Characterization of Clouds at Sub-Meter Scales by High Resolution Photography from the Surface

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August 25, 2016

www.ecd.bnl.gov/steve
CLOUDS AND EARTH’S CLIMATE SENSITIVITY
The expected steady-state increase in global mean surface temperature $\Delta T_s$ in response to sustained forcing $F$ is:

$$\Delta T_s(\infty) = S_{\text{eq}}F$$

$S_{\text{eq}}$ is “equilibrium” sensitivity of Earth’s climate system, $\text{K} / (\text{W m}^{-2})$.

**Equilibrium climate sensitivity ECS** (steady-state response to sustained $2 \times \text{CO}_2$ forcing) $\text{ECS} \ [\text{K} / (3.7 \ \text{W m}^{-2})] \equiv S_{\text{eq}} \times (3.7 \ \text{W m}^{-2})$

*Synonyms*: Equilibrium sensitivity, Climate sensitivity, Sensitivity, Doubling temperature $\Delta T_{2\times}$, all in units °C or K.

ECS $\approx 3 \ \text{K}$

It is essential to know the *climate sensitivity* and the *forcing* to interpret past change in Earth’s temperature and to project future changes.
Despite extensive research, climate sensitivity remains highly uncertain.
Uncertainty in total forcing, about a factor of 3, is due largely to aerosols.
EARTH’S ENERGY BUDGET

Net energy flux at TOA = Planetary heating rate = Forcing at TOA - Response coefficient . Change in surface temp

\[ N \equiv \frac{dH}{dt} = F - \lambda \cdot \Delta T_s \]

At new steady state: \( N = 0; \quad \Delta T_s(\infty) = \frac{F}{\lambda} \)

“Equilibrium” sensitivity: \( S_{eq}[\text{K} / (\text{W m}^{-2})] \equiv \lambda^{-1}; \quad \Delta T_s(\infty) = S_{eq}F \)

In general: \( \Delta T_s(t) = S_{eq}(F - N); \quad S_{eq} = \frac{\Delta T_s(t)}{F - N} \)

Equilibrium climate sensitivity (steady-state response to sustained 2 × CO\(_2\) forcing): \( \text{ECS} [\text{K} / (3.7 \text{ W m}^{-2})] \equiv S_{eq} \times (3.7 \text{ W m}^{-2}) \)
EXPECTED RELATION BETWEEN ECS AND FORCING

\[ \text{ECS} = (3.7 \ \text{W m}^{-2}) \times S_{\text{eq}} = (3.7 \ \text{W m}^{-2}) \frac{\Delta T_s}{F - N} \]

With CMIP5 Models

ECS vs \( F - N \) is straight line on log-log plot; slope = \(-1\).
\( \Delta T_s \) over 20\textsuperscript{th} century, 0.78 K; net TOA flux \( N \), 0.51 W m\(^{-2}\). Dashed lines account for uncertainties in \( \Delta T_s \) and \( N \).
SENSITIVITY OF GCMS TO CLOUD FEEDBACK

Dependence of equilibrium climate sensitivity on cloud feedback in 29 CMIP5 models: Temperature dependence of cloud radiative effect and cloud fraction in tropical maritime clouds

High-sensitivity models exhibit positive cloud feedback and vice versa. Albedo change is exhibited as change in cloud fraction.

Modified from Brient et al., J. Climate, 2016
ZONAL MONTHLY MEAN ALBEDO

20 GCMs: ERBE Satellite – Model

Modified from Bender et al., Tellus, 2006
CLOUD FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

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October 20, 2014

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WHAT IS A CLOUD?

AMS Glossary of Meteorology (2000)
A visible aggregate of minute water droplets and/or ice particles in the atmosphere above the earth’s surface.
Total cloud cover: Fraction of the sky hidden by all visible clouds.

Ramanathan, JGR (ERBE, 1988)
Cloud cover is a loosely defined term.

Clothiaux, Barker, & Korolev (2005)
Surprisingly, and in spite of the fact that we deal with clouds on a daily basis, to date there is no universal definition of a cloud. . . . Ultimately, the definition of a cloud depends on the threshold sensitivity of the instruments used.

Potter Stewart (U.S. Supreme Court, 1964)
I shall not today attempt further to define it, but I know it when I see it.
Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land

<table>
<thead>
<tr>
<th>Domain</th>
<th>Observations</th>
<th>Cloud cover</th>
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</thead>
<tbody>
<tr>
<td>Land</td>
<td>116 Millions</td>
<td>52.4 %</td>
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<tr>
<td>Ocean</td>
<td>43.3 Millions</td>
<td>64.8 %</td>
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<tr>
<td>Global</td>
<td>159 Millions</td>
<td>61.2 %</td>
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</table>
Most climate models exhibit low cloud fraction and compensate with high cloud albedo.
Different methods yield **substantial systematic differences in the mean**. Error of 0.1 in cloud fraction is ~ 7 W m\(^{-2}\) in shortwave, 4 W m\(^{-2}\) in longwave.
• For clouds with optical depth > 0.1 global cloud fraction is about 68%.
• Cloud fraction increases to 73% when including subvisible cirrus with optical depth down to 0.01 (e.g. CALIPSO) and decreases to about 56% for clouds with optical depth > 2 (e.g. POLDER).
• Key reasons for differences: *resolution* and *threshold*.
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Yoram Kaufman’s View of Clouds

Cloud optical depth $\tau = \int \sigma_{\text{ext}} dz$

$\sigma_{\text{ext}} = \text{extinction coefficient}$

WHAT AN AUDACIOUS CONCEPT!

To put an imager in space. . .

and invert radiance to obtain cloud optical depth.
Clouds are represented as rectangular parallelepipeds within grid cells. A fraction of a grid cell is filled with clouds. Clouds are stacked with random overlap, or maximum overlap if in adjacent layers.
AN ARTIST’S VIEW OF CLOUDS

Rene Magritte, The Infinite Recognition
DSCOVR-EPIC VIEW OF CLOUDS

RGB image. 4 M pixel. One pixel = 5.2 μrad = 8 km at nadir.
**STEVE’S VIEW OF A CLOUD**

RGB image obtained with zenith-pointing digital camera at surface. 12 M pixel, 16-bit. One pixel = 6 μrad = 12 mm at cloud height 2 km.
Cloud optical depth determined from blue channel of RGB image.
12 million independent determinations of COD from single image.
SOME CONTEXT

These are thin clouds.

Liquid water path: \[ L = \left(\frac{2}{3}\right) r_e \tau \]
\(\tau =\) optical depth; \(r_e\)
For \(\tau = 1\) and \(r_e = 6 \, \mu m\), \(L = 4 \, \mu m \Leftrightarrow 4 \, g \, m^{-2}\).

Compare typical precipitable water, 2 cm \(\Leftrightarrow 2 \times 10^4 \, g \, m^{-2}\).

Compare Turner CLOWD (BAMS, 2007), 100 g m\(^{-2}\).

Hard (impossible) to measure by radar, microwave.

These are thin clouds indeed!
FURTHER CONTEXT

24-Hour average cloud radiative effect at equinox
At midlatitude site

Optically thin clouds are radiatively very important!
Cloud optical depth determined from red channel of RGB image. Differs slightly from COD determined from blue channel.
Compare CODs from red and blue channels of RGB image. Agreement within 15% at higher COD.
HIGH RESOLUTION IMAGER

Fujifilm FinePix S1
16 Megapixels, $3456 \times 4608$
3 Color, RGB, 16 bit

1200 mm focal length
(35 mm equiv)

1 Pixel = 6 $\mu$rad

FOV $22 \times 29$ mrad
(2 $\times$ 3 sun diameters)

$350$
1200 mm EQUIVALENT FOCAL LENGTH

That's 1.2 meters!
NARROW FIELD OF VIEW

29 × 22 mrad ≈ 3 × 2 sun (or moon) diameters, 29 × 22 m at 1 km
HIGH RESOLUTION
RESOLVING POWER TESTS

Resolves 2 cm blocks at 1 km.
Line trace is 1 pixel wide across 4 cm blocks.
SPECTRAL SENSITIVITY CALIBRATION OF RGB CHANNELS

Cameras calibrated with XeHg arc lamp, integrating sphere, NIST calibrated photodiode.

Measurements are **hypospectral!** We use just red and blue channels.
WHAT A GREAT CAMERA!

[Image of an eagle]
SHORT RANGE CLOUD VARIABILITY

Moon diameter = 9 mrad.
CAMERA FIELD OF VIEW AND SOLAR EPHEMERIS

Narrow FOV Camera, 22 x 29 mrad = 2 x 3 sun diameters

Wide FOV Camera, 120 x 160 mrad

Sun, angular diameter 0.535° = 9.3 mrad

*Drawn 10 times actual angular dimension*

SGP, Oklahoma
2015-07-31
Times are UTC
Local sun time: UTC - 6.5 h

Measurements are hyper local!
7 MINUTES IN OKLAHOMA, WIDE FIELD OF VIEW CAMERA

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1 Photo every 4 s. Image is $\sim 120 \times 160$ mrad = $\sim 240 \times 320$ m @ 2 km.
7 MINUTES IN OKLAHOMA, NARROW FIELD OF VIEW CAMERA

1 Photo every 4 s. Image is \( \sim 20 \times 30 \text{ mrad} = \sim 40 \times 60 \text{ m} @ 2 \text{ km.} \)
ZENITH RADIANCE DEPENDENCE ON COD

Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

Unit: $W \text{ m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1} / W \text{ m}^{-2} \text{ nm}^{-1} = \text{ sr}^{-1}$

In absence of cloud, Rayleigh scattering only, low zenith radiance.
At low COD normalized zenith radiance increases with increasing COD.
At higher COD normalized zenith radiance decreases with increasing COD.
Dependence of NZR on COD is inverted to obtain COD from NZR. Inversion is valid only for COD ≤ 3. Must establish COD < 3.

The inversion is applied to yield COD on pixel-by-pixel basis.

Minima and maxima permit scaling counts to NZR in each channel.
CALIBRATION APPROACHES

Need to calibrate counts in Red and Blue channels to Radiance.

- Absolute calibration (calibrated lamp or radiometer accounting for geometric effects).
- Field transfer from calibrated zenith radiometer.
- Radiation transfer calculations:
  Two point calibration of NZR using minimum (Rayleigh) radiance and maximum (Bright Cloud) radiance.

Calibration on Dark and Bright scenes permits determination of NZR, COD, Cloud albedo at native resolution of images.

Concerns:

Aerosol contribution to nominal “Rayleigh” signal.

Dependence on assumptions in RT calculations such as 1-D plane parallel; cloud drop asymmetry parameter.
Organized structure is present down to 10 cm scale.
STRENGTHS AND ADVANTAGES

High resolution: 6 µrad nominal; 20 µrad actual.

Large number of independent measurements: 12 million nominal.

High dynamic range: 16 bit.

Black background of outer space: No surface influence (to first order); Rayleigh radiance is exactly calculable.

Readily available data acquisition hardware and image processing software.

Low cost.

Lots of data!
WEAKNESSES AND LIMITATIONS

Two-dimensional only.
Daytime only.
Hyperlocal.
Hypospectral (but 2 channels may be enough).
Limited to COD $\leq 3$ (but we see a path forward).

Lots of data!
SUMMARY

High resolution digital photography from the surface presents an unprecedented view of cloud structure.

Resolution is 3 to 5 orders of magnitude higher than existing approaches.

Radiance and optical depth of thin clouds are retrieved pixel-by-pixel from digital camera images at resolution of ~4 cm for cloud at 2 km.

Cloud radiance and optical depth exhibit rich spatial structure, for example order of magnitude variation over 40 m × 40 m domain.

Variation in radiance on scales down to ~10 cm is attributed to variation in cloud optical depth.