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The CHIMAERA system for retrievals of cloud top, optical and microphysical properties from imaging sensors

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A B S T R A C T

Continuity and consistency of geophysical retrieval products obtained from different Earth-observing spaceborne or airborne atmospheric multispectral imagers can be challenging due to inherent differences in the instruments and/or the use of different retrieval algorithms. The Cross-platform HIgh resolution Multi-instrument AtmosphEric Retrieval Algorithms (CHIMAERA) system addresses the latter aspect of the inter-sensor continuity problem for cloud property retrievals by removing retrieval methodology and implementation as a source of inconsistency when applied to instruments that share common measurement capabilities.

Transferring an existing retrieval algorithm to a new sensor oftentimes is a nontrivial task, as it is common for an algorithm code to be tightly coupled to the sensor for which it was developed. By creating a clear division between the science algorithm and the instrument I/O codes, CHIMAERA allows easy migration of science algorithms to different sensors. CHIMAERA is built from C and FORTRAN source code, and can operate in a variety of environments ranging from a personal laptop to a high-performance computing environment for near real-time satellite data production. It is highly adaptable, low-maintenance and allows for easy expansion such that adding new instruments into the system requires only instrument-specific I/O and provision of any external lookup tables specific to the instrument's spectral characteristics.

CHIMAERA currently officially supports 13 spaceborne and airborne atmospheric imagers from a single code base, and has been in use since 2007. This paper describes the engineering aspects of CHIMAERA and a few examples from its many current applications are briefly discussed.

1. Introduction

When new remote sensing instruments enter into operation, there are often significant obstacles to creating the science data products from their observations. (King et al., 2004; 2010; Hamann et al., 2014). The largest of those obstacles is that proven, well established remote sensing product algorithm codes are often tightly coupled to the instrument for which they were first developed. It thus becomes a significant and often error-prone effort to adapt the algorithm to a new instrument, and maintenance and improvement efforts can become more complicated as algorithm permutations multiply.

A good example is the use of the MODIS Airborne Simulator (MAS) (King et al., 1996) operated on NASA's ER-2 high altitude research aircraft since the early 1990s. MAS (and its successor eMAS) is a multispectral scanning spectrometer that provides information very similar to the space-borne imager MODerate resolution Imaging Spectroradiometer (MODIS) (Barnes et al., 1998), the flagship instrument on NASA's Earth Observing System (EOS) *Terra* and *Aqua* spacecrafts. MAS shortwave radiometric calibration historically has been tied to MODIS to ensure that it remains a valuable validation and development aid for space-borne remote sensing work. Such calibration methodologies are outlined in Peddle et al. (2001). Nevertheless, the cloud top (e.g., pressure, temperature, infrared thermodynamic phase), optical and microphysical (thermodynamic phase, optical thickness, particle effective size, water path) property retrieval algorithms applied to MAS observations prior to 2007 were in some respects inconsistent with their space-borne MODIS counterparts due to out of phase development cycles. To facilitate a unified cloud property retrieval approach across these space-borne and airborne imager assets, the Cross-platform HIgh resolution Multi-instrument AtmosphEric Retrieval Algorithms (CHIMAERA) system was developed and implemented for the first time on MAS during the 2007 Tropical Composition, Cloud and Climate Coupling (TC4) field campaign (King et al., 2010).

Though CHIMAERA was primarily developed to create a unified

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cloud property retrieval approach between MAS and MODIS, a parallel goal was to improve the ability to generate preliminary retrieval data products in the field. This is useful for both quality assessment of MAS measurements and retrievals as well as for in-field comparisons with other airborne instrument teams.

Since then, the CHIMAERA system expanded to officially support 13 spaceborne and airborne imagers. The newest iteration (Collection 6.1) of the operational NASA MODIS cloud products (Platnick et al., 2017) is applied to this imager set through a single shared code base. Several retrieval algorithm options are available and can be used with various supported imagers thus allowing the science community to harness the individual strengths of those different sensors to advance the knowledge of cloud properties.

Table 1 shows the full list of currently supported sensors and their cloud property product status. Cloud products identified as "production" mean that the continuous generation of science products has been demonstrated and the data products were made available to the general public through a NASA-supported archive and distribution facility. Other products are identified as having a "research" status, meaning they have been used for limited scientific purposes. Yet some others are indicated as being under "evaluation" and have not yet been used for science. An evaluation-level product may eventually be examined and validated enough to transition to a research product where data may be used for scientific publication. A research-level product may build up enough critical mass that it is deemed to be of production quality and is then made available to the public. That is, product status assignments are not static and the table is merely a snapshot of a highly dynamic effort.

Table 1
Listing of sensors supported by CHIMAERA, their platforms, and cloud properties product status as of July 2019.

Sensor Acronym	Platform	Orbit/ Retrieval Resolution	Evaluation (E), Research (R) or Production (P)	Full Sensor Name
AHI	Himawari-8	Geostationary 2km nadir	E	Advanced Himawari Imager
AMS	ER-2 and other aircraft	Airborne 50m	R	Autonomous Modular Sensor
ASTER	EOS Terra	Polar Orbit 15m – 1km	R	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS-C	ER-2 aircraft	Airborne 20m	E/R	Airborne Visible/ InfraRed Imaging Spectrometer
EPIC	Deep Space Climate ObserVatoRy	Lagrange-1 20km nadir	P	Earth Polychromatic Imaging Camera
eMAS	ER-2 aircraft	Airborne 50m	P	enhanced MODIS Airborne Simulator
MAS	ER-2 aircraft	Airborne 50m	P	MODIS Airborne Simulator
MASTER	ER-2 aircraft	Airborne 50m	P	MODIS-ASTER Airborne Simulator
MODIS	EOS Terra and Aqua	Polar Orbit 1km	P	MODerate resolution Imaging Spectroradiometer
RSP	ER-2 and other aircraft	Airborne 0.8°	R	Research Scanning Polarimeter
SEVIRI	Meteosat Second Generation	Geostationary 3km nadir	P	Spinning Enhanced Visible Infrared Radiometer Imager
SSFR	ER-2 and other aircraft	Airborne Integrated measurement, function of aircraft altitude	E/R	Solar Spectral Flux Radiometer
VIIRS	Suomi-NPP	Polar Orbit 800m	P	Visible Infrared Imaging Radiometer Suite

The CHIMAERA software system organization is shown in section 2 with system function examples described in section 3. Future development of the system are briefly discussed in section 4.

2. Software description

2.1. System overview

The CHIMAERA system was a direct descendant of the NASA operational Collection 5 (C5) MODIS cloud optical and microphysical properties product (archive identification names MOD06 and MYD06 for products from MODIS on the NASA Terra and Aqua satellites, respectively) (e.g., Platnick et al., 2003; 2017). The MODIS cloud product will be referred to hereafter as "MOD06" for brevity. The C5 MOD06 software required vendor toolkits and proprietary FORTRAN and C compilers that limited its execution exclusively to the MODIS Adaptive Processing System (MODAPS) that generates the MOD06 product. MODAPS is the operational production center for all MODIS Land and Atmosphere science data products. The main goal of CHIMAERA was to facilitate processing MOD06 in other system architectures and on other sensors, airborne science instruments in particular. Two major challenges had to be overcome to achieve this goal.

First, the format of the heritage MODAPS input parameter file was simplified for inter-platform compatibility and user access. This allowed for easier maintenance and debugging of the operational code. The original format was designed primarily for internal system use and not for a user-facing application such as CHIMAERA.

Second, the core science code was extracted and condensed into a set of generic science algorithm building blocks, which architecture is shown in Fig. 1. The blocks were further organized into components specific to a particular instrument (i.e., the 'head' block), common algorithm components that were then combined to form the CHIMAERA core, and a block for post-processing and output (the 'tail'). One exception to that general division was that the CHIMAERA core also contained code to read instrument measurements. The "Pixel-Level Science Algorithms" block represents any science algorithm that operates on a single pixel, thus making it a virtual block. The surrounding blocks are concrete. They only perform one function. This block is a virtual block. There is more than one pixel-level science algorithm within CHIMAERA that uses same exact surrounding infrastructure and processing flow.

2.2. CHIMAERA core

The CHIMAERA core is responsible for many tasks. The core blocks of Fig. 1 are further subdivided into three basic sections as illustrated in Fig. 2. The core section names are: CT_SHARED, OP_SHARED and IO_SHARED. This section describes the function of each core component.

The CT_SHARED section contains science algorithm blocks that are necessary to perform retrievals of cloud top properties such as cloud top pressure, temperature and height. They are still pixel-level science algorithms, but they are different enough to warrant separation from retrieval of optical properties. Detailed descriptions of relevant retrieval methodologies can be found in Baum et al. (2012), Heidinger (2011) and Heidinger et al. (2014).

The OP_SHARED section contains science algorithm blocks that are necessary to perform retrievals of cloud optical and microphysical properties such as cloud optical thickness and cloud effective radius. For the latest developments in science behind retrievals of cloud microphysics readers can refer to Platnick et al. (2017).

The IO_SHARED section is the only explicitly outward-facing part of

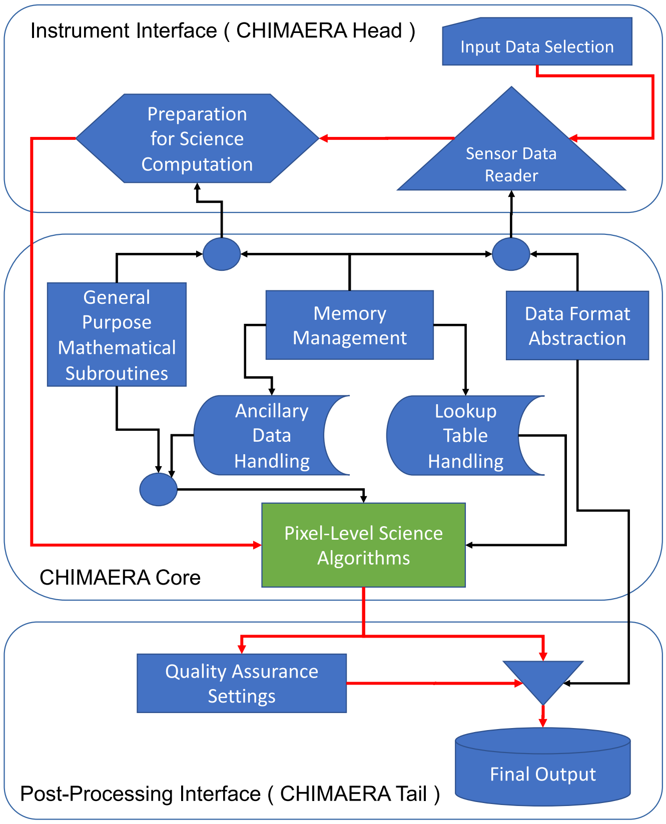

Fig. 1. General structure of CHIMAERA system showing the building block interconnections (black) and general processing flow (red).

the CHIMAERA system. Here, "outward-facing" refers to modules contained within the section that have no immediate dependencies except external libraries such as Network Common Data Form (NetCDF), Open Message Passing Interface (OpenMPI) or Hierarchical Data Format (HDF). These modules can be used by any code including projects independent of CHIMAERA itself. Examples of such codes include data analyses, new science algorithm mock-ups, data product gridding and aggregation, etc. The IO_SHARED section also contains instrument data readers for each instrument of Table 1. It had previously been common practice for these readers to be inserted directly into the code every time a reader was required for a task. Such practice is generally undesirable in software engineering. These readers tend to be rather lengthy pieces of source code. CHIMAERA provides a well-tested common set of instrument measurement readers. Those readers can be simply linked into one's code. Project quality can thus be improved by reduction of code length, improved maintainability and increased code reuse. A user debugging a mock-up of a new science algorithm that pushes off the CHIMAERA/IO_SHARED core section would only need to focus on whether their science is working and not on whether they read the data in correctly.

Both NetCDF and HDF file formats require multiple subroutine calls to read or write a variable. CHIMAERA/IO_SHARED section provides a powerful module that handles opening, closing, reading and writing of files and datasets of various formats, structures and types via single statements. The goal of this methodology is same as the goal of providing instrument readers. It improves readability and therefore maintainability of scientific code within and without CHIMAERA. There was a wish to speed data analysis and science algorithm development work while improving science quality at the same time. The CHIMAERA system is the tool that allows accomplishment of that.

Another good example of CHIMAERA core capability is ancillary data handling for retrieval algorithms. Various ancillary data are necessary during various retrievals. Atmospheric correction is one example of use of this ancillary data such as in Franklin and Giles (1995). Examples of ancillary data include surface albedo, vertical profiles of pressure and temperature, surface wind speed and direction and so on. There are many sources for this kind of information. Those sources often have very different data formats and content structure. CHIMAERA core transparently handles variety of ancillary data sources. The user only needs to specify the location of files they desire to use. If there is a need to switch an algorithm to a different source of specific ancillary information, a CHIMAERA user would only provide the new ancillary file names and possibly change a compiler switch. Without CHIMAERA core to help, a user may have to write their own code to handle a different ancillary data source or locate code from some outside

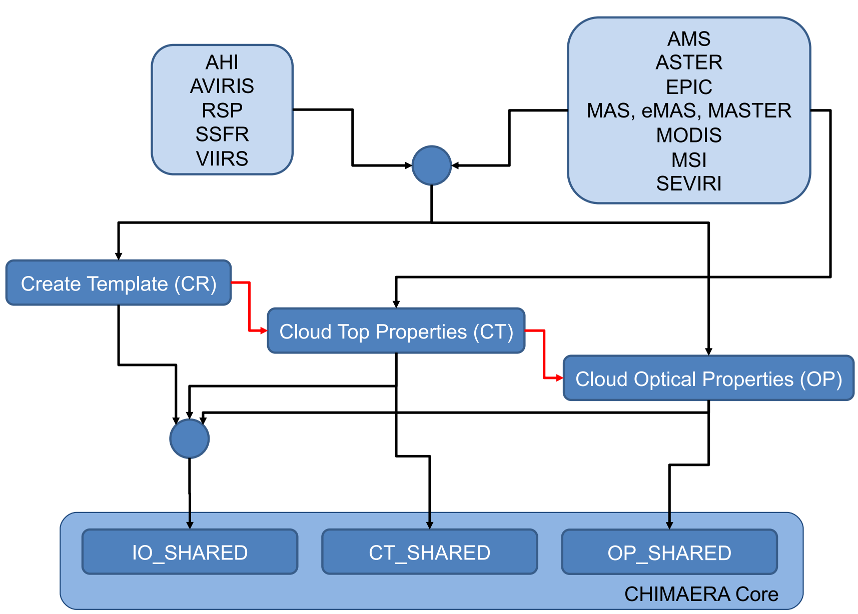

Fig. 2. CHIMAERA core sections and product linkage as of September 2018. The red lines indicate general process dependencies as discussed in section 2.3. The blank template is created first. Then cloud top properties are calculated. Finally the cloud optical and microphysical properties product is produced. Some instruments have their own cloud top properties product. Thus not all of them have a CT product within CHIMAERA.

source and then integrate it into their product. Such process creates distraction from the science problem via all the additional engineering required in order to begin solving. CHIMAERA works to minimize distractions.

Table 2 lists the ancillary sources that CHIMAERA handles. Each of these data sources is an option for any of the instruments listed in Table 1 at any time as applicable to instrument hardware capabilities.

Table 2
Ancillary data sources supported by CHIMAERA as of July 2019.

Ancillary Name	Content	Use	Source	Instrument Options
GEOS-5	Vertical profiles of pressure, temperature, moisture, ozone. Also surface temperature and pressure, column ozone amount, surface wind speed, snow and sea ice amounts	Atmospheric correction for visible, near- and shortwave-infrared channels. If applicable, thermal emission correction for thermal infrared channels	Rienecker et al. (2008)	All
NCEP GDAS	Vertical profiles of pressure, temperature, moisture, ozone. Also surface temperature and pressure, column ozone amount, surface wind speed	Atmospheric correction for, near- and shortwave-infrared channels. If applicable, thermal emission correction for thermal infrared channels	Derber et al. (1991)	All
NCEP Sea Ice product	Sea ice amount	Land surface albedo information	Derber et al., 1991, Moody et al., 2007	All
NSIDC snow product	Ground snow amount	Land surface albedo information	Moody et al., 2007, Robinson et al. (2014)	All
Gap-filled spectral surface albedo product	Spectral surface albedo for visible and near infrared channels	Land surface albedo information	Moody et al. (2008) Schaaf et al. (2011)	All
Broadband land surface emissivity product	Land emission information for thermal infrared channels	Land thermal emission correction	Seemann et al. (2008)	Not relevant for AVIRIS-C, EPIC, RSP and SSFR
ECMWF reanalysis product	Vertical profiles of pressure, temperature, moisture, ozone. Also surface temperature and pressure, surface wind speed	Atmospheric correction for visible, near- and shortwave-infrared channels. If applicable, thermal emission correction for thermal infrared channels	Dee et al. (2011)	All
TOAST column ozone product	Column ozone amount	Atmosperic correction of visible and near infrared channels	McPeters et al. (2013).	All

2.3. CHIMAERA 'heads', 'tails' and processing chain

The 'head' and 'tail' blocks are responsible for interlocking the necessary core blocks into a complete science data product for a specific instrument. 'Head' blocks consist of instrument-specific I/O code and general retrieval flow preparation. For example, a head block would signal the core that an instrument lacks a specific spectral channel as compared to the MODIS channel complement. Thus some parts of the MOD06 product would be skipped. A head block would also handle reading of sensor geometry and signaling ancillary data source selection.

'Tail' blocks deal with assignment of quality flags and other metadata to retrieval results, and output of the final data product. CHIMAERA maintains a set of retrieval quality flags common for all instruments. A tail block would handle selection of those flags that are relevant to a specific instrument. It would also add any extra flags that may be unique to that instrument. Similar considerations are true for the final file output. An instrument may only output a subset of variables normally present in a MOD06 product file or may output additional variables, unique to that instrument.

The supported airborne imagers yet again provide a good example of behavior described in the previous paragraph. The MODIS instrument has a single channel located in the 2 μm spectral window band. MAS, eMAS (King et al., 1996) and MASTER (Hook et al., 2001) have four channels within that band. The main retrieval of MOD06 cloud effective radius requires a single channel in the 2 μm window. Instead of using the core retrieval block once, the head block for an eMAS retrieval strings together multiple calls to the core retrieval block. It feeds data from the additional channels into the place reserved for data from a channel located inside the 2 μm window to produce previously unavailable science data without altering the core source code. On the other side, the tail block assigns additional quality assurance flags to these extra retrievals that would not be present in a MODIS data product. It then writes this additional data to disk.

The 'head' and 'tail' blocks are commonly kept together within CHIMAERA in a single product directory for each instrument.

Unlike its predecessor that could be neither compiled nor run outside MODAPS, CHIMAERA freely functions away from the production system. However it retains the general process execution chain used to create the MODIS cloud properties product at MODAPS. Naming of individual processes also remains consistent with MODAPS designation. This general organization has the cloud product creation split into three parts with general flow in Fig. 2.

The first part, designated as CR for CReate, writes a blank template file with all datasets and product metadata. All subsequent processes write to this template file. The current MODIS operational data processing Collection 6.1 (C6.1) cloud properties product contains 126 Scientific Data Sets (SDS), each with its own set of attributes and comments. It can take up to 90 minutes to compute the complete cloud product depending on the instrument. It is far easier to develop file structure and make changes to dataset names, types and attributes using a blank template that takes seconds to produce. It is also far easier to share the blank file with other collaborators. A complete cloud product file may be larger than 2 gigabytes whereas the template is only a few kilobytes in size.

The second major part, designated as CT for Cloud Top, runs the cloud top properties retrieval that writes into the previously created template algorithm retrievals of cloud top pressure, temperature and height along with several other useful parameters (Baum et al., 2012). This process has to run before the cloud optical property process since that algorithm requires a priori knowledge of cloud top pressure and temperature (Platnick et al., 2017).

Finally, the third part, designated by MODAPS as OP for Optical Properties, is the cloud optical and microphysical properties retrieval. It outputs values of cloud optical thickness, cloud effective radius, water path and uncertainties for each retrieval (Platnick et al., 2003, 2017). It is the largest part of the entire process in terms of both lines of code and computational complexity.

Within the CHIMAERA system there are also other processes executed before, after, or independent from, the main MOD06 code. For example, a process might be required to correct known issues with measurements from a specific instrument. A process may compute cloud mask or apply an altogether different retrieval algorithm. While the CHIMAERA system is highly modular, the CR-CT-OP process chain has some natural dependencies. However the individual algorithms can be developed and run completely independent of each other. Yet all of those algorithms refer back to a unified code base for their basic functions and all share a unified input specification.

Because CHIMAERA retained general MODAPS organizational structure, improvements to MOD06 can now be easily tested locally and the code sent to MODAPS for large-scale science tests without any additional changes for system integration.

CHIMAERA has been designed with minimal if any post-installation support required. Over the years of its existence the system continues to prove itself to be highly resilient with only a small amount of the team's time spent on support of existing installations.

All instruments and all instrument products supported by CHIMAERA use the same input parameter file format. If a processing system is set up to run CHIMAERA for one product from one instrument, then this processing system could begin processing other CHIMAERA-based products for the same instrument or process data from a different instrument supported by CHIMAERA with only minimal changes. Oftentimes the only change is a product code flag on the command line. The lengthy product integration process had been eliminated leading to rapid deployment of new science capabilities. For instance, a research-level MODIS above-cloud aerosol properties product (Meyer et al., 2015) was integrated into CHIMAERA, delivered to MODAPS, and entered near real-time production in a matter of weeks to support the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) field campaign because MODAPS already knew how to work with CHIMAERA. MODAPS used the existing setup instead of having to develop something new.

All that is needed to adapt the MODIS cloud product to a different sensor is an instrument measurement reader for that sensor and any required external look-up tables (LUTs) specific to the instrument. Format of all external look-up tables had been made standard so that all functionality of LUT management for all instruments is part of the CHIMAERA core. LUTs are specified externally via a parameter file. No science code change is required to update LUTs.

The retrieval algorithm developer provides the LUTs and code to read instrument measurements. The quickest way to creating a new head is to start from an already supported instrument that is the most similar to the new one. After external tables have been generated, the product migration can be completed by a single developer.

All that is necessary to add a new science algorithm is for a developer to provide a code module that operates on a single pixel, any additional algorithm-specific LUTs and a listing of any additional spectral channels the algorithm may require. The algorithm insertion can be easily completed by a single developer in a matter of a week or so.

Disagreements between retrievals during data intercomparisons are commonly due both to differences in the instruments themselves and differences in retrieval methodologies. Retrievals for two different instruments in CHIMAERA system execute same exact lines of science code. When comparing two CHIMAERA-based retrievals only actual instrument differences matter. These instrument differences may comprise differences in spectral response functions for an identical wavelength range, differences in spectral channel locations, calibration and/or spatial resolution. It is thus much easier to see effects of any calibration adjustment work. (MODIS-VIIRS science team, private communication).

3. Application examples

Since initial development in 2007, the CHIMAERA system facilitated a significant amount of cloud related research. A few examples are briefly discussed below.

Having a common output data structure allowed comparisons of data from instruments that had not been extensively considered before. In King et al. (2010), cloud retrievals from NASA airborne imagers (MAS and MASTER) were compared to concurrent retrievals from MODIS and the Multi-angle Imaging SpectroRadiometer (MISR) satellite instruments. This was the first time that cloud property retrievals from these instruments had been directly compared. Moreover the ability to directly execute a code developed for satellite processing on an airborne instrument was unique at the time as most airborne analyses did not include quality assessments and pixel-level retrieval uncertainty estimates. Previous comparisons to MODIS had been done with MAS but with non-identical retrieval algorithms being utilized (King et al., 2004).

Land surface remote sensing instruments such as ASTER (Yamaguchi et al., 1998) have sufficient spectral channels for cloud physics work at very high spatial resolution. ASTER had been integrated into the CHIMAERA system to provide a potential new source of information about quality of retrievals of cloud physics properties from MODIS and other similar moderate-resolution imagers. ASTER acquires data at a resolution of up to 15m and its ground track is aligned with MODIS Terra. The availability of MODIS-style retrievals from ASTER instrument allowed for initiation of research into contributions of sub-pixel inhomogeneity effects to uncertainty in MODIS 1-km resolution cloud properties retrievals. Errors due to sub-pixel inhomogeneity were quantified for the first time and some initial work on mitigation of those effects had been performed. These studies are ongoing and available results, together with more ASTER-specific research, are documented in Werner et al. (2016, 2018a, 2018b).

Migrating the operational MOD06 product first to SEVIRI (Hamann et al., 2014), and later to AHI/ABI in a research mode, using CHIMAERA introduced the time dimension to MOD06-like cloud property retrievals. Polar-oribiting passive imagers are capable of providing instantaneous global snapshots but temporal information is generally limited to poles and to areas where consecutive orbit swaths overlap. Next-generation geostationary imagers such as AHI (Bessho et al., 2016), SEVIRI (Schmetz et al., 2002) and ABI (Schmit et al., 2017) have expanded spectral and temporal resolution. The resolution improvements combined with standard fixed view geometry provided the potential for directly observing cloud property temporal evolution. CHIMAERA provided a smooth path of migration of mature MOD06 products to these new platforms. It offered complete science code reuse and thus leveraged these research efforts with the decades-long pedigree of MOD06 production.

Fig. 3 shows an example of near-simultaneous retrieval of cloud optical and microphysical properties from geostationary, polar-orbiting and airborne imagers in the Southeastern Atlantic Ocean during the first phase of ORACLES field campaign. The ORACLES campaign comprises three one-month intensive observation periods over five years designed to study climate impacts of African biomass burning aerosols. For more information about the campaign one may visit the ORACLES website located at (https://espo.nasa.gov/oracles/content/ORACLES) The points of view of these different sensors are very different. Yet CHIMAERA brings them all together through use of identical retrieval methodology for all these sensors. Such close connection enables application of new retrieval and analysis techniques such as the work of Werner et al. (2016, 2018a, 2018b) on estimation of impact of sub-pixel inhomogeneity and remediation of retrieval bias in lower resolution instruments when high resolution data are available. In this case eMAS would play the role that ASTER did in Werner et al. papers. Additionally CHIMAERA gives the ability to tie field campaign observations, including in situ, to satellite remote sensing to gain new insight into existing retrieval algorithms. CHIMAERA also allows detailed

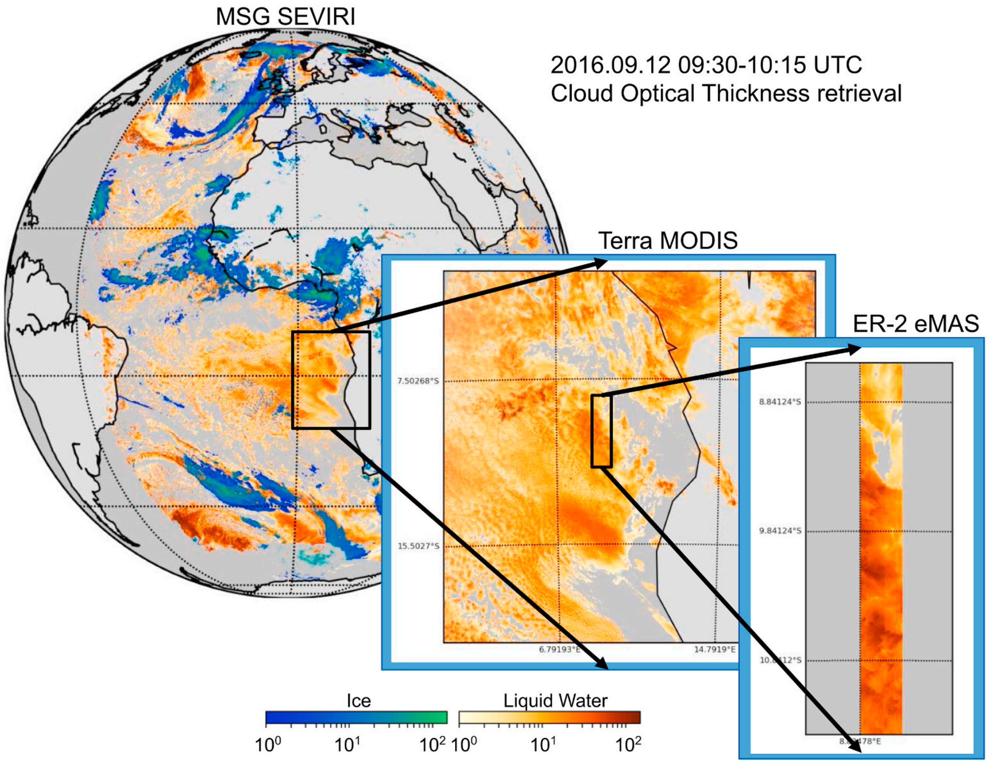

Fig. 3. Near-simultaneous retrieval of cloud properties from a geostationary instrument (MSG SEVIRI), a polar orbiter (Terra MODIS) and aircraft (ER-2 eMAS) during ORACLES. All retrievals were done by CHIMAERA system with the same exact retrieval methodology being used for all these sensors.

investigations of geostationary fixed view angle and spatial resolution biases with regard to forward model deficiencies in such conditions through use of higher resolution and variable view angles of polar orbiters and aircraft. The ORACLES data are still being processed and analyzed CHIMAERA would aid greatly in one of the goals of ORACLES to create fusion datasets similar to the ones described in Franklin and Blodgett (1993).

4. Summary and future directions

This paper describes the CHIMAERA system for cloud property retrievals.

There are a number of Earth-viewing atmospheric passive remote sensing instruments with similar capabilities for cloud property remote sensing (Table 1). The science algorithm building block architecture of CHIMAERA system that fully decouples the science from the sensor, ensures continuity and consistency of geophysical retrieval code across many different platforms. CHIMAERA allows for many sensors to appear as one from the point of view of a cloud property remote sensing algorithm.

All CHIMAERA products present a common simple interface to the outside that can interact equally easily with individual users or with an automated production data processing system.

CHIMAERA also provides an interface where unrelated analysis and algorithm mock-up codes have access to well tested instrument data readers and simplified I/O routines. Access to such interface greatly speeds analysis and algorithm development as error rates are greatly reduced.

The CHIMAERA system is constantly evolving. There are several new instrument options being presently considered. The CHIMAERA core is also growing. There are several science algorithms for the MODIS instrument within CHIMAERA that are in research stages. These algorithms will migrate to other sensors that have sufficient spectral coverage. The CHIMAERA core will grow additional sections to achieve maximum code reuse for science algorithm migration.

The CHIMAERA code is publicly available and distributed free of charge through MODAPS code repository. Interested parties may send a message to MODAPS at modiscm@ssaihq.com and obtain repository access.

Author contributions

Galina (Gala) Wind is the lead developer of CHIMAERA system. She created the original design and wrote the current set of instrument heads. She oversees the system design integrity and develops new instrument heads. She also creates and maintains atmospheric transmittance lookup tables for CHIMAERA.

Steven Platnick is the leader of Cloud Retrieval Group at NASA Goddard that develops and maintains CHIMAERA.

Kerry Meyer is a science algorithm developer for the CHIMAERA system. He has provided a number of new science algorithms for the MODIS instrument and is migrating them to other heads.

Tom Arnold maintains the MAS/eMAS/MASTER airborne retrieval suite of CHIMAERA.

Nandana Amarasinghe is in charge of creating and maintaining the cloud reflectance lookup tables that CHIMAERA uses for core retrieval of cloud optical and microphysical properties from various instruments.

Benjamin Marchant develops cloud thermodynamic phase algorithms for various instruments.

Chenxi Wang is a science algorithm developer for the CHIMAERA system. He is currently working on new cloud properties retrieval methods that could be used in absence of solar illumination.

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References

Barnes, W.L., Pagano, T.S., Salomonson, V.V., 1998. Prelaunch characteristics of the moderate resolution imaging spectroradiometer (MODIS) on EOS-AM1. IEEE Trans. Geosci. Rem. Sens. 36, 088–1100.
Baum, B.A., Menzel, W.P., Frey, R.A., Tobin, D.C., Holz, R.E., Ackerman, S.A., Heidinger, A.K., Yang, P., 2012. MODIS cloud-top property refinements for collection 6. J. Appl. Meteor. Clim. 51 (6), 1145–1163.
Bessho, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., Kumagai, Y., Miyakawa, T., Murata, H., Ohno, T., Okuyama, A., Oyama, R., Sasaki, Y., Shimazu, Y., Shimoji, K., Sumida, Y., Suzuki, M., Taniguchi, H., Tsuchiyama, H., Uesawa, D., Yokota, H., Yoshida, R., 2016. An Introduction to Himawari-8/9—Japan's new-generation geostationary meteorological satellites. J. Meteor. Soc. Japan 94, 151–183.
Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van deBerg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., allberg, P.K., Kohler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J.-N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc.137 553–597. https://doi.org/10.1002/qj.828.
Derber, J.C., Parrish, D.F., Lord, S.J., 1991. The new global operational analysis system at the National Meteorological Center. Weath. Forec. 6, 538–547.
Franklin, S.E., Blodgett, C.F., 1993. An example of satellite multisensor data fusion. Comp. Geo 19 (4), 577–583.
Franklin, S.E., Giles, P.T., 1995. Radiometric processing of aerial and satellite remote-sensing imagery. Comp. Geo 21 (3), 413–423.
Hamann, U., Walther, A., Baum, B., Bennartz, R., Bugliaro, L., Derrien, M., Francis, P.N., Heidinger, A., Joro, S., Kniffka, A., Le Gléau, H., Lockhoff, M., Lutz, H.-J., Meirink, J. F., Minnis, P., Palikonda, R., Roebeling, R., Thoss, A., Platnick, S., Watts, P., Wind, G., 2014. Remote sensing of cloud top pressure/height from SEVIRI: analysis of ten current retrieval algorithms. Atmos. Meas. Tech. 7, 2839–2867. https://doi.org/10.5194/amt-7-2839-2014.
Heidinger, A., 2011. ABI cloud height algorithm theoretical basis document. LAD: 04.24.2018. https://www.goes-r.gov/products/ATBDs/baseline/Cloud_CldHeight_v2.0_no_color.pdf.
Heidinger, A.K., Foster, M.J., Walther, A., Zhao, X., 2014. The pathfinder atmospheres–extended AVHRR climate dataset. Bull. Am. Meteorol. Soc. 95, 909–922. https://doi.org/10.1175/BAMS-D-12-00246.1.
Hook, S., Meyers, J., Thome, K.J., Fitzgerald, M., Kahle, A.B., 2001. The MODIS/ASTER Airborne Simulator (MASTER) – a new instrument for Earth science studies. Rem. Sens. Env. 76, 93–102.
King, M.D., Menzel, W.P., Grant, P.S., Myers, J.S., Arnold, G.T., Platnick, S.E., Gumley, L. E., Tsay, S.-C., Moeller, C.C., Fitzgerald, M., Brown, K.S., Osterwisch, F.G., 1996. Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor and surface properties. J. Atmos. Ocean. Technol. 13 (4), 777–794.
King, M.D., Platnick, S., Yang, P., Arnold, G.T., Gray, M.A., Riedi, J.C., Ackerman, S.A., Liou, K.N., 2004. Remote sensing of liquid water and ice cloud optical thickness and effective radius in the arctic: application of airborne multispectral MAS data. J. Atmos. Ocean. Technol. 21, 857–875. https://doi.org/10.1175/1520-0426.
King, M.D., Platnick, S., Wind, G., Arnold, G.T., Dominguez, R.T., 2010. Remote sensing of radiative and microphysical properties of clouds during TC 4 : results from MAS, MASTER, MODIS, and MISR. J. Geophys. Res. 115, D00J07. https://doi.org/10.1029/2009JD013277.
McPeters, R.D., Bhartia, P.K., Haffner, D., Labow, G.J., Flynn, L., 2013. The version 8.6 SBUV ozone datarecord: an overview. J. Geophys. Res. Atmos. 118, 8032–8039. https://doi.org/10.1002/jgrd.50597.
Meyer, K., Platnick, S., Zhang, Z., 2015. Simultaneously inferring above-cloud absorbing aerosol optical thickness and underlying liquid phase cloud optical and microphysical properties using MODIS. J. Geophys. Res. 120, 5524–5547. https://doi.org/10.1002/2015JD023128.
Moody, E.G., King, M.D., Schaaf, C.B., Hall, D.K., Platnick, S., 2007. Northern Hemisphere five-year average (2000-2004) spectral albedos of surfaces in the presence of snow: statistics computed from Terra MODIS land products. Remote Sens. Environ. Times 111, 337–345.
Moody, E.G., King, M.D., Schaaf, C.B., Platnick, S., 2008. MODIS-derived spatially complete surface albedo products: spatial and temporal pixel distribution and zonal averages. J. Appl. Meteor. Climatol. 47, 2879–2894.
Peddle, D.R., White, H.P., Soffer, R.J., Miller, J.R., LeDrew, E.F., 2001. Reflectance processing of remote sensing spectroradiometer data. Comp. Geo 27 (2), 201–213, 2001.
Platnick, S., King, M.D., Ackerman, S.A., Menzel, W.P., Baum, B.A., Riedi, J.C., Frey, R. A., 2003. The MODIS cloud products: algorithms and examples from Terra. IEEE Trans. Geosci. Rem. Sens. 41 (2), 459–473, 2003.
Platnick, S., Meyer, K.G., King, M.D., Wind, G., Amarasinghe, N., Marchant, B., Arnold, G.T., Zhang, Z.B., Hubanks, P.A., Holz, R.E., Yang, P., Ridgway, W.L., Riedi, J., 2017. The MODIS cloud optical and microphysical products: collection 6 updates and examples from Terra and Aqua. IEEE Trans. Geosci. Rem. Sens. 55 (1), 502–525.
Rienecker, M.M., Suarez, M.J., Todling, R., Bacmeister, J., Takacs, L., Liu, H.-C., Gu, W., Sienkiewicz, M., Koster, R.D., Gelaro, R., Stajner, I., Nielsen, J.E., 2008. The GEOS-5 data assimilation system - documentation of versions 5.0.1, 5.1.0, and 5.2.0. Tech. Rep. S. Gl. Mod. Data Assim. 27.
Robinson, D.A., Hall, D.K., Mote, T.L., 2014. MEaSUREs Northern Hemisphere Terrestrial Snow Cover Extent Daily 25km EASE-Grid 2.0, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, Colorado USA. https://doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0530.001 doi, Last access date: 07.25.2019.
Schaaf, C.L.B., Liu, J., Gao, F., Strahler, A.H., 2011. MODIS albedo and reflectance anisotropy products from Aqua and Terra. Land remote sensing and global environmental change: NASA's Earth observing system and the science of ASTER and MODIS. In: Ramachandran, B., Justice, C., Abrams, M. (Eds.), Remote Sensing and Digital Image Processing Series, vol. 11. Springer- Verlag, p. 873.
Schmetz, J., Pili, P., Tjemkes, S., Just, D., Kermann, J., Rota, S., 2002. An Introduction to Meteosat Second Generation (MSG). BAMS, pp. 977–992.
Schmit, T.J., Griffith, P., Gunshor, M.M., Daniels, J.M., Goodman, S.J., Lebair, W.J., 2017. A Closer Look at the ABI on the GOES-R Series. BAMS. https://doi.org/10.1175/BAMS-D-15-00230.1.
Seemann, S.W., Borbas, E.E., Knuteson, R.O., Stephenson, G.R., Huang, H.L., 2008. Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements. J. Appl. Meteor. Climatol. 47, 108–123.
Werner, F., Wind, G., Zhang, Z., Platnick, S., Di Girolamo, L., Zhao, G., Amarasinghe, N., Meyer, K., 2016. Marine boundary layer cloud property retrievals from high-resolution ASTER observations: case studies and comparison with Terra MODIS. Atmos. Meas. Tech. 9, 5869–5894. https://doi.org/10.5194/amt-9-5869-2016.
Werner, F., Zhang, Z., Wind, G., Miller, D.J., Platnick, S., 2018a. Quantifying the impacts of subpixel reflectance variability on cloud optical thickness and effective particle radius retrievals based on high-resolution ASTER observations. J. Geophys. Res. 123 https://doi.org/10.1002/2017JD027916.
Werner, F., Zhang, Z., Wind, G., Miller, D.J., Platnick, S., Di Girolamo, L., 2018b. Improving cloud optical property retrievals for partly cloudy pixels using coincident higher-resolution single band measurements: a feasibility study using ASTER observations. J. Geophys. Res. https://doi.org/10.1029/2018JD028902.
Yamaguchi, Y., Kahle, A.B., Tsu, H., Kawakami, T., Pniel, M., 1998. The advanced spaceborne thermal emission and reflection radiometer (ASTER). Geoscience and remote sensing, IEEE Geosci. Remote Sens. IEEE Trans. on 36, 1062–1071. https://doi.org/10.1109/36.700991.