Extending The CERES Cloud Climate Record Using MODIS and AVHRR Data

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Collaborators

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**Background**

- **Satellite cloud climatologies vary with sensor and algorithm**
  - ISCCP uses multiple LEO/GEO satellites & a VIS-IR method (Rossow et al.)
  - PATMOS-X uses AVHRR with a 4-channel technique (Heidinger et al.)
  - MODIS team uses MODIS with >10 channel method (King et al.)
  - CERES team uses MODIS with 4 and 12 channel technique (Minnis et al.)
  - Different NWP-based input atmosphere analyses (NCEP/NCAR, MERRA, MOA)
  - Different treatment of surface albedos & emissivities, & calibrations
  - Treatment of pixels (e.g., in blocks or individually)

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**Cloud Amount**

<table>
<thead>
<tr>
<th></th>
<th>total</th>
<th>high</th>
<th>mid</th>
<th>low</th>
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<tbody>
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<td>0.4</td>
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<tr>
<td>CAMR</td>
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</tr>
<tr>
<td>CALR</td>
<td></td>
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</table>

**Cloud Temperature (K)**

<table>
<thead>
<tr>
<th></th>
<th>total</th>
<th>high</th>
<th>mid</th>
<th>low</th>
</tr>
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<tr>
<td>CTL</td>
<td></td>
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</tbody>
</table>

GEWEX Cloud Assessment, Stubenrauch et al., 2011
Motivation

• Different approaches yield different answers that tend to reflect the uncertainties in the cloud record

  => How accurate are the trends? Are they independent of approach?

    - *The more techniques we use, the better we understand the uncertainties as long the methods are reasonable. We can use these uncertainties to constrain climate models*

• CERES is developing a climate data record (CDR) of clouds and radiation fluxes

  - 2000 (Terra), 2002 (Aqua), 2011 (S-NPP) ➔ 2016 (JPSS) ➔ 20??
  - CERES cloud algorithm differs from the MODIS Science Team algorithm
    - *Reasonable, relatively well validated & understood*
    - *Results constitute a cloud CDR*

• Can we extend that cloud CDR back in time?

  - AVHRR has the core channels used by the CERES cloud algorithms

• GOAL: Develop a cloud CDR from AVHRR data for NOAA NCDC that is consistent (as possible) with CERES, yet extends from ~1980 to the present

  - Extend CERES clouds back in time using an adaptation of CERES algorithm
  - ERBE has collected broadband radiation measurements from 1984-2003
    - *Make a CERES-like radiation product (led by S. Kato) using AVHRR clouds for NOAA NCDC and NASA MEaSUREs*
CDR Project Outline

- **Goals**
  - Calibrate AVHRR 0.64, 0.87, and 1.6-µm channels
  - Calibrate GOES & SMS imager 0.65-µm channels
  - Generate CERES-like cloud climatology from AVHRR record

- **Source Data**
  - AVHRR 1, 2, & 3: 1978 – present
  - SMS-1 & 2; GOES-1 thru present
  - SCHIAMACHY hyperspectral data (2004-2009)

- **Deliverables**
  - Calibrated 0.64, 0.86, and 1.6-µm radiances (calib. coefficients)
  - Cloud temperature, height, optical depth, effective particle size, water path, phase; surface skin temperature, spectral albedo

- **Essential Climate Variables addressed**
  - Cloud properties, radiation budget

- **Current/Expected User Communities:**
  - GEWEX, GCM community, energy, aviation, (re-)insurance
Calibration Methodology Description

- **3 Calibration Methods, all independently referenced to Aqua-MODIS**
  1) **Ray-matched coincident GEO counts and MODIS radiances** averaged over a 0.5°x0.5° ocean grid near the sub-satellite point (±15° lat by ±20° lon area)
  2) **Deep Convective Cloud Technique** (DCC; Doelling et al. 2013)
  3) **Invariant-site Approach** (Libya-4, Dome-C, etc.; Bhatt et al. 2012)
    - SCIAMACHY hyperspectral sensor used to account for spectral band differences for the visible channels (Doelling et al. 2013)
    - IASI hyperspectral sensor to be used to account for spectral band differences for the IR channels

- **Calibration of GEO sensors using the three methods above**
  - Use GEO-provided space count offset
  - Perform monthly calibration transfers to derive monthly gains
  - Compute timeline trend from monthly gains

- **Calibration of NOAA AVHRR sensors**
  - **During MODIS timeframe**
    - Simultaneous nadir overpass (SNO) comparisons with MODIS establish standard gain trend
    - Invariant-site and DCC techniques validated by SNO method during AVHRR-MODIS overlap period.
  - **Prior to MODIS,** use combination of invariant-site and DCC techniques referenced to Aqua-MODIS to determine AVHRR gain trend
GEO and AVHRR Calibration Examples

Meteosat-9 Calibration

GOES-12 Calibration

NOAA-16 AVHRR 0.65 micron Calibration

NOAA-9 AVHRR 0.86 micron Calibration
NASA LaRC AVHRR Cloud and Clear-Sky Radiation Property Climate Data Record: Production Approach

- Re-navigate, calibrate, and noise filter (pre-NOAA-15 3.7 μm channel) AVHRR observations

- Adapt CERES Ed4 mask to AVHRR (0.65, 0.86, 3.7, 11, 12 μm @ ~4 km)
  - Test & tune mask using MODIS (1 km)
    - CERES Ed4 uses AVHRR channels + 1.38, 2.1, 8.5, 13.3 μm
  - Apply to NOAA-18, compare with Aqua MODIS, CALIPSO, MODIS-ST, PATMOS-X
    - Test and tune using scenes across diverse regions, surface types, and seasons
    - Make changes as necessary, up to 1-hour time difference between A-Train & N18
  - Apply to AVHRR back to TIROS-N (1978-2010)
    - TIROS-N, NOAA-6, -8, and -10 will be processed later due to lack of 12 μm channel
    - Need method for cloud detection/retrieval when 1.6 μm replaces 3.7 μm (N-15/17)

- Adapt CERES Ed4 Cloud Property Retrieval System to AVHRR
  - Adapt algorithm to limited AVHRR channels
  - Apply to AVHRR back to TIROS-N (1978-2010), compare with PATMOS-X and ISCCP
NASA LaRC AVHRR Cloud and Clear-Sky Radiation Property Climate Data Record: Ancillary Inputs

- NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) 3-D thermodynamic and ozone profiles at 42 vertical levels with surface fields and snow/ice cover maps at a 0.5 x 0.66° spatial resolution. MERRA data quite comparable to GEOS-5

- 10-minute spatial resolution land surface elevation, land and water maps, IGBP ecosystem, and surface emissivity from CERES MODIS framework

- Dynamically generated clear sky overhead albedo maps based on CERES Ed4 logic and clear-sky AVHRR observations

- Cloud microphysical models for spherical water droplets and roughened ice crystals

- Directional and bi-directional reflectance models for IGBP land surface types and ice- or snow-covered surfaces
AVHRR 3.7 µm BT are “binned” with increasing bin separation at colder temperatures.

CERES cloud detection (and retrievals) utilize 3.7 µm information, thus we attempt to minimize errant/noisy results over extremely cold polar scenes using a conservative cloud mask.
AVHRR Data Challenges: Navigation Error

- Navigation error of > 100 km can be present within AVHRR data due to issues such as insufficient knowledge of satellite image acquisition times and satellite attitude angles, in addition to limited accuracy of orbit modeling.

- Global database of ground control points used to correct navigation to within 1/3 of an AVHRR Global Area Coverage FOV (1-2 km).
AVHRR Product Examples: 3-Channel False Color Composite
AVHRR Product Examples: Cloud Mask

Cloud Mask Category 2008275 S1812 E2007 UTC
AVHRR Product Examples: Effective Cloud Temperature

Cloud Effective Temperature 2008275 S1812 E2007 UTC

TEFF (degrees_Kelvin)
AVHRR Product Examples: Cloud Phase

Cloud Phase 2008275 S1812 E2007 UTC

Legend:
- WATER >273 K
- WATER < 273 K
- LQ CLD WEAK
- ICE
- ICE CLD WEAK
- CLEAR
- NO CLD RETRIVAL
- BAD RETRIVAL
- SNOW/ICE

PHASE (count)
AVHRR Product Examples: Cloud Optical Depth
AVHRR Product Examples: Cloud Base Pressure

Cloud Base Pressure 2008275 S1812 E2007 UTC

PBOT (hPa)
AVHRR Product Examples: Water Droplet Effective Radius

Effective Water Radius 2008275 S1812 E2007 UTC

REFF (microns)
AVHRR Product Examples: Ice Water Path
Objective Overshooting Convective Cloud Top (OT) Detection

• A method to objectively detect overshooting convective cloud tops using IR imagery was initiated within the NASA Applied Sciences program for aviation safety applications and was completed by the GOES-R ABI Algorithm Working Group (Bedka et al. 2010-2012)

• This objective OT detection algorithm utilizes IR BT and spatial gradient thresholding with NWP tropopause temperature information to identify OTs at their characteristic spatial scale

• OT detection output is used within the CERES Ed4 and LaRC AVHRR frameworks to elevate cloud top heights above the tropopause based on difference between 11 µm BT and tropopause temp, using 8 K/km lapse rate derived from CloudSat and MODIS OT observations

White: Region meets OT detection criteria

Black: Region not cold enough relative to surrounding anvil
Objective Overshooting Convective Cloud Top Detection: NOAA-18 over The Congo
OT detections will be produced for all AVHRR observations from 1978-2010 within a Cloud Property Climate Data Record being developed at NASA LaRC.
NOAA AVHRR Global Gridded Overshooting Top Detections
0100-0300 AM/PM Local Time, 17 Years of Orbits

OT detections will be produced for all AVHRR observations from 1978-2010 within a Cloud Property Climate Data Record being developed at NASA LaRC.

NOTE
RESULTS NOT YET FILTERED BY ATMOSPHERIC STABILITY TO REMOVE DETECTIONS IN ENVIRONMENTS NOT SUPPORTIVE OF CONVECTION

Diurnal Cycle of GOES & SEVIRI OT Activity
Time Periods Shown in Animation

Equatorial Crossing Time of NOAA Polar Satellites

Updated on 03/10/2013 08:46
Global Cloud Fraction: October 2008, Day+Night

- **LaRC NOAA-18**
- **CERES Edition 4**
- **MODIS Science Team (Col. 5)**

<table>
<thead>
<tr>
<th></th>
<th>Day</th>
<th>Night</th>
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</thead>
<tbody>
<tr>
<td>LaRC</td>
<td>0.642</td>
<td>0.666</td>
</tr>
<tr>
<td>NOAA-18</td>
<td>0.644</td>
<td>0.680</td>
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<tr>
<td>CERES</td>
<td>0.650</td>
<td>0.688</td>
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<tr>
<td>PATMOS-X</td>
<td>0.676</td>
<td>0.706</td>
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<tr>
<td>CALIPSO</td>
<td>0.679</td>
<td>0.729</td>
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</table>

Zonal Average Cloud Fraction: Total All Cloud Types

- ISCCP
- MODIS Science Team
- CERES
- PATMOS-X
- LaRC Modular AVHRR
- CALIPSO

Cloud Fraction
- Day
- Night

NASA
### NASA LaRC AVHRR Cloud Mask Validation vs. CALIPSO

<table>
<thead>
<tr>
<th>Area Type</th>
<th>Land</th>
<th>Water</th>
<th>% of Clear and Cloudy AVHRR Pixels Correctly Identified</th>
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<tbody>
<tr>
<td>Polar Day Land</td>
<td>83.0%</td>
<td>91.7%</td>
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<tr>
<td>Polar Night Land</td>
<td>72.7%</td>
<td>84.1%</td>
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<tr>
<td>Mid-Lat Day Land</td>
<td>87.4%</td>
<td>88.5%</td>
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<tr>
<td>Mid-Lat Night Land</td>
<td>87.1%</td>
<td>89.8%</td>
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<tr>
<td>Tropical Day Land</td>
<td>84.3%</td>
<td>84.4%</td>
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<tr>
<td>Tropical Night Land</td>
<td>86.0%</td>
<td>86.3%</td>
<td></td>
</tr>
</tbody>
</table>

Percentages similar to CERES-CALIPSO comparisons
Monthly Average Cloud Optical Depth
October 2008, Daytime

LaRC NOAA-18

CERES Edition 4

MODIS Science Team (Col. 5)

Zonal Average Cloud Optical Depth: Day All Cloud Types

MODIS Science Team

CERES

PATMOS-X

Modular AVHRR

Latitude

Zonal Average

Cloud Optical Depth

0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5 25.0 27.5 30.0

0.0 1.5 3.0 4.5 6.0 7.5 9.0 10.5 12.0 13.5 15.0 16.5 18.0 19.5 21.0 22.5 24.0 25.5 27.0 28.5 30.0

Cloud Optical Depth

NASA
Impact of Spatial Resolution on Cloud Property Retrievals
U.S. Central Plains, Aqua MODIS, April 2008

### CLOUD FRACTION

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<tr>
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<th>ICE</th>
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<tbody>
<tr>
<td></td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
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<tr>
<td>Day</td>
<td>0.29</td>
<td>0.30</td>
<td>0.30</td>
<td>0.17</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Night</td>
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<td>0.24</td>
<td>0.24</td>
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Domain-averaged cloud fraction not changing with resolution

### CLOUD PRESSURE

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<tr>
<td></td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
</tr>
<tr>
<td>Day</td>
<td>693.21</td>
<td>699.37</td>
<td>707.20</td>
<td>400.36</td>
<td>404.42</td>
<td>410.41</td>
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<tr>
<td>Night</td>
<td>763.35</td>
<td>763.67</td>
<td>765.26</td>
<td>317.67</td>
<td>319.20</td>
<td>322.5</td>
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<tr>
<td>Total</td>
<td>720.44</td>
<td>723.82</td>
<td>728.99</td>
<td>345.94</td>
<td>348.79</td>
<td>353.83</td>
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Cloud heights lower at 4 km for both water and ice

### OPTICAL DEPTH

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<th></th>
<th>ICE</th>
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<td></td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
<td>1km</td>
<td>2km</td>
<td>4km</td>
</tr>
<tr>
<td>Day</td>
<td>20.19</td>
<td>18.95</td>
<td>17.62</td>
<td>23.76</td>
<td>23.54</td>
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<td>Night</td>
<td>11.56</td>
<td>11.28</td>
<td>10.80</td>
<td>5.78</td>
<td>5.71</td>
<td>5.64</td>
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<tr>
<td>Total</td>
<td>17.08</td>
<td>16.24</td>
<td>15.25</td>
<td>12.12</td>
<td>12.08</td>
<td>12.1</td>
</tr>
</tbody>
</table>

COD reduced by 11% at 4-km resolution only for water clouds
AVHRR/CERES Zonal Average Cloud Optical Depth
Ice vs. Water Cloud

ICE CLOUD

GOOD AGREEMENT OVER THE TROPICS AND MID-LATITUDES FOR ICE CLOUDS

WATER CLOUD

CERES OPTICAL DEPTH HIGHER IN ALL NON-POLAR REGIONS FOR WATER CLOUDS
Monthly Average Cloud Top Pressure
October 2008, Daytime

LaRC NOAA-18

CERES Edition 4

MODIS Science Team

PATMOS

ISCCP

Zonal Average Cloud Top Pressure: Day All Cloud Types

ISCCP

MODIS Science Team

CERES

PATMOS-X

LaRC Modular AVHRR

NASA
Pixel Level Cloud Top Height Validation Using CALIPSO, October 2008: WATER CLOUD

Optically Thick ($\tau > 8$) Water Cloud

Optically Thin Water Cloud

Daytime

Night-time
Pixel Level Cloud Top Height Validation Using CALIPSO, October 2008: ICE CLOUD

- **Optically Thick** ($\tau > 8$) Ice Cloud
- **Optically Thin** Ice Cloud

**Daytime**

**Night-time**
Correlated k-distribution radiative transfer approach used to compute atmospheric transmissivity. This is then used to derive a surface IR temperature from the observed 11-μm clear-sky TOA IR temperature.

- Application of surface emissivity model yields land/ocean surface skin temperature.

- Sea-surface temperature to be compared with current climatologies (NOAA OI, GHR SST, MICROS ACSPO). Land surface temperature validated with ARM IR thermometers and compared with MODIS Land Surface Temperature product.
Summary and Future Work

- CERES cloud mask/retrieval logic has been adapted to operate with AVHRR data with the goal to extend the CERES cloud climate data record back to ~1980.

- Monthly and seasonally averaged comparisons show that AVHRR results are consistent with CERES and fall within the bounds of other global climatologies prior to the MODIS era.

- Efforts currently being directed toward improving retrievals over snow/ice surfaces and improving processing framework to reliably process large data volumes.

- Need to develop mask/retrieval scheme when AVHRR channel 3 switches from 3.7 to 1.6 $\mu$m and older AVHRR’s without a 12 $\mu$m channel.

- Deriving trends in global cloud cover will be challenging due to changing observation times caused by degrading AVHRR orbits.
  - Combine AVHRR results with new cloud climatology being derived from historical GEO imagers based on CERES cloud mask and retrieval logic (NASA MEaSUREs project).
Unique Hail Model for Europe

- 40 countries explicitly modelled
- First model for the insurance market to cover such a variety and number of countries
- Model based on ~ 38,000 individual historic convective storms
- 9 years of MSG SEVIRI satellite overshooting cloud top detection information a key component of the model
- Simulation of 8,000 years
- ~ 560,000 stochastic events
- Country-specific vulnerability curves
Impact of Resolution on Retrieved Cloud Optical Depth
Aqua MODIS, April 2008

ICE

WATER

OPTICAL DEPTH (DAY)
AVHRR Data Challenges
Striping in 3.7 μm Channel, prior to NOAA-15