NASA Satellite Observations of Clouds, Ash, and Dust

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1. Introduction

Ash (from volcanic emissions) and dust (blown by wind from bare soils and arid surfaces) belong to a broad group of tiny solid or liquid particles suspended in the atmosphere, and collectively referred to as 'aerosols', which include desert and soil dust, volcanic ash, wildfire smoke, black carbon, sea salt, natural and anthropogenic sulfate, nitrate, and organic aerosols. Although ash and dust have distinct sources and are often recognized by trained analysts on satellite imagery based on context, they and the other aerosols are generally retrieved together from satellite data and, since they are hard to separate in automated satellite remote sensing, aerosols will be treated together in this paper.

Clouds and aerosols are the dominant visible features in the atmosphere and occupy a prominent place in earth observation and related science. Clouds have a dominant influence on the earth's radiation budget, weather, and eventually climate, whereas aerosols not only have similar effects in the atmosphere, but also, depending on their physical and chemical properties, they can serve as the nuclei upon which water vapor condenses to form clouds, and can affect the microphysical and radiative properties of existing clouds, thereby indirectly leading to additional cloud effects on radiation, precipitation, and climate. Furthermore, depending on aerosol composition, properties, and three-dimensional atmospheric distribution, they can affect air quality and the environment significantly. Therefore, both clouds and aerosols are very important meteorologically and climatically, and constitute the foci of major atmospheric research programs, to which many of the NASA remote sensing and modeling efforts are devoted.

Although NASA has networks of ground-based monitoring systems for aerosols, and utilizes quite a large set of airborne assets to monitor both clouds and aerosols, most of its activities on cloud and aerosol monitoring are based on earth observation satellites. Remote sensing of clouds and aerosols is conducted with two main sensor types: passive and active. Passive remote sensors measure reflected sunlight, whereas active sensors generate their own energy, which they direct toward the target (in this case the earth) and quantify the returned signal, such as in the case of radars (for clouds) and lidars (for both aerosols and clouds). Table 1 lists the acronyms and meanings of the satellites and sensors described in this white paper, along with their respective operating agencies. Although clouds and aerosols have distinctly different characteristics, nevertheless, since they often occur together in the atmosphere, and sometimes look alike in true color imagery, similar remote sensing parameters are often retrieved and used in describing them. These include optical depth or thickness, particle/droplet/crystal type or shape, effective radius (of aerosol particles or cloud droplets/crystals), size distribution, layer height, layer thickness, vertical distribution, and several other parameters. Such remotely sensed parameters are used in many research and operational activities, as well as in international environmental and climate assessments, some of which will be highlighted in later sections.

Table 1: Acronyms of Satellites and Sensors described in this paper, preceded by those of the Agencies that operate these Satellites and the respective Countries or Regions they belong to

Agency	**Description**	**Country/Region**
CNES	Centre Nationale d'Études Spatiales	France
ESA	European Space Agency	Europe
NASA	National Aeronautics and Space Administration	USA
NOAA	National Oceanic and Atmospheric Administration	USA

Satellites	**Description**	**Agency**
Aqua	N/A*	NASA
Aura	N/A*	NASA
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	NASA, CNES
CloudSat	Cloud Satellite	NASA
GOES	Geostationary Operational Environmental Satellite (series 1 - 15)	NOAA
ICESat	Ice, Clouds, and Land Elevation Satellite	NASA
MSG	Meteosat Second Generation	ESA
NOAA	National Oceanic and Atmospheric Administration (series 1 - 19)	NOAA
NPP	NPOESS Preparatory Project	NASA, NOAA
PARASOL	Polarization and Anisotropy of Reflectance for Atmospheric Science coupled with Observations from a Lidar	CNES
SeaWiFS	Sea-viewing Wide Field-of-view Sensors	NASA
Terra	N/A*	NASA
TRMM	Tropical Rainfall Measuring Mission	NASA

Sensors	**Description**	**Satellite**
AIRS	Atmospheric Infrared Sounder	Aqua
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System	Aqua
AMSU	Advanced Microwave Sounding Unit	Aqua
AVHRR	Advanced Very High Resolution Radiometer	NOAA
CALIOP	Cloud and Aerosol Lidar with Orthogonal Polarization	CALIPSO
CPR	Cloud Profiling Radar	CloudSat
HIRS	High-resolution Infrared Sounder	NOAA
IMG	Imager	GOES
MISR	Multi-angle Imaging Spectroradiometer	Terra
MODIS	Moderate-resolution Imaging Spectroradiometer	Terra, Aqua
OMI	Ozone Monitoring Instrument	Aura
SEVIRI	Spinning Enhanced Visible and Infrared Imager	MSG
VIIRS	Visible Infrared Imager Radiometer Suite	NPP
VIRS	Visible and Infrared Scanner	TRMM

*N/A means "Not Applicable" or "Not Available"

2. Satellite Measurement of Clouds and Aerosols

Although clouds and aerosols often occur together in the atmosphere, sometimes look alike in true color imagery, and are characterized from space using similar remote-sensing parameters, actual retrieval of cloud and aerosol parameters from satellite radiance measurements is done differently and separately, as described in the following subsections.

2.1 Clouds

Important satellite-derived cloud information needed for both research and applications include cloud detection, cloud-top properties (pressure, temperature, height), optical properties (optical thickness, effective emissivity of non-opaque clouds, effective particle radius), microphysical properties (thermodynamic phase, water content, moments of the size distribution other than effective size), and macrophysical quantities (integrated water path).

Passive Observations:

NASA passive imagers (e.g., MODIS, MISR) and sounders (e.g., AIRS) provide detailed horizontal spatial information about clouds on a near daily global basis (e.g., MODIS, AIRS). Each sensor's cloud team produces and archives both Level-2 (pixel level) and Level-3 (spatial and temporal aggregations) products.

MODIS:

The MODIS instruments on Terra (launched December 1999) and Aqua (May 2002) provide cloudy FOV detection/masking and cloud products that include both cloud-top properties (temperature, pressure, effective emissivity) and optical/microphysical/macrophysical parameters (thermodynamic phase, optical thickness, effective particle radius, water path, multilayer detection) along with a variety of Quality Assessment information. Baseline pixel-level uncertainties are provided for cloud optical properties. MODIS processing streams based on a consistent set of algorithms are referred to as data "Collections". The implementation and evaluation of code refinements for Collection 6 reprocessing is ongoing, with production nominally expected to begin in early 2012. Online data and search tools are available at http://ladsweb.nascom.nasa.gov/.

The MODIS imager provided a major step forward in spectral, spatial, and radiometric capability relative to the polar orbiting AVHRR observations that had begun in 1978, most notably, two on-board characterization sub-systems (solar diffuser and solar diffuser stability monitory, spectral radiometric and characterization assembly).

AIRS:

With over 2300 spectral channels and state of the art onboard calibration, the AIRS infrared (IR) grating spectrometer has significantly improved sounding capability over previous generation sensors (e.g., the NOAA High-resolution Infrared Radiation Sounders, HIRS). In addition, hyperspectral IR observations provide important cloud information. The AIRS standard cloud products include cloud-top temperature, pressure, and effective emissivity and have been validated against independent observations from CloudSat and CALIPSO [e.g. *Kahn et al.*, 2008]. In the Version 5 algorithm, up to two cloud layers are inferred from fitting observed AIRS radiances to calculations. Cloud-top pressure and temperature are reported at the AMSU resolution (~40 km at nadir), whereas effective emissivity is reported at the native AIRS resolution (13.5 km). Spatially matched IR-derived cloud products from AIRS and MODIS have been shown to be radiatively consistent to each other [*Nasiri et al.*, 2011].

The AIRS team's most recent algorithm release and reprocessing effort is Version 5 (V5). However, the V6 algorithm development is progressing (currently scheduled for release in late 2011). The AIRS Team is considering reporting the cloud top temperature and pressure fields at the native AIRS resolution. Three new cloud fields will be added to the Level-2 (pixel-level) product: (1) ice cloud optical thickness, (2) ice cloud effective diameter, and (3) cloud-top thermodynamic phase. Error estimates and scalar averaging kernels are reported for the retrieved cloud parameters. Data are available at http://disc.sci.gsfc.nasa.gov/AIRS.

MISR:

The Multi-angle Imaging SpectroRadiometer (MISR) on Terra provides unique information via nine cameras with different view angles in the visible and near-infrared wavelengths. The change in reflection at different view angles affords the means to distinguish different types of atmospheric particles (aerosols), cloud forms, and land surface covers. Combined with stereoscopic techniques, this enables both the detection of clouds as well as cloud height, cloud motion vectors, and cloud albedo. Information on data access is at http://www-misr.jpl.nasa.gov/getData/accessData/.

Active Observations:

NASA's active atmospheric sensors allow for detailed information about cloud and aerosol vertical structure.

CALIPSO and CloudSat

Precise detection of cloud physical height, as well as cloud base and cirrus optical thickness for non-opaque clouds, is provided by the CALIOP lidar on CALIPSO. Vertical structure of extinction, thermodynamic phase, and ice-water content are also available up to an optical depth of about 3. CALIPSO also flies a multichannel IR imager (IIR) from CNES that, in conjunction with CALIOP lidar measurements, allows for independent retrievals of cirrus optical thickness, effective particle size, and ice-water content. Data are available at http://eosweb.larc.nasa.gov/.

The CPR, which is a 94 GHz radar on CloudSat, provides vertical information on liquid and ice water content, along with information about lite precipitation processes. Both CALIPSO and CloudSat were co-manifest and launched in April 2006. Data is available through http://www.cloudsat.cira.colostate.edu/dataHome.php.

The afternoon constellation or A-Train (Aqua, CloudSat, CALIPSO, PARASOL, Aura) allows for synergistic multi-sensor cloud observations closely matched in time and space.

2.2 Aerosols (Ash, Dust, and other atmospheric particles)

Because aerosols originate from many, diverse sources, and exhibit an enormous range of chemical compositions and physical properties, they are especially challenging to study, particularly from space. The NASA satellite sensors that are known to provide standard aerosol products include MODIS, MISR, OMI, SeaWiFS, and CALIOP. The aerosol parameter most commonly derived from satellite remote-sensing data is the total-column, mid-visible, aerosol extinction optical depth or thickness (AOD or AOT or $_a$), which is a dimensionless measure of aerosol amount, based on the fraction of incident light that is either scattered or absorbed by particles, integrated over the entire atmospheric column. Depending on sensor characteristics, some other aerosol parameters, including aerosol type and shape, refractive index, effective radius, size distribution, scattering and absorption properties, can be retrieved with more or less larger uncertainty than $_a$. In addition, because of its multi-angular capability, MISR is able to provide maps of aerosol plume height near wildfire, volcano, and desert dust sources using digital stereo restitution techniques. Similarly, lidar profiles acquired through active remote sensing by CALIOP enable the mapping of aerosol vertical distribution as well as the recognition of multiple aerosol layers.

3 Characteristics and availability of satellite data products

Satellite cloud and aerosol data products exist in a variety of spatial and temporal resolutions, depending on orbital and sensor characteristics, as well as retrieval algorithm constraints. Table 2 lists the main satellite sensors that have provided these data products over the years, as well as the basic parameters provided, their nominal spatial resolution, and period of data availability. It is pertinent to mention that some of the sensors (MODIS and AIRS) offer a real-time direct broadcast (DB) of their data, which can be received at ground stations equipped with DB receivers. The International MODIS/AIRS Processing Package (http://cimss.ssec.wisc.edu/imapp/) is available for download and installation at such ground stations for immediate data processing upon reception. This DB feature is particularly important for near-real-time applications.

Table 2: Satellite sensors and associated cloud and aerosol products (all sensors are passive except where indicated otherwise in parenthesis)

Sensor (Type)	Satellite	Measurement Type	Product Identifier	Relevant Parameters*	Spatial Resolution	Data Period	Comments, Reference
Passive Sensors							
MODIS	Terra	Cloud	MOD06	COD, CER, CFR, CTP, CTT, CAL, LWP	1 x 1 km	2000 -- Present	DB capable with IMAPP
		Aerosol	MOD04	AOD, AEX, FMF	10 x 10 km	2000 -- Present	*Remer et al*. (2005); *Levy et al*. (2010)
	Aqua	Cloud	MYD06	COD, CER, CFR, CTP, CTT, CAL, LWP	1 x 1 km	2002 -- Present	
		Aerosol	MYD04	AOD, AEX, FMF	10 x 10 km	2002 -- Present	
MISR	Terra	Cloud	MIL2TCAL, MIL2TCST	CAL, CTH, CFR, CTY, CWV	CTH: 1.1 km CAL,CTY: 2.2 km CFR: 17.6 km CWV: 70.4 km	2000 -- Present	
		Aerosol	MIL2ASAE	AOD, ATY, AEX, SSA;	17.6x17.6 km;	2000 -- Present	*Kahn et al*. (2010);

				small, medium, large fractions; non-spherical fraction; near-source plume height	plume height at 1.1 x 1.1 km		*Martonchik et al*. (2009
OMI	Aura	Aerosol	OMAERUV	AI, AAOD, AOD	13.7x23.7 km	2004 -- Present	DB capable
AIRS	Aqua	Cloud		CTP, CTT, CFR		2002 -- Present	DB capable with IMAPP
TOMS	Nimbus-7	Aerosol		AI	40x40 km	1978 -- 1993	*Torres et al*. (2002)
	Meteor-3	Aerosol		AI	40x40 km	1991 -- 1994	*Torres et al*. (2002)
	Earth Probe	Aerosol		AI	40x40 km	1996 -- 2005	*Torres et al*. (2002)
Active Sensors							
CALIOP (Lidar)	CALIPSO	Aerosol	05kmALay 05kmAPro	ALH, AOD, ATY AOE, ATY	30 m x 5 km 60 m x 5 km	2006 - Present	*Winker et al*., 2009, 2010
		Cloud	05kmCLay 05kmCPro 01kmCLay 333mClay	CLH, COD, CTY, IWP COE, CTY, IWC CLH, CTY CLH, CTY	30 m x 5 km 60 m x 5 km 30 m x 1 km 30 m x 333 m	2006 - Present	*Winker et al*., 2009, 2010
IIR	CALIPSO	Cloud	L2_Track/Swath	COD, CER, CLH, IWP	1x1 km	2006 - Present	Retrievals from passive IR + lidar
CPR (Radar)	CloudSat	Cloud	2B-TAU, 2B-CWC-RVOD	COD, IWC, LWP	1.4 x 1.7 km	2006 - Present	

* Meanings of Acronyms used for parameters
AAOD: Absorption Aerosol Optical Depth or Thickness
AEX: Aerosol Ångström Exponent
AER: Aerosol Effective Radius
AI : Aerosol Index
ALH: Aerosol Layer Height
AOD: Aerosol Optical Depth or Thickness
AOE: Aerosol Optical Extinction
ATY: Aerosol Type
CAL: Cloud Albedo
CER: Cloud Effective Radius
CFR: Cloud Fraction
COD: Cloud Optical Depth or Thickness
COE: Cloud Optical Extinction
CLH: Cloud Layer Height (base and top)
CTH: Cloud Top Height
CTP: Cloud Top Pressure
CTT : Cloud Top Temperature
CTY: Cloud Type (this is texture-based description of cloud type for MISR)
CWV: Cloud Wind Vector
FMF: Aerosol Fine Mode Fraction
IWC: Cloud Ice Water Content
IWP: Cloud Ice Water Path
LWP: Cloud Liquid Water Path

SSA: Aerosol Single Scattering Albedo

4 From satellite products to operations

Different cloud and aerosol products retrieved from NASA satellites are being used in a variety of operational systems across the world, as summarized in the following examples:

(i) **Assimilation into the ECMWF forecast:** The European Centre for Medium–Range Weather Forecasts (ECMWF) uses new linearized moist physics schemes to assimilate cloud optical depths retrieved from MODIS in the ECMWF operational four–dimensional assimilation system (4D–Var) (Benedetti and Janisková, 2008).

(ii) **Operational air quality forecasting:** Under a special partnership arrangement between three US agencies NASA, NOAA, and the Environmental Protection Agency (EPA), NASA satellite aerosol products from MODIS are utilized in conjunction with EPA ground-based measurements and NOAA modeling to enhance air-quality forecasting within the framework of **IDEA** (Infusing satellite Data into Environmental air quality Applications). Further information can be found at http://www.star.nesdis.noaa.gov/smcd/spb/aq/.

(iii) **Assimilation into the Navy's Fleet Numerical Forecast:** The US Naval Research Laboratory (NRL) assimilates NASA satellite aerosol products from MODIS and MISR into their aerosol transport models in an effort to improve aerosol and visibility forecasting capability using near real time observations (e.g. Zhang et al., 2008).

(iv) **NASA GMAO Aerosol Assimilation:** The NASA Global Modeling and Assimilation Office (GMAO) current near real-time (NRT) system runs at a nominal 25-km global resolution, and includes 15 aerosol tracers. The aerosols are transported within the GCM (GEOS-5), with aerosol processes derived from the NASA Goddard Chemistry Aerosol Radiation and Transport (GOCART) model that simulates major tropospheric aerosol components, including sulfate, dust, black carbon (BC), organic carbon (OC), and sea-salt aerosols. The system currently assimilates MODIS aerosol optical depth retrievals in NRT, driving the system with estimates of biomass burning derived from MODIS fire radiative power retrievals. Example GMAO NRT data for a recent field experiment is available at http://gmao.gsfc.nasa.gov/projects/DISCOVER-AQ/.

In addition, many of the NASA satellite products beyond clouds and aerosols are provided online for research and applications, public information, outreach, or education.

(i) **NASA Earth Observatory (http://earthobservatory.nasa.gov/):** This award-winning NASA Earth Observatory web site regularly features spectacular satellite imagery of important environmental phenomena around the world and provides genuine but simplified scientific explanation of what is being visualized for public enlightenment and education. It attracts tremendous readership from a large number of people from all segments of the global population.

(ii) **LANCE (http://lance.nasa.gov/):** The Land Atmosphere Near Real-time Capability for EOS (LANCE) web site, as the name suggests, provides near real-time data products (i.e. generated within 3 hours of the time of observation) from various sensors aboard satellites that are part of the NASA Earth Observing Systems (EOS), namely: Terra, Aqua, Aura. The MODIS Rapid Response web site, well known within the remote sensing community during the last decade for its rapid delivery of quick visualizations of Terra- and Aqua-MODIS imagery is now part of LANCE, whose user community includes various agencies interested in monitoring natural and man-made hazards.

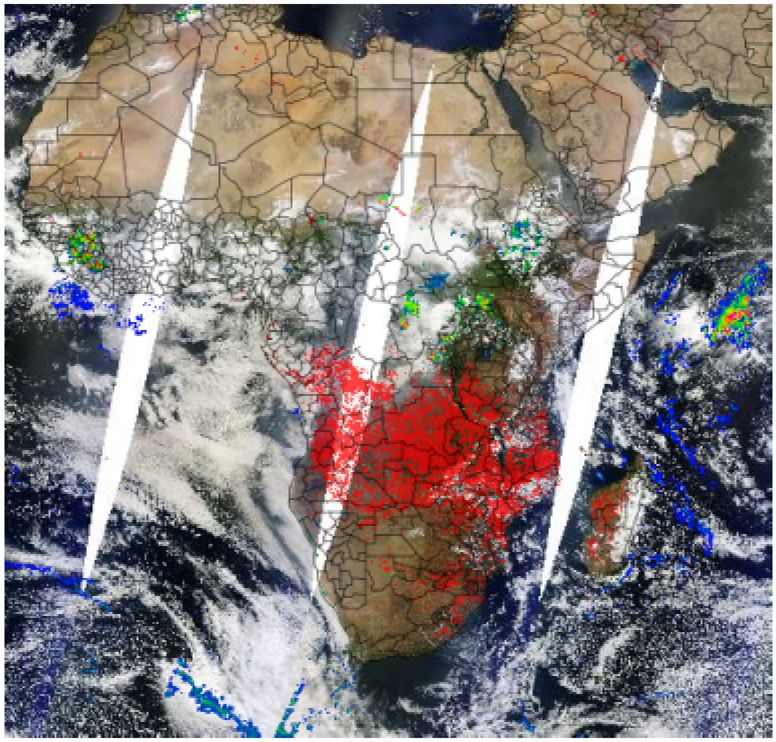

Figure 1. Example of Rapid Response Web Mapping Service, showing true color MODIS color composite image of Africa and surrounding regions, with overlays of fire locations observed by MODIS (in red) and rain rates derived from AMSR-E (in the rainbow colors).

(iii) **SERVIR (http://www.servirglobal.net/en/Home.aspx):** A unique partnership formed between NASA and the United States Agency for International Development (USAID) has resulted in the creation of several nodes for serving NASA satellite data and related modeling to various developing parts of the world. There are currently three SERVIR nodes serving the regions of Mesoamerica, East Africa, and the Himalayas, with several more currently under consideration.

(iv) **FIRMS (http://maps.geog.umd.edu/firms/):** Although fires are not clouds or aerosols, they emit smoke, whose particles constitute one of the dominant aerosol types. Due to demand by various agencies for rapid fire-location information from satellite observations for disaster mitigation and air-quality forecasting, the Fire Information for Resource Management Fire System (FIRMS) was created to serve various needs of that nature. FIRMS, which is housed at the University of Maryland College Park was borne out of long-standing collaboration between scientists at the University and NASA. Many agencies including the US Forest Service (USFS), the National Oceanic and Atmospheric Administration (NOAA), the Naval Research Laboratory (NRL), as well as other regions of the world access and use FIRMS services.

5 International climate assessments and related programs

During the last decade, numerous environmental assessments have been conducted by various national and international agencies based on data products from NASA satellites.

(i) **GEWEX Cloud Assessment:** Under the auspices of the Global Energy and Water Cycle Experiment (GEWEX), an assessment of the MODIS, MISR, AIRS, and CALIOP standard cloud products (among others) has been undertaken by a number of investigators including the NASA algorithm teams. The teams have also participated in the continuing GEWEX Cloud Assessment study [e.g., *Stubenrauch and Kinne*, 2009; *Stubenrauch et al.*, 2011]. While such assessments will continue, observations from CALIOP represent an accurate standard against which other products can be compared, and the uncertainties and/or issues for most of these products are now understood and have been documented.

(ii) **GEWEX Aerosol Assessment:** Like for clouds, GEWEX is also collaborating with NASA to conduct an assessment of aerosol retrievals from multiple satellite sensors, including AVHRR (from NOAA) MODIS, MISR, OMI, and TOMS (from NASA), as well as POLDER (from the French Space Agency, CNES). This assessment is currently ongoing, and the preliminary report is expected to be released sometime in 2012.

(iii) **LRTAP (http://www.htap.org/):** Observational data from several NASA satellites were used to make estimates of transcontinental transport of pollutants, as a contribution to the World Meteorological Organization's (WMO) Long-range Transport of Air Pollution (LRTAP) task force on Hemispheric Transport of Air Pollution (HTAP) in the Northern Hemisphere whose report was published in 2010.

(iv) **IPCC Assessment reports (http://www.ipcc.ch/):** NASA satellites provided observational constraints on climate modeling for estimating the magnitudes of climate forcing by clouds, aerosols, and various other factors for inclusion in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR), and now also for the development of the Fifth Assessment Report (AR5).

(v) **AEROCOM (http://dataipsl.ipsl.jussieu.fr/AEROCOM/aerocomhome.html):** The international Aerosol Comparisons between Observations and Models (AEROCOM) initiative involves a large group of scientists interested in the comparison of various aspects of aerosol distributions, characteristics, and impacts. Several NASA models and satellite observations (especially MODIS, POLDER, MISR, CALIOP, AVHRR, SeaWiFS, and TOMS) are involved in this project.

6 Research activities based on the satellite products

Numerous ongoing research activities based on NASA satellite data products may eventually be transitioned or contributed to operational or assessment activities. Some of such research activities fall under a few prominent themes recognized within the atmospheric science communities, as detailed in the following subsections.

6.1 Volcanic Ash Plumes

Iceland's Eyjafjalljökull volcano erupted repeatedly between 14 April and 23 May 2010, sending ash plumes across the skies of Europe, disrupting air traffic, and stranding travelers for up to several weeks. During the early eruptions, much of the European airspace was shut down, but by early May, selective closures allowed many more flights to proceed, vastly reducing the impact on society. The SEVIRI sensor aboard the European Meteosat geosynchronous platform made the primary satellite contributions to the improved near-real-time response. However, detailed plume height analysis from the MISR sensor aboard the NASA Terra platform and the CALIOP lidar on the CALIPSO satellite, as well as data from other polar-orbiting satellites, are playing key roles in improving ash plume modeling and prediction internationally, aimed at planning for future volcanic events.

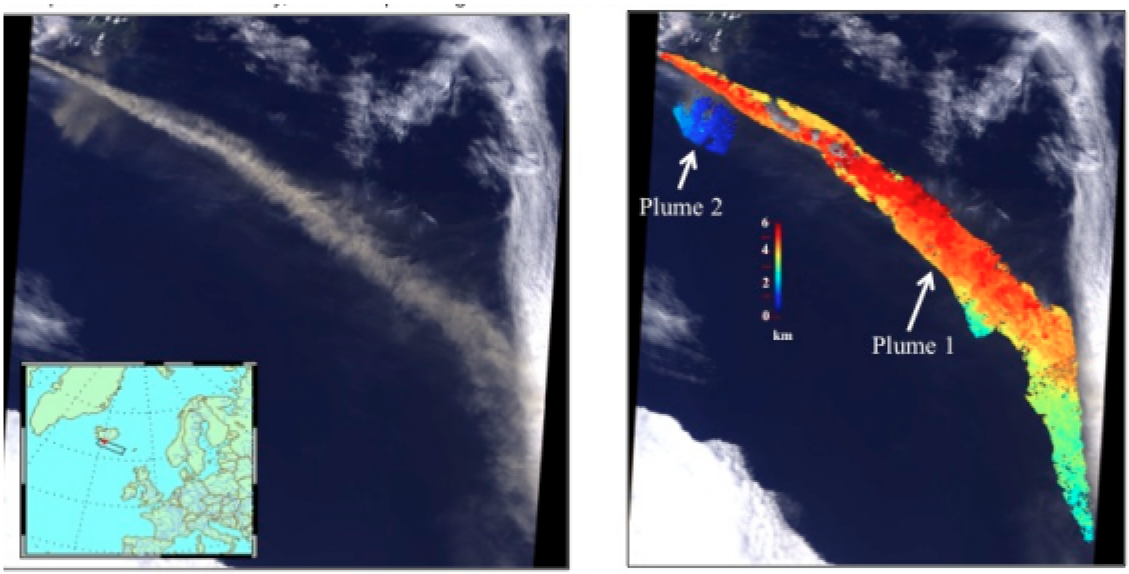

Figure 2: On 07 May 2010 at 12:39 UT, the Multi-angle Imaging SpectroRadiometer (MISR) instrument aboard the NASA Earth Observing System's Terra satellite captured the true-color, nadir-viewing image at left, along with eight other images at viewing angles ranging from +70 to -70 along a 380-km-wide ground track. Aerosol amount and type, as well as plume vertical extent and ambient wind vectors, are derived from the MISR multi-spectral, hyper-stereo observations. The image at right shows plume height derived for this event using the MISR INteractive eXplorer (MINX) algorithm. Two volcanic plumes are highlighted: More than 400 km of the main plume (Plume 1) falls within the field-of-view; it is injected to about 6 km and descends to about 3 km toward the east. Plume 2 is remobilized ash residing near the surface. The volcano itself if located at the upper left in these images (see inset map in the left image).

6.2 Biomass burning smoke emissions

Biomass burning smoke emissions are required to drive models that predict and monitor the impacts of various smoke constituents on air quality, weather, and climate. For a long time, researchers have relied on small-scale experimental biomass burning and auxiliary data to estimate smoke emissions (e.g. Crutzen and Andreae, 1990; Andreae and Merlet, 2001). New satellite measurements of fires, aerosols, and trace gases from NASA and a few other Agencies have revolutionized biomass burning emissions research by providing global coverage at daily or even higher frequencies. Henceforth, satellite data represent the primary source of information for mapping of biomass burning activity and evaluation of smoke emissions at regional to global scales (e.g., *Freitas et al*., 2005; *Davies et al*., 2009; *Ichoku et al*., 2008; *Kahn et al*., 2008; *Reid et al*., 2009; *van der Werf et al*., 2010). Thus, the uncertainty on biomass burning emissions is becoming narrower, and emissions products are generated and provided to the user community and operational agencies for air-quality and climate applications (e.g. http://www.nrlmry.navy.mil/flambe/, http://ess1.ess.uci.edu/~jranders/data/GFED2/, http://opendap.nccs.nasa.gov/dods/Emissions/QFED).

6.3 Aerosol-cloud interaction

Aerosol particles affect solar radiation by direct scattering and absorption, but can also change cloud properties through the subset of particles that act as cloud condensation nuclei (CCN) and ice nuclei (IN), a pathway referred to as the "indirect aerosol effect" (IAE). While the IAE is a continuum of effects and consequences, it is often considered the manifestation of two primarily different aerosol-cloud interaction mechanisms. One mechanism is the radiative effect due to cloud microphysical changes only (no change in cloud water or other properties). Here, the greater availability of CCN or IN yields clouds with more numerous but smaller cloud particles and therefore larger optical thicknesses (commonly referred to as the "Twomey effect" or 1st IAE). A second mechanism encompasses the effect of aerosols on cloud water, e.g., a decrease in cloud particle size decreasing precipitation efficiency and thereby increasing cloud lifetime, fraction, and/or physical thickness. This 2nd IAE can modify both cloud radiative and macrophysical properties. Other microphysical consequences have been invoked for convective clouds (e.g., effect on freezing level and dynamic development) while the non-microphysical "semi-indirect effect" of absorbing is thought to be an important modifier to cloud properties in some regimes and time periods. Satellite observational studies are challenging due to the inherent difficulties involved in trying to quantify these distinct processes from instantaneous measurements and incomplete cloud dynamic/thermodynamic information.

While a summary of recent research is beyond the scope of this white paper, the unprecedented combination of coincident and synergistic A-Train constellation observations (atrain.nasa.gov) from active and passive imagers has opened up new observational investigations into these various mechanisms. Of special note has been the use of combined MODIS and CALIPSO lidar aerosol observations, and MODIS and CloudSat cloud observations.

7 Conclusions and future perspectives

NASA Earth observation satellites have contributed immensely toward effective monitoring of meteorological and other physical phenomena that affect the society both directly and indirectly. Clouds and aerosols, as well as the events that produce them, such as convection, volcanic eruptions, fires, and dust storms, are extremely dynamic and can change dramatically in a matter of minutes; making them difficult to be captured adequately with instantaneous observations made once or twice a day from polar-orbiting research satellites operated by NASA. Although the existing geostationary satellites operated by the meteorological agencies of the US and other countries offer sub-hourly observation frequency that improves monitoring, they currently observe at coarse spatial resolution, typically with pixel sizes of about 4x4 km, compared to 1x1 km or better resolution from the polar-orbiting satellite sensors. Such coarse-resolution data are not able to represent fine-scale phenomena, such as the aerosol emission sources or locations of discrete convective events including pyro-cumulus processes. For instance, a comparative study between fire measurements from SEVIRI and MODIS shows that SEVIRI underestimates MODIS by more than 40% because of its inability to detect the relatively smaller fires (Roberts et al., 2005).

A new generation of geostationary satellite sensors are needed to enable adequate coverage of meteorological and other environmental phenomena from satellite at a wide variety of spatial and time scales. Since current geostationary satellite sensors already offer sub-hourly observation frequencies, improvements in spatial resolution, accuracy, and precision are needed in order to meet the desired goals. In response to recommendations by the National Research Council (NRC) Earth Science Decadal Survey released in 2007, NASA is developing the concept for a geostationary satellite mission called GEOCAPE, which may include some of such improvements. In any event, since geostationary satellites are typically located over fixed points on the earth, NASA polar-orbiting satellites with one or more overpasses per day are still needed to compliment them and provide calibration between multiple geostationary satellite sensors. This is also important because, compared to satellite sensors operated by other agencies, most NASA satellite sensors are very well calibrated and provide high quality radiance measurements that are accurately geo-referenced, and can therefore serve as reference for cross-calibration of satellite measurements.

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