerosols and clouds and is further used to retrieve aerosol properties by the MODIS and MISR algorithms. The corresponding level 2 MODIS and MISR (version F09, V002) AOT images are shown in Fig. 2(a) and (b), respectively. MODIS uses multispectral methods, state-of-the-art cloud clearing techniques, and predefined aerosol models to retrieve the AOT value at 10 km² [12]. On the other hand, MISR uses multispectral multangle information and pre-defined aerosol models to provide AOT retrievals over 17.6 km² [14]. Both algorithms continue to undergo developments and refinements with intensive validation against ground and suborbital measurements. The CERES can be used directly to obtain TOA short-wave fluxes due to smoke aerosols, provided the aerosols can be identified using MODIS and MISR data. This multisensor combination is powerful for studying aerosol radiative effects from an observational perspective [2].

### III. METHODOLOGY

One of the goals of this paper is to demonstrate fusion of CERES SSF and MISR level 2 aerosol products and show some selected examples related to aerosol research. To merge MISR level 2 aerosol (MIL2ASAE) products with CERES SSF (FM1, Edition2B) in space and time, a collocation algorithm is first developed. Since the three sensors are all on the same satellite, collocation by time is simple.

A simple flowchart of the algorithm is shown in Fig. 3, and since handling MISR data sets is not straightforward, the methodology is described in detail. Each CERES SSF file includes all geophysical parameters (such as TOA short- and long-wave fluxes), geolocation information, and Sun–satellite geometry, along with MODIS spectral AOTs and the MODIS cloud fraction within each CERES footprint. There are about 160 parameters in the CERES SSF file, and any of these...
parameters in combination with the MISR products can be obtained from our general-purpose software. The CERES SSF files contain data for a 1-h observation period, and date–time information is part of the filename. A typical CERES SSF file is named CER_SSF_Terra-FM1-MODIS_Edition2B_YYYYMMDDHH.hdf from the Terra satellite where CER indicates CERES, FM1 denotes that the data are from the cross-track scanner, and YYYY, MM, DD, and HH are the year, month, day, and hour, respectively.

The MISR products do not contain geolocation information such as latitude and longitude in the same file. However, the new data ordering tools provide some options to the user to add this information in the data file. The geolocation information is fixed for the 233 predefined MISR orbits and is available as separate files. The typical file naming of the geolocation file is MISR_AM1_AGPathnumber_F01_24.hdf. Similar to the CERES SSF, the MISR data files contain many parameters, including spectral AOT, single-scattering albedo, Angstrom parameters.
Fig. 2. Midvisible AOT from level 2 aerosol products from (a) MODIS and (b) MISR for the images shown in Fig. 1. Missing values in AOT are due to clouds.

coefficient, and size-fractioned AOTs. A total of 121 parameters are available from the MISR aerosol product, and our software is flexible enough to accommodate any combination of these parameters to be collocated with CERES SSF in space and time. Although each MISR path contains 180 blocks, due to seasonal variations in the portion of the Earth that is in daylight, only up to 142 blocks contain valid data points. Valid MISR aerosol retrieval blocks are identified using start and end block numbers provided in the data file. Then, the date and time parameters obtained for the same blocks. The MISR does not provide date and time for each pixel, but it provides information for the center of each block. Interpolation is performed to obtain the time information for each pixel within a given block. MISR latitude and longitude data are in a 1.1-km² resolution, whereas MISR aerosol products are in a 17.6-km² resolution. For each valid data pixel, the corresponding latitude and longitude is obtained by selecting the center latitude and longitude of the box of 16 × 16 pixels in geolocation data.

The main collocation algorithm is divided into two sections. The first section deals with collocation in time, whereas the second deals with collocation in space. Since both the CERES and the MISR are onboard Terra, they provide near-simultaneous observations. The key issue in time collocation is how to find the appropriate MISR file corresponding to the CERES observation period, and this is done by checking both day and time information. Since the MISR filename does not have date–time information, this becomes a cumbersome process. To increase searching efficiency, a separate database of date and time corresponding to the various orbits and path numbers are used to select the proper file corresponding to each CERES file. On proper selection of MISR file, the CERES SSF observation date and time information is matched with the MISR date/time, and then, the collocation in space begins. Since the sensors are on the same satellite, the observation time is almost the same, and therefore, temporal collocation is not necessary. To make the computer code more efficient and useful to the users, spatial collocation is performed only over the user-selected area of interest, which can be input to the algorithm by providing the latitude and longitude of the four corners of a region. Since the CERES and MISR have different ground resolutions, exact or one-to-one collocation in space may not be possible. Another important thing to note is the CERES pixel size, which can be larger than 100 km² at the edge of the CERES swath due to panoramic distortion, is an important factor when collocating MODIS and CERES. However, since the MISR swath is narrow, and it is in the middle of the CERES swath, panoramic distortion in the MISR is not significant. The CERES pixel shape and size is not fixed, and it is therefore difficult to define its size parameters. Our algorithm uses two different averaging methods: one is simple arithmetic/weighted average, and the other one uses the CERES PSF average. In the first method, the CERES pixel is assumed to be...
Fig. 4. (a) Latitude and longitude of MISR, MODIS, and CERES pixels for a small portion of the swath and (b) the collocation of one CERES pixel with multiple MISR pixels. The location of the CERES pixel is shown by a large unfilled circle, MODIS by a small unfilled circle, and MISR pixel by a medium filled circle. The CERES pixel CS1 in (a) is shown in greater detail in (b). The MODIS pixels are labeled MD, and the MISR pixels are labeled MS.

IV. APPLICATION OF MERGED MODIS–MISR–CERES DATASETS

We provide three selected examples of the collocated aerosol and flux data from MODIS, MISR, and CERES over three different regimes [Fig. 5(a)–(e)]. Also included in one case study is the comparison of the MISR AOT with ground-based sunphotometer values.

A. MISR, MODIS, and AERONET AOT

Fig. 5(a) shows the level 2 AOT from the MODIS and MISR over the Sahara Desert for January 16, 2006. Two whole MODIS swaths and a partial swath show the large MODIS coverage over this area. Note that the MODIS AOT retrievals are only available over cloud-free vegetated surfaces (dark target) and, therefore, are restricted to latitudes between 0° N and 15° N in the area of study, and no retrievals are available in the desert regions shown in gray color. The MISR, on the other hand, has three narrow swaths during this day but has complete aerosol retrievals over all surface types, except in cloudy conditions that can be used to fill in AOT values where MODIS retrievals are not available. Also shown in black dots are several Aerosol Robotic Network (AERONET) locations that are currently the standard for validating aerosol retrievals. Comparisons between satellite retrievals and AERONET locations are important for testing the robustness of the satellite retrievals. An intercomparison of the MISR 17.6-km² AOT retrievals with ±30 min of AOT values from AERONET is shown in Fig. 5(b). This intercomparison is performed on all the AERONET stations shown in Fig. 5(a) during January to March 2006. An excellent correlation between the two retrievals indicates the high quality of the MISR retrievals over bright targets such as deserts and is especially useful in these areas where MODIS retrievals are not possible.

B. Use of MODIS, MISR, and CERES for Estimating LWRE

Including MISR into the CERES SSF product will enable us to estimate TOA long-wave radiative effect (LWRE) as a function of aerosol properties even over bright surfaces. The LWRE is defined as the difference in CERES TOA long-wave fluxes with and without the presence of aerosols. Fig. 5(c), which was adapted from [2], shows the spatial distribution of MISR AOT for September 2000 over the Sahara Desert [2]. In 428
the Sahara Desert regions, MODIS retrievals were not available, and therefore, the MISR AOT values were used in conjunction with the CERES data for addressing dust radiative effects. MODIS cloud information was used to remove cloud contamination within the CERES pixel since the MODIS offers more channels and a higher spatial resolution to detect clouds. During this month, closer to the equator, biomass burning activities are responsible for the high AOT observed in this region. Away from the equator, dust aerosols increase the AOT, and several regions labeled 1–6 in Fig. 5(c) indicate the high AOT that MISR retrieves. The collocated MODIS–MISR–CERES data sets can then be used to address the effects of dust aerosols on the radiative balance of the Earth–atmosphere system. Fig. 5(d) shows the long-wave TOA dust aerosol radiative forcing. Positive aerosol LWRE values indicate that the aerosols emit at a colder temperature when compared to the Earth’s surface, thereby reducing the amount of Earth-emitted radiation back to space, thereby creating a “warming effect” that is opposite in effect to that of the short-wave reflective nature of other aerosols [2]. This example clearly shows the potential of using MODIS and MISR aerosol properties over bright targets along with CERES observations, which is not possible by using one sensor alone.

C. Use of MODIS, MISR, and CERES for Studying Biomass Burning Aerosols

We move from a highly reflective background in Africa, where dust is prevalent, to another example over South...
of retrieved products (level 2) at different spatial and temporal

time consuming and laborious. However, there are a variety
merging of radiance level data (level 1), this could often be

different processing levels. While some applications require

due to the complexities in merging data and the volume of

However, most studies to date largely focus upon single-sensor
role of aerosols on the energy balance of the Earth–atmosphere

These can be used to further improve our understanding of the

ing aerosols are prevalent. In South America, each year during

the dry season, agricultural activities result in several teragrams
of smoke aerosols that are released into the atmosphere. These
aerosols affect the regional radiative balance significantly.

MODIS and MISR can be used to map the spatial distribution of
aerosols. Retrieved AOT and aerosol properties from MISR can
be used to further study aerosol forcing as a function of various
aerosol properties. Fig. 5(e) presents the time series of aerosol
properties from MISR and short-wave forcing over the Amazon
basin (20° S–0° N and 65° S–45° S) during August and September 2003 estimated using merged MODIS–MISR–
CERES data sets. Again, cloud clearing of CERES pixels has
been done using MODIS data. MISR retrieval produces aerosol
parameters, including the AOT due to small-, medium-, and
large-sized particles, as well as the total AOT at 0.55 μm,
along with single-scattering albedo and Angstrom coefficient.

The short-wave forcing is the difference in the TOA short-wave
flux between clear and aerosol regions, which is an important
parameter for climate research.

This time series shows diurnally averaged short-wave aerosol
radiative forcing (DSARF) and the associated aerosol proper-
ties. The DSARF is defined as the difference between clear-
sky ($F_{clr}$) and aerosol-sky fluxes ($F_{aero}$) that is adjusted for
diurnal effects [22]. $F_{clr}$ corresponds to cloud- and aerosol-
free fluxes, while $F_{aero}$ corresponds to cloud-free fluxes from
regions where aerosols are present [2]. Here, it is important
to note that during August and September, the study region in
South America is dominated by anthropogenic biomass burning
aerosols, and hence, the term “radiative forcing” is used instead
of “radiative effects” [7].

Fig. 5(e) clearly shows that both AOT and DSARF increases
from August to September, which was mainly due to the
increase in biomass burning activities in the region. Also, the
AOTs due to medium-sized particles contribute more in total
AOT during August, but small mode contribution is more in
September compared to any other size mode. For comparison,
the MODIS total AOT is shown as black dots, and it compares
remarkably well with the MISR total AOT shown in blue over
this region. Further analysis is provided in Patadia et al. [18]
who quantitatively discuss what portion of the AOT and forcing
comes from various particle sizes. Collocated data sets such as
these can be used to further improve our understanding of the
role of aerosols on the energy balance of the Earth–atmosphere
system.

V. SUMMARY

There are many satellite sensors that are currently in orbit
for studying the Earth–atmosphere in an integrated fashion.
However, most studies to date largely focus upon single-sensor
approaches for studying specific problems. This is largely
due to the complexities in merging data and the volume of
data involved. There are various methods for merging data at
different processing levels. While some applications require
merging of radiance level data (level 1), this could often be
time consuming and laborious. However, there are a variety
of retrieved products (level 2) at different spatial and temporal
resolutions that could be merged to address scientific issues. While the ideal scenario is to have a unified cloud-clearing algorithm across all sensors and then retrieve aerosol properties and convolve it within the CERES footprint, this is not the current practice. Therefore, some of the product level data fusion has to be done by individual researchers.

In this paper, we have combined three data sets, namely the MODIS, the MISR, and the CERES for studying common problems in aerosol research. Note that the MODIS and CERES have already been merged at NASA Langley (the CERES SSF 520 product). We merge the level 2 MISR aerosol product with the CERES SSF data. Each data set has numerous retrieved parameters and different algorithms for creating these parameters. We have not attempted to discuss the algorithms, the retrievals, or the accuracies since they are not the focus of this paper. Our major goal has been to raise the awareness of multisensor data fusion from sensors on a single satellite and provide a simple framework for merging data. In the process, we have also provided some selected examples. These are not meant to be exhaustive by any means. However, our examples indicate the robustness of the data fusion methods and value-added information, since the geophysical parameters such as AOT and short- and long-wave forcing are consistent with other research studies. We now have software in place that can be used to merge these types of data sets for aerosol and possibly cloud research. With the series of satellites as part of the A-train that will obtain data over a pixel within seconds to several minutes of each other, collocation issues could be another challenging, and further research is necessary to merge data from multiple satellites for addressing research questions.

ACKNOWLEDGMENT

The authors would like to thank the Atmospheric Sciences 542 Data Center at the NASA Langley Research Center, from which 543 the data were obtained.

REFERENCES


Multisensor Data Product Fusion for Aerosol Research

Pawan Gupta, Falguni Patadia, and Sundar A. Christopher

Abstract—Combining data sets from multiple satellite sensors is a powerful method for studying Earth-atmosphere problems. By fusing data, we can utilize the strengths of the individual sensors that may not be otherwise possible. In this paper, we provide the framework for combining level 2 data products, using data from three sensors aboard the National Aeronautics and Space Administration (NASA)'s Terra satellite. These data include top-of-the-atmosphere (TOA) radiative energy fluxes obtained from the Clouds and the Earth's Radiant Energy System (CERES), aerosol optical thickness from the multispectral Moderate Resolution Imaging Spectroradiometer (MODIS), and aerosol properties from the Multi-angle Imaging SpectroRadiometer (MISR). The CERES Single Scanner Footprint (SSF) contains the pixel level CERES TOA fluxes and the level 2 MODIS aerosol data. We specifically focus upon fusing the CERES SSF with the MISR aerosol products. Although this project was undertaken specifically to address aerosol research, the methods employed for fusing data products can be used for other problems requiring synergistic data sets. We present selected case studies over different aerosol regimes and indicate that multisensor information provides value-added information for aerosol research that is not available from a single sensor.

Index Terms—Aerosol forcing, aerosols, climate, Clouds and the Earth's Radiant Energy System (CERES), data fusion, Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR).

I. INTRODUCTION

ONE OF the major goals of the National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS) program is to study the Earth-atmosphere system in an integrated fashion [1]. As part of this vision, a series of individual and multisensor satellites was launched. The first EOS satellite, Terra, launched in December 1999, carried five sensors, including the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Measurement of Pollution in the Troposphere (MOPPIT) instrument, and the Clouds and the Earth’s Radiant Energy System (CERES). Since then, other satellites have been added, including: Aqua (in May 2002), which was dedicated to studying the Earth’s water cycle; the Aura (in July 2004), for studying air quality and stratospheric ozone; the Polarization and Anisotropy of Reflectances for 46 Atmospheric Science coupled with Observations from a Lidar (PARASOL), for studying clouds and aerosols; and the upcoming Orbiting Carbon Observatory (OCO) mission, for studying 49 atmospheric carbon dioxide. In April 2006, the Cloud–Aerosol 50 Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) 51 and CloudSat were also launched, and this combination of 52 Aqua, Aura, PARASOL, OCO, CALIPSO, and CloudSat flying in formation within approximately 15 min of each other in a 53 low orbit is called the A-Train, which will further enhance our 55 research capabilities.

There is an increasing need to address scientific questions 57 with combinations of data sets, utilizing the strengths of individual sensors and constraining weaknesses of others. These 59 combined data sets can provide value-added information that 60 would not be possible from one sensor only. In this paper, we 61 discuss the concept of combining CERES, MODIS, and MISR 62 (all aboard Terra) in the context of aerosol research.

CERES is a coarse spatial resolution (20 km<sup>2</sup>) at nadir) broad-band sensor that was designed to study top-of-the-atmosphere (TOA) fluxes. MODIS and MISR have higher resolutions (<1 km), enabling better study of clouds and aerosols. MODIS 67 has a larger horizontal swath, but MISR can address angular information [2]. MODIS and MISR data, averaged to CERES 69 resolution, can help interpret CERES data as a function of 70 clouds and aerosols. In fact, the CERES team has done merging 71 of MODIS onto the CERES footprint, and this data set is called the CERES Single Scanner Footprint (SSF) product [3]. 72 Level 1B MISR data have also been merged onto CERES SSF 74 [4] but is not fully operational. In this paper, we combine both MODIS and MISR level 2 with CERES SSF data.

There are several data streams and products that are useful for atmospheric aerosol, cloud, and radiation budget research. 78 In this paper, we focus primarily on examples related to the study of aerosols. The fundamental data product from satellite sensors are geo-referenced calibrated radiances at the sensors’ original resolution. These data are known as level 1B. Retrieved 82 geophysical parameters are known as level 2 and are usually derived at predefined spatial resolutions (e.g., 10 km<sup>2</sup> for MODIS aerosol retrieval). Level 3 data are products provided on a regular latitude/longitude grid (e.g., 1×1° for MODIS aerosols). 86 Each of these data is suited for different applications, ranging from image-based classification to validation/intercomparisons, to scientific applications such as the study of aerosol radiative forcing and assimilation into global climate models. 90

Several scientific questions related to air quality and radiative effects of aerosols, can be addressed using merged aerosol and 92
radiation level 2 data products. Specifically, the combination of MODIS, MISR, and CERES can help estimate aerosol radiative effects. Until recently, MODIS aerosol products were not delivered over bright targets such as deserts. While the MODIS deep blue algorithm [19], [20] now provides aerosol retrievals over bright surfaces, it is not yet fully evaluated and has not yet been fully processed for all Terra-MODIS data. MISR data, on the other hand, have been validated over bright surfaces [5]. Since MISR is limited in horizontal swath, as compared to MODIS, but provides better retrievals in bright areas, it is desirable to merge the two. While cross-sensor MODIS/MISR validation [5] is not the focus of this paper, we use the MODIS and MISR products together to estimate the aerosol properties for specific cases (presented in Section IV).

It is generally believed that aerosols affect the climate system significantly [6]. Since the launch of Terra and other satellites, there is a shift from modeling-based assessments to increasingly observational based approaches [7] for estimating climate effects of aerosols. Another aspect of moving toward an observational approach for studying aerosol radiative effects is the integration of energy budget (CERES) and imager (MODIS/MISR) data sets from Terra [2], [8]. This method provides an independent assessment of aerosol radiative effects, which can be compared against modeling-based approaches. While the CERES provides broadband TOA fluxes, multispectral and multangle measurements from MODIS and MISR are needed to detect clouds and aerosols within the CERES footprint and provide geophysical quantities such as aerosol optical thickness (AOT) and particle size. Thus, combinations of sensors can then be used to answer questions such as “What is the radiative forcing of aerosols?” and “What is the radiative forcing efficiency (aerosol forcing per unit optical depth), and how does radiative forcing vary as a function of aerosol properties?” The goal of this paper is to raise awareness of multisensor data fusion to provide a framework for merging level 2 aerosol data products at different spatial resolutions and to finally provide some examples related to estimation of aerosol radiative effects.

Data fusion can be defined as the merging of data from multiple sensors and related information from different databases to achieve improved accuracy and more specific inferences [9]. Merging multiple satellite data sets utilizes the strengths of individual sensors, while constraining weaknesses of others. Past research studies have successfully utilized merged satellite data sets to assess landslide hazards using supervised classification [12]. In the context of aerosol research, data fusion can be done on different levels of data, such as radiance level 1B data [4], geophysical parameters level 2 data (this paper), and gridded level 3 data sets [10].

There are various issues related to data fusion, including (but not limited to) data versions, error analysis of the individual and the merged data products, and validation of these products. For example, the CERES algorithm is processed at NASA Langley with its own set of cloud and aerosol clearing algorithms. MODIS aerosol product (MOD04) is generated at the NASA Goddard Space Flight Center and then merged at NASA Langley by the CERES science team called the CERES SSF product. While the MODIS aerosol algorithm goes through changes, and while newer versions are available (currently collection 5), the CERES SSF product may not reflect the MODIS product changes immediately due to data processing timelines. The MISR level 2 data products that are developed at the Jet Propulsion Laboratory are run routinely at NASA Langley, although these products are not merged within the CERES product routinely. Therefore, the best possible scenario for independent users interested in data fusion is to obtain the CERES SSF and merge the MISR aerosol products into the CERES footprint, which is the focus of this paper.

II. DATA

In this section, we briefly describe the satellite sensors and data sets that are relevant to this paper. All of the data sets are in hierarchical data format (hdf) and were obtained through the NASA Langley Distributed Active Archive Center (http://eosweb.larc.nasa.gov). The MODIS, MISR, and CERES on Terra are in a polar-orbiting Sun-synchronous orbit at 705 km, with a descending equatorial crossing time of 10:30 A.M. The Terra satellite began collecting data in February 1999. Nearly 1 TB of global CERES, MODIS, and MISR data were collected and processed for this research.

MODIS is a multispectral imaging radiometer that provide measurements of the Earth’s land, ocean, and atmosphere with 36 spectral bands, covering the wavelength range from 0.405 to 14.385 μm with a swath width of 2330 km and providing global coverage in 1–2 days [11]. The applicable MODIS data set in this paper is the aerosol level 2 (collection 4) MOD04 products 177 at a 10-km² resolution, containing, among other parameters, the AOT, the fine mode fraction, and the cloud fraction. A description of the MODIS aerosol retrieval algorithm and validation strategies is fully explained in [12]. Table I shows some commonly used MODIS level 2 (MOD04) parameters for aerosol research that are already merged within the CERES SSF files.

The MISR on Terra images the Earth in four spectral bands (0.446, 0.557, 0.671, and 0.866 μm) and has nine push broom cameras operating at nine different angles with a swath width of about 360 km [13]. Due to the narrow swath width, near 187 global coverage is obtained only over 9 days at the equator and 188 2 days near the poles. There are 233 distinct repeating orbits 189 called paths, which are repeated every 16 days and are labeled 190 according to the Landsat Worldwide Reference System. To simplify the processing and storing of these data over a large geographical area, each MISR path is divided into a series of predefined uniform-sized boxes along the ground track. Each path is divided into 180 blocks, measuring 563.2 km 195 (cross-track) by 140.8 km (along-track). For a given path, a 196 numbered block always contains the same geographic location.

The relevant MISR data set for this paper is the level 2 aerosol data (MIL2ASAE), containing AOT values for three different size ranges of particles, 200 single-scattering albedo, and other related parameters (Table I). These level 2 geophysical parameters are provided in a 202 17.6-km² spatial resolution. A detailed description of the aerosol algorithm is given in [14]. Geographical information on a Space Oblique Mercator (SOM) grid is given in the MISR Ancillary Geographic Product (AGP), Geographical positions 206
of MISR pixels in terms of latitude and longitude are provided in a 1.1-km$^2$ grid resolution and stored in separate files for each fixed MISR orbit. These 233 files corresponding to 233 distinct MISR orbits provided as separate parameters can be used to geolocate the level 2 data products (Table I). The CERES provides broadband radiative energy measurements at the TOA, both in the long and short waves [15]. Each CERES instrument has three channels: 1) a short-wave channel for measuring reflected sunlight (0.3–5 $\mu$m); 2) a long-wave channel for measuring Earth-emitted thermal radiation in the 8–12-$\mu$m “window” region; and 3) a total channel for radiation between 0.3 and 200 $\mu$m. The Terra carries two identical CERES instruments: one operates in a cross-track scan mode (FM-1) and the other in a biaxial scan mode (FM-2) for developing angular models to convert the measured broadband radiances to fluxes. On Terra, the CERES has a spatial resolution of approximately 20 km$^2$ (equivalent diameter) at nadir.

For each CERES footprint, the MODIS AOT and other relevant aerosol information from MODIS are convolved using point spread functions (PSFs) and matched in space and time to the CERES measurement [16] and are available as the CERES SSF product. Therefore, for each CERES footprint, the PSF-weighted cloud fraction and aerosol properties such as optical depth are provided only from the MODIS data. The CERES SSF data can be ordered online for user-selected regions and parameters of interest. There are 160 parameters for each pixel, ranging from geolocation information, Sun–satellite geometry, cloud and aerosol information, and CERES radiative energy fluxes (Table I).

For illustrative purposes, Fig. 1 shows an example of an aerosol event observed by the three different sensors from Terra on October 26, 2003. Fig. 1(a) shows a true-color composite of channel 0.67 $\mu$m in red, channel 0.55 $\mu$m in green, and channel 0.47 $\mu$m in blue around the west coast of the U.S. from the MODIS level 1B data. Fig. 1(b) shows the MISR (version F09, V002) data for the same day using similar bands as MODIS. Both MODIS and MISR clearly show the large smoke plumes from the west coast of California. The CERES short-wave flux is shown in Fig. 1(c) from this period, and the image appears blocky when compared to the MODIS and MISR imagery due to the large pixel size of the CERES scanner. Note the large swath width of the MODIS and CERES when compared to the MISR. Dark areas correspond to ocean background, whereas smoke plumes from the fires and the clouds appear brighter due to higher reflectivity when compared to the background. This difference in contrast between the background and aerosols is used to separate aerosols and clouds and is further used to retrieve aerosol properties by the MODIS and MISR algorithms. The corresponding level 2 MODIS and MISR (version F09, V002) AOT images are shown in Fig. 2(a) and (b), respectively. MODIS uses multispectral methods, state-of-the-art cloud clearing techniques, and predefined aerosol models to retrieve the AOT value at 10 km$^2$ [12]. On the other hand, MISR uses multispectral multiangle information and predefined aerosol models to provide AOT retrievals over 17.6 km$^2$ [14]. Both algorithms continue to undergo developments and refinements with intensive validation against ground and suborbital measurements. The CERES can be used directly to obtain TOA short-wave fluxes due to smoke aerosols, provided the aerosols can be identified using MODIS and MISR data. This multisensor combination is powerful for studying aerosol radiative effects from an observational perspective [2].

### III. METHODOLOGY

One of the goals of this paper is to demonstrate fusion of CERES SSF and MISR level 2 aerosol products and show some selected examples related to aerosol research. To merge CERES and MISR level 2 aerosol (MIL2ASAE) products with CERES SSF (FM1, Edition2B) in space and time, a collocation algorithm is first developed. Since the three sensors are all on the same satellite, collocation by time is simple.

A simple flowchart of the algorithm is shown in Fig. 3, and since handling MISR data sets is not straightforward, the methodology is described in detail. Each CERES SSF file includes all geophysical parameters (such as TOA short- and long-wave fluxes), geolocation information, and Sun–satellite geometry, along with MODIS spectral AOTs and the MODIS cloud fraction within each CERES footprint. There are about 160 parameters in the CERES SSF file, and any of these

### TABLE I

<table>
<thead>
<tr>
<th>CERES SSF products</th>
<th>MISR level 2 aerosol products</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CERES SW TOA flux</td>
<td>1 RegBestEstimateSpectralOptDepth (0.46, 0.55, 0.67, 0.86)</td>
</tr>
<tr>
<td>2 CERES LW TOA flux</td>
<td>2 RegBestEstimateAngstromExponent</td>
</tr>
<tr>
<td>3 CERES WN TOA flux</td>
<td>3 RegBestEstimateSpectralSSA (0.46, 0.55, 0.67, 0.86)</td>
</tr>
<tr>
<td>4 PSF-wtd MOD04 cloud fraction land</td>
<td>4 RegBestEstimateSpectralOptDepthFraction</td>
</tr>
<tr>
<td>5 PSF-wtd MOD04 aerosol types land</td>
<td>5 RegBestEstimateNumberFraction</td>
</tr>
<tr>
<td>6 PSF-wtd MOD04 corrected optical depth land (0.47, 0.55, 0.66)</td>
<td>6 RegBestEstimateVolumeFraction</td>
</tr>
<tr>
<td>7 PSF-wtd MOD04 cloud fraction ocean</td>
<td></td>
</tr>
<tr>
<td>8 PSF-wtd MOD04 effective optical depth average ocean (0.47, 0.55, 0.66, 0.86, 1.24, 1.64, 2.1)</td>
<td></td>
</tr>
<tr>
<td>9 PSF-wtd MOD04 optical depth small average ocean (0.55,0.86,2.1)</td>
<td></td>
</tr>
</tbody>
</table>
parameters in combination with the MISR products can be obtained from our general-purpose software. The CERES SSF files contain data for a 1-h observation period, and date-time information is part of the filename. A typical CERES SSF file is named CER_SSF_Terra-FM1-MODIS_Edition2B_YYYYMMDDHH.hdf from the Terra satellite where CER indicates CERES, FM1 denotes that the data are from the cross-track scanner, and YYYY, MM, DD, and HH are the year, month, day, and hour, respectively.

The MISR products do not contain geolocation information such as latitude and longitude in the same file. However, the new data ordering tools provide some options to the user to add this information in the data file. The geolocation information is fixed for the 233 predefined MISR orbits and is available as separate files. The typical file naming of the geolocation file is MISR_AM1_AGP_Pathnumber_F01_24.hdf. Similar to the CERES SSF, the MISR data files contain many parameters, including spectral AOT, single-scattering albedo, Angstrom...
Fig. 2. Midvisible AOT from level 2 aerosol products from (a) MODIS and (b) MISR for the images shown in Fig. 1. Missing values in AOT are due to clouds.

Fig. 3. Flowchart of the space and time collocation between the CERES SSF and MISR level 2 products. The CERES SSF product contains the CERES and merged MODIS data, and MIL2ASAE and MIB2GEOP are the MISR aerosol product data set and the geolocation files, respectively.

The main collocation algorithm is divided into two sections. The first section deals with collocation in time, whereas the second deals with collocation in space. Since both the CERES and the MISR are onboard Terra, they provide near-simultaneous observations. The key issue in time collocation is how to find the appropriate MISR file corresponding to the CERES observation period, and this is done by checking both day and time information. Since the MISR filename does not have date–time information, this becomes a cumbersome process. To increase searching efficiency, a separate database of date and time corresponding to the various orbits and path numbers are used to select the proper file corresponding to each CERES file. On proper selection of MISR file, the CERES SSF observation date and time information is matched with the MISR date/time, and then, the collocation in space begins. Since the sensors are on the same satellite, the observation time is almost the same, and therefore, temporal collocation is not necessary. To make the computer code more efficient and useful to the users, spatial collocation is performed only over the user-selected area of interest, which can be input to the algorithm by providing the latitude and longitude of the four corners of a region. Since the CERES and MISR have different ground resolutions, exact or one-to-one collocation in space may not be possible. Another important thing to note is the CERES pixel size, which can be larger than 100 km$^2$ at the edge of the CERES swath due to panoramic distortion, is an important factor when collocating MODIS and CERES. However, since the MISR swath is narrow, and it is in the middle of the CERES swath, panoramic distortion in the MISR is not significant.

The CERES pixel shape and size is not fixed, and it is therefore difficult to define its size parameters. Our algorithm uses two different averaging methods: one is simple arithmetic/weighted average, and the other one uses the CERES PSF average. In the first method, the CERES pixel is assumed to be...
Fig. 4. (a) Latitude and longitude of MISR, MODIS, and CERES pixels for a small portion of the swath and (b) the collocation of one CERES pixel with multiple MISR pixels. The location of the CERES pixel is shown by a large unfilled circle, MODIS by a small unfilled circle, and MISR pixel by a medium filled circle. The CERES pixel CS1 in (a) is shown in greater detail in (b). The MODIS pixels are labeled MD, and the MISR pixels are labeled MS.

To obtain the MISR product value at CERES pixel location and resolution, the spherical distance that accounts for the curvature of the Earth between the MISR and CERES pixel is calculated. All the MISR pixels falling within the circle with the radius that is half of the diagonal of the CERES pixel are averaged using two different methods. The first method uses the arithmetic average of all MISR parameters (e.g., AOT) falling within the circle. The second method uses the distance weighted average, where all the MISR pixels falling within the CERES circle receive a weight between 0 and 1 based on how close it is from the center of the CERES pixel. There are numerous weighting function options that are available, and we used the inverse distance weighting, where weights are a decreasing function of distance. The third option (second averaging approach) used is the CERES PSF weighted average [17] value of MISR AOT at the CERES footprint. The CERES convolution algorithm weights the MISR pixel based on where it is located within the 387 CERES pixel [4].

IV. APPLICATION OF MERGED MODIS–MISR–CERES DATASETS

We provide three selected examples of the collocated aerosol and flux data from MODIS, MISR, and CERES over three different regimes [Fig. 5(a)–(e)]. Also included in one case study is the comparison of the MISR AOT with ground-based sunphotometer values.

A. MISR, MODIS, and AERONET AOT

Fig. 5(a) shows the level 2 AOT from the MODIS and MISR over the Sahara Desert for January 16, 2006. Two whole MODIS swaths and a partial swath show the large MODIS coverage over this area. Note that the MODIS AOT retrievals are only available over cloud-free vegetated surfaces (dark target) and, therefore, are restricted to latitudes between 0° N and 15° N in the area of study, and no retrievals are available in the desert regions shown in gray color. The MISR, on the other hand, has three narrow swaths during this day but has complete aerosol retrievals over all surface types, except in cloudy conditions that can be used to fill in AOT values where MODIS retrievals are not available. Also shown in black dots are several Aerosol Robotic Network (AERONET) locations that are currently the standard for validating aerosol retrievals. Comparisons between satellite retrievals and AERONET locations are important for testing the robustness of the satellite retrievals. An intercomparison of the MISR 17.6-km AOT retrievals with ±30 min of AOT values from AERONET is shown in Fig. 5(b). This intercomparison is performed on all the AERONET stations shown in Fig. 5(a) during January to March 2006. An excellent correlation between the two retrievals indicates the high quality of the MISR retrievals over bright targets such as deserts and is especially useful in these areas where MODIS retrievals are not possible.

B. Use of MODIS, MISR, and CERES for Estimating LWRE

Including MISR into the CERES SSF product will enable us to estimate TOA long-wave radiative effect (LWRE) as a function of aerosol properties even over bright surfaces. The LWRE is defined as the difference in CERES TOA long-wave fluxes with and without the presence of aerosols. Fig. 5(c) shows the spatial distribution of MISR AOT for September 2000 over the Sahara Desert [2]. In 2006
Fig. 5. Case studies of data fusion. (a) Spatial distribution of MISR and MODIS derived AOT on January 16, 2006 over North Africa. (b) MISR AOT versus AERONET AOT. (c) MISR AOT for September 2004. (d) CERES-derived long-wave dust aerosol radiative effect (from [2]). (e) Time series of MODIS- and MISR-derived aerosol properties, along with the CERES biomass burning aerosol effect over the Amazon basin during August and September 2003.

the Sahara Desert regions, MODIS retrievals were not available, and therefore, the MISR AOT values were used in conjunction with the CERES data for addressing dust radiative effects. MODIS cloud information was used to remove cloud contamination within the CERES pixel since the MODIS offers more channels and a higher spatial resolution to detect clouds. During this month, closer to the equator, biomass burning activities are responsible for the high AOT observed in this region. Away from the equator, dust aerosols increase the AOT, and several regions labeled 1–6 in Fig. 5(c) indicate the high AOT that MISR retrieves. The collocated MODIS–MISR–CERES data sets can then be used to address the effects of dust aerosols on the radiative balance of the Earth–atmosphere system. Fig. 5(d) shows the long-wave TOA dust aerosol radiative forcing. Positive aerosol LWRE values indicate that the aerosols emit at a colder temperature when compared to the Earth’s surface, thereby reducing the amount of Earth-emitted radiation back to space, thereby creating a “warming effect” that is opposite in effect to that of the short-wave reflective nature of other aerosols [2]. This example clearly shows the potential of using MODIS and MISR aerosol properties over bright targets along with CERES observations, which is not possible by using one sensor alone.

C. Use of MODIS, MISR, and CERES for Studying Biomass Burning Aerosols

We move from a highly reflective background in Africa, where dust is prevalent, to another example over South...
V. SUMMARY

There are many satellite sensors that are currently in orbit for studying the Earth–atmosphere in an integrated fashion. However, most studies to date largely focus upon single-sensor approaches for studying specific problems. This is largely due to the complexities in merging data and the volume of data involved. There are various methods for merging data at different processing levels. While some applications require merging of radiance level data (level 1), this could often be time consuming and laborious. However, there are a variety of retrieved products (level 2) at different spatial and temporal resolutions that could be merged to address scientific issues.

While the ideal scenario is to have a unified cloud-clearing algorithm across all sensors and then retrieve aerosol properties and convolve it within the CERES footprint, this is not the current practice. Therefore, some of the product level data fusion has to be done by individual researchers.

In this paper, we have combined three data sets, namely the MODIS, the MISR, and the CERES for studying common problems in aerosol research. Note that the MODIS and CERES have already been merged at NASA Langley (the CERES SSF product). We merge the level 2 MISR aerosol product with the CERES SSF data. Each data set has numerous retrieved parameters and different algorithms for creating these parameters. We have not attempted to discuss the algorithms, the retrievals, or the accuracies since they are not the focus of this paper. Our major goal has been to raise the awareness of multisensor data fusion from sensors on a single satellite and provide a simple framework for merging data. In the process, we have also provided some selected examples. These are not meant to be exhaustive by any means. However, our examples indicate the robustness of the data fusion methods and value-added information, since the geophysical parameters such as AOT and short- and long-wave forcing are consistent with other research studies. We now have software in place that can be used to merge these types of data sets for aerosol and possibly cloud research. With the series of satellites as part of the A-train that will obtain data over a pixel within seconds to minutes of each other, collocation issues could be more challenging, and further research is necessary to merge data from multiple satellites for addressing research questions.

ACKNOWLEDGMENT

The authors would like to thank the Atmospheric Sciences 452 Data Center at the NASA Langley Research Center, from which the data were obtained.

REFERENCES

Falguni Patadia received the M.Sc. degree in physics from Devi Ahilya University, Indore, India, in 2000 and the M.Tech. degree in space and atmospheric sciences from the Physical Research Laboratory, Ahmedabad, India, and Andhra University, Visakhapatnam, India, in 2003. She is currently working toward the Ph.D. degree in atmospheric science at the University of Alabama, Huntsville. Her current research interests mainly include the study of atmospheric aerosols, satellite remote sensing of aerosols and particulate matter air quality, Earth–atmosphere radiation budget, and data fusion from multiple satellite and surface based methods.

Pawan Gupta received the M.Sc. degree in physics from Devi Ahilya University, Indore, India, in 2000 and the M.Tech. degree in space and atmospheric sciences from the Physical Research Laboratory, Ahmedabad, India, and Andhra University, Visakhapatnam, India, in 2003. He is currently working toward the Ph.D. degree in atmospheric science at the University of Alabama, Huntsville. His current research interests include satellite remote sensing of aerosols and cloud properties and surface-based measurements for studying the role of tropospheric aerosols on Earth’s radiation budget.

Sundar A. Christopher received the Ph.D. degree in atmospheric sciences from Colorado State University, Fort Collins, in 1995. He received the M.S. degree in meteorology from the South Dakota School of Mines and Technology, Rapid City, and the M.S. degree in industrial/organizational psychology from the University of Alabama, Huntsville (UAH). He is currently a Professor in the Department of Atmospheric Sciences and the Associate Director of the Earth System Science Center at UAH. His research interests include satellite remote sensing of clouds and aerosols and their impact on air quality and global and regional climate.