CERES Ed4 Cloud Properties

P. Minnis, D. Doelling (calibration), W. L. Smith (offline val)

*NASA Langley Research Center, Hampton, VA, USA*

S. Sun-Mack (QB), Q. Trepte (mask), F-L. Chang (CO2, ML),
T. Chee (web, DM), R. Arduini (RTM), K. Bedka (OT tops),
S. Bedka (SIST), R. Brown (QC), Y. Chen (clr props, test runs),
S. Gibson (graphics), E. Heckert (web, IG), G. Hong (night tau), M.
Khaiyer (val), R. Palikonda (offline testing), R. Smith (web, NPP),
D. Spangenberg (polar), Y. Yi (thickness), C. Yost (phase)

*SSAI, Hampton, VA, USA*

P. W. Heck (retrieval algo)

*CIMSS, U. Wisconsin, Madison, Wi, USA*

P. Yang, Y. Xie (ice cloud models)

*Texas A&M Univ., College Station, TX, USA*

*ERB Workshop, Paris, France, September 13-16, 2010*


Ed2: GEOS-4
Ed4: GEOS-5

CERES Cloud Analysis Framework

Ed2: 1 map/channel
Ed4: snow/snow-free maps available

Ed4: Revised 0.65 & 2.13 µm corrections

Ed2: old empirical ocn model
Ed4: wind-dependent theoretical ocn model

Ed2: nominal calibrations
Ed4: normalized calibrations
Evaluation of Ed3β Cloud Mask
Mean Cloud Amounts from Terra MODIS January 2006

Cloud amounts generally increased at all locations, especially small cumulus.
Cloud Amount

2004, AM + PM, Ocean

A little much in polar night?
Comparison of Monthly Mean Global Cloud Amounts

- CERES Ed2 less than others, ~0.11 less than CALIPSO
  - over land, 0.15 less
- CERES Ed3 > ISCCP, ~0.06 less than CALIPSO, V2
  - over land, 0.10 less
CERES (Ed4) Cloud Mask Changes since Apr 2010 STM

Highlights:

1. Added Terra VIS reflectance adjustment using Aqua VIS as reference
2. Tested adjusted Terra 3.8-μm brightness temperature calibration
3. Reduced false clouds in various areas:
   - Polar night
   - Sun Glint ocean
   - Thin Cirrus
4. Tested impact of replacing GEOS4 MOA with “final” G5 MOA in CERES Ed4 cloud mask
Impact of using “final” G5 MOA in CERES Ed4 cloud mask
Skin Temperature Difference (K), $T(G5) - T(G4)$, 15 Dec 2007

Daytime
Skin Temperature Difference (K), $T(G5) - T(G4)$, 15 Dec 2007
Night
TOA 11 um Clear Sky T - MODIS obs. T11
Terra 20071225 Daytime, strong clear and snow, glint < 50%
TOA 11 um Clear Sky T - MODIS obs. T11
Aqua 20071225 Daytime, strong clear and snow, glint < 50%
TOA 11 um Clear Sky T - MODIS obs. T11
Aqua 20071225 Nighttime, strong clear and snow
Mean Zonal Temperature Difference (K), Night, 15 Dec 2007

Greatest changes over sea ice, minimal changes over most ocean areas.
Cloud Fraction Difference, C(G5) – C(G4)
Dec 15, 2007

Greatest differences over land at night

Greatest differences over ocean at night
Zonal Average Cloud Fraction Differences, Dec 15, 2007

Day

Night

Zonal Average Cloud Fraction Differences, Dec 15, 2007
## Cloud Fraction Difference, C(G5) - C(4), Terra
### Dec 15, 2007

<table>
<thead>
<tr>
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<th>ocean</th>
<th>total</th>
</tr>
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<tr>
<td><strong>Day</strong></td>
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<tr>
<td>Global:</td>
<td>-0.0007</td>
<td>-0.0008</td>
<td>-0.0003</td>
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<tr>
<td>Polar:</td>
<td>0.0001</td>
<td>-0.0135</td>
<td>-0.0041</td>
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<tr>
<td>NonPolar:</td>
<td>-0.0007</td>
<td>-0.0000</td>
<td>-0.0001</td>
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| **Night** |        |        |        |
| Global:   | -0.0204 | -0.0267 | -0.0229 |
| Polar:    | 0.0027  | -0.0061 | -0.0000 |
| NonPolar: | -0.0235 | -0.0291 | -0.0260 |

Introducing GEOS-5 reduces cloud fraction by a noticeable amount at night.
MODIS Correction of V5 Terra and Aqua Normalization to Aqua by Cross-Calibration
0.65 & 3.75 µm
VIS Channel Normalizations

• From earlier study*
  - Aqua 0.65-µm gain = 1.01 * Terra gain
  - After Nov 2003, Aqua gain = 1.027 * Terra gain

• New
  - Aqua gain stable from launch to present
  - After June 2009, Aqua gain = 1.004* Terra gain
  - Terra has 1.3% linear change in response across scan angle
    - corrected in MODIS Collection 6

Normalized Aqua Deep Convective Cloud (DCC) VIS Albedo Trends 2002 - 2010

Red – means
Black – mode values

- DCC mean albedo trend
  \( \sim -0.01\%/\text{year} \)

- DCC mode albedo trend
  \( \sim 0.07\%/\text{year} \)

=> Aqua very stable
Normalized Terra Deep Convective Cloud (DCC) VIS Albedo Trends 2002 - 2010

**Before Nov 2003:**
\[ \text{Gain1} = \text{Gain0} \]

**After:**
\[ \text{Gain1} = \text{Gain0} \times 1.0117 \]

**Before June 2009:**
\[ \text{Gain2} = \text{Gain1} \]

**After:**
\[ \text{Gain2} = \text{Gain1} \times 0.978 \]
Shortwave Infrared (3.8 µm) Channels

Daytime slope

Terra vs Aqua MODIS

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<th>Aqua</th>
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<tr>
<td>MAX</td>
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<td>MIN</td>
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<tr>
<td>RNG</td>
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<tr>
<td>NADIR</td>
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<tr>
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<td>MAX</td>
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<tr>
<td>RNG</td>
<td>30.58</td>
<td>30.80</td>
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Night slope

Terra vs Aqua MODIS

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<tbody>
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<td>215.63</td>
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<td>62.32</td>
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<td>SDV</td>
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<td>11.23</td>
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<tr>
<td>MAX</td>
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<td>MIN</td>
<td>225.13</td>
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<tr>
<td>RNG</td>
<td>38.23</td>
<td>44.79</td>
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- Aqua 0.57 K warmer than Terra during daytime
- Nonlinear difference at night at low temperatures
Spatially Matched Aqua and Terra V5 Data, 5 June 2005

- 10’ averages
- sample every 50 points

New fit to slightly to left of V4 fit from ray-matched data
MODIS V5 3.75 µm BT, Terra vs Aqua, Density Plot
Nighttime, 20070605, all sky
MODIS V5 3.75 µm BT, Terra vs Aqua
After New Correction

20070605  
MODIS V5 3.75 BT, Terra vs Aqua
Nighttime, 20070605, 10 mins map, All sky

20071225  
MODIS V5 3.75 BT, Terra vs Aqua
Nighttime, 20071225, 10 mins map, All sky
Small differences due to viewing angle changes during daytime

Large differences over polar night areas

Cloud Fraction Difference, C(nom) - C(corr)
Terra
Dec 15, 2007
Zonal Average Cloud Fraction Differences, $C(nom) - C(corr)$
Terra 15 Dec 2007

Day

Small daytime decreases over land using correction

Night

large decreases over land & ocean during polar night
Cloud Fraction Difference, C(nom) - C(corr), Terra
Dec 15, 2007

<table>
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<tr>
<th></th>
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<tr>
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<td>Polar</td>
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<td>NonPolar</td>
<td>0.0014</td>
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Night:

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<tbody>
<tr>
<td>Global</td>
<td>0.0133</td>
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<td>Polar</td>
<td>0.0808</td>
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<td>NonPolar</td>
<td>0.0042</td>
<td>0.0093</td>
<td>0.0075</td>
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Introducing 3.7-µm calibration change reduces cloud fraction slightly during daytime, but by a large amount at night over areas where it is too large from Ed3.
Reduce False Clouds in Polar Night
Terra 2007050106R59

Clear Sky Restoral
T6.7 - T11 > 10K
T13.3 - T11 > 3K
Reduce False Clouds in Polar Night

Terra 2007050121R66

Clear Sky Restoral
T6.7 - T11 > 10K
T13.3 - T11 > 3K

Do not get rid of all false clouds!
Comparisons with CALIPSO V3 Cloud Fractions
Cloud Fraction difference (V2-V3), Day

July 2008

Cloud Fraction difference (V2-V3), night
Ceres
July 2008

CALIPSO V3

CERES

Cloud Fraction Difference (CALIPSO V3 – CERES)

Night Time

Global: 0.11 0.14
Polar: 0.12 0.11
NonPolar: 0.11 0.14

July 2008

Ocean

Land
Comparison of Cloud Fraction
CALIPSO Version 3
CERES Ed4 preliminary
July 2008

• Daytime in much better agreement than in past

• Nighttime Ed4 too low
  - likely due to new G5
  - thresholds must be tuned
Cloud Retrievals

- Retrieve $T_c$, phase, $\tau$, $R_e$ from radiances
- Compute LWP or IWP
- Determine $Z_c$ & $p_c$ from $T_c$
- Estimate $Z_t$, $p_t$, $T_t$, $H$ from empirical models

---

Ed2: Thick cloud defaults
Ed4: Thick cloud solutions?

Ed2: $P_c$, $T_c$, $Z_c$, $P_t$, $H$ (old)
Ed4: $P_c$, $T_c$, $Z_c$, $P_t$, $Z_t$, $H$ (new) + ML properties

Ed2: 1.6/2.1 $\mu$m for $\tau$ over snow
Ed4: 1.24 $\mu$m for $\tau$ over snow

Ed2: 3.8 $\mu$m only for Re, smooth hex xtals
Ed4: 3.8 & 2.1 $\mu$m for Re, rough hex xtals

---

Tile cloudy pixels' radiances

Tile clear radiances, layer spectral transmission

$\text{SZA} < 82^\circ$?

Snow/ice surface

apply SIST

apply VISST

apply SINT

cloud optical properties & $T_{eff}$

compute heights & pressures

output: tile with cloudy & clear pixel properties
Effective cloud height/pressure retrieval

- $Z_c$ from $T(Z)$ [$p_c$ from $T(p)$], height (pressure) corresponding to $T_c$ where the temperature profile is $T(Z)$ [$T(p)$].

- For $p < p_h$, $T(Z) = T(Z_{nwa})$

- For $p > 700$ hPa, $T(Z) = T(Z_{lap})$, where

  $$T(Z_{lap}) = T(z + z_o) = T_o - \Gamma^* (z - z_o)$$

  $T_o$ = skin temperature

- For $p_h < p < 700$ hPa,

  $$T(Z) = \{(p - p_h) * T(Z_{lap}) + (700 - p) * T(Z_{nwa})\} / (700 - p_h)$$

- For $E_d^2$, $p_h = 500$ hPa, $\Gamma = 7.1$ K km$^{-1}$

- For $E_d^4$, $p_h = 600$ hPa, $\Gamma$ is regionally & seasonally dependent
Cloud Height Changes

• Regionally and seasonally dependent lapse rate for low clouds
  - year of Aqua & CALIPSO data analyzed
  - see Sun-Mack talk for more detail

• Overshooting convective cloud heights included in output
  - overshooting tops identified
  - lapse rate used to take top higher
  - tropopause height no longer cap on CERES cloud tops

• Changes in CO2 retrievals
  - Chang talk
Lapse Rate, Land (Snow Free) Day Time

- Spring (Mar, Apr, May)
- Summer (Jun, Jul, Aug)
- Fall (Sep, Oct, Nov)
- Winter (Dec, Jan, Feb)
Histogram of Cloud Top Height Difference  
December 2007, Day Time, Ocean (Snow Free)

**Ed3 B2:**
Mean Diff = -0.0514 km  
Stand. Deviation = 0.562 km

**Ed3:**  
Mean Diff = 0.0520 km  
Stand. Deviation = 0.549 km
Thick Ice Cloud Top Height Changes

- Ice cloud $T_t = T_c - T(\varepsilon)$, little change for $\varepsilon > 0.99$
- $T_t$ and $T_c$ are different thick ice clouds; not much difference for water

Cloud-top vs effective height April 2007 CERES MODIS & CALIPSO

Empirical corrections included in Ed4 for $\tau > 10$, ice only

Using Objective Overshooting Top Detections To Improve CERES Convective Cloud Top Height

- Height adjustment in overshooting top (OT) regions integrated into CERES Ed3 cloud algorithms
  - OT algorithm utilizes gradients in 11-µm channel temperatures for detection (Bedka et al., *JCAM*, 2010)
  - OT algorithm validated using 1.5 yrs of CloudSat OT observations: POD=75%  FAR: 16%

- Example below shows new height adjustment to $Z_c$ better matches CloudSat heights
  - Additional 0.5-km increase will be applied to estimate $Z_t$
Improvements in Cloud Thickness Parameterizations

- Ed4 using CALIPSO/CloudSat-based thickness parameterizations
Ice Clouds over Ocean Tropical (20N-20S)

Bias reduced from 2.36km to 0.13km
rms reduced 1.42km
Water Clouds over Ocean Mid Lat (50-20 N/S)

Bias reduced from 0.9 to 0.04km
rms reduced 0.4km
Water Clouds over Land
Tropical (20N-20S)

Bias reduced from 1.7 to 0.5 km
rms reduced by 0.7 km
Cloud Thickness Summary

• New parameterizations for Ed4 dramatically decrease thickness biases found in Ed2 results

• Parameterization based on single-layer clouds
  - can be applied *post facto* to multilayered clouds

• Additional improvements possible
  - reduce rms by modeling as function of cloud type
  - not until Ed5
SIST / BSM Cloud Phase

Without BTD fits (original data)

With BTD fits

• Applied fits to Ice/Water and Ice/NoRtrvl cases for nighttime pixels over ocean

• More (supercooled) water cloud, less ice cloud, over ocean using fits to guide phase selection process; more realistic distributions
Nocturnal Phase Classification Summary

• Diurnal difference in ice cloud percentage reduced
  - remainder may be due to overlapped clouds

• Final testing this week
New Roughened Surface Ice Crystal Models for Ice Cloud Retrievals

• Goal: Use a simple ice crystal model that minimizes angular dependencies and still yields IWP values comparable to those of Ed2.

• Ed2: uses smooth hexagonal columns
  Ed4: use smooth, rough, or bubbled hexagonal columns

• Test models using MODIS & MISR data (similar to POLDER approach)
  - Xie et al., TGRS, 2010, to be submitted
  - Rough model yields lowest variation of tau with scattering angle

• Ed4 will use rough models for 0.65, 1.24, 1.61, and 3.8 µm
  smooth models for infrared channels
Ice Clouds

- Ice cloud model uses smooth hexagonal column distributions to retrieve ice cloud properties (black curve)

- Roughened crystals yield smoother phase functions, smaller asymmetry factors, \( g \)

from Yang et al. (2008, TGRS)
Reflectance fields for smooth & roughened ice hexagonal columns

Change in reflectance depends on De and $\tau$

- Rough ($\sigma = 0.5$) – smooth 0.65-$\mu$m reflectance differences for hexagonal column distributions are positive at many angles, but not all. Greater changes realized for $\sigma = 0.5$
- Positive change indicates decrease in tau for rough model.
Scattering Phase Functions for Various Hexagonal Plate & Column Habit Configurations for Distributions Yielding De = 50 µm

- Homogeneous plate (HP) or Column (HC), smooth, no bubble
- Rough (RP or RC), $\sigma = 1.0$, no bubble
- Inhomogeneous (IP or IC), $C_{\text{bubble}} = 0.5$, smooth
Bidirectional Reflectances for Various Hexagonal Plate & Column Habit Configurations for Distributions Yielding $D_e = 50 \, \mu m$

$\theta_0=30^\circ$, $D_e=50 \, \mu m$, and $\lambda=0.866 \, \mu m$
• Retrieve tau using all 9 MISR views with a given Habit
• Find De from MODIS yielding minimum error in all 9 views
Ice cloud models and standard deviations of cloud optical thickness for MODIS and MISR granules for 5-minute intervals
2 July 2009 and 19 February 2010

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<th>$\varepsilon$</th>
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<td>HP</td>
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<table>
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<th>$\varepsilon$</th>
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<td>IP</td>
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- RC yields best average std dev = 0.173
- IP second with std dev = 0.204
Normalized Density of Ice Cloud Tau Differences for Various Habit Configurations for Terra/MISR Data, 2 July 2009

- RC yields best average std dev = 0.368
Ice cloud models and standard deviations of cloud optical thickness for MODIS and MISR granules for 2 July 2009

MX are habit mixtures of various proportions

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<th>Ice cloud model</th>
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<th>C_{RC}</th>
<th>C_{IC}</th>
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<td>0.2528</td>
<td>0.2243</td>
<td>0.40737</td>
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- M3 yields best average std dev = 0.365
- RC not much worse, std dev = 0.368

*Xie et al., 2010 submitted*
Impact of Rough Ice Crystal Model on τ Retrieval, Aqua MODIS, 15 July 06, 15 UTC

\[ \sigma = 1.0 \]

- Scan angle changes from > 90° to < 90° near center of image going right to left
- τ decreases on right side & increases on left, except near edges of cloud
Impact of Using Rough Ice Crystal Model on $\tau$ Retrieval, GOES-12 over ARM SGP

9 March 2004

- Roughened crystal, $\sigma = 1.0$, yields better agreement for these cases
- $\tau$ decreases in afternoon, not morning

13 March 2004

- $Z_e$ is steady or increases (not shown)

Original results from Min et al. (2004, JGR)
Retrieval of Properties over Snow

• For optical depth, Ed2 used 1.6 μm for Terra & 2.1 μm for Aqua
  - $\tau(2.1) < \tau(1.6)$ because of coding error and 2.13-μm limits

• 2.13-μm channel only good for small optical depth clouds

• 1.24-μm channel will be used for Ed4
  - used by MODIS Atmosphere Team (e.g., MOD06)?

• Requires good estimates of background albedos
  - need both snow-covered & snow-free monthly albedo maps
Diffuse Cloud Albedos from Adding-Doubling Computations

2.13-µm
- water limit: $\tau = 16$
- ice: $\tau < 8$

1.6 µm
- ice limit: $\tau = 16$

1.24 µm
- ice limit: $\tau > 32$

1.24 µm channel has more promise for getting most of full range of $\tau$
- MODIS team using 1.24 µm over snow
Snow-free or Permanent Snow

- snow albedos nearly equal to or slightly greater than snow-free albedos

Clear-sky Overhead-Sun, 1.24-µm Albedo
April 2007

Snow Covered
Final Clear Sky Snow Cover Overhead Sun 1.24 -µm Albedo Maps
Retrieval Clouds over Snow Summary

- 2.13-μm channel only good for small optical depth clouds
- Observations confirm 1.24-μm channel as the best option
- Requires good estimates of background albedos
  - use both snow-covered & snow-free albedo maps
  - monthly dependent
- Final implementation testing ongoing
  - complete retrieval code
Cloud Particle Size

- new definition for particle size, \( R_e = D_{eg}/2 = f(D_e)/2 \)
  \[ R_e = (7.918 \times 10^{-9}D_e \times D_e + 1.0013 \times 10^{-3}D_e + 0.4441) \times D_e \]

- 2.1-\(\mu\)m particle sizes being retrieved now along with 3.8-\(\mu\)m Re
Modified CO2 Absorption Technique (MCO2) Cloud Heights

- MCAT simultaneously solves for cloud and background (cloud or surface) radiating temperatures & pressures using 10.8 and 13.3 µm channels
  - Chang et al., JGR, 2010a,b

- CERES multilayer algorithm uses VISST/SIST to estimate tau & MCAT to estimate emissivity
  - if tau too large to explain emissivity, ML ID applied
  - various levels of confidence result

- If ML ID positive, properties for both low and high clouds are retrieved

- Final tuning performed for Ed4
  - full explanation in Chang talk
Illustration of Terra MCAT Retrievals, 15 Aug 2007
Illustration of Aqua MCAT Retrievals, 15 Aug 2007
Ed3 Cloud Properties on SSF

- All Ed2 parameters
- SSF-79, 79a: CWG Tskin, CWG PW
- SSF-94a, b: Cloud top temperature, height
- SSF 102a: Mean cloud base temperature
- SSF 108-110: re(1.6), Re(1.6), log[tau(1.6)]
- SSF 110a-c: re(2.1), Re(2.1), log[tau(2.1)]
- SSF 111: CO2 layer coverage
- SSF 111a-c: emissivity, pc, Tc for CO2
- SSF 112: CO2 Zc
- SSF 114a-l: multilayer, single-layer properties (n x 4)
  - coverage, OD, log(OD), emissivity, pt, Tt, Zt
  - Rere(3.7), re(3.7), Re(3.7)
  - Rere(2.1), re(2.1), Re(2.1)
New Product, ISCCP Simulator

200708 Terra, CERES ISCCP Cloud Fraction, Day Time, ICE Clouds (Ed3-Beta2)

200708 ISCCP Global Averaging of CloudFrac

ICE Clouds Over Land

<table>
<thead>
<tr>
<th>Pressure (mb)</th>
<th>90S–90N</th>
<th>[ 100% ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–440</td>
<td>0.057</td>
<td>0.024</td>
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<tr>
<td></td>
<td>Cirrus</td>
<td>Deep Convective</td>
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<tr>
<td>440–680</td>
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<td>Alto–Cumulus</td>
<td>Alto–Stratus</td>
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<td>1000–880</td>
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<td>Cumulus</td>
<td>Stratus</td>
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</tbody>
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OptDepth: O.0–3.0  3.0–23  23–380
GLOBAL Cloudy PIXELS: 399043297
GLOBAL Clear PIXELS: 321342912

ICE Clouds Over Ocean

<table>
<thead>
<tr>
<th>Pressure (mb)</th>
<th>90S–90N</th>
<th>[ 100% ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–440</td>
<td>0.091</td>
<td>0.028</td>
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<td></td>
<td>Cirrus</td>
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<tr>
<td>440–680</td>
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<tr>
<td></td>
<td>Alto–Cumulus</td>
<td>Alto–Stratus</td>
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<tr>
<td>1000–880</td>
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<td></td>
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<td>Stratus</td>
</tr>
</tbody>
</table>

OptDepth: O.0–3.0  3.0–23  23–380
GLOBAL Cloudy PIXELS: 251341024
GLOBAL Clear PIXELS: 701059056

color: cloud fraction
number: frequency
New Display Interface and Parameters

Terra Satellite Imagery

Make your selections below. If an option is greyed out that means that combination is not possible with the selections already made. You must select Date first.

QC Param | Select Date | Select Zone | Select Parameter | Select Phase | Select Time of Day | Select Scene
--- | --- | --- | --- | --- | --- | ---
VISST | Select One | MultiLat | Select One | Ice | Select One | Ocean
VISST_Hist | 200401 | | CloudFrac | Day | |
CO2 | 200601 | | Emissivity | Night |
MultiLayer | 200410 | | WaterPath | |
ISCCP | 200407 | | EffTemp | |
ISCCP_chart | 200404 | | TopTemp | |

Water OD

Ice OD
Wrap-up Work for Final Ed4

• 0.64-µm Terra-Aqua differences: which is reference channel? Aqua
• Mask: test impact of 3.8 (night polar) & 0.64-µm (tau increase) calib changes
  impact of final GEOS-5? decreases nocturnal clouds, tuning needed
• Cloud phase
  - finalize nocturnal BSM/TSM algorithm & test; testing now
  - tweak daytime phase selection to properly detect altocumulus liquid
• Rough models? Final testing; rough selected, global tests this week
• Using CO2: do not apply cloud-top height correction for thin cirrus? No change
• Cloud-top heights
  - test for potential ML clouds first to prevent overcorrecting No change
  - test seasonal lapse rates, Reduces std dev (Sun-Mack talk)
• ML algorithm see Chang talk
  - use only two most certain categories? Decide when to perform retrieval
  - use only over non-snow sfcs?
• 2.13-µm saturation & models
  - test 1.24-µm retrievals over snow; clr albedos defined, testing this week
  - test 2.1-µm ice cloud Re retrievals, using Yang models

Bottom line: final testing underway for next 3 weeks