Cloud Properties from Satellite Observations: what has been achieved?

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thanks to contributions from many colleagues

ISCCP at 30, 22-24 Apr 2013, CUNY
continuing exploitation of A-Train synergy: vertical structure, thermodynamic phase

GEWEX assessments of clouds & of radiative fluxes essential for climate studies & model evaluation

continuing exploitation of ISCCP weather states

synergetic climate & process studies: aerosol – cloud – precipitation – radiation - dynamics coupled with modelling

new missions (IASI, Megha-Tropiques, etc)

-> many exciting presentations during this symposium!
Interpretation of retrieved cloud properties:
How does the use of different instruments affect averages & distributions of cloud properties?
(What did we learn from GEWEX Cloud Assessment?)

Synergy of passive & active remote sensing:
statistical models of cloud vertical structure
(important for radiative flux computation in atmosphere & at surface)
- ISCCP model based on radiosonde obs, evaluated with CALIPSO-CloudSat
- classification of IWC profiles

Synergy of variables:
upper tropospheric humidity – cirrus
(improvement of vertical resolution by IASI)
Clouds are extended objects of many very small liquid / ice particles.

Cirrus (high ice clouds)

Cumulonimbus (vertically extended)

Satellite radiometers

Bulk quantities

At spatial & temporal scales to resolve weather & climate variability

Cloud structures over Amazonia

Cumulus (low fair weather clouds)
Geostationary satellites (fixed along equator) : 
frequent observation (30min-3hours), but 5-6 satellites to cover whole Earth 
Polar orbiting satellites (heliosynchoneous) : 
observations at same local time, twice per day

to resolve diurnal cycle: ISCCP uses combination of both!
Cloud properties from space

Satellite radiometers measure (>1980)
- emitted, reflected, scattered radiation

Cloud detection
Inverse radiative transfer

Cloud properties

- information on uppermost cloud layers
- ‘radiative’ cloud height
- perception of cloud scenes depends on instrument / retrieval performance on thin Ci

⇒ cloud property accuracy scene dependent:
most difficult scenes: thin Ci overlying low clouds, low contrast with surface (thin Ci, low cld, polar regions)

Active instruments (A-Train, > 2005)
lidar - radar synergy ⇒ information on all cloud layers; however: sparse sampling
lidar: sensitive to thin (subvis) Ci, however: only ‘apparent’ cloud base (COD<3)
Instruments exploiting the EM spectrum

**IR-NIR-VIS Radiometers**
good spatial resolution (1-5km), multi-spectral channels (1-8)
1) COD (day, assumption on microphysics), CT, CP  
2) CWP, CRE (day, VIS-NIR difference)

**IR Sounders**
15km res, CO₂ absorption band  
1) CP, CEM (no assumption on microphysics)  
2) spectral difference (8-12μm) -> CRE, CWP (only Ci)

**multi-angle VIS-SWIR Radiometers**
1/20km res, sensitive to clouds with COD>2, Rayleigh scattering, O₂ abs. band, only day  
multi-angle scattering -> cloud top (CZ)  
polarization -> CT independent phase

thin Ci over low clouds: Interpretation of Cloud height

How does this affect climatic averages & distributions?
# Cloud Assessment

2005-2012

**Global gridded L3 data** (1° lat x 1° long): monthly averages, variability, Probability Density Functions

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Year Range</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISCCP</td>
<td>1984-2007</td>
<td>(Rossow and Schiffer 1999)</td>
</tr>
<tr>
<td>MODIS-CERES</td>
<td>2001-2009</td>
<td>(Minnis et al. 2011)</td>
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<tr>
<td>AIRS-LMD</td>
<td>2003-2009</td>
<td>(Stubenrauch et al. 2010; Guignard et al. 2012)</td>
</tr>
<tr>
<td>HIRS-NOAA</td>
<td>1982-2008</td>
<td>(Wylie et al. 2005)</td>
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</table>

**Relatively new retrieval versions:**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Year Range</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR-GRAPE</td>
<td>2003-2009</td>
<td>(Sayer et al. 2011)</td>
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</table>

**Complementary cloud information:**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Year Range</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALIPSO-ScienceTeam</td>
<td>2007-2008</td>
<td>(Winker et al. 2009)</td>
</tr>
<tr>
<td>CALIPSO-GOCCP</td>
<td>2007-2008</td>
<td>(Chepfer et al. 2010)</td>
</tr>
<tr>
<td>MISR</td>
<td>2001-2009</td>
<td>(DiGirolamo et al. 2010)</td>
</tr>
<tr>
<td>POLDER</td>
<td>2006-2008</td>
<td>(Parol et al. 2004; Ferlay et al. 2010)</td>
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</table>
Global averages & ocean-land differences

**Cloud Amount (Cover): 0.68 ± 0.03**

- for clouds with COD>0.1
- + 0.05 subvisible Ci, → 0.56 (clds with COD > 2)

  synoptic (day-to-day) variability : 0.25-0.30
  inter-annual variability : 0.025

  **0.10-0.15 larger over ocean than over land**

**Effective Cloud Amount: 0.50 ± 0.05**

- (weighted by cloud IR emissivity)
- synoptic (day-to-day) variability : 0.26-0.28

  **0.05-0.12 larger over ocean than over land**

**Cloud ‘radiative’ Temperature: 260 ± 2 K**

- synoptic (day-to-day) variability : 15-20 K
- inter-annual variability : 2 K

  **7-9 K warmer over ocean than over land**

**Cloud Top Temperature (including subvis Ci): 250 K**
High clouds (even optically thick ones) need up to 3 km to attain COD of 1, (esp. in tropics)

Low clouds seem to have sharper cloud tops than high-level clouds
How many of detected clouds are high, midlevel & low clouds?

CAHR (high clds out of all clds) depends on sensitivity to thin Ci (30% spread)

42% are high clouds (COD>0.1) -> 20% with COD>2 (MISR, POLDER)

eff high cloud amount agrees: 0.17 -> another sign of missing thin cirrus

16% (±5%) are midlevel clouds
thin Ci over low cloud misidentified as midlevel clouds by ISCCP, ATSR, POLDER

42% are single-layer low clouds, 60% are low clouds (MISR, CALIPSO, surface observer)

20% more low clouds over ocean; 10% more high / midlevel clouds over land, optically thinner over land, -> effective cloud amount similar

CALIPSO only considers uppermost layers to better compare with other datasets
Sun / atmospheric circulation -> geographical cloud distribution

InterTropical Convergence Zone:
high convection + cirrus anvils

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uncertainty on regional variability:
max-min[CAHR-<CAHR>] 6 clim
Latitudinal & seasonal variations

high-level clouds

latitudinal & seasonal variations similar!
(except polar regions & HIRS CALR over ocean)

single-layer low clouds
Diurnal cycle of clouds

Complex Empirical Orthogonal Functions, project. on distorted diurnal harmonics

stubenrauch et al. 2006

cairns, 1995

- Low clouds over land: significant diurnal cycle, max early afternoon
- Low clouds over ocean: max in early morning
- High clouds: max in evening
- Mid clouds: max in early morning or late at night
- Cirrus: increase during afternoon & persist during night, thickening

annual average diurnal cycle for low cloud

annual average diurnal cycle for high cloud
Diurnal differences

afternoon – morning

Diurnal cycle on average smaller than regional differences & seasonal cycle

slightly more clouds in the morning over ocean, more clouds in the afternoon over land

CAHR difference negligible over ocean, slightly larger in the afternoon over NH midlatitude land
global CA within ±0.025, CT within ±2K (∼ interannual mean variability)

**Investigation of possible artifacts in ISCCP cloud amounts** (W. B. Rossow, Ann. 2 of WCRP report)

- radiance calibration changes
- geographic coverage changes
- day-night coverage changes
- satellite viewing geometry changes

Conclusion: these causes reduce magnitude of CA variation only by 1/3
Thermodynamic phase & retrieval of optical / microphysical properties

Retrieval of optical / bulk microphysical properties needs thermodynamic phase distinction:

- polarization (POLDER, CALIPSO)
- multi-spectral (PATMOS-x, MODIS, ATSR)
- temperature (ISCCP, AIRS, TOVS)

\[ R_{VIS} \rightarrow COD \]
\[ R_{VIS} \& R_{SWIR} \rightarrow COD \& CRE \]  
(smaller particles reflect more)

**assumptions in radiative transfer:** particle habit, size distribution, phase

\[ WP = \frac{2}{3} x COD \times \rho \times CRE \] (vertically hom.)

IR: small ice crystals in semi-transparent Ci lead to slope of CEM’s between 8 & 12 \( \mu \text{m} \)
Effective Cloud Particle radii:
- Liquid: $14 \pm 1 \mu m$  
- Ice: $25 \pm 2 \mu m$

Cloud Water Path:
- Liquid: $30 - 60 \text{ gm}^{-2}$  
- Ice: $60 - 120 \text{ gm}^{-2}$

distributions depend on retrieval filtering & partly cloudy fields
(MODIS-ST, ATSR retrieval filtering COD > 1)
Interpretation of cloud climatologies in terms of TOA fluxes

use COD-CP histograms (*monthly 1° x 1° map resolution*) in radiative transfer

<table>
<thead>
<tr>
<th>ISCCP</th>
<th>PATMOSx</th>
<th>AIRS-LMD</th>
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</thead>
<tbody>
<tr>
<td>0.21</td>
<td>0.13</td>
<td>0.29</td>
</tr>
<tr>
<td>0.13</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>0.19</td>
<td>0.24</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Differences in COD-CP distributions lead to differences in radiative effects (transformation of IR emissivity to COD -> COD < 10 => underestimation of SW effect)

Cloud Radiative Effect per cloud type (each scene 100%): *(Chen et al. J. Climate 2000; using GISS radiative transfer code)*

<table>
<thead>
<tr>
<th>CP</th>
<th>SW CRE</th>
<th>LW CRE</th>
<th>net CRE</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-25</td>
<td>-87</td>
<td>31</td>
<td>5</td>
</tr>
<tr>
<td>-29</td>
<td>-81</td>
<td>13</td>
<td>-16</td>
</tr>
<tr>
<td>-34</td>
<td>-75</td>
<td>4</td>
<td>-30</td>
</tr>
</tbody>
</table>

ISCCP properties included in radiative flux computations => FD dataset *(Zhang et al. 1995, 1997, 2004, etc)*
Comparison of cloud radiative effects at TOA

Using radiative transfer code of Fu & Liou (fixed re L: 10\(\mu\)m, I: 30\(\mu\)m), transform COD to LWC / IWC for corresponding CP layer (like in Zelinka et al. J. Climate 2012)

(GEWEX CA COD-CP histograms are not weighted by CA)

AIRS – ISCCP LW radiative effect similar, SW effect underestimated by AIRS

(because of saturation when transforming emissivity to optical depth)
Clouds with same IWP may have different IWC and De profiles -> influence on radiation?

Is it possible to give a shape probability in dependence of cloud properties or atmospheric properties?

increasing IWC compared to const. IWC leads to stronger cooling of atmosphere

-> analysis using AIRS - lidar-radar GEOPROF (Mace et al. 2009) - liDARraDAR data (Delanoë & Hogan 2010)
### IWC profile classes & dependency on IWP

Feofilov et al., EGU 2013

#### Table: IWC profile classes and dependency on IWP

<table>
<thead>
<tr>
<th>IWP (g/m²) (occurrence)</th>
<th>constant</th>
<th>trapezia</th>
<th>low trian</th>
<th>upp trian</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 (51%)</td>
<td>54%</td>
<td>20%</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>10-30 (29%)</td>
<td>31%</td>
<td>48%</td>
<td>13%</td>
<td>8%</td>
</tr>
<tr>
<td>30-100 (17%)</td>
<td>28%</td>
<td>56%</td>
<td>14%</td>
<td>3%</td>
</tr>
<tr>
<td>100-300 (3%)</td>
<td>26%</td>
<td>51%</td>
<td>21%</td>
<td>2%</td>
</tr>
<tr>
<td>300-1000 (&lt;1%)</td>
<td>38%</td>
<td>35%</td>
<td>26%</td>
<td>1%</td>
</tr>
</tbody>
</table>

- **Constant & Trapezia** correspond to 80% of the profiles
- Lower triangle increases with IWP from 10 to 25%
- Upper triangle only for IWP < 30 g/m²
- Strong vertical wind might affect occ of low / upp triangles
- Nearly independent of location / season!

Using constant instead of increasing IWC profile might underestimate radiative cooling of atmosphere by 1 – 2 Wm⁻²
Detection of ice supersaturation (ISS)

IR Sounders retrieve water vapour within atmospheric layers of km’s

=> underestimation of $R_{\text{H,ice}}$:

AIRS peak for cirrus at 70% (instead of 100%)

improved spectral resolution:

IASI peak for cirrus at 80-85%

Lamquin et al., ACP 2012

ISS often occurs in vertical layers < 500 m

RHi (%), radiosondes
Conclusions

- Satellite instruments: unique possibility to study cloud properties over long period.
- GEWEX Cloud Assessment:
  - first coordinated intercomparison of L3 cloud products of 12 global ‘state of the art’ datasets
  - common database facilitates further assessments, climate studies & model evaluation
- ISCCP: only dataset that directly resolves diurnal cycle (3-hourly) & covers whole globe
- geographical distributions, latitudinal & seasonal variations agree well
- accuracy is scene & instrument dependent (interpretation of cloud height):
  - differences can be mostly understood by different performance to identify Ci
  - problems in some retrieval methods, misidentification water-ice clouds
- histograms are important (esp. for optical and microphysical properties)
- cloud products adequate for model evaluation & monitoring regional variability
- longterm datasets -> robust statistics & explore rare events
- global monitoring of cloud properties very difficult

- even if instantaneous cloud properties are not very accurate, synergy of different variables provides invaluable potential for improving understanding of clouds

next step: GEWEX integrated dataset