Long Term Cloud Property Datasets from MODIS and AVHRR Using the CERES Cloud Algorithm

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Objectives & Motivation

• Create a long-term consistent cloud property data record from polar-orbiting satellites using the same algorithm, or at least one that is as close as possible

• CERES algorithm used to interpret longest record of radiation budget measurements
  - radiance conversion to flux based on CERES scene ID
  - CERES since 2000
  - ERBE record being revised using CERES-like AVHRR clouds

• Important for climate to have variety of interpretations to assess uncertainties

Imagers and Satellites

• MODerate-resolution Imaging Spectroradiometer (MODIS)

• Advanced Very High Resolution Radiometer (AVHRR)
  - TIROS-N, NOAA satellites, MetOp (1978-present)

• Visible Infrared Imaging Suite (VIIRS)
  - Suomi National Polar-orbiting Partnership (SNPP, 2012 - present)
  - Joint Polar Orbiting Satellite System (JPSS, 2017 - ?)
Challenges to Developing Long-term Cloud Climatologies

- Multi-channel calibration stability
  - AVHRR, no onboard solar channel calibration
  - AVHRR, dual and single gain instruments
  - noise

- Multi-instrument spectral response function (SRF) differences
  - even in same series, SRFs can differ

- Varying orbit configurations
  - NOAA drifting satellites (nominally 0730 and 1400 ECTs)
    - *some maintained, some not*
  - MetOps (0930 ECT) and NOAA-17 (nominally 1000 ECTs)
  - Terra (1030 ECT), Aqua/SNPP (1330 ECT)

- Auxiliary data variations
  - CERES uses fixed GEOS-5 product

- Sensor resolution differences
  - MODIS: 1 km, AVHRR GAC ~2 km, VIIRS: 375-750 m

- Imager channel complement differences

ISCCP was first face these challenges and paved the way
Calibrations

- Attempted to normalize all to Aqua MODIS C5, assumes lifetime stability
  - Terra MODIS and SNPP VIIRS visible channel (0.65 µm)
  - Terra 3.7-µm channel
  - AVHRR visible channels (0.65 µm)

- Combines SNO, DCC, & Pseudo-invariant calibration sites (PICS)
- No attempt to adjust thermal channels

[Doelling et al. 2015, Bhatt et al. 2015]

- RMS generally < 1% among the techniques
Methodologies: Satellite CLOud and Radiative Property retrieval System (SatCORPS)

• CERES Edition 4: same as Edition 2 *(Minnis et al. 2011)*, except
  - uses 0.65 (τ), 3.8 (Re, phase), 11 (Tcld), and 12 (detection, phase)
  - roughened hexagonal column ice crystal model *(Yang et al. 2008)*
  - 13.3 μm for high cloud Tcld supplement, polar night detection, multilayered
  - low cloud heights from regional lapse rates of *Sun-Mack et al. (2014)*
  - more sensitive cloud mask for cumulus + 1.38 μm for thin cirrus detection
  - 6.5 μm used for polar night cloud detection, 1.24 μm for τ over snow
  - new thickness parameterizations, OT adjustment of top heights
  - GEOS-5 NWA input throughout (Ed2 used GEOS-4 to 2008, then GEOS-5)
  - multilayer clouds and multispectral Re retrievals

• AVHRR Edition 1: SatCORPS-A1 (for 5-channel, 3.8-μm day only)
  - uses 0.65 (τ), 3.8 (Re, phase), 11 (Tcld), and 12 (detection, phase)
  - roughened hexagonal column ice crystal model *(Yang et al. 2008)*
  - low cloud heights from regional lapse rates of *Sun-Mack et al. (2014)*
  - visible or BTD(11-12) used over snow => low τ
  - new thickness parameterizations
  - MERRA NWA input throughout
  - SW and LW fluxes based on new radiance correlations with CERES

• VIIRS Edition 1, same as CERES Ed4, except
  - no 6.5 or 13.3 μm used
  - revised water droplet reflectance model
### Properties Saved

#### Standard, Single-Layer VISST/SIST

<table>
<thead>
<tr>
<th>Cloudy Pixels Only</th>
</tr>
</thead>
</table>
| 0.65, 0.86, 1.6 µm Reflectances
| 3.7, 6.7, 10.8 µm Temp
| 12 or 13.3 µm Temp
| Broadband TOA Albedo*
| Broadband OLR*
| **Clear-sky Skin Temp** (Scarino et al. 2013)
| Pixel Lat, Lon
| Pixel SZA, VZA, RAZ
| **Mask, Phase**
| **Optical Depth** $\tau$, IR emissivity
| **Cloud effective particle size**
| Liquid/Ice Water Path
| **Effective Temp**, height, pressure
| Top/ Bottom Pressure
| Top/ Bottom Height
| **Overshooting tops** ** (Bedka et al. 2010)**

#### Multi-Layer, CERES Only

**Upper & lower cloud**

- Multilayer ID (single or 2-layer)
- **effective temperature** optical depth, thickness
- **effective particle size** ice or liquid water path
- **height, top/base height** pressure

* CERES only has fluxes in SSF (cloud properties averaged to CERES scanner footprint)
** Only for AVHRR, used in CERES to alter height of OTs
Mean Clear-sky $T_{skin}$, October 2008

Day

Night

Other parameters

Overshooting Top Detections
17 years, 1-3 AM/PM LT

1-Degree Gridded Overshooting Top Pixels Per Year
## Validation & Comparisons

<table>
<thead>
<tr>
<th>Land Surface Type, Geographic Region, and Time of Day of Comparison</th>
<th>Fraction of Correctly Identified AVHRR Clear and Cloudy Pixels</th>
<th>Number of Matches</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAYTIME (0° ≤ SZA &lt; 82°)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land, 60 S – 60 N, No Snow/Ice Cover</td>
<td>0.848</td>
<td>285570</td>
</tr>
<tr>
<td>Land, Polar, No Snow/Ice Cover</td>
<td>0.878</td>
<td>30665</td>
</tr>
<tr>
<td>Ocean, 60 S – 60 N, No Snow/Ice Cover</td>
<td>0.875</td>
<td>844315</td>
</tr>
<tr>
<td>Ocean, Polar, No Snow/Ice Cover</td>
<td>0.943</td>
<td>70071</td>
</tr>
<tr>
<td>Land &amp; Ocean, Global, Snow/Ice Covered</td>
<td>0.825</td>
<td>404235</td>
</tr>
<tr>
<td><strong>NIGHT (SZA ≥ 82°)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land, 60 S – 60 N, No Snow/Ice Cover</td>
<td>0.870</td>
<td>288234</td>
</tr>
<tr>
<td>Land, Polar, No Snow/Ice Cover</td>
<td>0.875</td>
<td>23678</td>
</tr>
<tr>
<td>Ocean, 60 S – 60 N, No Snow/Ice Cover</td>
<td>0.888</td>
<td>879729</td>
</tr>
<tr>
<td>Ocean, Polar, No Snow/Ice Cover</td>
<td>0.951</td>
<td>100782</td>
</tr>
<tr>
<td>Land &amp; Ocean, Global, Snow/Ice Covered</td>
<td>0.715</td>
<td>727283</td>
</tr>
</tbody>
</table>
Mean Cloud Fractions, Day, February 2012

Aqua CERES Ed4  SNPP VIIRS Ed1

CALIPSO  SatCORPS-A1 NOAA-19 AVHRR
Cloud Fraction Comparisons with Other Methods
Day + Night, October 2008

### Results
- Typical for all months
- SatCORPS close to CALIPSO, but $0.026 < \text{CERES Ed4}$

### Means
- CALIPSO: 0.703
- CERES: 0.671
- SatCORPS: 0.697
- MODIS-ST: 0.679
- PATMOS-X: 0.631* (cloudy + probably cloudy)
- CLARA: 0.623
- ISCCP: 0.649

*Notes:
- * denotes cloudy + probably cloudy
Multiyear Seasonal Mean Cloud Fractions: Day + Night

CALIPSO (2007-2014)

SatCORPS N18/19 (2005-2012)

JJA

SON
Cloud-Top Height Differences: Imager – CALIPSO, 60°N – 60°S

VIIRS, July 2013

Aqua, July 2013

N18, JAO 2008

All = Single + Multilayer

• Low cloud tops: -0.24 to 0.33 km bias
  - SDD: 1.41 – 1.75 km
• High cloud tops: -3.52 to -3.02 bias
  - SDD: ~4.1 km

Single Only

• Low cloud tops: -0.24 to 0.33 km bias
  - SDD: 1.41 – 1.75m
• High cloud tops: -3.52 to -3.02 bias
  - SDD: ~4.1 km
Impact of Spatial Resolution on Cloud Property Retrievals

Mean cloud properties from 30 days of MODIS data over central USA, April 2008

<table>
<thead>
<tr>
<th>Phase</th>
<th>WATER</th>
<th>ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 km</td>
<td>2 km</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>Night</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>0.23</td>
<td>0.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CLOUD FRACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
</tr>
<tr>
<td>Night</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CLOUD TOP PRESSURE (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
</tr>
<tr>
<td>Night</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

- slight increase (~0.01) in daytime cloud fraction expected
- 3.4 mb (~39 m) in increase (drop) liquid cloud pressure (alt)
- 2.9 mb (~62 m) in increase (drop) liquid cloud pressure (alt)
- 6% drop in optical depth expected in water clouds, no change in ice
Impact of GAC Averaging on Cloud Optical Depth Retrievals

- Dual gain satellites average 4 AVHRR 1-km pixel counts to obtain a 2-km GAC pixel
  - if pixels from both ranges averaged, then wrong average radiance computed
  - retrieved optical depth will be affected
  - no problem in homogeneous areas and very low sun

- Four 1-km HRPT tropical images were analyzed along with corresponding GAC image

\[
\frac{[\tau(\text{HRPT}) - \tau(\text{GAC})]}{\tau(\text{GAC})}
\]

- cloud fraction change minimal
- cloud height change similar to MODIS study
- water cloud \( \tau \) drops by 13%, ice cloud tau by 5%; total \( \sim 10\% \)
Adjusting Means for Drifting Orbits

- To compare trends, must use same local time because of diurnal variability
- Normalize to Aqua MODIS 1330 ECT using normalization factors from N16 record
  - use monthly polynomial fits as function of ECT

- Significant changes in cloud height and optical depth with local time
- All observations adjusted to 1330 ECT using ratios $X(1330)/X(\text{hour})$
Mean Non-polar Daytime Cloud Fraction

AVHRR (1982-2015)

MODIS (2000-2014)
MODIS (2000-2014)

Mean Non-polar Daytime Cloud Optical Depth

AVHRR (1982-2015)
• Trends total: Terra 27 m/dec, Aqua 65 m/dec, AVHRR 73 m/dec
  - MISR (1030 UTC): 44 ± 22 m/dec
  (Davies et al. GRL, 2012)
• AVHRR 1-km lower than Aqua on average
  - more small CU, no 13.3 or 1.38 µm
  - resolution effects
Conclusions

• Cloud property record derived from nearly identical algorithms from MODIS & AVHRR data (1982 – present, 1978-82 soon)
  - VIIRS to be added

• Results are mostly consistent, some differences due to
  - channel complements
  - spatial resolution
  - spectral bandwidths and noise (3.7 µm especially)
  - calibrations (e.g., Aqua MODIS VIS drifting, no AVHRR IR normalization)
  - sampling times
  - auxiliary data (NWP model analyses)

• small trend in cloud effective height during first decade of 2000
  - similar to that found using MISR data
  - consistent with SAGE trend in 80’s and 90s

• Additional refinements needed to maximize compatibility
Future

• CERES Edition 5
  - use MODIS Collection 6 data, correct for Aqua drift after 2008
  - use new ice crystal and droplet models
  - adjust lapse rate constraints
  - apply optimal cloud-over-snow retrievals

• SatCORPS-A1b
  - Intercalibrate AVHRR IR channels for 35+ year time series
  - Improve low cloud height, relax constraints
  - Enhance overshooting top detection w/ improved IR & VIS pattern recognition
  - Test and possibly employ NASA MERRA-2 reanalysis
  - Enhance dynamic range of ice cloud optical depths at night using neural network
    - Add multilayer cloud and aerosol optical depth retrievals
    - Improve retrievals over snow/ice & cirrus retrievals during day
    - Examine GEOSat diurnal cycles to further enhance ECT corrections

• VIIRS Edition 2
  - use new ice crystal models
  - adjust lapse rate constraints
  - apply optimal cloud-over-snow retrievals