Collection 005 Change Summary for the MODIS Cloud Optical Property (06_OD) Algorithm

Version 2.2 (26 December 2005)

(see red entry on p. 15 for document version 2.2 update)

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High Impact Change Summary:

The Collection 005 changes providing the biggest impact (improvement) are (in no particular order):

- Improve cloud phase algorithm
- Improve ice libraries
- New clear sky restoral algorithm (for flagging heavy aerosol and sunglint)
- Improve surface albedo maps

Detail on these four items is provided in the top four entries below.

Change Detail:

Listed below is a detailed summary of the changes implemented in the Collection 005 version of the Cloud Optical Property algorithm. The high impact changes (outlined above) are listed first.

High Impact Changes

- **Improve cloud phase algorithm.** First, the cloud phase algorithm has been updated to fully comply with existing flow charts. All thresholds had been updated. All logic had been verified against the desired operation. Second, the **IR phase decision has been corrected.** It is possible for the IR phase decision tree to return *no answer*. In this case the cloud phase is now correctly set to 'unknown.' Third, the **(Riédi) SWIR thresholds have been modified.** The band used in SWIR reflectance ratio threshold depends on underlying surface type. Different thresholds were implemented for snow and ice surfaces. In addition, there were numerous phase logic changes and the addition of thermal sanity checks. [For detailed logic flow, see Diagrams 1, 2, and 3 at end of document.]

- **Improve ice libraries.** New ice-crystal cloud radiative transfer models were used to generate an improved ice reflectance library. The new ice libraries affect the cloud retrievals in several ways. First, the libraries are better behaved numerically. As a result, there was a marked reduction in the failure of the 3.7 µm ice cloud retrieval. With new libraries there are almost as many ice retrievals in 3.7 µm as there are in 2.1 µm retrievals, a great improvement over the old ice library. The main 2.1 µm retrieval did not change in any significant fashion. Average difference in r_e between the old and new libraries was within 2 µm. Replaced 12 Collection 004 radiative transfer libraries for ice clouds with 13 new Baum et al. (2005) ice libraries (r_e = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 90 µm). It should be noted that this change affects the L2 and L3 range of Cloud Effective Radius

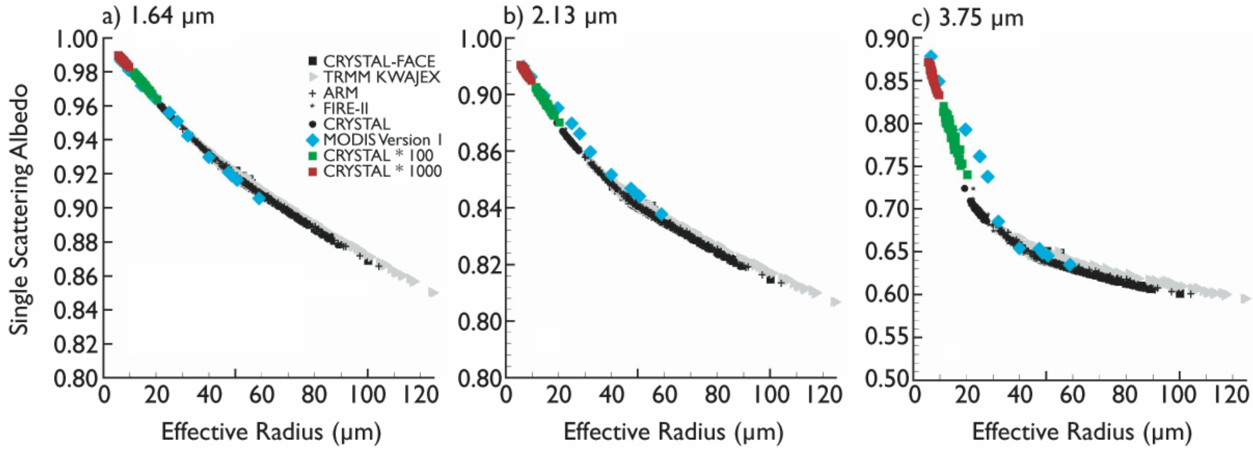

Figure 1. MODIS band-averaged single scattering albedo calculated from in situ particle size distributions assuming a mixture of ice particle habits. Superimposed on the data are the results from a sensitivity involving the CRYSTAL-FACE particle size distributions in which the number of particles with sizes less than 20 μm were multiplied by a factor of 100 (green symbols) or multiplied by a factor of 1000 (red symbols). The twelve MODIS version 1 models (collection 4) are superimposed for reference (blue symbols) (after Baum et al. 2005).

and Cloud Water Path for ice clouds, where the Collection 004 solution range was approximately *6 to 60* and *0 to 4000*, respectively. For Collection 005, the solution range of Cloud Effective Radius and Cloud Water Path for ice clouds is *5 to 90* and *0 to 6000*, respectively. [For an example of the ice cloud single scattering albedos of the new and old ice libraries, see Figure 1.]

- **New clear sky restoral algorithm includes sunglint & heavy aerosol (smoke/dust) detection.** Implemented a new and improved *clear sky restoral* (CSR) algorithm. This algorithm attempts to identify retrievals that are poor retrieval candidates, typically these are pixels (incorrectly) identified as cloudy by the decision tree, that were actually non-cloudy—it then "restores" a clear sky assignment to those pixels. Examples of these scenes might be those with elevated dust, smoke, and sunglint. Scenes processed as cloud and subsequently determined to be non-cloud scenes are assigned the retrieval "fill value" and marked as "failed" in the QA. To implement this, the dimensions of the array used in the spatial variability test were expanded and the test threshold values were increased. The result of this is to reduce the number of false clouds (false cloud retrievals). The new algorithm includes 1.38 μm, cloud phase, 250 m spatial variability, and spectral tests. [For detailed logic flow, see Diagrams 4 and 5 at end of document.] [Figure 2 shows an example of this new flag].

- **Improve surface albedo maps.** A newly developed high-resolution spatially complete snow-free surface albedo dataset was added. This dataset was created by employing an ecosystem-dependant temporal interpolation technique to fill missing or seasonally snow-covered data in the official MODIS land surface product, as described in Moody et al (2005). This dataset is stored in equal-angle grids for ease-of-use and has high temporal (16 day) and spatial (2 km) resolution for all MODIS bands of interest. Consequently, seasonal, spectral, and spatial variations of surface albedos are now accurately represented (cf. Figure 3).

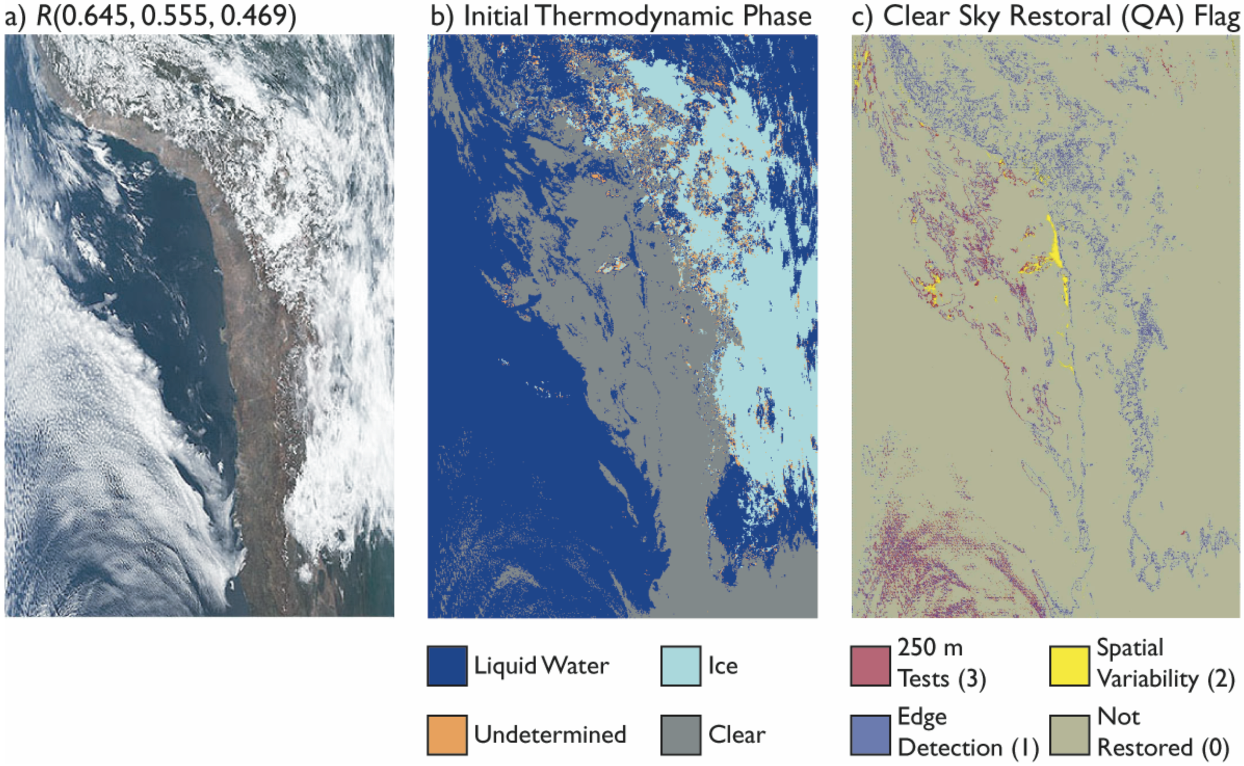

Figure 2. Clear Sky Restoral. Panel (a) is a true color composite of one Terra/MODIS granule off Peru on February 12, 2001 at 15:10 UTC. Panel (b) is the initial assessment of which pixels are clear and which are cloudy, and what is their thermodynamic phase. Panel (c) is the new Collection 005 Clear Sky Restoral Flag that is stored in the Cloud Optical Properties QA Flag array (Quality_Assurance_1km SDS). This flag shows where the cloud detection (flow chart) logic initially determined a cloud to be present, but after running the pixel through the *Clear Sky Restoral* algorithm (where further logical tests are applied), clear sky was "restored" and the cloud retrieval was set to fill (missing).

Additional Albedo Dataset Improvements

- **New snow albedo.** Spectral snow albedo has been derived from MOD43B3 spectral surface albedo data as a function of MOD12Q1 ecosystem classification. This lookup table provides hemispherical multi-year average statistics such that the values provide "average" snow conditions. Five years (2000-2004) of high quality MOD43B3 data was collocated

  with Near Real-Time Ice concentrations and Snow Extent (NISE) data to generate the statistics. Figure 4 provides a sample of vegetated, forest, and other ecosystem multi-year hemispherical snow albedo statistics computed from Collection 004 2000-2004 MOD43B3 data.

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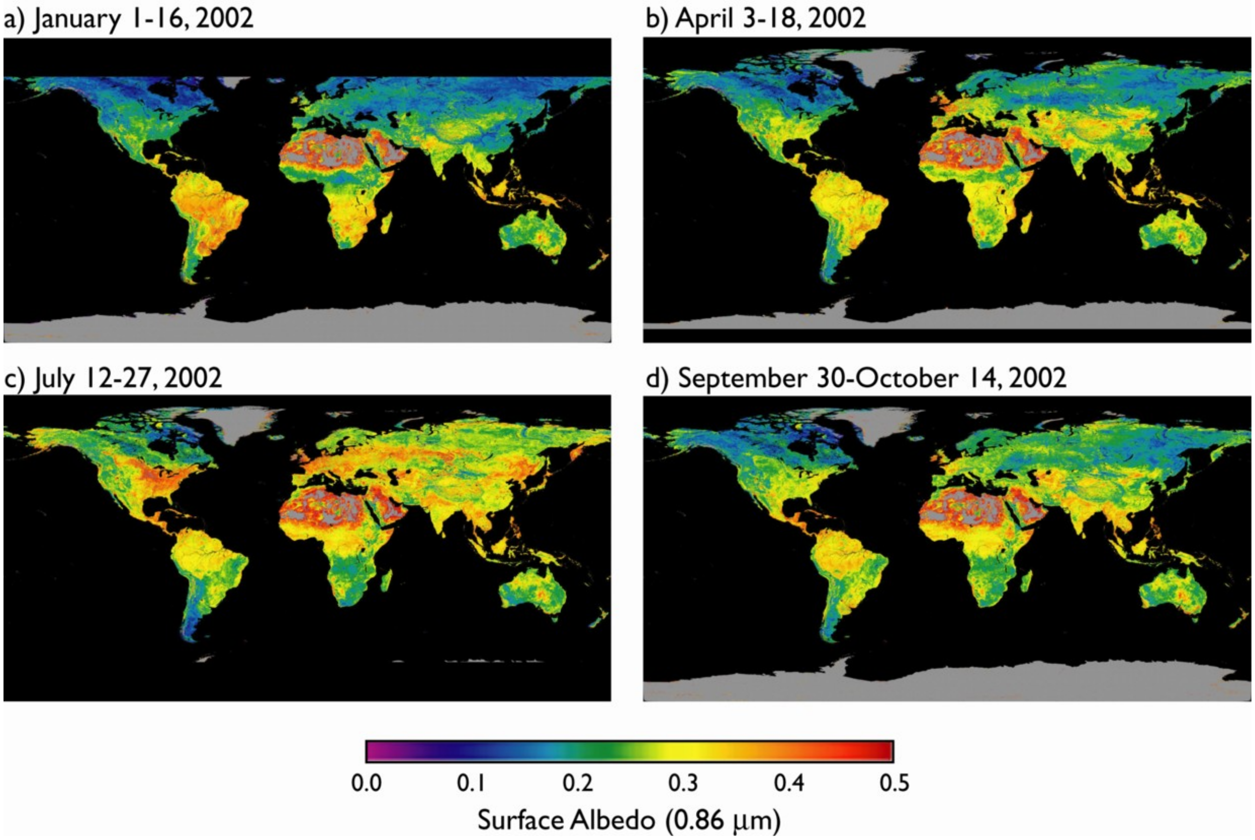


Figure 3. Spatially complete white-sky albedo at 0.86 µm after the temporal interpolation technique was applied for the 16-day periods of (a) January 1-16, (b) April 3-18, (c) July 12-27, and (d) September 30-October 14, 2002 (after Moody et al. 2005).

- **Use of snow-free albedo maps with snow albedo statistics.** Uses snow/ice index from the daily 0.25° Near Real-Time Ice and Snow Extent (NISE) dataset to determine the occurrence of snow on the surface beneath the clouds being analyzed. The snow albedo statistics are used in tandem with the snow-free spatially complete surface albedo map (cf. Figure 3) to provide dynamically tailored surface albedo maps that are a necessary boundary condition in the estimation of cloud optical thickness and effective radius. This algorithm starts with a base 16-day discrete wavelength snow-free spatially complete surface albedo

  map, defines where the snow is present (via NISE) and the underlying IGBP ecosystem class, and then overlays snow albedo values using the lookup table of snow albedo statistics (cf. Figure 5). This is necessary to set the underlying boundary condition and albedo for the cloud optical property retrieval, and is far more detailed than in Collection 004, which uses a uniform snow albedo for all surfaces, regardless of vegetation canopy.

- **Snow albedo in coastal regions**. Due to the limitations of microwave retrievals, the NISE data does not determine snow/sea ice in coastal regions. As a workaround, Rich Frey (University of Wisconsin) implemented an interpolation technique using surrounding non-coastal pixels in combination with the NOAA sea ice product. This technique has been tested in MOD35 production, and was implemented for the current MOD06OD delivery. This will allow proper assignment of snow/sea ice albedo in coastal regions, thereby reducing errors associated with improper albedo assignment. MOD06 albedo

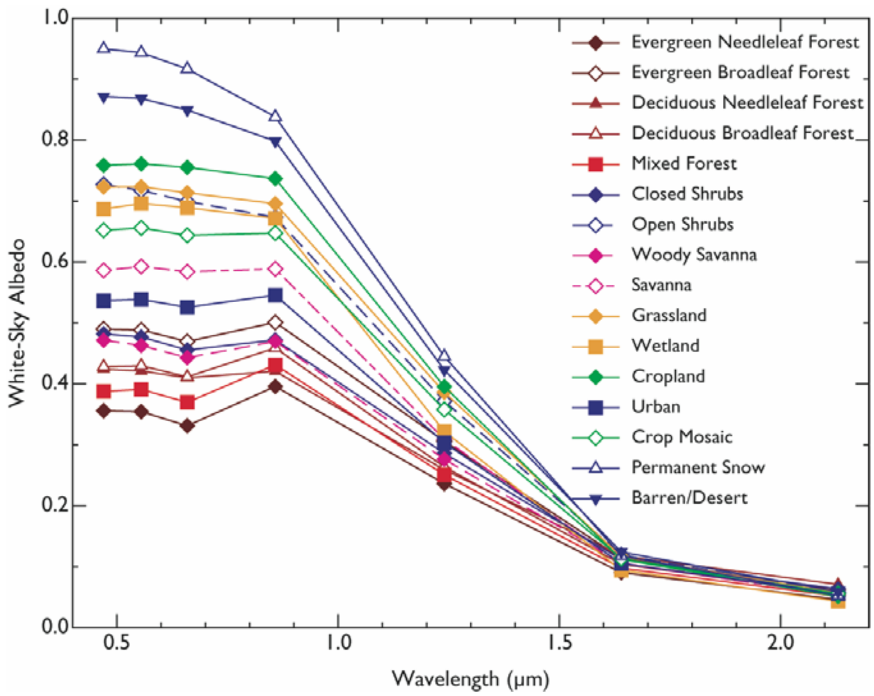


Figure 4. Northern hemisphere multi-year average white-sky spectral snow albedo as a function of select IGBP ecosystem classifications from 2000-2004 MOD43B3 data.

modules are updated to utilize the 16-day average maps.

- **Greenland surface albedo correction.** Greenland and some oceanic snow/ice scenes were assigned correct surface albedos and subsequent retrievals performed with the inappropriate non-snow/ice shortwave band. This has been corrected. Such scenes are now correctly retrieved using the 1.2 μm band.

- **Updated IGBP ecosystem map.** The static MOD12Q1 IGBP ecosystem classification map used in MOD06 retrievals was updated to the most recently produced version. MOD12Q1 production occurs off-line when a significant number of observations can be used to update the classifications. The current MOD12Q1 operational map updates the majority of the world, but especially in urban areas. In the previous operational map, urban areas were not properly represented. An update to the MOD12Q1 processing algorithm corrected this issue such that urban areas are now fully represented.

- **Surface type & surface albedo matching.** The MOD06 surface albedo code was modified to return surface type index values with the surface albedos. This ensures that surface type is always consistent with the surface albedo. Close examination of early test results revealed that the surface type processing path reported by the MODIS Cloud Mask (MOD35) could sometimes replace the surface type reported earlier in the algorithm. This could lead to a mismatch between surface albedo and surface type (land/water/snow-ice). It should be noted that the Wisconsin team that authored the Cloud Mask algorithm did not recommend the use of the surface type report in MOD35 as a surrogate for surface type determination.

- **3.7 μm albedo correction.** Corrected a bug in the indexing of the albedo arrays to correct the 3.7 μm albedos. This change affects the 3.7 μm effective radius retrieval. If the albedo is incorrect for thin clouds then the retrievals will be incorrect also.

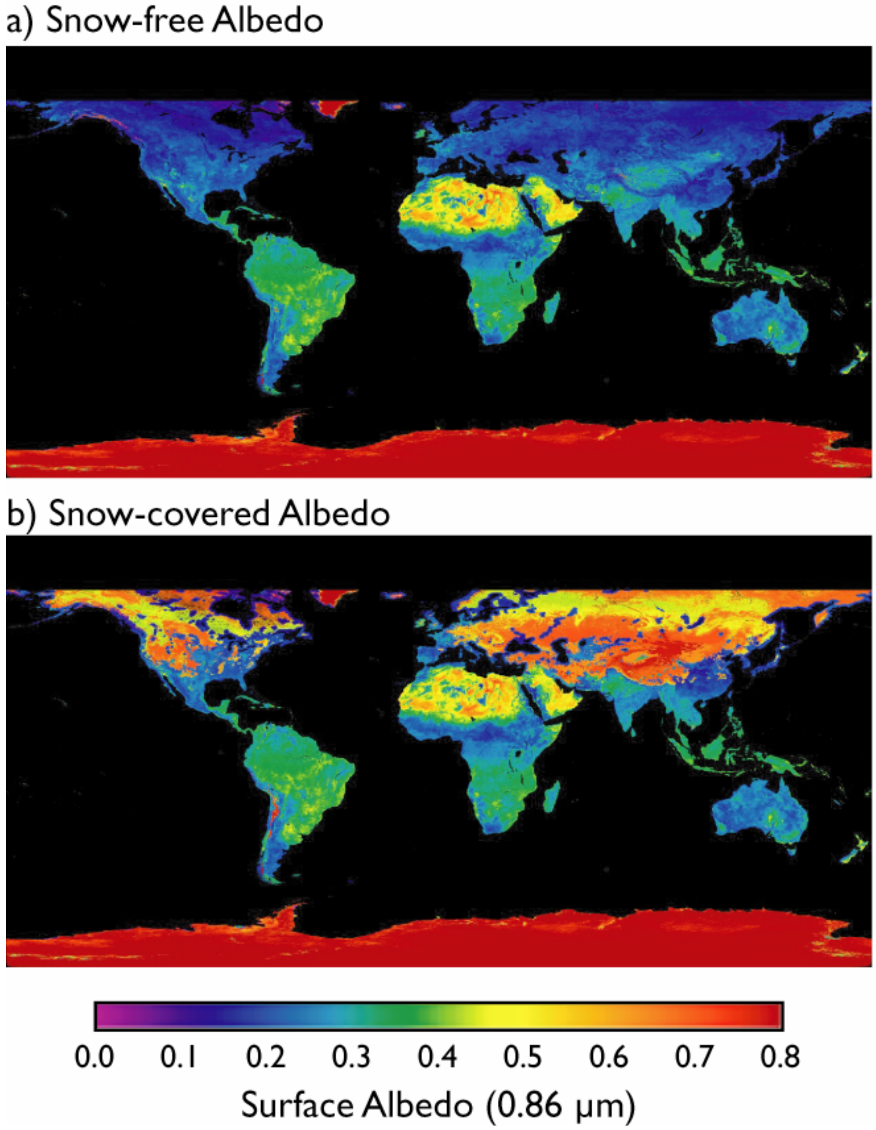


Figure 5. Spatially complete white-sky albedo at 0.858 μm from January 1-16, 2002, without (top) and with (bottom) overlaid snow albedo values. Snow albedo values are provided from the 2000-2004 hemispherical snow albedo statistics by overlaying the NISE snow extent and type product, and then defining the snow albedo values from the lookup table and MOD12Q1 ecosystem classification.

Primary Cloud Optical Property Algorithm Improvements

- **Improve primary cloud optical property retrieval.** Several serious logic errors were found in the solution logic and solution interpolation. These errors led the code to incorrectly set many retrievals to fill values. New solution logic was implemented to better handle unusual solution vectors and cases where the visible reflective band of interest saturates—the result: high, thick clouds no longer fail. Numerous floating point exceptions have been resolved in the algorithm. Some of these were due to NAN ("Not a Number") values in static input files. These static files are updated. Finally, when Cloud Top Properties is fill (e.g., if less than 4 out of 25 1-km pixels are "cloudy") then cloud optical properties are not retrieved.

- **Improved effective radius solution logic.** A new robust quadratic interpolation for effective radius solution was implemented. Updated and corrected logic checks for anomalous solution interpolations and multiple solutions.

- **Uncertainty constants.** The relative surface spectral albedo uncertainty is assumed to be 15% of the pixel-dependent surface albedo value, for all spectral bands. Calibration and model uncertainty are combined into a single error source that is set to 5% relative for all spectral bands. The relative uncertainty in the above-cloud precipitable water amount (derived from model analysis and the MODIS cloud-top pressure retrieval) is assumed to be 20%; this partial column water vapor amount is used for atmospheric corrections that infer cloud-top radiances in all relevant spectral bands. These uncertainties for individual retrieval error components fundamentally impact the resulting retrieval uncertainty calculation for cloud optical thickness, effective radius, and water path, all of which are new in Collection 005. [Figure 6 shows a collection 5 retrieval example, with uncertainties, over a complex Greenland granule with both liquid water and ice clouds over the bright Greenland continent and nearby ocean, some of which contains sea ice under the clouds.]

- **Eliminate saturation and failed retrievals for large Cloud Optical Thickness (τ_c) and small Cloud Effective Radius (r_e).** If reflectance saturates at 0.86 µm, switch to 0.66 µm band. If cloud optical thickness (τ_c) □ 100 and indeterminate, still retrieve cloud effective radius (r_e), which is well determined for large visible band reflectance (R_{vis}). Set the *Band Used for Primary Optical Thickness Retrieval* flag in processing (runtime) QA. [Figure 7 shows a collection 5 retrieval example of a west African granule with both liquid water and ice clouds over land and ocean, in which collection 5 retrievals do not fail over thick ice clouds where collection 4 was saturated and had failed. In addition, sunglint contamination in collection 4 was properly screened out in collection 5.]

- **Cloud edge detection.** Implemented a cloud edge detection and removal scheme to dispose of (possibly) partly-cloudy pixels, which tend to be less reliable (accurate). This was implemented by re-setting "successful" retrievals to fill values (missing) if they are adjacent to non-retrieval (fill/missing) pixels. The cloud retrievals are affected in such a way that many of the small optical thickness, large effective radius retrievals (thought to be of questionable quality) from cloud edges, disappear.

- **Thermal sanity checks for warm and cold clouds.** Delete all *sanity checks* for cold clouds, which were automatically set to ice in Collection 004 when the cloud top temperature $T_{\mathrm{CLOUD\ TOP}} < 233$ K. Due to possible bias for optically thin clouds, this cold *sanity check* was eliminated in Collection 005 and only the warm *sanity check* (if $T_{\mathrm{CLOUD\ TOP}} > 273$ K then set to liquid water) was retained (cf. Diagram 2 at end of this document).

- **Removal of 0.0 cloud optical thickness.** If a cloud optical thickness less than 0.005 is computed, it is stored in the 06_L2 file as 0 (due to integer*2 packing (digitizing)). This was causing a problem in the L3 algorithm in the log of cloud optical thickness computation (since log 0 is undefined). The L2 retrieval for cloud optical thickness was hardwired to 0.01 for numbers computed less than 0.01. The cloud retrievals are affected such that there are no more cloud optical thickness retrievals of integer value of 0 stored in the HDF file (i.e., falling between 0 and 0.01).

- **New solar zenith angle threshold.** Set to 81.4°. (Previously set to 87° for Collection 004 and earlier). Solar zenith angle must be less than this specified threshold to retrieve, and the radiative transfer libraries are calculated only out to 85°. This was done so that the cloud optical property retrieval area matches the "daylight" area computed for the Cloud

Mask and is within the range of angles contained in the library computations. This eliminated the no retrieval "ring" that was visible in L3 global cloud optical property data near the polar darkness zone.

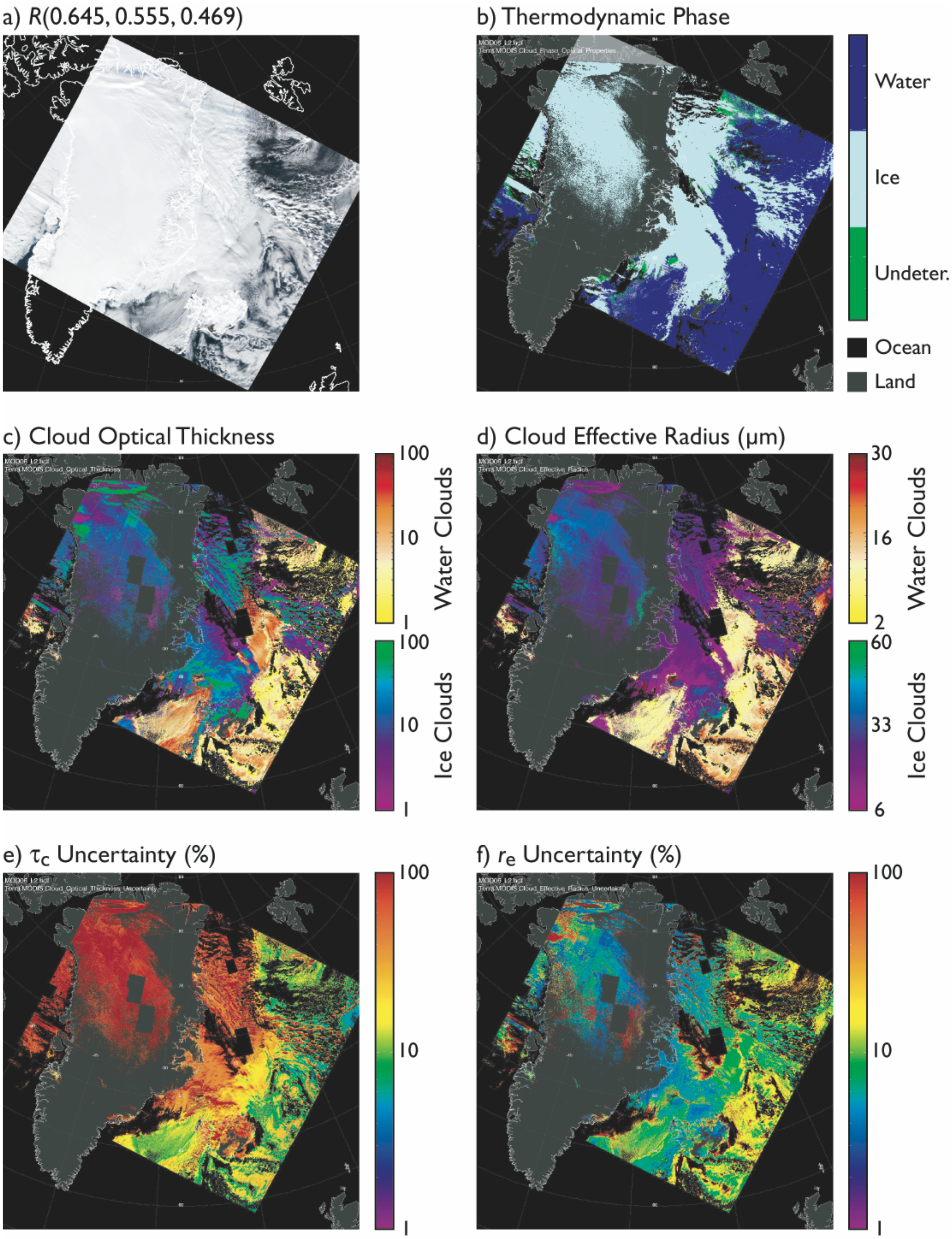


Figure 6. Cloud optical thickness and effective radius retrieved on March 22, 2001 over Greenland and the nearby Atlantic Ocean. This figure shows (a) the true color image that is often difficult to distinguish clouds from snow and sea ice, (b) the thermodynamic phase of all clouds identified for this scene, (c) the cloud optical thickness of liquid water and ice clouds, and (d) cloud effective radius of all liquid water and ice clouds. Panels (e) and (f) show the new algorithm applied to this scene of Terra data, and shows the percent uncertainty in retrieved cloud optical thickness and effective radius (log scale).

- **New ice water density constant.** Set to 0.93 g/cm^3. (Previously set to 1.0 g/cm^3 for Collection 004 and earlier). This constant is used in the corrected Collection 005 equation to compute Cloud Water Path for ice clouds (see below).

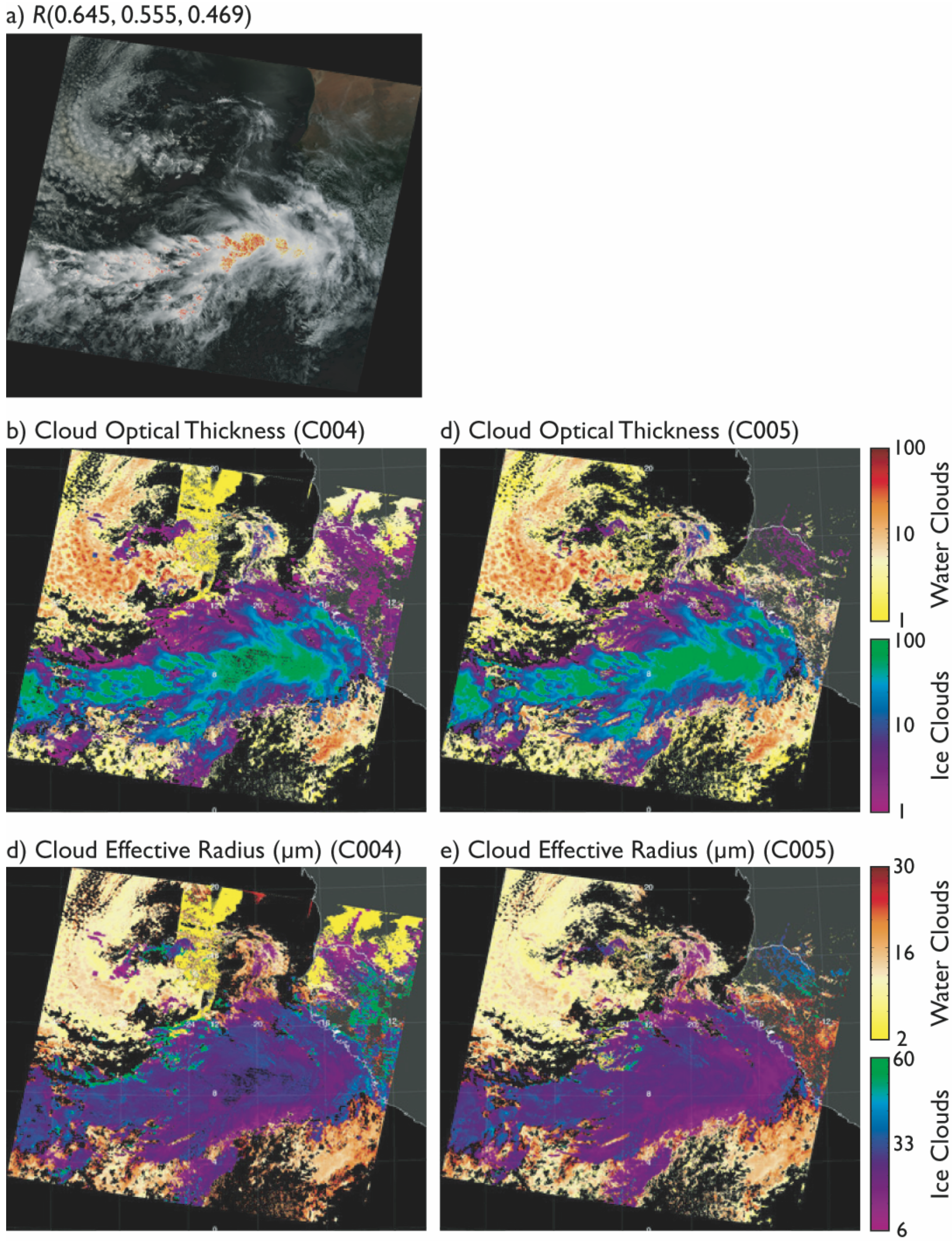


Figure 7. Cloud optical thickness and effective radius retrieved from Terra/MODIS data on July 25, 2001 over the west Africa and the nearby Atlantic Ocean.. This figure shows (a) the true color image that shows a region of problematic ocean sunglint and low level dust outflow from the African continent, (b) and (c) the cloud optical thickness for collection 4 and 5, and (d) and (e) the cloud effective radius for collection 4 and 5. The primary improvements depicted are: (i) correct handling of ocean sunglint (no longer misidentified as cloud in collection 5), (ii) correct handling of dust over land (no longer misidentified as cloud in Collection 005), and (iii) a marked reduction in failed retrievals (esp. in the middle of the thick ice cloud region).

- **Correct cloud water path formula.** In Collection 004 a bug was found in the calculation of cloud water path, where the constant ratio factor was incorrectly set to ¾ rather than

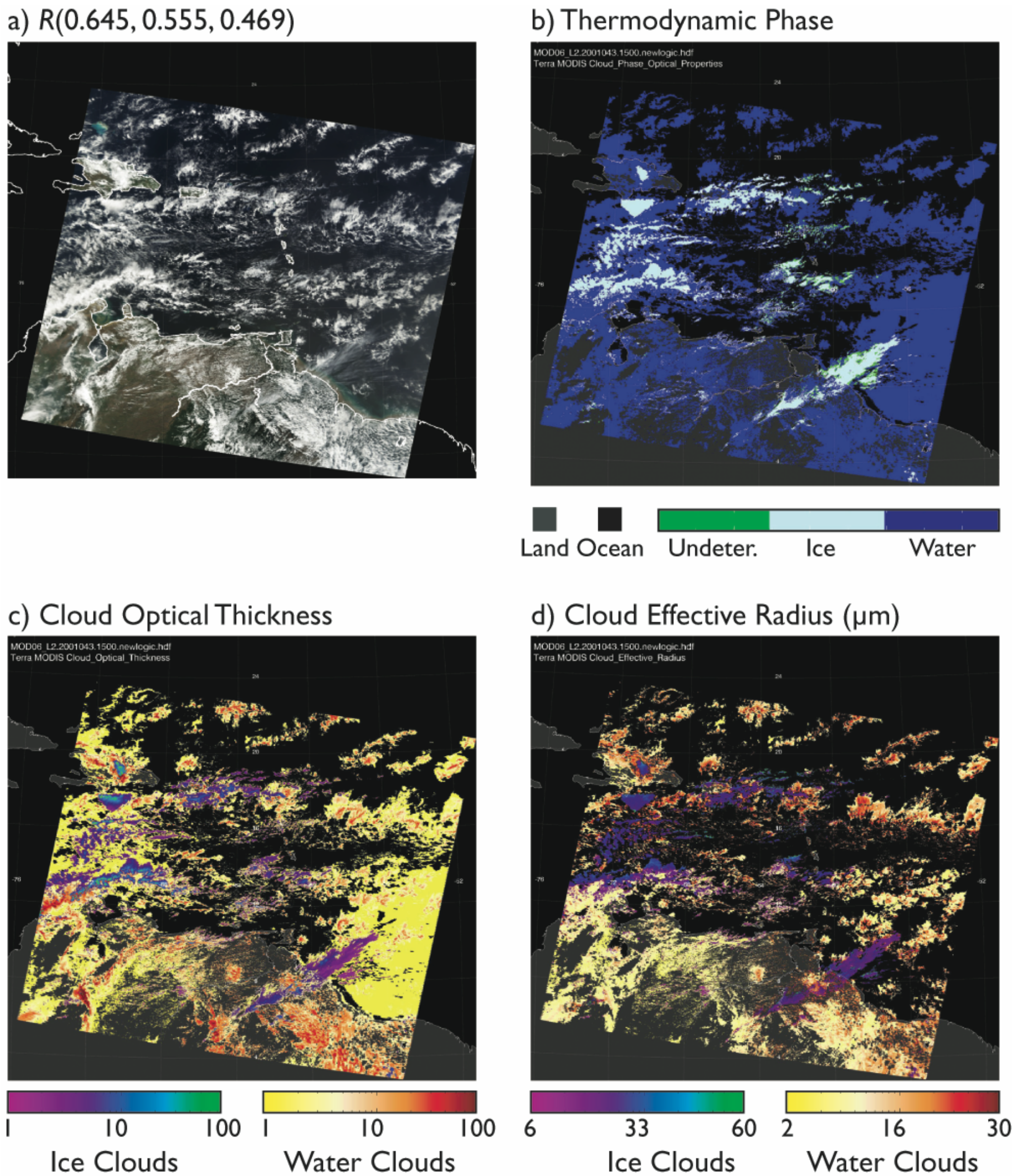


Figure 7'. Cloud optical thickness and effective radius retrieved from Terra/MODIS data on February 12, 2001 over the Caribbean Sea and northern South America. This figure shows (a) the true color image that shows a region of cumulus humilus clouds over the ocean, (b) the thermodynamic phase of all clouds identified for this scene, (c) the cloud optical thickness of liquid water and ice clouds, and (d) cloud effective radius of all liquid water and ice clouds. Panels (b) and (c) show the widespread occurrence of optically thin liquid water clouds of the Caribbean, while panel (d) shows fewer successful cloud effective radius retrievals.

$^2/_3$. This change of ratio affects the computation of Cloud Water Path for both liquid water and ice clouds. In addition, a density adjustment for ice clouds was added in Collection 005 (further reducing the computation of ice cloud water path provided the cloud optical thickness (τ_c) and cloud effective particle radius (r_e) do not change). In summary, the Collection 005 Cloud Water Path will be correctly computed as:

*Cloud Water Path = (2/3) * CloudOpticalThickness * CloudEffectiveRadius (for liquid water clouds)*
*Cloud Water Path = (2/3) * CloudOpticalThickness * CloudEffectiveRadius * 0.93 (for ice clouds)*

3.7 μm Cloud Effective Radius Retrieval Improvements

- **Correct 3.7 μm retrieval logic.** Numerous corrections were made to the 3.7 μm retrieval logic leading to a significant improvement in 3.7 μm radius retrieval quality and a decrease in the number of failed retrievals.

- **Update solar spectral irradiance at 3.7 μm.** Change F_0 (3.7 μm) from 11.297 $Wm^{-2}\mu m^{-1}$ (Thekaekara, 1974) to 11.739 $Wm^{-2}\mu m^{-1}$ (Fontenla irradiance model).

Supplementary 1.6/2.1 μm Cloud Optical Property Algorithm Addition (New SDSs)

- **Add supplementary 1.6/2.1 μm cloud optical property retrieval.** In addition to the primary cloud optical property retrieval that has been in place since launch, a new supplementary cloud optical property retrieval using the 1.6 and 2.1 μm bands was added for Collection 005. This new retrieval, computed only for clouds over ocean and snow/ice surfaces, was performed for comparison with the standard retrieval. Three parameters are computed in the cloud optical property retrieval algorithm: cloud optical thickness, cloud effective particle radius, and cloud water path. This new 1.6 / 2.1 μm retrieval is run over ocean and snow/ice surfaces only, so non-snow land will contain all fill values. (Note that the "ocean" ecosystem also includes deep inland waterways.) The new SDS (short) names are:
  Cloud_Optical_Thickness_1621,
  Cloud_Effective_Radius_1621, and
  Cloud_Water_Path_1621

Transmittance Improvements

- **Transmittance table and read logic update.** Modify water vapor transmission when the precipitable water above cloud PW_C < minimum or > maximum values in the transmission look-up table.

- **New transmittance library.** Updated (re-computed) atmospheric transmittance library corrects numerous anomalies present in earlier version. Previously it was possible to "run off" the edges of the transmittance array (too little or too much water vapor). Also a "step-back" algorithm had been implemented in order for the code to still return a reasonable value for transmittance even though the exact point the code landed on is a fill value. This has a minimal impact on the retrievals because "running off" the edge of a transmittance table is an infrequent occurrence. The stepping back vs. hard-coding transmittance value to 1.0 also has minimal effect, as there are very few points that have that issue. The answers for those points would be improved, while other data would not be affected.

- **Ozone transmittance correction.** Read ozone data and perform a simple calculation of ozone transmittance in the Chappuis band, which only affects cloud retrievals over snow-free land where the 0.66 μm band is used for cloud optical thickness retrievals. This is a new Collection 005 enhancement (the correction was not performed in Collection 004).

Rayleigh Correction Improvements

- **Rayleigh correction for non-zero land surface albedo.** Fixes τ_C □ 1 restriction for cloud retrievals over land, where the Rayleigh correction is implemented, and makes use of the spatially-complete surface albedo at 0.66 μm. Collection 004 had incorrectly implemented Rayleigh correction, which is applied only over land when the 0.66 μm band is used in cloud optical property retrievals, and only has a minor effect for thin clouds and for all clouds when the solar zenith and/or view zenith angles are large.

QA Array Changes and Enhancements

- **New quality assurance (QA) array assignments.** Many new QA flags were defined (and some previously un-set flags were deleted) in the Quality_Assurance_1km SDS. Most new flags were related to the 1.6/2.1 μm retrieval, multi-layer cloud flag, and new clear-sky restoral. [A newly developed Collection 005 version of the QA Plan detailing all of these changes is available at modis-atmos.gsfc.nasa.gov/_docs/QA_Plan_2005_06.pdf.]

- **QA Implementation.** New software logic was implemented such that future updates to the QA flag array can be more easily integrated. New logic now correctly sets QA confidence flags for Cloud_Water_Path (not set in Collection 004).

- **Set QA confidence flags based on new joint histogram boundaries.** Use a Collection 005 version of QA confidence flag assignments based on cloud optical thickness vs. cloud effective radius retrieval joint histogram. A new QA implementation had been corrected to comply with the updated Collection 005 QA matrix. This change impacts the Level 3 QA-weighted statistics. The cloud optical property retrieval itself is not affected by this change.
  [For detail, see Diagram 6 at end of document.]

New Uncertainty Analysis (New SDSs)

- **Uncertainty analysis.** Estimated cloud optical thickness, cloud effective radius, and cloud water path percent uncertainties were added. New logic, including a non asymptotic solution path, was implemented. Three new SDSs were defined:
  Cloud_Effective_Radius_Uncertainty,
  Cloud_Optical_Thickness_Uncertainty, and
  Cloud_Water_Path_Uncertainty.

- **Uncertainty analysis for 1.6/2.1 μm retrieval.** Estimated percent uncertainties for the supplementary 1.6 /2.1 retrieval were added. Three new SDSs were defined:
  Cloud_Effective_Radius_Uncertainty_1621,
  Cloud_Optical_Thickness_Uncertainty_1621, and
  Cloud_Water_Path_Uncertainty_1621.

New Multi-layer Cloud Detection Algorithm (New SDSs)

- **Multilayer cloud detection.** A new multilayer cloud detection algorithm was implemented. This algorithm determines if a scene (pixel) contains a single layer or multiple layers of clouds. The information is stored in a new SDS named "Cloud_Multi_Layer_Flag". This multilayer cloud information is also combined with the cloud phase information and stored in a new QA flag named *Primary Cloud Retrieval Multilayer Cloud & Phase Flag* stored in the "Quality_Assurance_1km" SDS. [Figure 8 shows an example of this new flag]. [For detail on reading the QA flag noted above, see

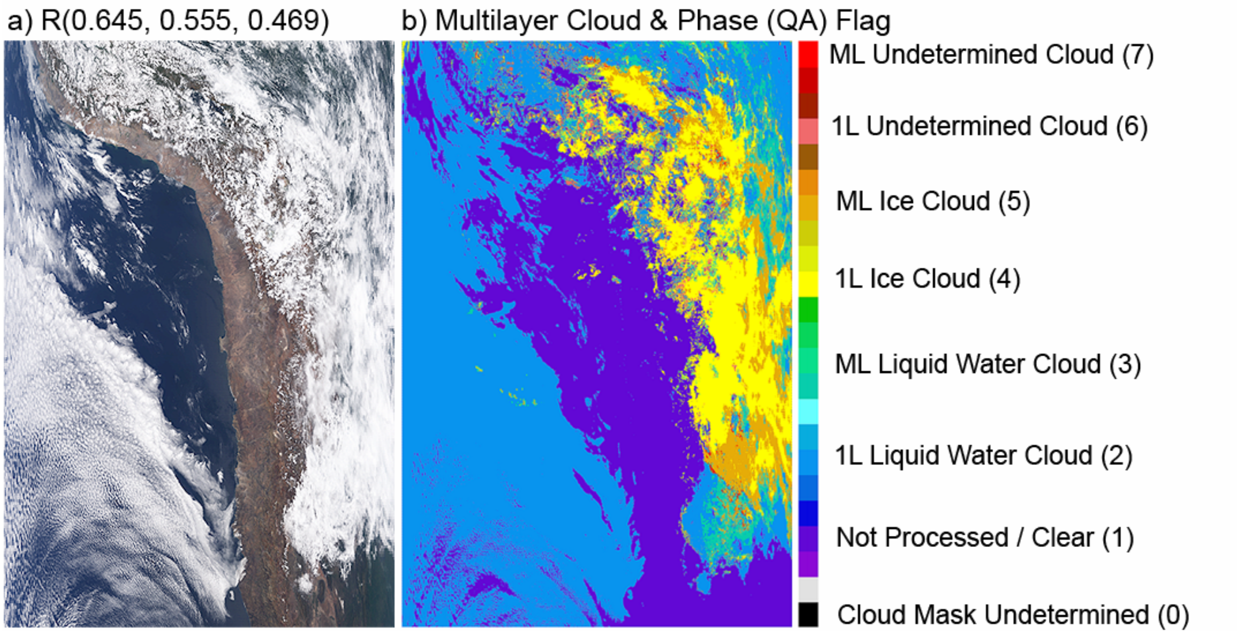


Figure 8. Multilayer cloud detection. Panel (a) is a true color composite of one Terra/MODIS granule off Peru on February 12, 2001 at 15:10 UTC. Panel (b) is the new Collection 005 Multilayer Cloud & Phase Flag that is stored in the Cloud Optical Properties QA Flag array (Quality_Assurance_1km SDS). This flag combines cloud phase determination (predominant phase: liquid water cloud, ice cloud, etc.) with multilayer cloud detection (1L = single layer cloud, ML = multiple layers of clouds).

page 21 of the Collection 005 version of the QA Plan at modis-atmos.gsfc.nasa.gov/_docs/QA_Plan_2005_06.pdf.]

New Stand-alone Cloud Phase SDS

- **A separate SDS for cloud phase was implemented.** A new SDS with (short) name "Cloud_Phase_Optical_Properties" was defined. This new SDS duplicates information previously stored only in one of the QA flags (Primary Cloud Retrieval Phase Flag) in the "Quality_Assurance_1km" SDS. This information was duplicated and separated into a stand-alone SDS to make it more accessible to users. Note that cloud phase information is still available in the QA flag array in Collection 005.

Existing SDS Name Changes

- **Renamed SDSs.** Two SDS name changes were implemented in Collection 005:
  Effecitve_Particle_Radius was changed to Cloud_Effective_Radius and
  Water_Path was changed to Cloud_Water_Path.
  These changes were made to make the content of these data sets more obvious to users.

Inventory Metadata Correction

- **Inventory metadata implementation.** Inventory metadata computation errors were detected and fixed. Inventory Metadata are searchable strings, stored within each HDF file, which can be used to assist users to select granules that meet predetermined criteria. Four percentages are computed for each and every MOD06 granule (HDF file):
  SuccessCloudOptPropRtrPct_VIS *(successful retrievals only)*,
  CloudCoverFractionPct_VIS *(successful & unsuccessful retrievals)*,

WaterCloudDectectedPct_VIS *(successful & unsuccessful retrievals)*, and IceCloudDetectedPct_VIS *(successful & unsuccessful retrievals)*.
[For detail on reading these inventory metadata strings, see Appendix B of the Collection 005 version of the QA Plan at modis-atmos.gsfc.nasa.gov/_docs/QA_Plan_2005_06.pdf.]

Miscellaneous Improvements

- **Correction to NISE usage in coastal zones.** A correction in the usage of the ice and snow maps was implemented. NISE "Coastal Mixed Snow/Ice" flagging is indicative of undetermined snow/ice characteristics in coastal areas.

- **Usable L1B reflectance measurement check.** Added a check on the band-specific values of the L1B reflectance measurement uncertainty index (stored in the L1B HDF file in SDS names: "EV_1KM_RefSB_Uncert_Indexes", "EV_500_Aggr1km_RefSB_Uncert_Indexes", and "EV_250_Aggr1km_RefSB_Uncert_Indexes"). These L1B SDSs are used, in part, to avoid processing failed 1.6 µm (band 6) detectors on the Aqua MODIS instrument, and will also come into play should other band detectors fail during the life of Aqua MODIS and/or Terra MODIS. This uncertainty index has a valid range from 0 to 15. Values of 0 to 14 denote increasing levels of relative uncertainty in the reflectance measurement. An index of 15 denotes an unusable (failed) detector with no specified uncertainty. In the L2 Cloud Optical Properties algorithm (for either Aqua or Terra), a cloud optical and microphysical retrieval (i.e., optical thickness, effective radius, water path) that uses a L1B reflectance measurement having an uncertainty index of 15 is not processed and the corresponding L2 Cloud Optical Property SDS is set to the fill value (-9999).

- **Correct handling of fill value geolocation.** Fill value (missing) geolocation points were being reported as fatal errors in the ancillary module code. This has been addressed. The code now correctly identifies such points and sets ancillary fields to the fill value; subsequent retrievals fail without impacting the granule as a whole

References:

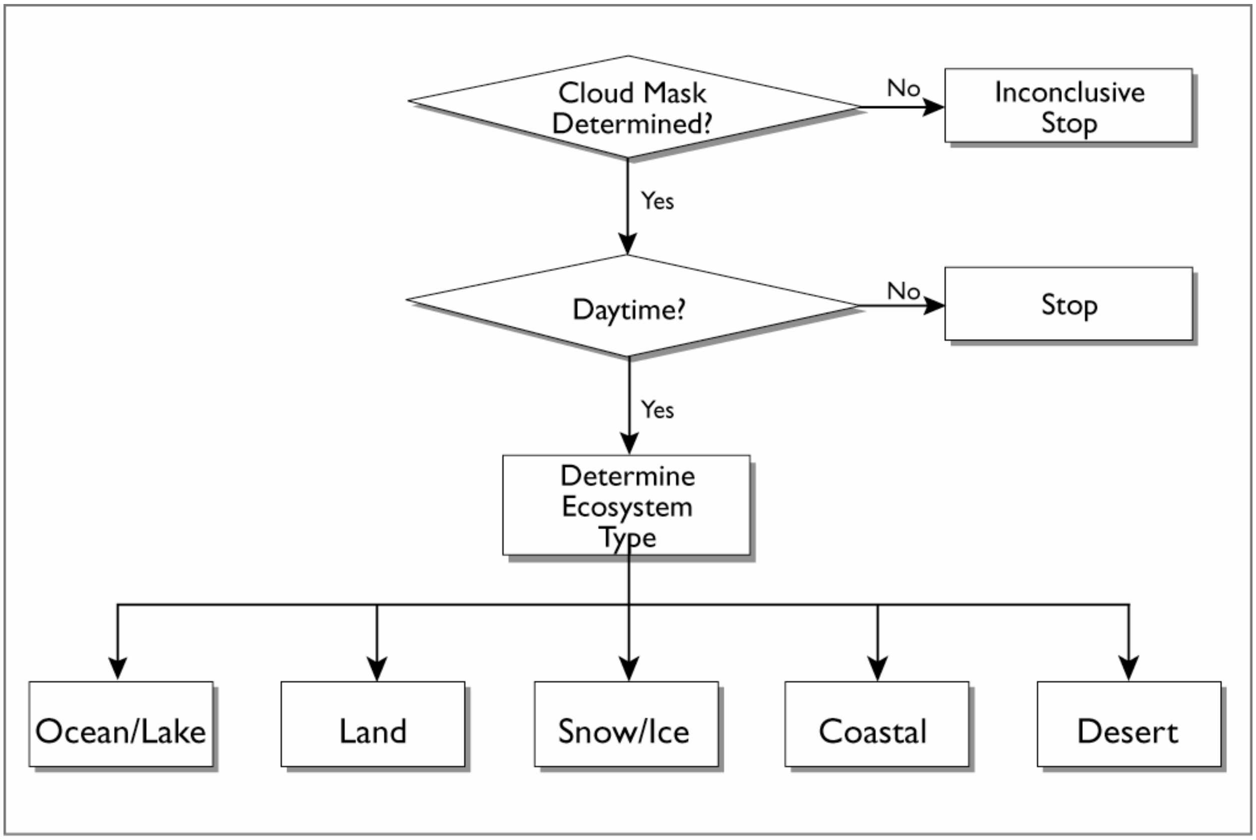
Baum, B. A., P. Yang, A. J. Heymsfield, S. Platnick, M. D. King, Y. X. Hu, and S. M. Thomas, 2005: Bulk scattering properties for the remote sensing of ice clouds. 2: Narrowband models. *J. Appl. Meteor.*, **44**, 1896-1911.

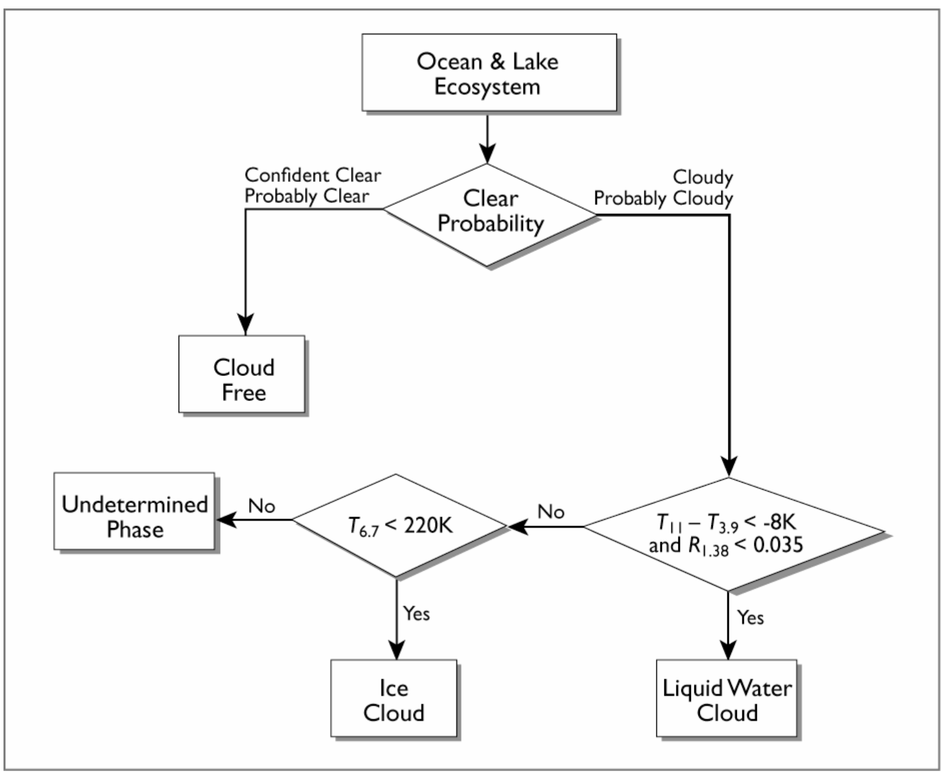
Moody, E. G., M. D. King, S., Platnick, C. B. Schaaf, and F. Gao, 2005: Spatially complete global spectral surface albedos: Value-added datasets derived from Terra MODIS land products. *IEEE Trans. Geosci. Remote Sens.*, **43**, 144-158.

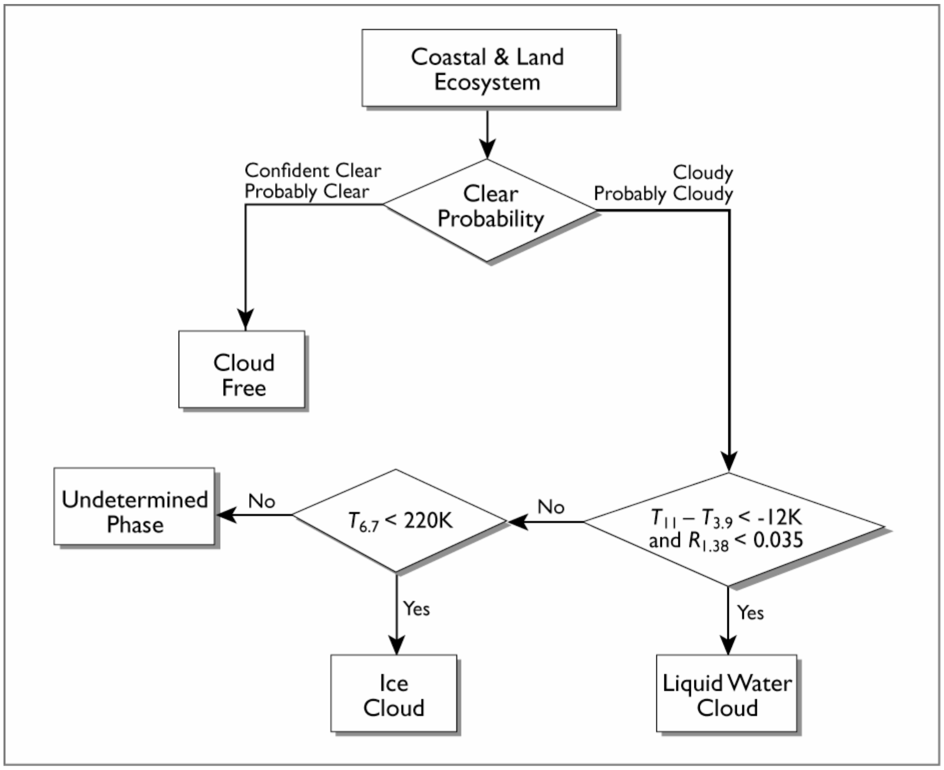
Thaekaekara, M. P., 1974: Extraterrestrial solar spectrum, 3000-6100 A at 1-A intervals. *Appl. Opt.*, **13**, 518-522.

Fontenla spectral irradiance model, private communication.

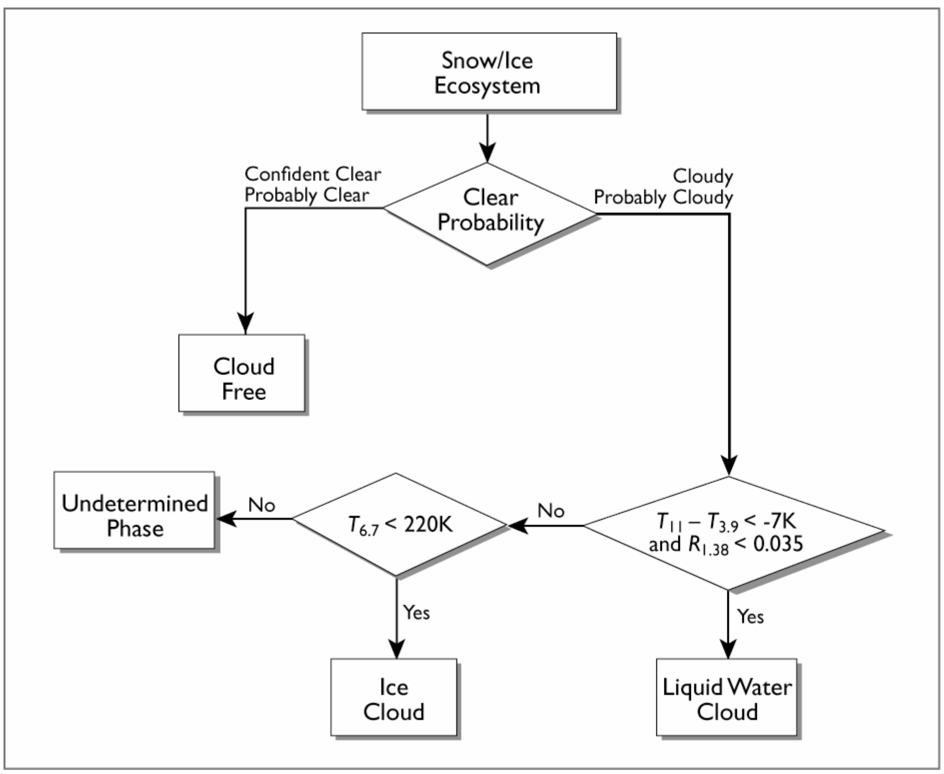
Diagram 1. Cloud Mask Initial Phase Determination Algorithm: Logic Flow Charts







Coastal & Land Ecosystem
Confident Clear
Probably Clear
Clear Probability
Cloudy
Probably Cloudy
Cloud Free
Undetermined Phase
No
$T_{6.7}$ < 220K
No
$T_{11} - T_{3.9}$ < -12K and $R_{1.38}$ < 0.035
Yes
Yes
Ice Cloud
Liquid Water Cloud



Snow/Ice Ecosystem
Confident Clear
Probably Clear
Clear Probability
Cloudy
Probably Cloudy
Cloud Free
Undetermined Phase
No
$T_{6.7}$ < 220K
No
$T_{11} - T_{3.9}$ < -7K and $R_{1.38}$ < 0.035
Yes
Yes
Ice Cloud
Liquid Water Cloud

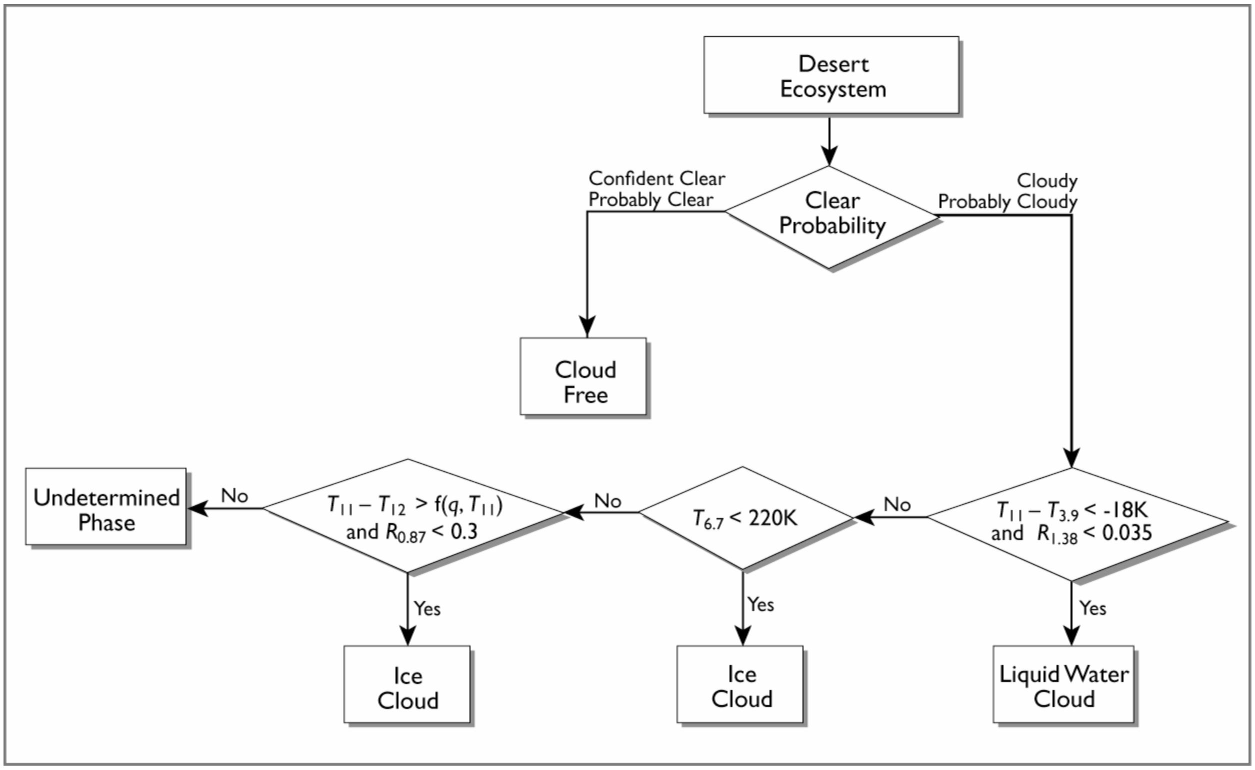
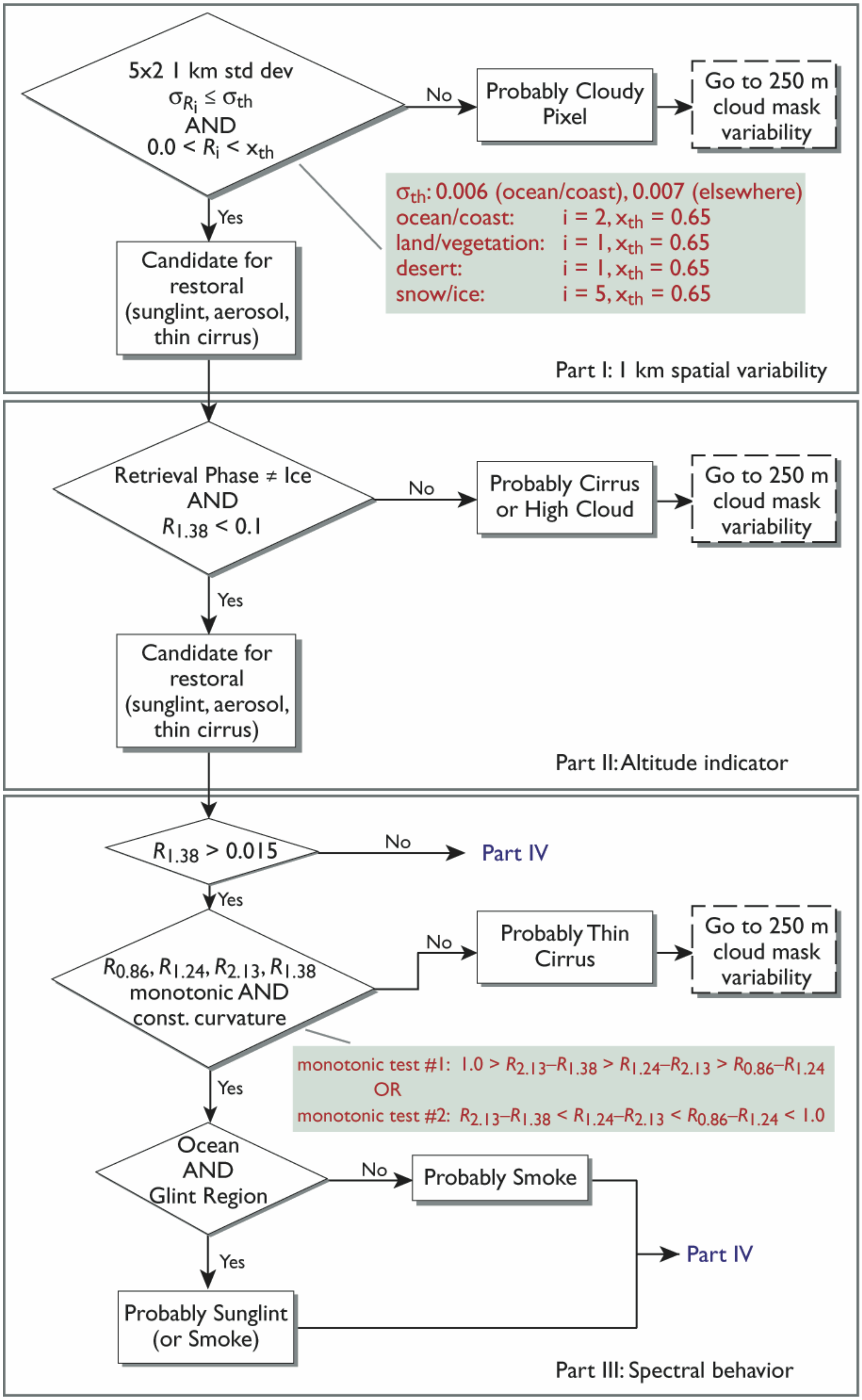
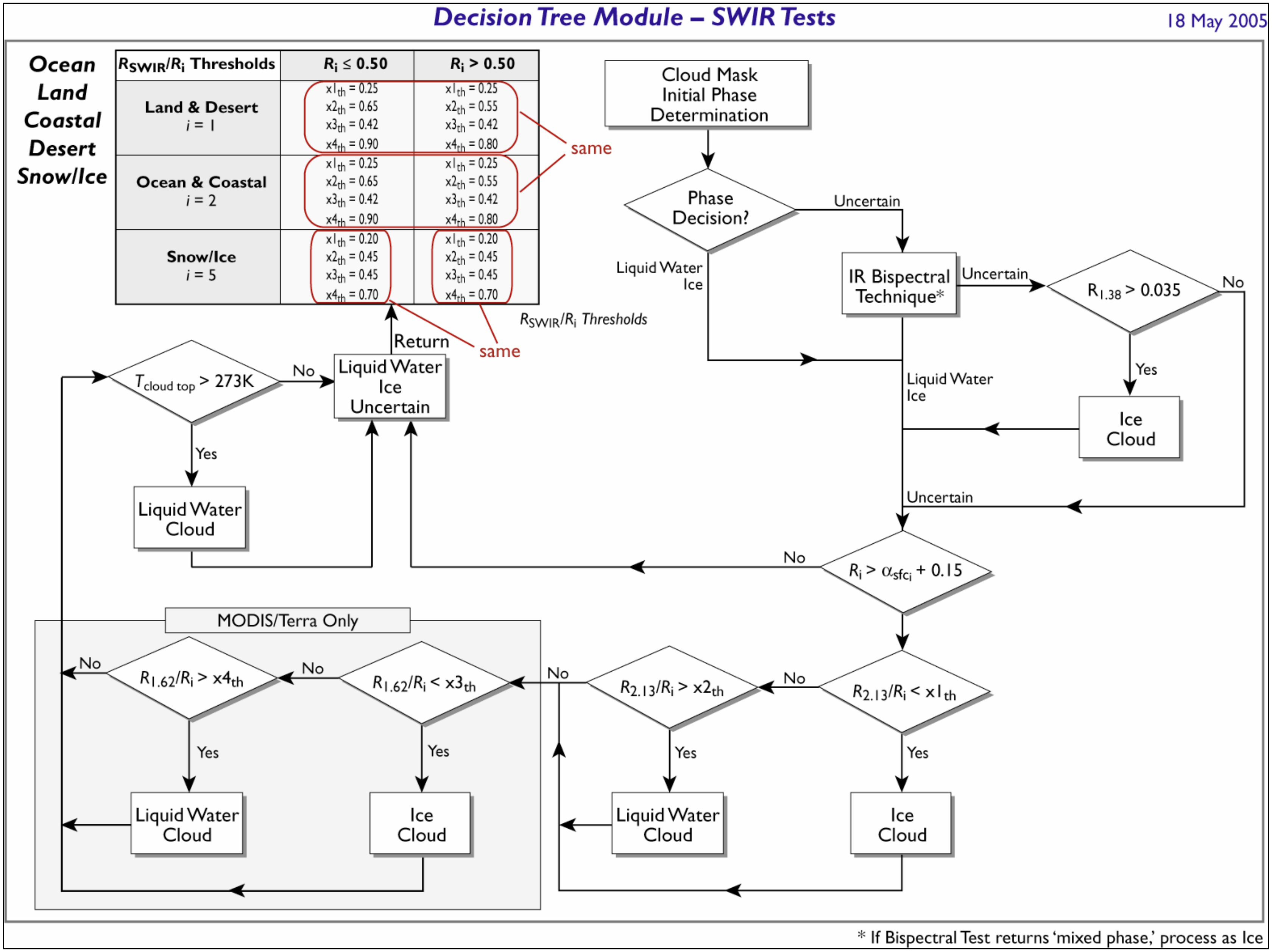

Desert Ecosystem
Clear Probability
Confident Clear
Probably Clear
Cloudy
Probably Cloudy
Cloud Free
$T_{11} - T_{3.9} < -18K$ and $R_{1.38} < 0.035$
Yes
Liquid Water Cloud
No
$T_{6.7} < 220K$
Yes
Ice Cloud
No
$T_{11} - T_{12} > f(q, T_{11})$ and $R_{0.87} < 0.3$
Yes
Ice Cloud
No
Undetermined Phase

Diagram 2. Primary Cloud Retrieval Phase Algorithm: Logic Flow Chart


5x2 1 km std dev
$\sigma_{R_i} \le \sigma_{th}$
AND
$0.0 < R_i < x_{th}$
No
Probably Cloudy Pixel
Go to 250 m cloud mask variability
σ_{th}: 0.006 (ocean/coast), 0.007 (elsewhere)
ocean/coast: $i = 2, x_{th} = 0.65$
land/vegetation: $i = 1, x_{th} = 0.65$
desert: $i = 1, x_{th} = 0.65$
snow/ice: $i = 5, x_{th} = 0.65$
Yes
Candidate for restoral (sunglint, aerosol, thin cirrus)
Part I: 1 km spatial variability
Retrieval Phase ≠ Ice
AND
$R_{1.38} < 0.1$
No
Probably Cirrus or High Cloud
Go to 250 m cloud mask variability
Yes
Candidate for restoral (sunglint, aerosol, thin cirrus)
Part II: Altitude indicator
$R_{1.38} > 0.015$
No
Part IV
Yes
$R_{0.86}, R_{1.24}, R_{2.13}, R_{1.38}$
monotonic AND
const. curvature
No
Probably Thin Cirrus
Go to 250 m cloud mask variability
monotonic test #1: $1.0 > R_{2.13}-R_{1.38} > R_{1.24}-R_{2.13} > R_{0.86}-R_{1.24}$
OR
monotonic test #2: $R_{2.13}-R_{1.38} < R_{1.24}-R_{2.13} < R_{0.86}-R_{1.24} < 1.0$
Yes
Ocean
AND
Glint Region
No
Probably Smoke
Part IV
Yes
Probably Sunglint (or Smoke)
Part III: Spectral behavior



R_{SWIR}/R_i Thresholds	$R_i \leq 0.50$	$R_i > 0.50$
Land & Desert $i = 1$	$x1_{th} = 0.25$ $x2_{th} = 0.65$ $x3_{th} = 0.42$ $x4_{th} = 0.90$	$x1_{th} = 0.25$ $x2_{th} = 0.55$ $x3_{th} = 0.42$ $x4_{th} = 0.80$
Ocean & Coastal $i = 2$	$x1_{th} = 0.25$ $x2_{th} = 0.65$ $x3_{th} = 0.42$ $x4_{th} = 0.90$	$x1_{th} = 0.25$ $x2_{th} = 0.55$ $x3_{th} = 0.42$ $x4_{th} = 0.80$
Snow/Ice $i = 5$	$x1_{th} = 0.20$ $x2_{th} = 0.45$ $x3_{th} = 0.45$ $x4_{th} = 0.70$	$x1_{th} = 0.20$ $x2_{th} = 0.45$ $x3_{th} = 0.45$ $x4_{th} = 0.70$

Diagram 3. IR Bispectral Phase Algorithm: Logic Flow Chart

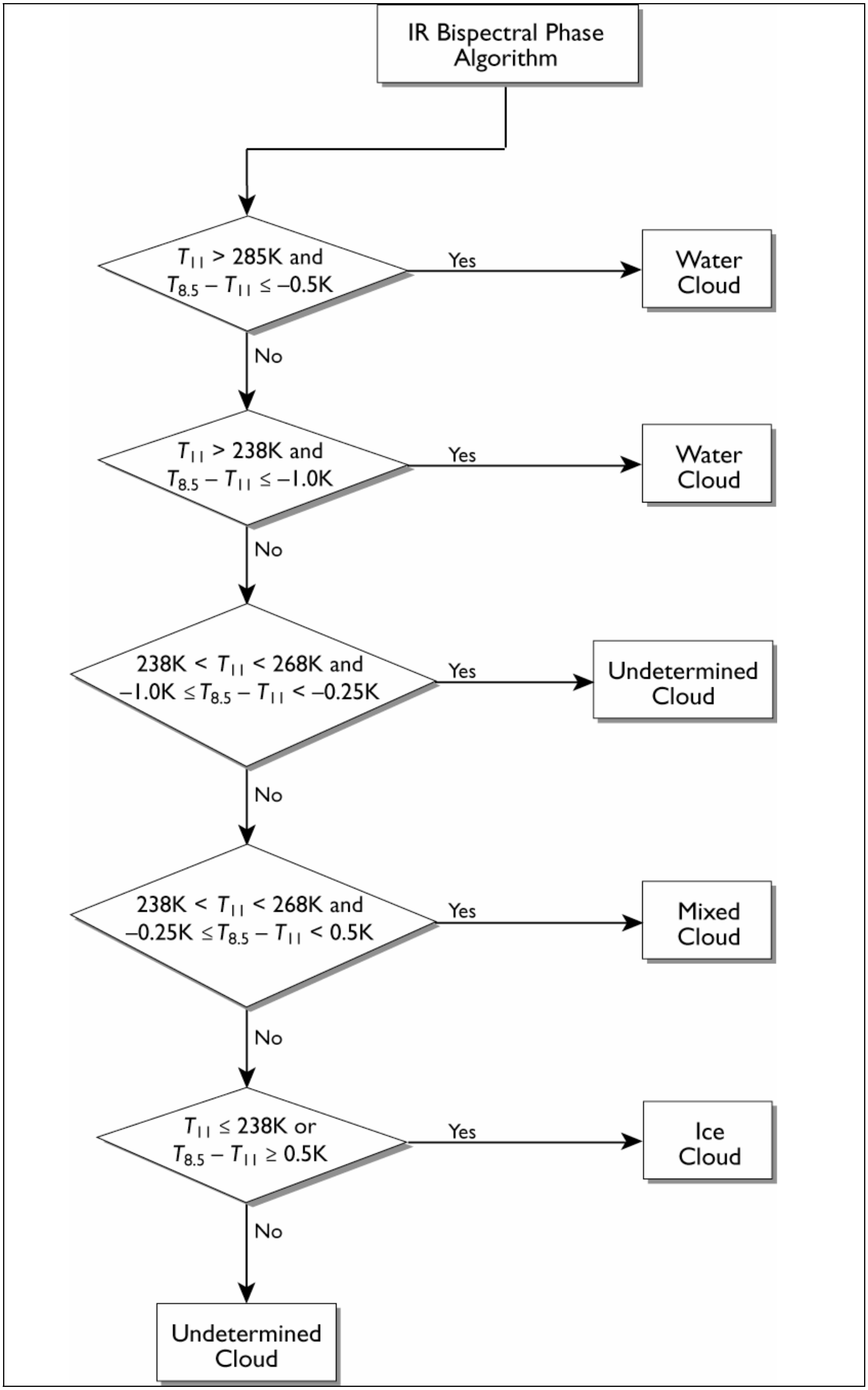


Diagram 4. Clear-Sky Restoral Algorithm (part 1): Logic Flow Chart

Clear-Sky Restoral Module (p. 1)

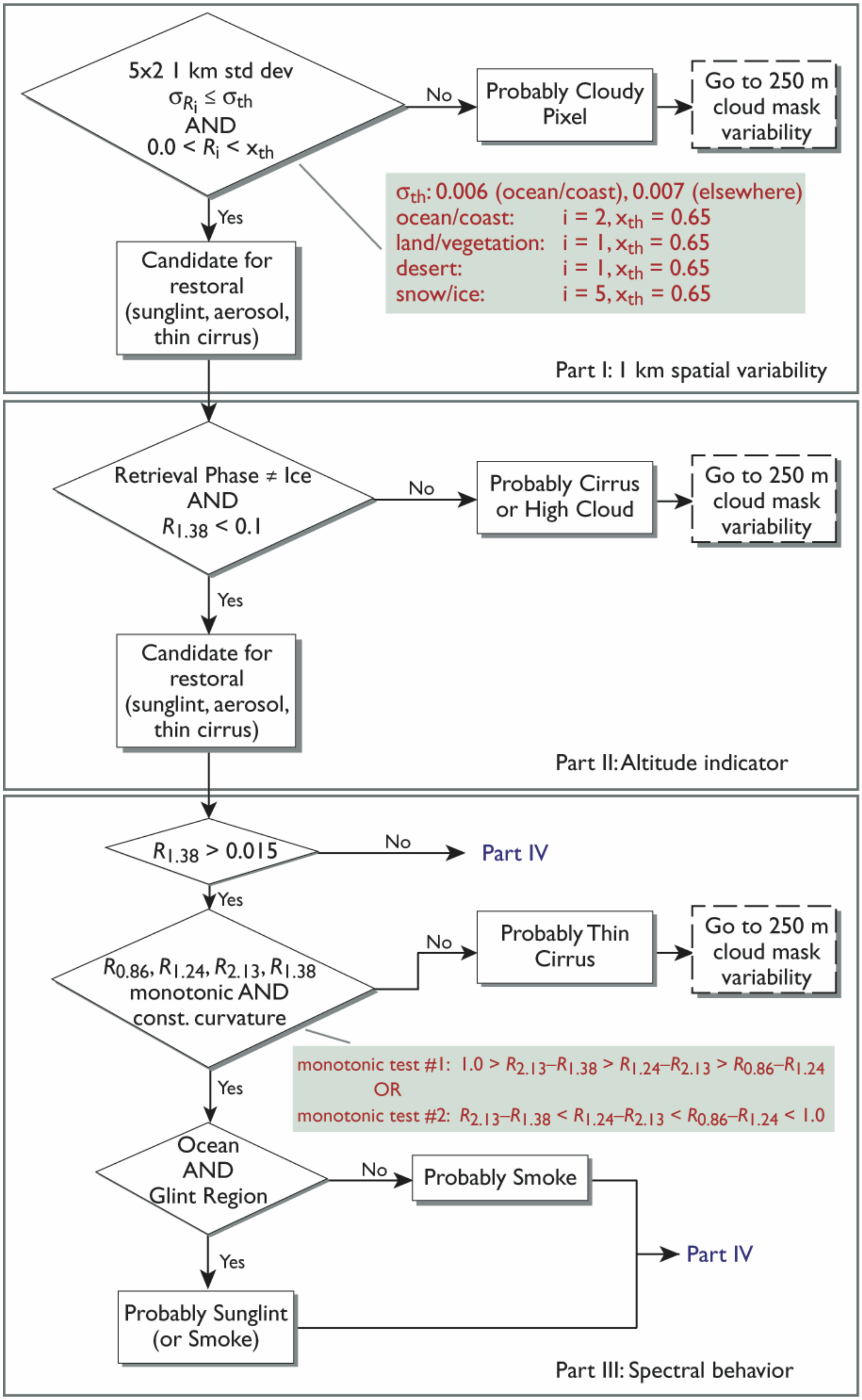


Diagram 5. Clear-Sky Restoral Algorithm (part 2): Logic Flow Chart

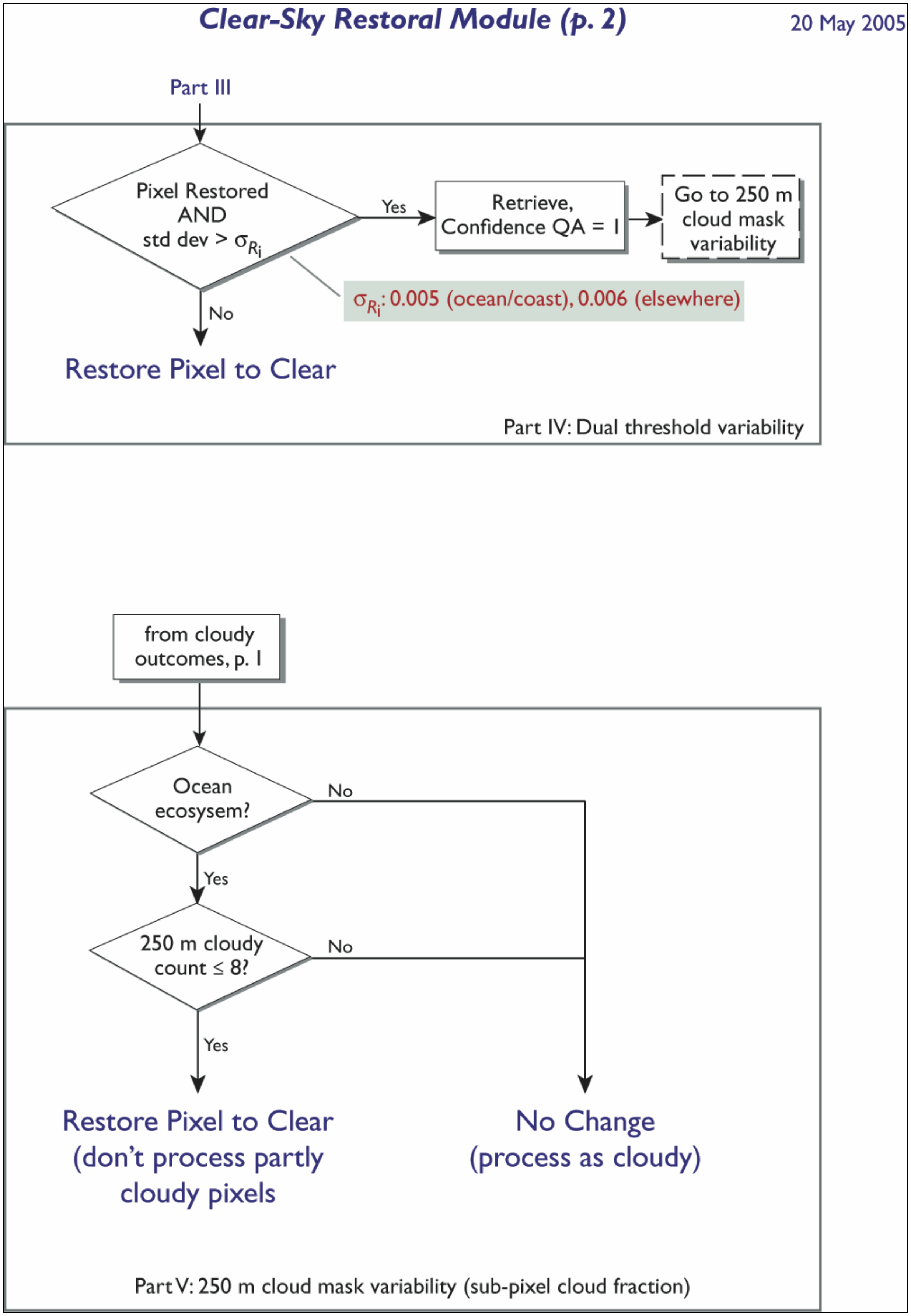


Diagram 6. QA Confidence Flag Assignment Diagrams