Space-based passive aerosol remote sensing from the Multi-angle Imaging SpectroRadiometer (MISR) aboard NASA's Terra satellite

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Abstract

The Multi-angle Imaging SpectroRadiometer (MISR) instrument has been acquiring multi-angle imagery of the Earth aboard NASA's Terra satellite since February 2000, providing an ongoing record of atmosphere and surface properties more than two decades long. MISR offers a combination of moderately high spatial resolution imagery at nine view angles in each of four visible/near-infrared spectral bands, global coverage about once per week, and carefully maintained onboard radiometric calibration. Unique algorithms retrieve aerosol column-amount and constraints on particle microphysical and optical properties, as well as the heights and motion vectors of aerosol plumes from sources such as wildfires, volcanic eruptions, and dust storms. Applications of MISR aerosol data to climate and air quality are discussed here along with a summary of some key scientific findings enabled by the instrument's unique measurement approach.

Key words: Aerosols, climate, air quality, multi-angle, MISR

1. Introduction

Aerosols – suspensions of airborne particulate matter – affect Earth's climate directly, by scattering and absorbing sunlight, as well as indirectly, through their influence on cloud formation, properties, and lifetime. Inhaled aerosols also represent a major risk to human health. The frequent global coverage that space-based passive imagers provide represents a considerable strength for mapping in both space and time the wide variety of aerosol sources and the diversity of particle properties and abundances over large regions. Under most daylight, cloud-free observing conditions, passive aerosol remote sensing can provide total-column aerosol amount, usually reported as the mid-visible aerosol optical depth (AOD), and – depending on the observing technique – some information about particle optical and microphysical properties. Such data are valuable for validating and even constraining climate models [1][2]. Monitoring air quality entails identifying the near-surface aerosol concentration, along with particle size and for many applications, detailed particle composition. In combination with aerosol vertical distribution from other sources, passive aerosol sensors can also contribute to mapping the near-surface concentration of particles smaller than 2.5 μm in diameter ($PM_{2.5}$).

The Multi-angle Imaging SpectroRadiometer (MISR) instrument aboard NASA's Terra satellite has been obtaining global coverage about once per week since late February 2000. MISR acquires imagery at nine view angles between 70.5° in the forward direction through nadir, to 70.5° in the backward direction over all locations, in each of four spectral bands (446, 558, 672, and 866 nm), with resolution between 275 m and 1.1 km across a 400-km swath width [3]. Although MISR global coverage is less frequent than that of broad-swath, single-angle imagers such as the MODerate resolution Imaging Spectroradiometer (MODIS), the instrument's multi-angle data make column-effective particle size, shape, and light-absorption retrieval possible (Figure 1a), contributing particle type information needed for both climate and air quality applications [4][5].

The multi-angle views also offer enhanced sensitivity to AOD compared to single-view instruments, due in part to the systematic variation in observed atmospheric path length, and in part to inherently multi-angle techniques that improve surface-atmosphere discrimination [6][7][8]. In addition, when imaged from multiple angles by MISR, aerosol layer height can be derived stereoscopically from the geometric parallax observed among contrast features in aerosol plumes (Figure 1c), such as the those from wildfire, dust, and volcanic sources [9].

2. Aerosol retrieval capabilities

Aerosol optical depth and its spectral dependence. Given the enhanced ability to separate surface reflection from atmospheric signals, MISR-retrieved AOD quality stands out among contemporary satellite AOD products over bright surfaces, such as desert regions [10]. AOD performance has been assessed by statistical comparisons with near-coincident surface-based AERONET [11] and Marine Aerosol Network (MAN) [12] sun photometer measurements, often stratified by region or expected aerosol air mass type [13][14], along with comparison among AOD products from different satellite instruments [15][16].

The MISR aerosol product was originally reported at 17.6 km horizontal resolution; beginning in 2017 the entire dataset was reprocessed at 4.4 km resolution with an upgraded algorithm that includes pixel-level uncertainty estimates, enhanced cloud screening, and improvements to the underlying measurement radiometric calibration [17][18]. Global, pixel-level uncertainties for the 4.4 km AOD product show an essentially normal distribution, with the estimated peak at about 0.018 and FWHM (Full Width at Half Maximum) ~0.01 over ocean, and correspondingly, ~0.027 and ~0.02 over land [18]. Over-ocean comparisons with near-coincident MAN sun photometer AOD yield a root-mean-square error (RMSE) of 0.035 and essentially zero bias; 87% of retrievals fall within ±(03+0.1*AOD), the envelope of expected error (EE). Comparisons with AERONET, mostly over land, yield an RMSE of 0.154, with 56% within the EE envelope. One persistent limitation of the MISR product is AOD underestimation at high aerosol concentrations [13], an issue common to current retrievals from many satellite instruments.

MISR-retrieved AOD spectral dependence, usually represented as the negative log of the AOD spectral slope (i.e., the Ångstrom Exponent or ANG), has also been assessed against AERONET sun photometer measurements. The MISR-retrieved, column-effective ANG is related to particle size, although interpretation is complicated in the common situation when multiple aerosol modes exist in the atmospheric column. MISR ANG exhibits a correlation coefficient (r) of 0.71 and RMSE of 0.41 against AERONET (mostly over land), and values of 0.85 and 0.31, respectively over ocean, based on MAN comparisons [18]. This sensitivity is more than sufficient sensitivity to distinguish coarse-mode from fine-mode-dominated aerosol loading over land and water.

Column-effective particle properties. MISR particle size distribution, shape, and light absorption results are much more sensitive than AOD to retrieval conditions. In particular, sensitivity to particle properties diminishes when the mid-visible AOD falls below about 0.15 or 0.2, depending largely on surface brightness and contrast, and also when the Sun is high in the sky, generally near the solar equator, as the range of scattering angles between the incident solar and MISR viewing angles captured by the nine MISR cameras is reduced [5]. Validation of the particle property results is also more difficult than for AOD, as coincident *in situ* particle characterization occurs mainly during occasional aircraft field campaigns; assessments of column-effective particle properties from ground-based sky scan retrievals entail many more assumptions and uncertainties than direct-sun AERONET AOD measurements [19]. Nevertheless, theoretical sensitivity studies that use cluster analysis to interpret forward radiative transfer simulation results for a range of assumed particle properties, taking account of expected measurement uncertainty, demonstrated pre-launch that three-to-five bins in particle size (e.g., “small,” “medium,” and “large”), two-to-four bins in single-scattering albedo (SSA), and spherical vs. non-spherical shape could be distinguished under good retrieval conditions [4]. The measurements are also able to distinguish spectrally independent (flat) light absorption, typical of some pollution particles, from particles that absorb preferentially in the blue, such as brown wildfire smoke (Figure 1d, 1e). Additional assumptions are required to interpret these particle optical properties in terms of dust, smoke, sea salt, or other particle compositions. Subsequent analysis of actual retrievals in places and at times when specific aerosol types occur, such as non-spherical, medium-large mineral dust or small, spherical, light-absorbing wildfire smoke, showed that the theoretically derived qualitative particle property distinctions are reflected in the MISR product [5]. Further confirmation was obtained from aircraft field observations, and by comparisons with AERONET retrievals. The MISR retrieval algorithm contains a look-up table of aerosol components and mixtures, and tests a range of particle optical models for agreement with the observed multi-angle, multi-spectral radiances; by examining the range of models that pass the algorithm acceptance criteria, the validation work also confirmed how particle-type discrimination is affected by retrieval conditions [5].

Plume heights. Multi-angle imagery makes it possible to derive the elevation of spatially contrasting features in aerosol plumes from the observed stereoscopic parallax (Figure 1c). With coverage from MISR’s nine cameras, the associated motion vectors of plume elements are also retrieved, enabling a correction to the heights calculated geometrically for plume proper motion [20][21]. High-confidence results require well-defined plume contrast features, which are found most frequently within tens to a few hundred km of wildfire smoke, desert dust, and volcanic sources. In practice, humans are usually best at identifying the boundary within which plume features are defined sufficiently well to maximize retrieval quality. As such, a computer-aided tool, the MISR INteractive eXplorer (MINX), was developed [9]. The user outlines the plume area and indicates the source location and wind direction in imagery displayed on-screen; the program then derives the zero-wind and wind-corrected heights of contrast features at 1.1 km horizontal resolution, along with the motion vectors, using each of the MISR blue and red band data sets. Vertical resolution is between 250 and 500 m, though uncertainty in the wind-corrected heights increases when the plume proper motion is aligned close to the MISR orbit track. In its operational, global-observing mode, MISR reports the radiances from all bands of the nadir-viewing camera in the red band for the eight off-nadir cameras on a 275 m grid; the other 24 off-nadir spectral channels are reported at 1.1 km. As a result, when plume contrast features are sufficiently well defined, red-band retrievals provide higher vertical resolution. However, for optically thinner plumes, the blue-band results are usually superior, as AOD is usually higher at shorter visible wavelengths and over some regions, contrast relative to the surface is improved.

3. Applications of MISR data to climate and air quality

Climate applications: Aerosol transport and radiative forcing. MISR revisit frequency of a given target is about once in eight days near the equator, increasing to once every two days near the poles. As such, the main contributions MISR makes to larger climate forcing and most aerosol transport questions is in the context of constraints on, and/or validation of, climate model simulations and their underlying parameterizations of geophysical processes. MISR AOD, particle property, and plume-height products have all contributed to improved modeling of aerosol transports and radiative forcing.

MISR AOD, with its strengths relative to many broader-swath but single-view instruments over brighter land surfaces, has contributed to the several-decades-long record of global, satellite-derived, monthly AOD, used as primary observational constraints on climate and aerosol-transport models, e.g., [1][22]. Global aerosol direct radiative forcing is often estimated from climate models constrained by such aggregates of satellite AOD, e.g., [23][24]. This advance is a primary reason the Intergovernmental Panel on Climate Change increased the estimate of aerosol direct radiative forcing scientific understanding from “very low” in their assessment report of 2001 (based upon models developed prior to the launch of NASA’s Earth Observing System satellites), to “medium-low” in their assessment six years later [25][26]. Yet, further refinement is needed, as global observational constraints on aerosol light-absorption and vertical distribution are still inadequate to reduce aerosol direct forcing uncertainty to a level comparable to that of greenhouse gases.

These aggregated satellite AOD products have also been applied to constrain long-range aerosol transport, especially across the Atlantic from North Africa [27][28] and across the Pacific from Central Asian sources [29]. Aerosol transport models represent aerosol sources using a source strength and an injection height. MISR plume heights have shown that aerosol injections, especially from wildfires and volcanoes, are frequently energetic enough to penetrate the planetary boundary layer (PBL) and enter the free troposphere, e.g., [30][31]. One limitation of these data, especially for wildfires, is the Terra satellite’s 10:30 AM local time equator-crossing, as peak wildfire activity usually occurs in late afternoon. Yet, ~18% of wildfires in the MISR record injection heights above the PBL, and several studies have shown that downwind aerosol transport simulations improve when a climate or air quality model is initialized with MISR stereo-derived plume injection heights rather than with the nominal model assumptions [32][33]. As user involvement is required to obtain high-quality aerosol plumes heights using MINX, a three-year (2008-2010) global climatology was developed [34]; many additional plumes have been digitized and are posted on a publicly accessible website [35].

Climate applications: Process studies. Some of the most notable contributions of MISR aerosol data amount to constraints on processes that must be represented accurately in climate models. On a regional scale, the seasonal variation of aerosol air mass types over the Indian subcontinent and surroundings has been mapped, using MISR-retrieved particle shape and size constraints to separate pollution particles from desert dust [36]. Also, the ability to distinguish non-spherical desert dust from smaller, spherical wildfire smoke emanating from North Africa helped demonstrate how the Madden-Julian Oscillation (MJO) mediates trans-Atlantic dust transport [37][38]. Several studies correlated MISR-retrieved dust optical depth with short- or long-term meteorological phenomena, establishing connections between regional drought conditions and dust mobilization and transport [39][40]. Similarly, the ability to identify and quantify atmospheric dust motion vectors, along with plume-heights and optical depth, was used to locate Middle Eastern and North African dust sources, regions where sources are typically obscured from satellite view by accumulated background dust loading [41][42]. Among studies with implications for the efficacy of aerosol-related climate feedbacks, the presence of smoke aerosols has been shown to suppresses the diurnal cycle of cloud formation in sub-Saharan Africa [43]. Also, smoke particles from fires in the dry savannah of Central Africa are more light-absorbing than those produced over the more humid Maritime Continent, based on MISR-retrieved particle properties [44].On the scale of individual aerosol plumes, MISR data have been used to characterize the nature and downwind evolution of particles. Near-source plumes are especially good targets for such analysis, as the AOD usually provides ample signal/noise for high-quality aerosol-type retrievals. However, in most cases retrievals must be performed at 1.1 km pixel resolution to resolve plume features; this is made possible by the MISR Research Aerosol retrieval algorithm (RA) [45]. To obtain sufficient particle-property discrimination for this application, enhanced radiometric calibration beyond the original MISR engineering specifications is also required [46]. Most of the two-decades-long

MISR record of volcano observations for the Kamchatka Peninsula and Iceland has been analyzed with the RA, in conjunction with thermal anomalies from MODIS and SO_2 gas mapping from orbiting ultraviolet imagers [47][48]. Ash is readily distinguished from sulfate/water particles in these plumes, and processes such as size-selective and size-independent particle settling, hydration or volatile deposition on existing particles, and new particle formation can be inferred from retrieved downwind changes in AOD, particle size, and light-absorption. Similarly, the occurrence and evolution of black and brown smoke particles in wildfire plumes have been derived, and from the geometrically retrieved motion vectors and downwind distances, the timescales for particle transitions have been obtained as well [49].

Another promising application of MISR multi-angle remote sensing is retrieving aerosol amount and properties over shallow, turbid, and eutrophic water, offering improved "atmospheric correction" for surface characterization for some of the most biologically productive coastal regions and trans-oceanic aerosol transport pathways, globally. The technique has been developed and demonstrated with the MISR RA [50] [51], a version of which will likely be implemented in a future release of the MISR operational product.

Air quality applications. Progressively more sophisticated methods have been developed to make use of the coverage-limited but unique MISR remote-sensing data to help characterize near-surface aerosol amount and properties over regions under-sampled by ground stations alone. Generally, the near-surface $PM_{2.5}$ concentration has been obtained by scaling the satellite-retrieved AOD from MISR and other instruments based on the vertical distribution and other atmospheric properties obtained from aerosol transport models, e.g., [50][53][54]. Because a key strength of the space-based observations is long-term stability, aggregated satellite AOD products, parsed vertically using the GEOS-Chem model, were used to produce a 20-year record of estimated global, near-surface, population-weighted $PM_{2.5}$ concentrations and trends [55]. This record has been used in many health impacts investigations including the Global Burden of Disease [56], which identifies airborne PM as the top environmental health risk worldwide, and in a study of the impact of the global COVID-19 lockdown [57], which derived regionally-dependent $PM_{2.5}$ concentration changes resulting from a combination of meteorology and emission reductions. In the AOD aggregation [55], MISR contributes primarily in situations where the more frequently sampled satellite products have difficulty obtaining good retrieval results.

The earliest application of MISR particle microphysical property data along with AOD for air quality assessment made use of the distinction between non-spherical mineral dust and spherical particles, which include most anthropogenic aerosol pollution, over the continental United States [58][59]. In this case, AOD plus particle shape and size information were obtained from the MISR operational aerosol product, and the GEOS-Chem model provided the vertical distribution and near-surface spherical-particle speciation. A regression model approach was used to transform the satellite data to near-surface $PM_{2.5}$ and the added MISR particle type constraints improved agreement between the satellite $PM_{2.5}$ estimates and U.S. Environment Protection Agency (EPA) surface-based measurements, especially in the western U.S., where non-spherical mineral dust is common but is often transported aloft from distant sources [59].

Among the challenges in applying these approaches is that the particle-property retrievals are much more sensitive than AOD alone to retrieval conditions, as noted above in Section 2. Airborne high-spectral-resolution lidar (HSRL) measurements coincident with MISR overpasses of Mexico City in 2006 were used to explore the limits of MISR aerosol-air-mass-type mapping. Using the combination of particle properties from the MISR RA, the distributions of dust (non-spherical), smoke (spherical, more light absorbing in the blue), and pollution (spherical, spectrally flat absorption) aerosols were mapped over the city [60]. Taking the assessment of air quality over urban areas a step further, support vector machine analysis was applied to six years of the 4.4 km MISR particle-type data over Ulaanbaatar, Mongolia. The study determined that $PM_{2.5}$ and sulfate particles could be mapped in good agreement with ground-based measurements, provided the surface was not snow-covered [61]. Of additional interest for air quality in urban areas, where there might be many local sources, are the spatial scales of PM variability. This question was examined using several dense ground-station networks and MISR retrievals over southern California [62], with the conclusion that the MISR 4.4 km data capture most of the km-scale variability in $PM_{2.5}$ and in PM with particle diameters between 2.5 and 10 μm in that region, although in the winter season the larger particles showed indications of sub-km variability that was not reflected in the satellite observations.

To maximize the use of MISR particle property information, the spherical light-absorbing AOD from the MISR RA was associated with organic matter and light-absorbing carbon components in the CMAQ air quality model, the MISR spherical non-absorbing AOD with model inorganic ions, sea salt, and non-absorbing organic matter, and the non-spherical AOD with dust [63]. Using a spatial statistical weighting approach, this work merged the model with available ground station data over California's San Joaquin Valley and weighted the satellite contribution increasingly with distance from the stations.

Low-cost, surface-based optical particle counters (OPCs) have the potential to monitor air quality in under-served areas of the world; however, they are difficult to calibrate, and current sensors are insensitive to the majority of urban pollution particles, which tend to be smaller than about 0.5 microns in diameter. Another new technique, using the size range where the OPCs overlap MISR RA retrievals, was used to combine the two data sets and obtain near-surface concentrations of pollution particles over Nairobi, Kenya [64].

Given the complex and non-linear relationship between MISR-retrieved aerosol microphysical properties and ground level $PM_{2.5}$ composition, advanced statistical models with more flexible structures are often required. As a first attempt, a Generalized Additive Model (GAM) was developed to link MISR fractional AODs scaled by GEOS-Chem aerosol vertical profiles with ground-level fine particle sulfate concentrations over the continental US on a 50-km resolution grid [65]. This and a follow-up study [66] demonstrated that using the boundary-layer fraction of satellite-retrieved AOD instead of the total column can significantly improve model performance and reduce the prediction bias. Similar GAM models were developed to estimate ground-level concentrations of daily $PM_{2.5}$ sulfate, nitrate, organic carbon (OC) and elemental carbon (EC) in Southern California between 2001 and 2015 using 4.4 km resolution MISR data [67]. Predicted concentrations by these GAMs capture both regional patterns and finer-scale characteristics of the four chemical constituents in urban areas of Los Angeles, other counties, and the Central Valley and showed the effectiveness of air pollution controls in reducing particle concentrations over time. Machine learning models have been applied to estimate $PM_{2.5}$ speciation using MISR retrievals. Recently, a set of random forest models was developed to estimate daily $PM_{2.5}$ sulfate, nitrate, OC and EC concentrations in California at 1 km resolution using MISR fractional AOD combined with CMAQ simulation results [68]. In addition to the higher spatial resolution, machine learning models also achieved higher model correlation compared with the GAMs (Figure 1b).

4. Conclusion

MISR has demonstrated the contributions multi-angle imaging can make to both climate and air quality studies, and has produced a record of results more than two decades long during the NASA Earth Observing System era. A comprehensive bibliography of aerosol studies involving

MISR data is available online [69]. The MISR Aerosol Products are available, free of charge, from the NASA Atmospheric Science Data Center [70]. Future multi-angle remote sensing promises to provide enhanced capabilities for distinguishing aerosol types by adding channels in the ultraviolet and infrared, along with polarization sensitivity, as well as increased spatial resolution stereoscopic observations of aerosol plumes. Multiple instruments in polar orbit could increase both global coverage frequency and diurnal temporal resolution. Along with the possibility of acquiring well-calibrated, high-resolution data from newly deployed imagers in geostationary orbit, instruments planned for NASA's upcoming Multi-Angle Imager for Aerosols (MAIA) and Atmospheric Observing System (AtmOS) missions will begin to address this potential, building upon the MISR legacy.

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Figure Caption

Figure 1. (a) Global MISR aerosol type map for July 2007, showing the broad categories of spherical non-absorbing, spherical light-absorbing, and non-spherical aerosol types, as well as finer distinctions (from [5]). (b) Model-predicted annual mean $PM_{2.5}$ sulfate and EC concentrations in California, constrained by MISR species-related fractional AOD (from [68]). (c) True-color context image of the Government Flats fire plume, 21 August 2013, acquired by the MODIS instrument coincident with the MISR observations. Annotations show MISR-derived plume-age estimates and four regions where particle properties change significantly. (d) MISR stereo-derived, wind-corrected (blue) and zero-wind (red) downwind plume height profile for the Government Flats fire plume. The surface elevation is indicated in green. (e) Mid-visible fractional aerosol amount identified as black smoke and (f) brown smoke for the same fire, derived with the MISR RA. The fire source is indicated by a red star in panels c-f. (from [49]).