Operational Global Passive Remote Sensing of Cloud Optical and Microphysical Properties
Current Capabilities and Issues

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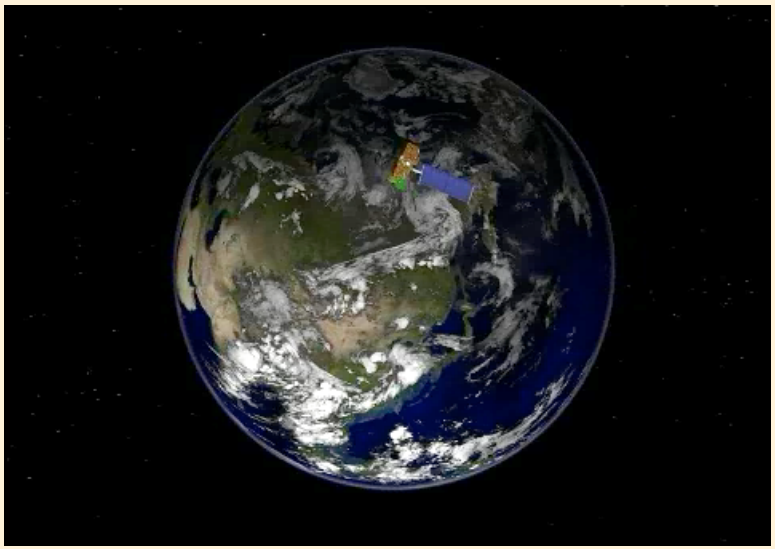
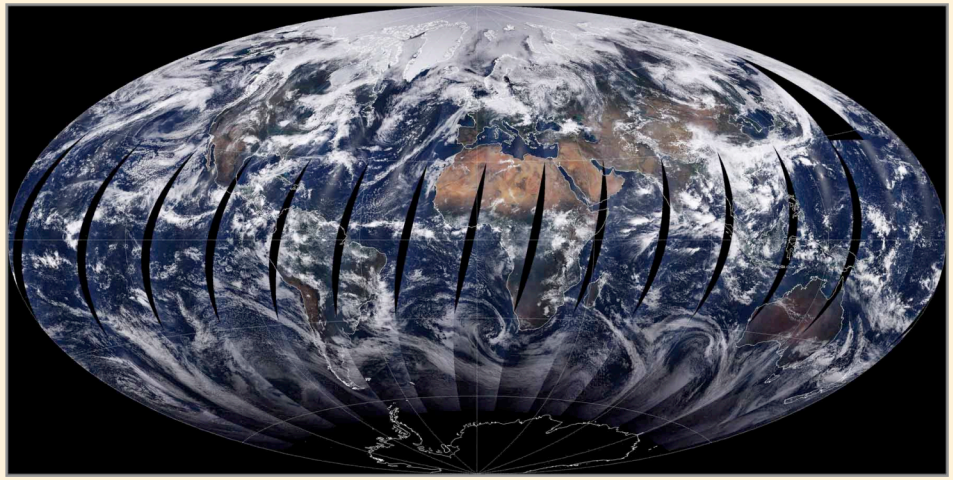


Outline

- The user community?
- Overview of common/current optical and microphysical retrieval approaches
- Sources of retrieval uncertainty, and examples from MODIS
- Future operational platforms
- Summary and some thoughts

Global & Operational



MODIS true-color daily composite

- Global
  - Daily or near-daily coverage
  - Retrievals over all ecosystems (ocean, vegetation, arid, snow/ice)
  - Retrievals for all cloud types and thermodynamic phases
  - Excludes specialized algorithms for specific cloud or case studies
- Operational
  - Algorithm processing without intervention
  - Algorithm consistency, reprocessing efforts, documentation
  - Code for integration into data processing and archive infrastructure
  - Computational efficiency

    MODIS data granule (5 minutes of data) with typical cloud fraction contains ~ 2×10^6 1km retrievals (MOD06)

The User Community

- Applications
  - Development of cloud climatologies (monthly, annual, inter-annual trends)
  - Radiation budget applications
  - Model validation (climate and forecast)
  - Model data assimilation
  - Physical process studies, including studies involving other physical retrievals (e.g., aerosols)

- With possible exception of the last item, individual pixel-level accuracies are not the relevant issue, but rather uncertainties in the spatially and temporally aggregated statistics (means and higher-order moments, pdfs).

Cloud optical, microphysical properties

- Optical thickness, particle size (effective radius), water path
- **1 km** spatial resolution, daytime only, liquid water & ice clouds
- Solar reflectance technique, VIS through MWIR:

  single water non-absorbing band (0.65, 0.86, 1.2 μm) + each absorbing band (1.6, 2.1, 3.7 μm) => **3 separate effective radius retrievals**, **2.1 μm size retrieval is primary**.

- Land, ocean, snow/sea ice surfaces
  - using: 0.65 μm (land), 0.86 μm (ocean), 1.2 μm (snow/ice)

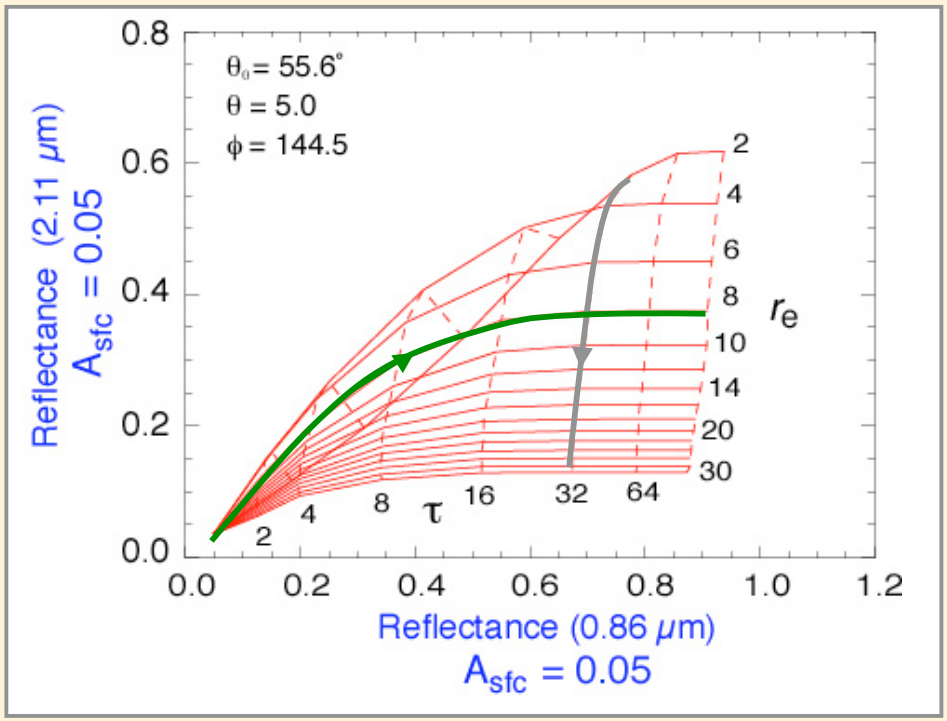
MODIS 1st satellite sensor with all useful SWIR, MWIR bands

Cloud optical, microphysical properties, *cont.*

- Critical input (especially for global processing):
  - Cloud mask: to retrieve or not retrieve?
  - Cloud thermodynamic phase: liquid water or ice libraries?
  - Cloud top temperature, ancillary surface temperature: needed for 3.7 μm emission characterization (band contains solar and emissive signal), T(sfc) from NCEP, DAO, etc.
  - Atmospheric correction: requires cloud top pressure, ancillary information regarding atmospheric moisture & temperature (e.g., NCEP, DAO, other MODIS products)
  - Surface albedo: for land, ancillary information regarding snow/ice extent (e.g., NISE)

Overview of Operational Solar-Reflectance Cloud Optical and Microphysical Retrievals

retrieval space example



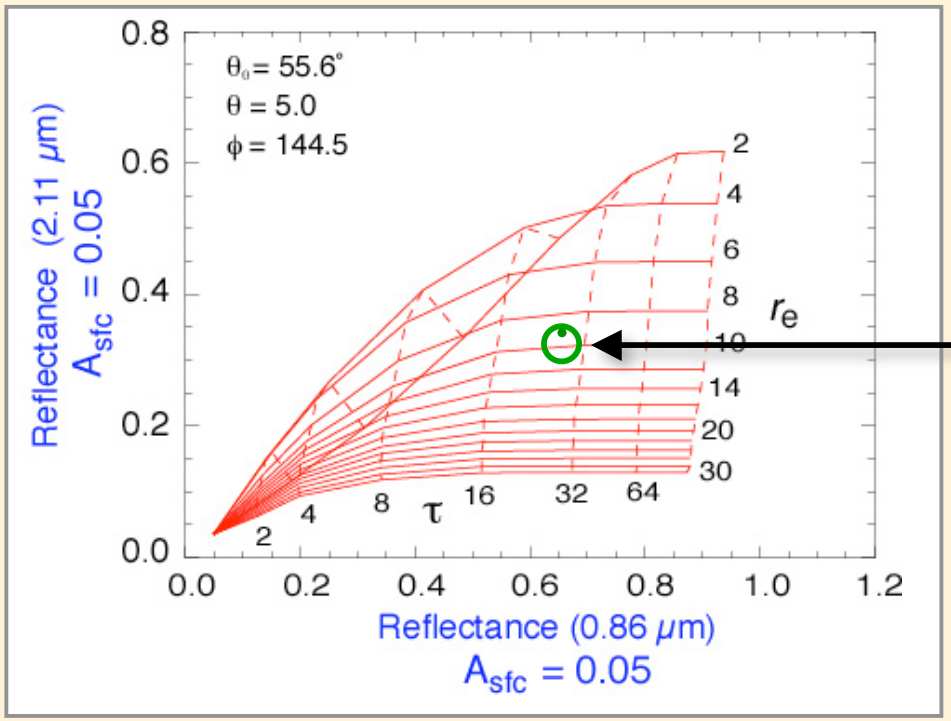
2.1 μm absorption increases with particle size, little effect at 0.86 μm

2.1 μm reflectance reaches limiting values with optical thickness

Liquid water cloud
ocean surface

Overview of Operational Solar-Reflectance Cloud Optical and Microphysical Retrievals

2-band retrieval space example

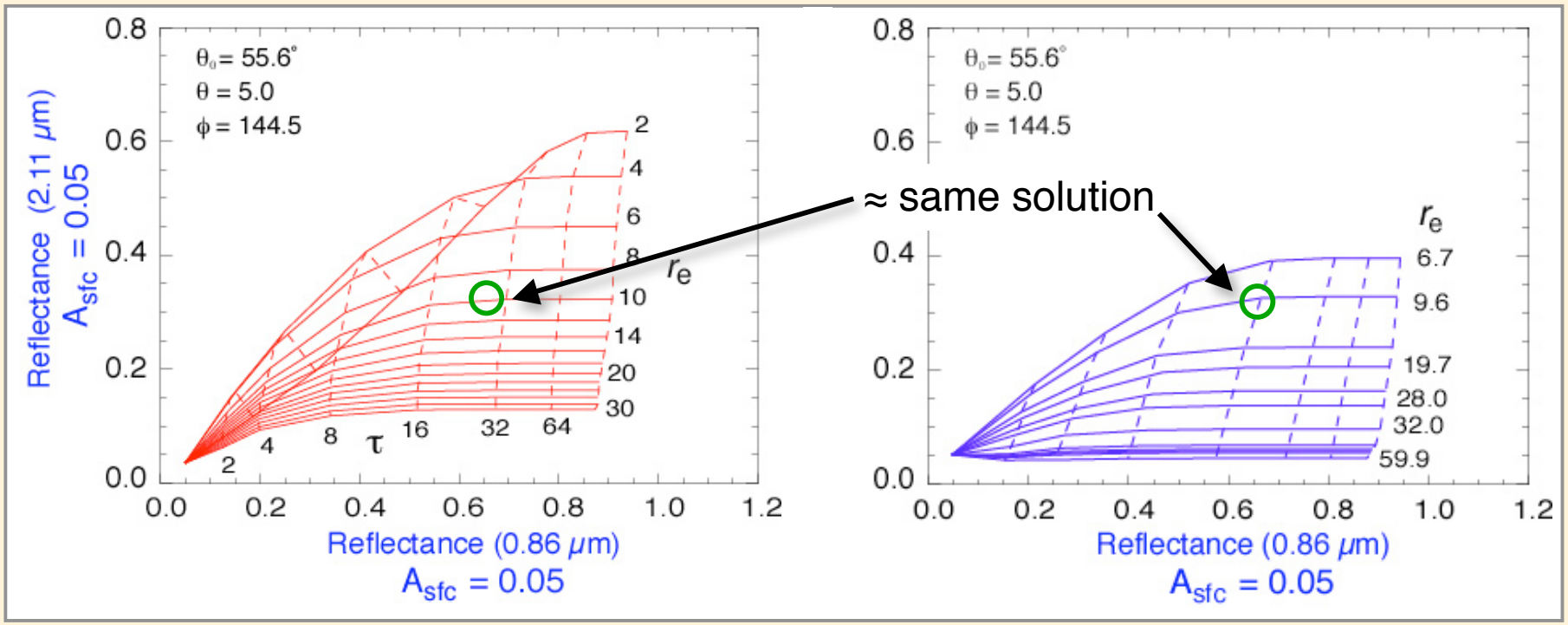


ex. reflectance measurement (+ uncertainty)

Liquid water cloud
ocean surface

Overview of Operational Solar-Reflectance Cloud Optical and Microphysical Retrievals

2-band retrieval space example

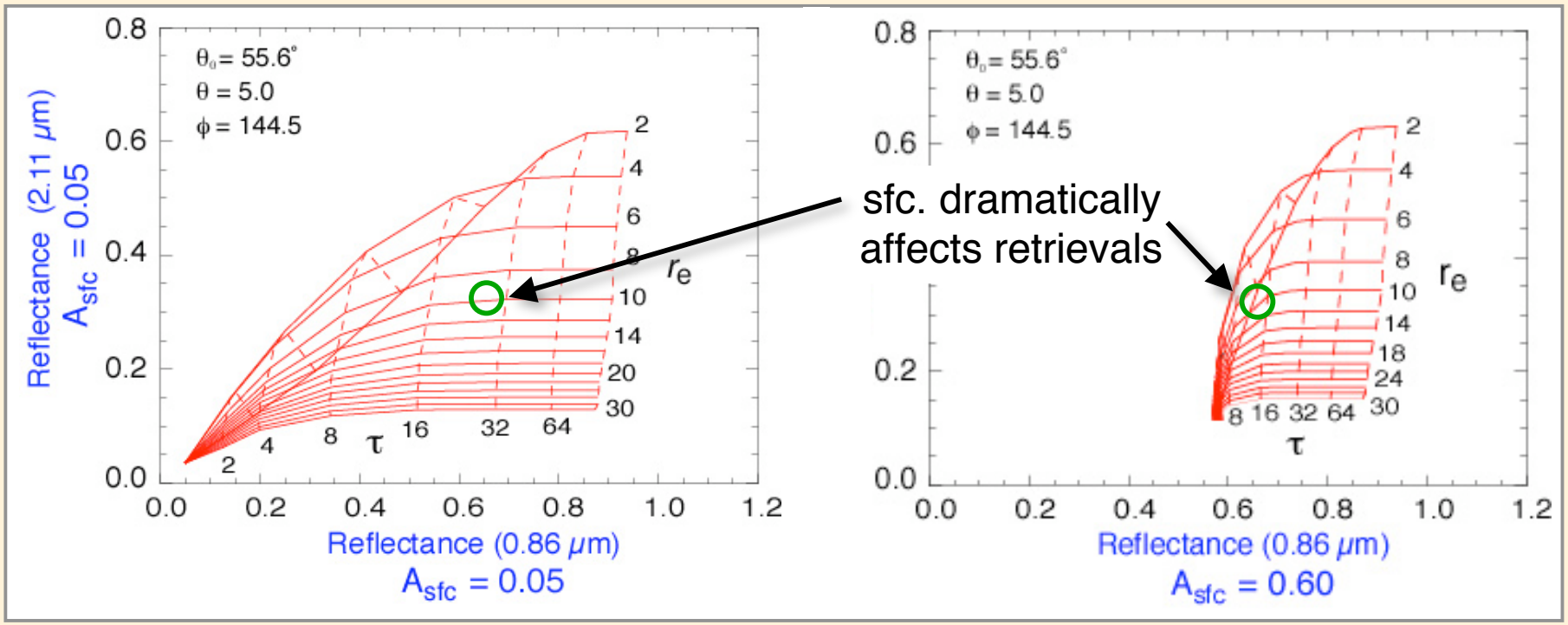


Liquid water cloud
ocean surface

Ice cloud
ocean surface

Overview of Operational Solar-Reflectance Cloud Optical and Microphysical Retrievals

2-band retrieval space example



Liquid water cloud
ocean surface

Liquid water cloud
ice surface

Sources of Retrieval Uncertainty for τ, r_e Retrievals

- Instrument
  - Calibration (radiometric and spectral)
  - Other characterization issues (spectral cross-talk, point spread function, etc.)
- Ancillary or other retrieval input
  - Cloud detection
  - Cloud thermodynamic phase
  - Cloud-top height (for atmospheric corrections) and cloud-top temperature*
  - Ancillary model information (above-cloud water vapor, surface temperature*)
  - Ancillary surface spectral albedo maps, ancillary snow/sea ice mask
- 1D model
  - Ice clouds (habit/size distributions)
  - Liquid water cloud size distribution (e.g., v_e)
  - Water indices of refraction, accuracy of radiative transfer calculations, etc.
- Non-1D effects
  - Vertical, multilayer clouds
  - Sub-pixel cloud fraction
  - Full 3D structure

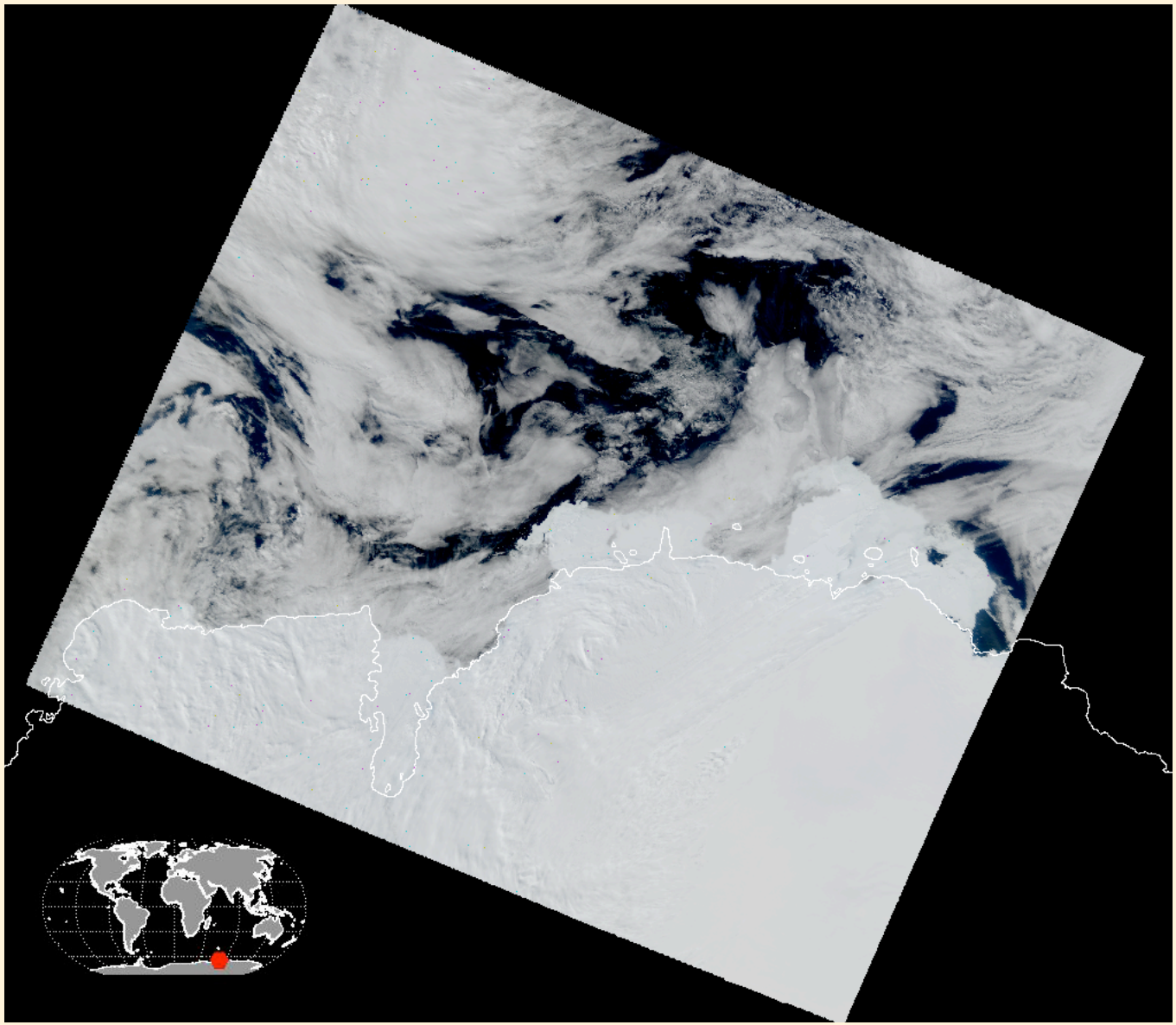
Items that are relatively "straightforward", at least in principle, to incorporate into a quantitative uncertainty estimate

** for 3.7 μm r_e retrievals*

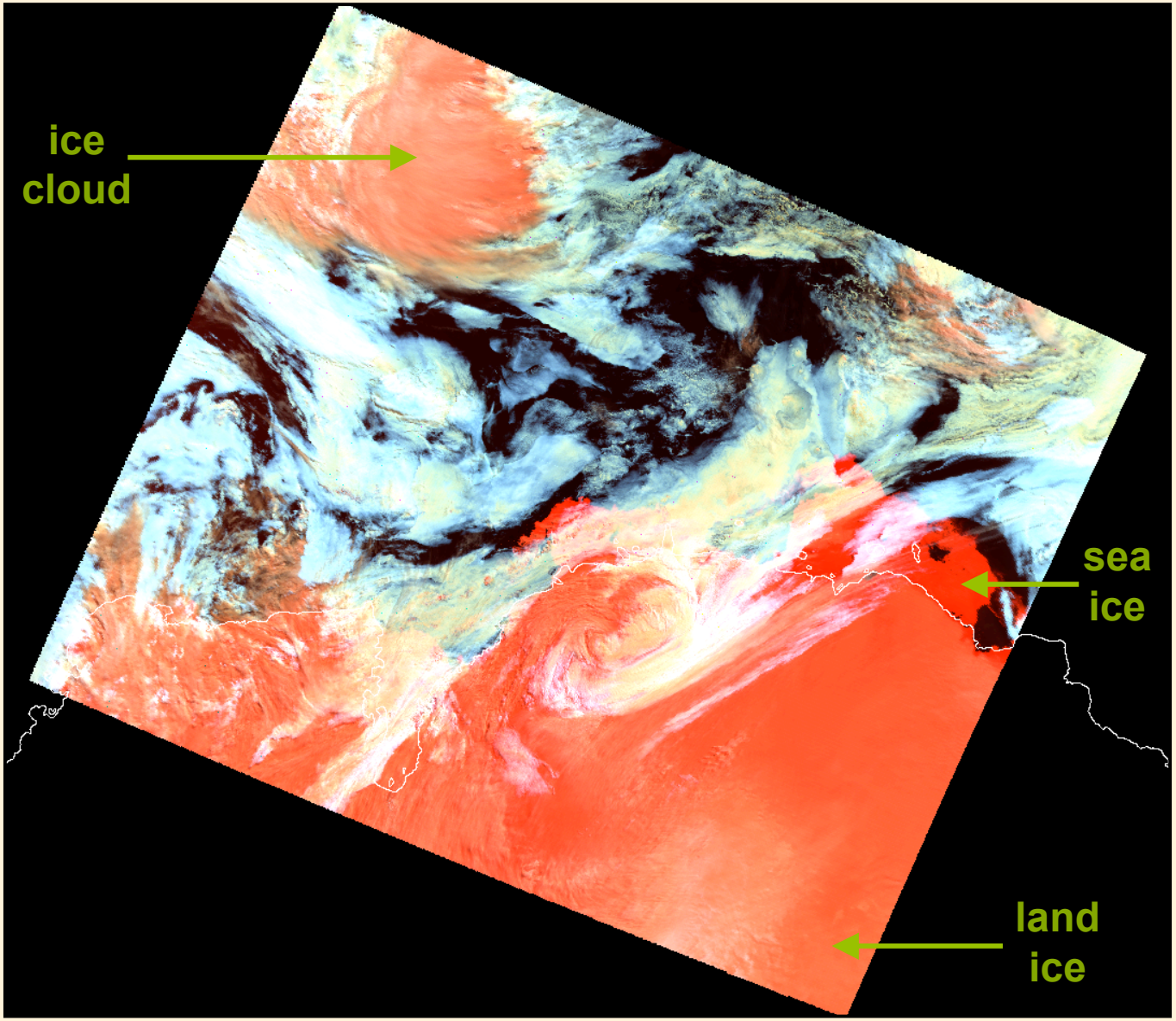
MODIS (MOD06) Uncertainty Estimates

- New for collection 5 processing stream (starting this fall)
- Pixel-level uncertainty estimated via effect of each error source on inference of above-cloud spectral reflectance + sensitivity derivatives (e.g., $\partial \tau / \partial R_\lambda$, $\partial r_e / \partial R_\lambda$) evaluated at the retrieval solution
- Uncertainty in aggregated Level-3 means (1° grid, daily, 8-day, and monthly) assumes correlation of pixel-level uncertainties for a daily grid box, no correlation between multi-day grid boxes
- Includes assumptions on a subset of uncertainties
  - Instrument calibration + fixed model uncertainty (5% relative)
  - Uncertainty in above-cloud column water vapor (20% relative)
  - Uncertainty in specification of surface spectral albedo (15%), where land and snow/ice albedo maps are derived from MODIS operational albedo product (MOD43) with spatial/temporal interpolation scheme based on ecosystem retrievals (MOD12)
- To the extent that other error sources are uncorrelated with this subset, represents a minimum or baseline *rms* uncertainty

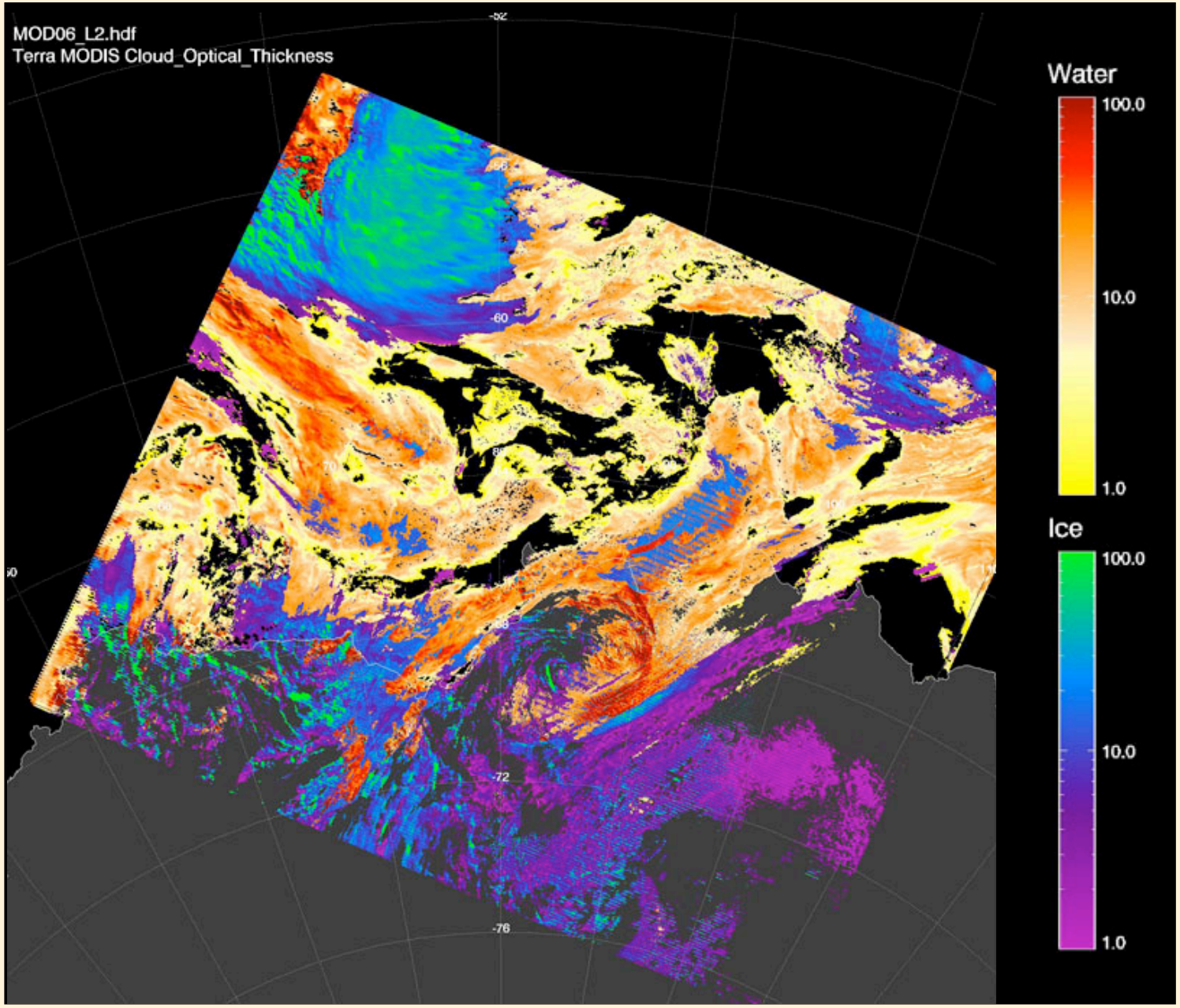
MODIS Terra example 12 Feb 2001, VIS/NIR composite



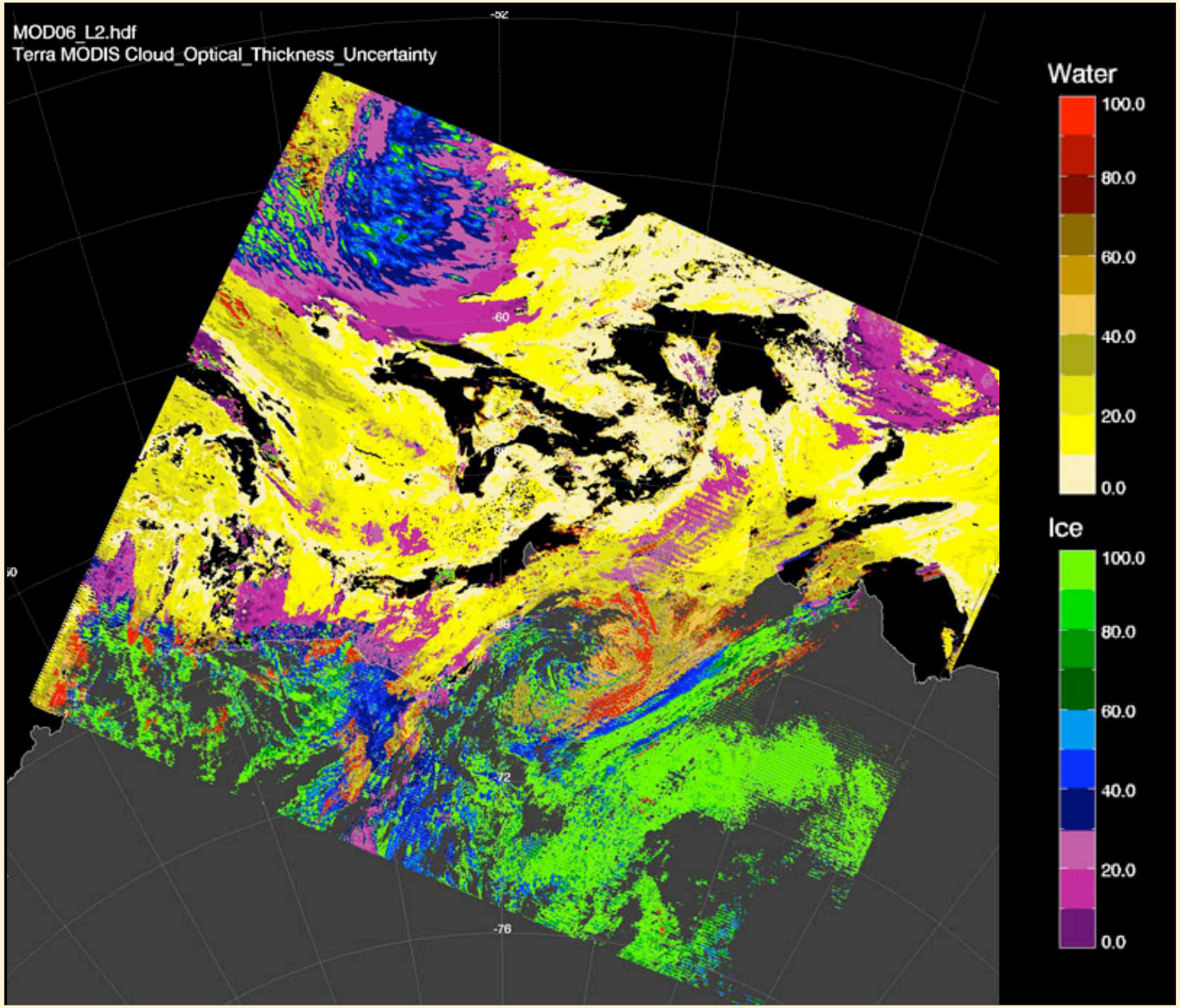
MODIS example, SWIR composite



MODIS example, τ_c retrieval (collect 5, prelim)

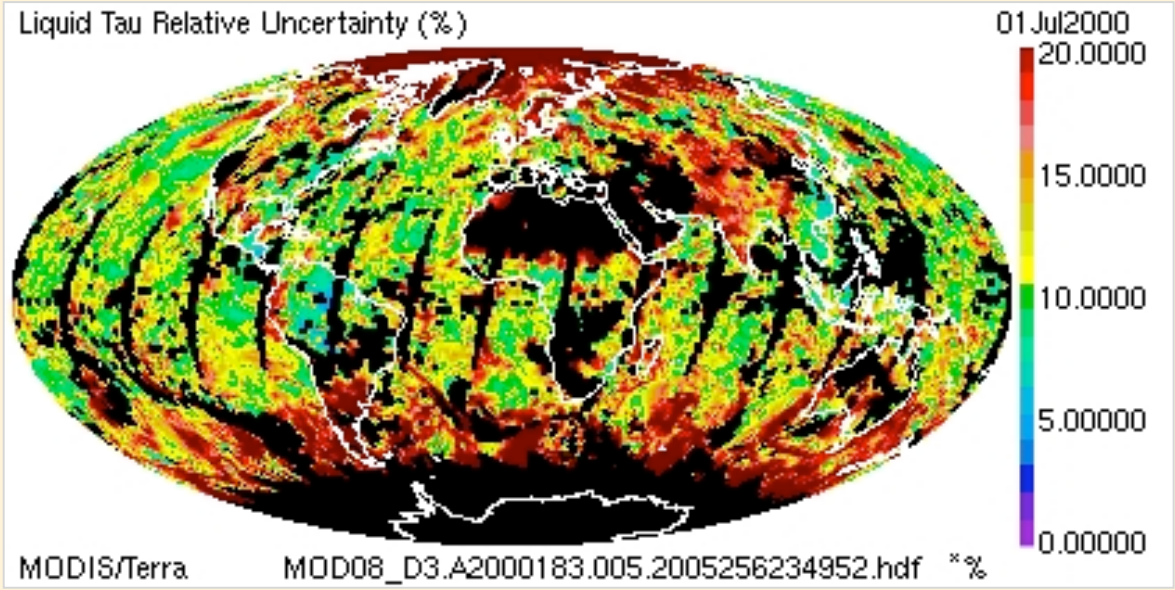


MODIS example, $\Delta\tau_c/\tau_c$ (%) (collect 5, prelim)

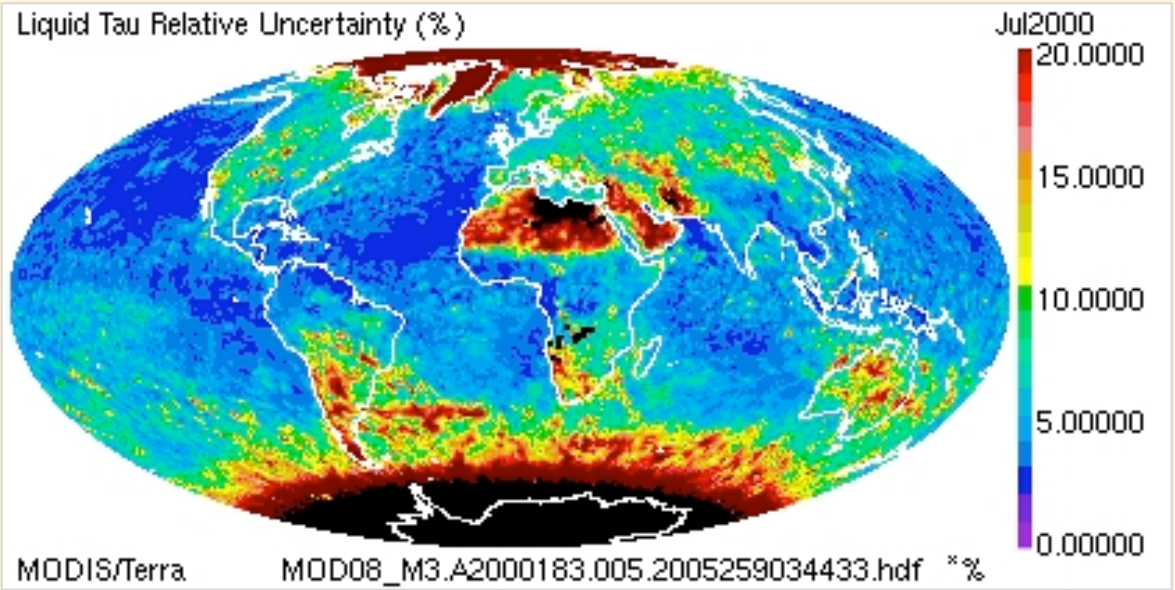


MODIS Terra example, $\Delta\tau_c/\tau_c$ (%) (collect 5, prelim)

liquid water cloud
daily aggregation
(1 July 2000)

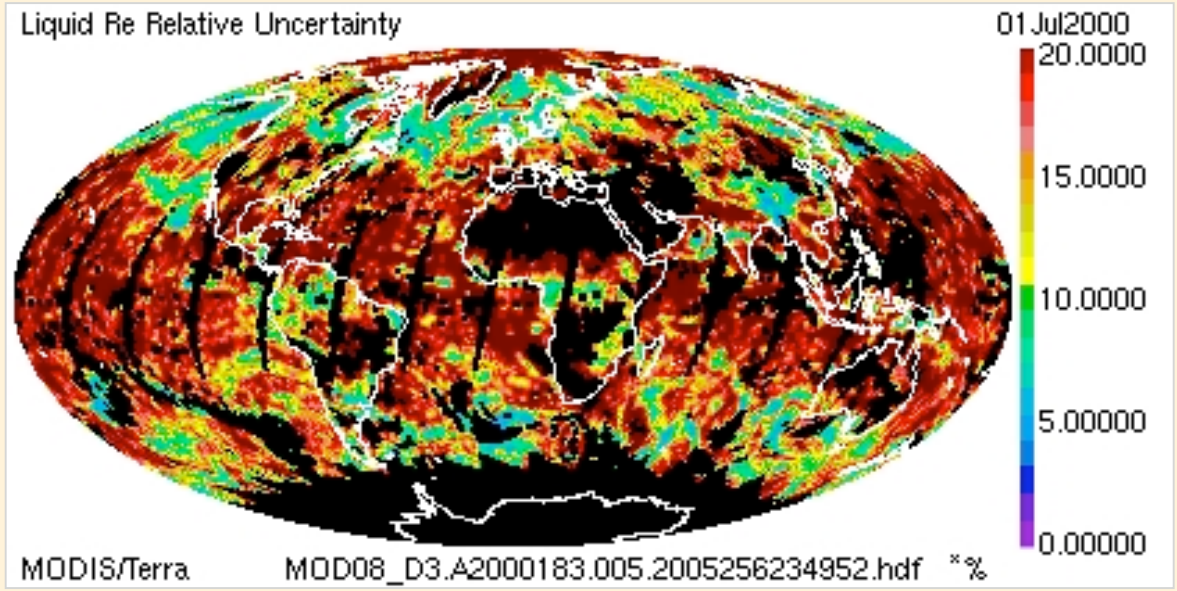


liquid water cloud
monthly aggregation
(July 2000)

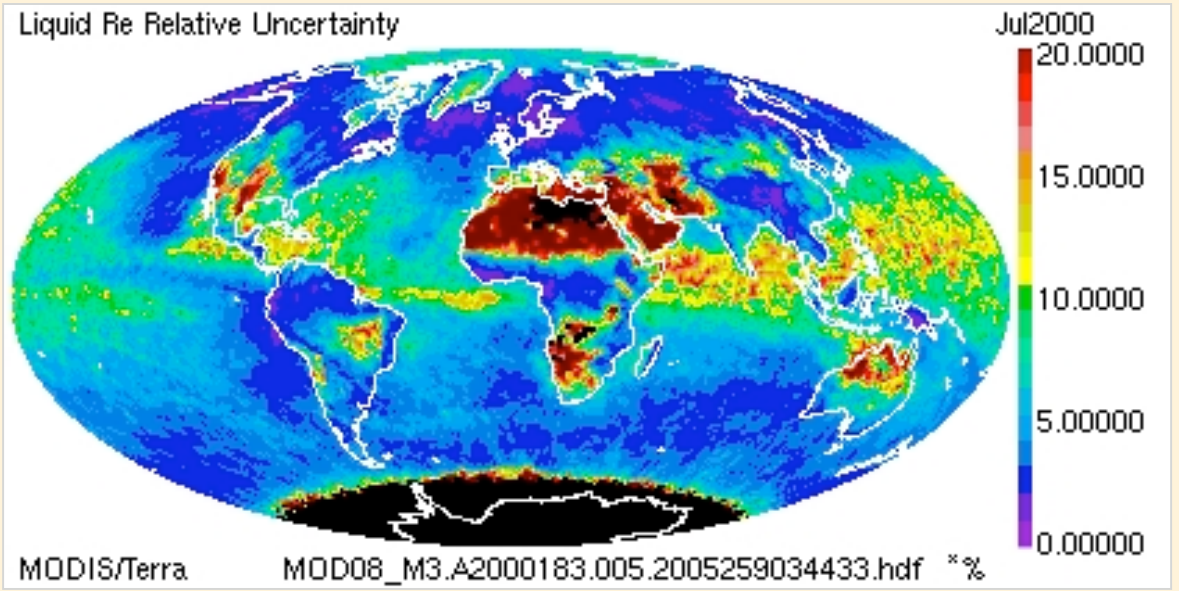


MODIS Terra example, $\Delta r_e / r_e$ (%) (collect 5, prelim)

liquid water cloud
daily aggregation
(1 July 2000)



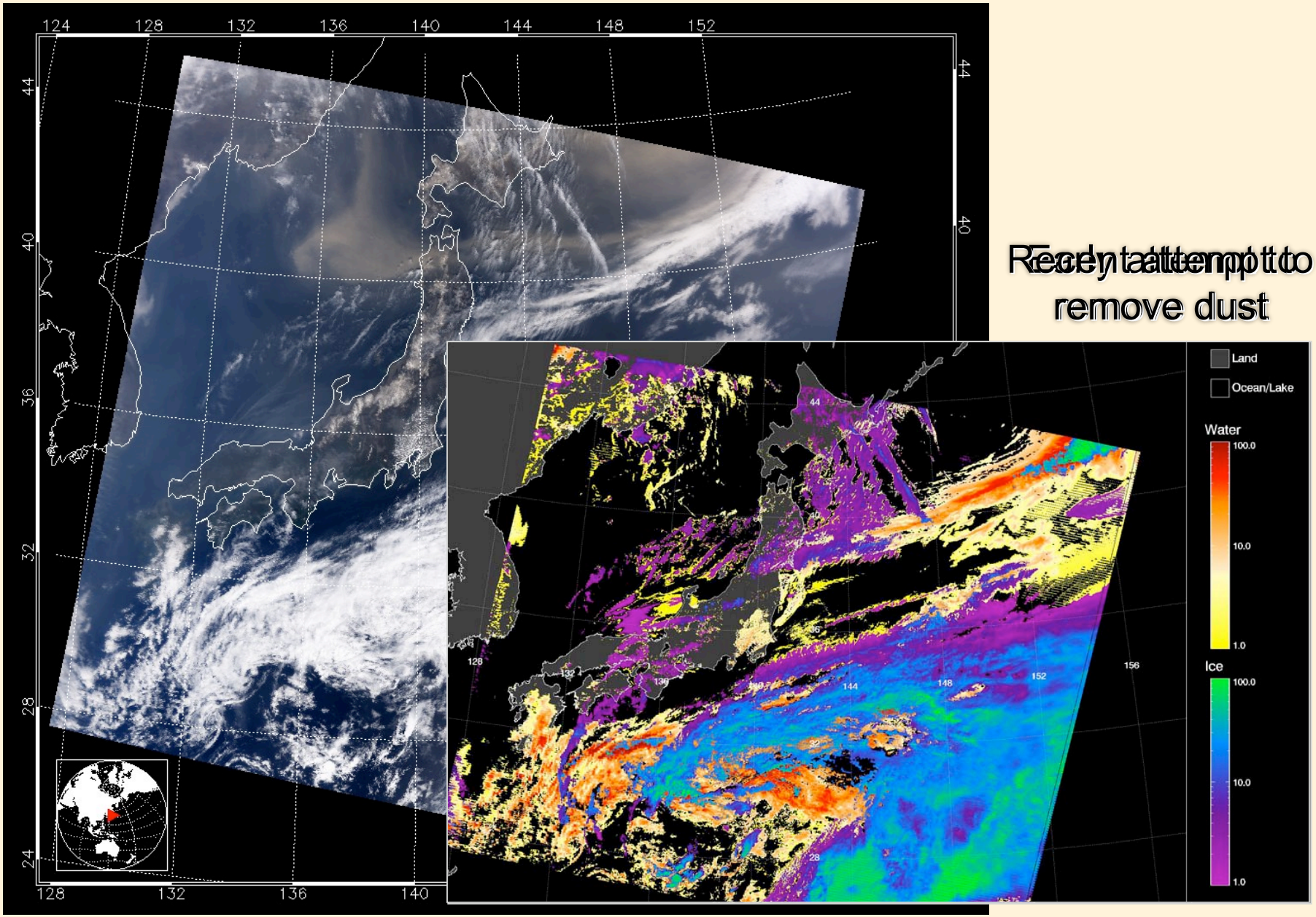
liquid water cloud
monthly aggregation
(July 2000)



MODIS (MOD06) Collection 5 Attempts to Flag or Eliminate Other Error Sources from the Retrieval PDF

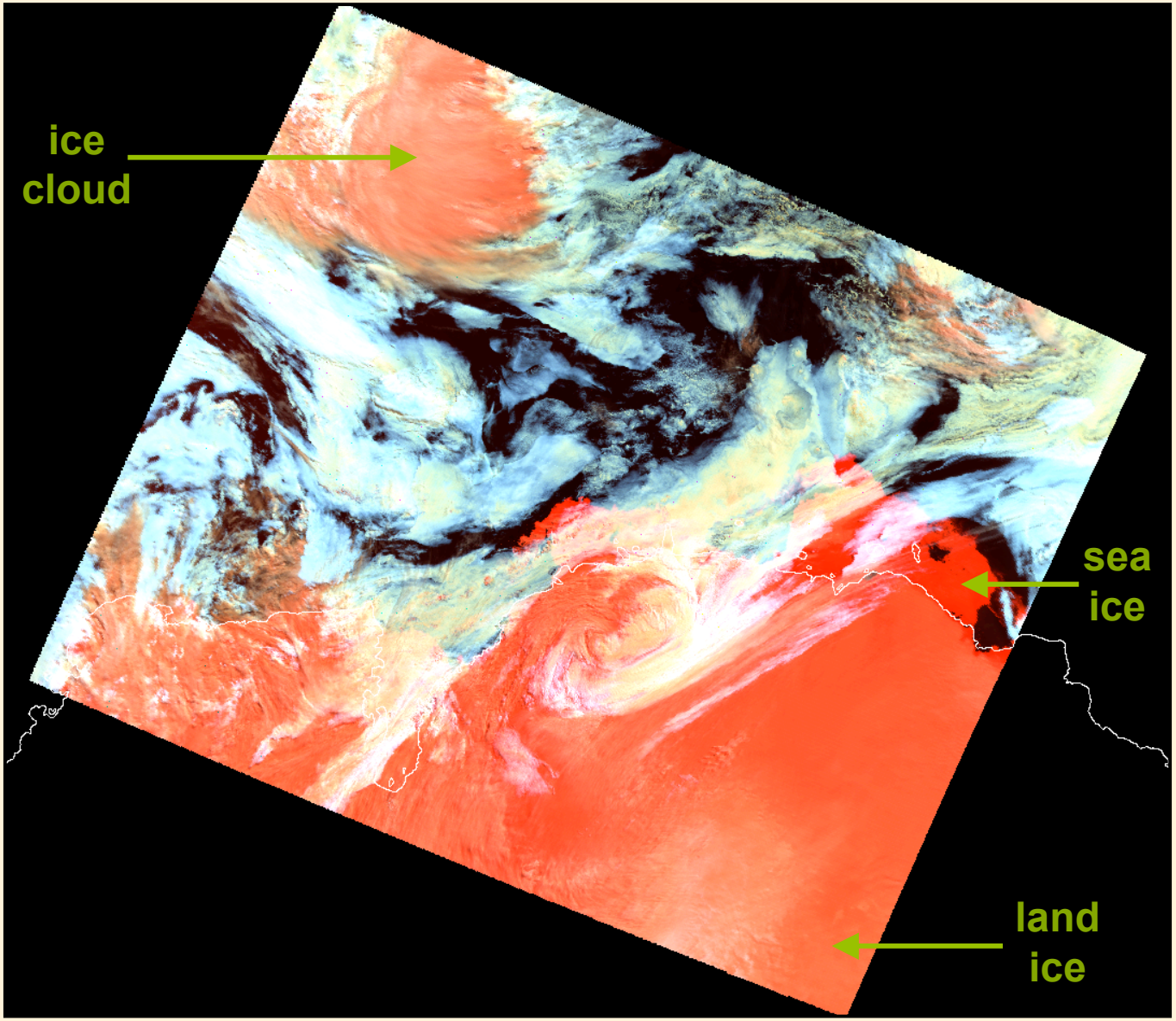
- Combination of spatial and spectral tests to eliminate false cloud retrievals for heavy aerosol and sun glint
- Sub-pixel variability
  - Use MODIS 250m bands over the ocean
  - Elimination of cloudy edge pixels
- First try at multilayer cloud detection (cirrus over lower level cloud)

MODIS Terra example, Asian Dust Outbreak 10 April 2001

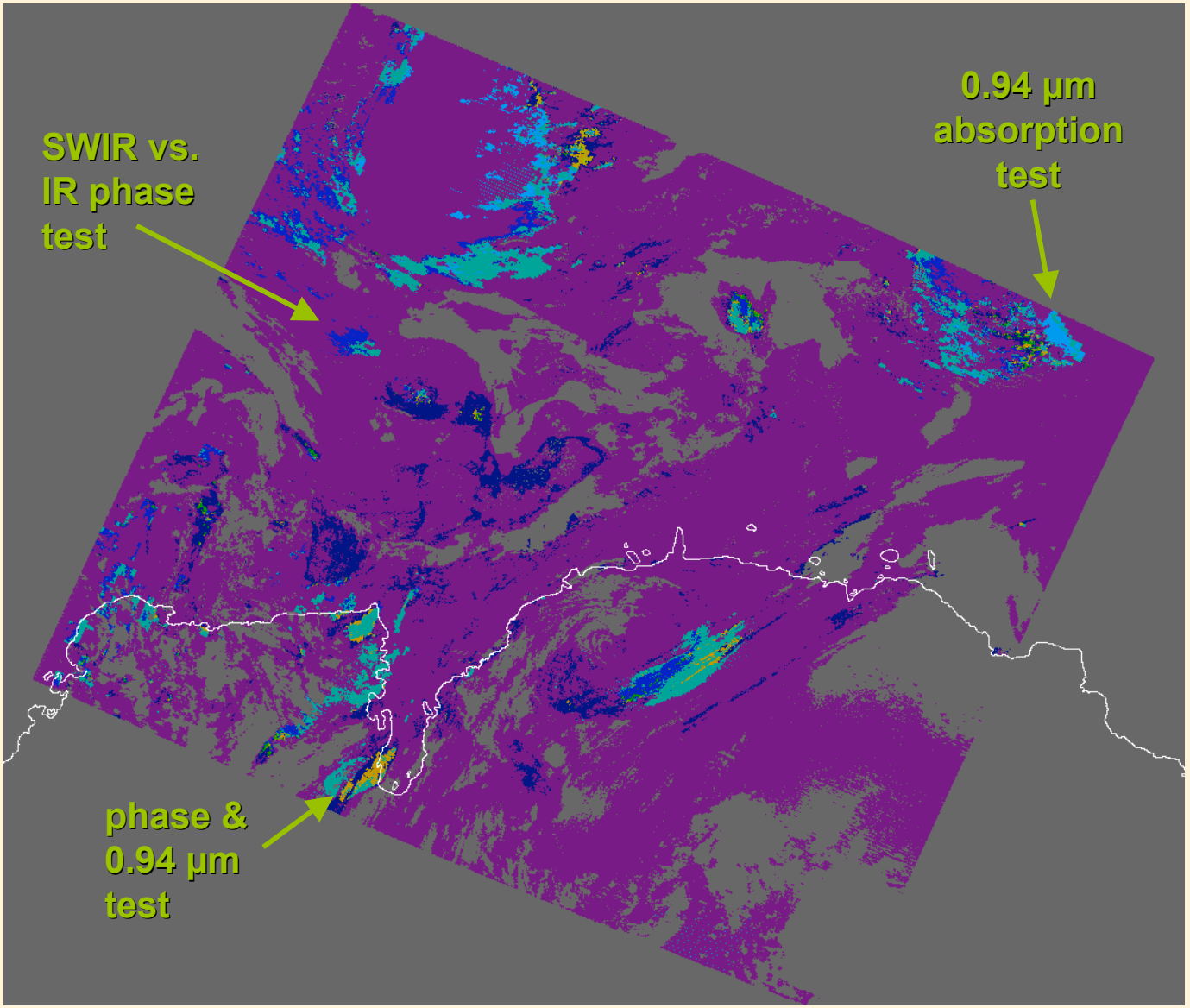


Recent attempt to remove dust

MODIS example, SWIR composite



MODIS example, multilayer/multiphase flag (collect 5, prelim)



Solar Reflectance Satellite Measurement Summary (*incomplete*)

Measurement	Example Instruments		
	Heritage	Current/Recent	Future
Spectral, Spatial (radiometric imagers)	**AVHRR**, **Landsat TM, SPOT** (*CNES*), **CZCS**	**MODIS**, **GLI** (JAXA, *ADEOS-II*), **ATSR** (UK, *ERS-1,2*), **ASTER** (Japan), **ETM+**, **SeaWiFS, MERIS** (ESA, *Envisat*)	**VIIRS** (*NPP*, *NPOESS*)
Directional		**MISR** (imager), **ATSR, ASTER**, **POLDER**	**APS** (*Glory*)
Polarization		**POLDER** (CNES, *ADEOS-I,II*)	**APS, PARASOL** (CNES, *A-train*)

Key: Instrument development/management (other than US), *Satellite platform*

Future Cloud Observations from Space

In the coming decade(s)

- Active missions:
  - NASA ESSP CloudSat/CALIPSO: NET launch date of 26 October 2005. Nominal 2 year missions.
  - ESA Earth Explorer Mission EarthCARE: 2012?, w/multispectral imager, lidar, radar (doppler), broadband radiometers
- Current multi-decadal satellite cloud climatologies are based on passive observations (e.g., ISCCP, HIRS). Passive remote sensing will continue to play the major role in satellite observations through the coming decade(s)
  - Polar: NASA NPP: ~2008 launch, NPOESS platforms: ~2010-2020 w/EOS heritage algorithms, MetOp platforms: 14 yr program starting in 2006 (?)
  - GEOS: MSG, MTG (2015), GOES-R (2012)
- NOTE: CloudSat/ CALIPSO can assist high resolution passive imagers with vertical cloud structure assessments, but not horizontal (~2.5 & 5 km effective along-track footprint for CloudSat and CALIPSO, respectively).

Summary and Thoughts

- Some cloud retrievals traditionally thought to be basic and fundamental are ill-defined
  - Cloudy or clear (depends on the part of the spectrum, among other things)? Cloud-top height (radar vs. lidar vs. IR vs. polarization)? Cloud phase? Cloud effective particle size (local quantity, not vertically integrated as with τ)?
- All retrievals (w/out exception) have issues with portions of the retrieval pdf space. Simple statistics can be biased due to missing and/or error-prone portions of the pdf. Comparing means between algorithms should be undertaken with great caution.
- Current operational cloud algorithms benefit from well characterized instruments. Pixel-level and aggregation uncertainty estimates (for a subset of error sources) will be included in upcoming MODIS data sets.
- Future research missions (e.g., CloudSat/CALIPSO) will allow for synergistic studies, especially the inclusion of vertical cloud structure into a retrieval algorithm.

Summary and Thoughts (2)

- Other synergistic efforts that have/will help understand operational passive cloud retrievals:
  - Radiation budget studies (e.g. CAVE) with CERES/VIRS (TRMM), CERES/MODIS (Terra, Aqua); multilayer/phase detection and retrievals using imager + microwave (e.g., VIRS+TMI, MODIS+AMSR-E, *Bing Lin, LaRC*); multidirectional effects: MODIS+MISR, MODIS+POLDER (variety of on-going work)
- Retrieval validation is difficult because of spatial/temporal matching with ground, aircraft, or other satellite instruments, and fundamental differences in the "validating" instruments information content and uncertainties
  - However, even previous generation instruments/retrievals can give a certain degree of consistency with TOA radiation budget (ISCCP, Zhang et al., 2004)

Summary and Thoughts (3)

- I3RC: to impact global retrieval data sets (in order of importance) …
  - Identification of problematic pixels for 1D retrievals (where "problematic" is defined w.r.t. their collective effect on the aggregation pdf)
  - Estimate of 1D aggregation uncertainties due to 3D effects for inclusion in overall uncertainty estimation
  - Estimate of pixel-level 1D retrieval uncertainties due to 3D effects for inclusion in overall uncertainty estimation
  - Implementation of an operational 3D retrieval would be last on the list of priorities (though could be an inherent part of reporting uncertainty estimates for 1D retrievals)