CLOUD FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

AND WHAT CAN WE LEARN FROM HIGH RESOLUTION DIGITAL PHOTOGRAPHY OF CLOUDS?

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BECS Seminar

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Upton NY USA
December 5, 2014

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CLOUD FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

SHORT ABSTRACT

No.
No.
No.

I come to bury cloud fraction, not to praise it.

- Shakespeare, 1599
CAN CLOUD FRACTION BE DEFINED?
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*.  

WHY DO WE WANT TO KNOW CLOUD FRACTION?

Clouds have a strong impact on Earth’s radiation budget: -45 W m\(^{-2}\) shortwave; +30 W m\(^{-2}\) longwave.

Slight change in cloud fraction could augment or offset greenhouse gas induced warming – cloud feedbacks.

Accurate representation of cloud radiative effects is essential in climate models.

Getting cloud fraction “right” is an evaluation criterion for global climate models.
ZONAL MONTHLY MEAN ALBEDO
20 GCMs – Difference vs. ERBE Satellite

Obs < Model – Model is bright

Obs > Model – Model is dark

Modified from Bender et al., Tellus, 2006
WHY DO WE WANT TO KNOW CLOUD FRACTION?

One commonly encounters analyses such as

Here the outgoing long-wave flux for a unit area with fraction $A_c$ covered by clouds (i.e., $A_c$ is the overcast fraction of the sky) will be considered and the following symbols are defined.

- $F_c$: flux from the clear-sky regions;
- $F_0$: flux from the overcast sky;
- $F$: cloudy-sky (clear plus overcast) flux;
- $A_c$: cloud-cover fraction.

With the above definitions, one can write

$$F = F_c(1 - A_c) + F_0 A_c$$

This assumes that there are unique values for $F_c$, $F_0$, and $A_c$. 
CAN CLOUD FRACTION BE MEASURED?
Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land

Oktas – eighths of the sky

<table>
<thead>
<tr>
<th>Domain</th>
<th>Observations</th>
<th>Cloud cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>116</td>
<td>52.4</td>
</tr>
<tr>
<td>Ocean</td>
<td>43.3</td>
<td>64.8</td>
</tr>
<tr>
<td>Global</td>
<td>159</td>
<td>61.2</td>
</tr>
</tbody>
</table>
OPTICALLY THIN CLOUDS CAN BE PREVALENT IN TROPICS

Subvisible cirrus detected by lidar from space, DJF

$0.01 \leq \tau \leq 0.03$

Martins Noel & Chepfer, JGR, 2011
Annual cloud fraction varies widely as a function of location.

*Mace, ... Stephens, Trepte, Winker, JGR 2009*
MEASUREMENTS OF GLOBAL CLOUD FRACTION

- Global total cloud amount (fractional cloud cover) is about 0.68 (±0.03), when considering clouds with optical depth > 0.1.
- The value increases to 0.73 when including subvisible cirrus with optical depth down to 0.01 (e.g. CALIPSO) and decreases to about 0.56 for clouds with optical depth > 2 (e.g. POLDER).

Modified from Stubenrauch, Rossow, ... Ackerman, ... Chepfer, DiGirolamo, ... Winker et al., BAMS, 2013
PERSISTENT VERY THIN CIRRUS AT MIDLATTITUDE SITE

Optical depth of cirrus layer estimated from lidar return as 0.003 to 0.004.

Kienast-Sjögren et al., 9th Int. Symp. on Tropospheric Profiling, 2012
The effects of clouds on Earth’s radiation balance are examined as the difference between the cloud-free and the all-sky radiative fluxes. This difference is defined as cloud-radiative forcing (cloud radiative effect).

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<th>Cloud-Free</th>
<th>CRE</th>
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<td>287.7</td>
<td>-48.4</td>
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<td>234.5</td>
<td>265.6</td>
<td>31.1</td>
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<tr>
<td></td>
<td>W m(^{-2})</td>
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<td>W m(^{-2})</td>
<td>W m(^{-2}) %(^{-1})</td>
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Uncertainties \(\sim 5\) W m\(^{-2}\).

*For global-average cloud cover 70%.

\textit{Two planets for the price of one – Cess}
MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION

Cloud Radars (FOV 0.2°; 3.5 mrad)
Ground

Satellite

Cloud Lidars (FOV 80 µrad)

ARSCL
Active Remote Sensing of CLouds

Domain 55-140 km on a side

TSI (FOV 100°)
Total Sky Imager

Although different approaches yield different instantaneous, local CF, they would be expected to yield the same average CF.

Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014
Different methods yield *substantial systematic differences in the mean*. Error of 0.1 in cloud fraction is \( \sim 7 \text{ W m}^{-2} \) in shortwave, \( 4 \text{ W m}^{-2} \) in longwave.
CORRELATION OF CLOUD FRACTION BY DIFFERENT METHODS

Hourly cloud fraction at SGP by ARSCL AND GOES, May, 2009

All points, May, 2009

Points within 5% of 0 or 1 in both data sets excluded

Excluding all-cloud and no-cloud scenes reduces variance accounted for by the regression from 78% to 44%.
TOTAL SKY IMAGER

Uplooking convex mirror; downlooking camera

Opaque and thin cloud masks as fraction of pixels

Provides thin and thick cloud fraction in 100° and 160° cones about zenith.

Thin and thick cloud based on Red/(Red + Blue) thresholds.
TIME SERIES OF CLOUD FRACTION BY MULTIPLE METHODS

ARM SGP site (north central OK) May 13, 2009

Substantial variation among methods.
Substantial fluctuation in TSI images taken at 30-second intervals.
TOTAL SKY IMAGES AND CLOUD MASKS FROM TSI ALGORITHM

ARM SGP site (north central OK) May 13, 2009, 1416-1417

TSI threshold misses thin visible clouds
Substantial changes at 30-s intervals as clouds are blown by wind.
REASONS FOR DIFFERENCES IN MEASURED CLOUD FRACTION

*Trivial*

Mismatch of spatial and/or temporal domain.

View angle – sidewall effect – cloud aspect ratio.

*Intrinsic*

Spatial resolution.

Threshold.
AND IF WE KNEW CLOUD FRACTION, WOULD IT BE OF ANY USE TO US?
CLOUD RADIATIVE EFFECT

Dependence on shortwave optical depth and cloud-top temperature

24-Hour average CRE, north central Oklahoma, at equinox

CRE is initially linear in optical depth, saturating at high optical depth.
Net CRE depends on optical depth and cloud-top temperature even in sign.
WHAT CAN WE LEARN FROM HIGH RESOLUTION SURFACE-BASED IMAGING OF CLOUDS?
YOU CAN OBSERVE A LOT JUST BY LOOKING

-Yogi Berra
WHAT CAN WE LEARN FROM HIGH RESOLUTION SURFACE-BASED IMAGING OF CLOUDS?
MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION

Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014

High resolution, narrow field of view camera brings complementary perspective to study of cloud amount and properties.
OBSERVATION GEOMETRY

Solar zenith angle and azimuth shown for July 15, 2014 from 6 am to 6 pm EDT

- Sun, Angular Diameter
  \[0.535^\circ = 9.3 \text{ mrad}\]

- Camera FOV, 22 x 29 mrad
  \[= 2 \times 3 \text{ sun diameters}\]

Both drawn 10 times actual angular dimension
Simple question. But what is the answer?
ZENITH RADIANCE

How does it depend on cloud optical thickness??

Initially, with thin cloud it increases. Why??

Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006
ZENITH RADIANCE

How does it depend on cloud optical thickness??

Without cloud, Rayleigh only. Cloud scatters some sunlight straight down.

Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006
With increasing cloud optical thickness zenith radiance decreases as reflectance increases and transmittance decreases.
ZENITH RADIANCE
How does it depend on cloud optical thickness??

Optical thickness is not uniquely defined for a given zenith radiance.

Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006
STRENGTHS AND ADVANTAGES

High resolution: 6 μrad nominal (6 mm at 1 km); 20 μrad actual.
Large number of independent measurements: 14 M pixel nominal.
High dynamic range: 16 bit.
Multispectral: three wavelengths nominal: Red, Green, Blue.
Black background of outer space: No surface effects (to first order); Rayleigh radiance is exactly calculable.
No side-wall issues; no correction sky cover to ground cover.
Readily available data acquisition hardware and software.
Available, easy-to-use image-processing software.
Simplicity: Get going right away.
Low cost.
Lots of data!
WEAKNESSES AND LIMITATIONS

Two-dimensional only.
Daytime only.
Limited wavelength range.
Small fraction of sky.
Extremely local.
Aerosol masquerades as cloud.
Lots of data!
CAMERA WAVELENGTH RESPONSE

Integrating sphere with NIST traceable photodiode

Red and Blue are fairly well separated.
Red and Blue are fairly well separated. Sun and Sky spectra overlap both Red and Blue, but with different weights. This can be exploited in distinguishing cloudy and cloud-free sky.
RESOLVING POWER TEST AT 1 km

Pixel number

RGB count

Pixel number
IMAGE PROCESSING AND ANALYSIS TOOLS

Natural color  Expand  Expand  Expand

Red  Red/(Red+Blue)  Pixelate  Threshold
DETERMINING CLOUD FRACTION

Cloud mask as function of threshold Red/(Red + Blue)

Threshold 0.35 0.40 0.45
Cloud Fract 0.618 0.587 0.542

Cloud fraction is constrained between ~0.54 and ~0.62.
DETERMINING CLOUD FRACTION

Cloud mask as function of threshold \( \text{Red}/(\text{Red} + \text{Blue}) \)

Natural color  Red  Red/(Red + Blue)

![Natural color image](image1)
![Red image](image2)
![Red/Blue image](image3)

![PDF graph](image4)

Threshold  0.20  0.25  0.30
Cloud Fract  0.92  0.81  0.54

Cloud fraction is indeterminate.
Cloud fraction in zoom area is indeterminate.
EFFECT OF RESOLUTION ON CLOUD FRACTION

Resolution artificially degraded from 6 μrad to 2 × mrad at constant threshold

As resolution is degraded, cloud fraction increases.
EFFECT OF THRESHOLD AND RESOLUTION ON CLOUD FRACTION

Cloud fraction as resolution is artificially degraded from 6 μrad to 20 × 30 mrad, as function of threshold.

As resolution is degraded, cloud fraction tends to increase if threshold is below mean, and vice versa.
Cloud fraction depends strongly on threshold and resolution.
SUMMARY ON CLOUD FRACTION

CAN IT BE DEFINED? NO!

CAN IT BE MEASURED? NO!

AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY? NO!
CLOUD FRACTAL DIMENSION DEPENDENCE ON THRESHOLD
All pixels with any cloud are counted as cloud – Box counting method

Cloud fractal dimension depends strongly on threshold.
The color of the original image is accurately reconstructed by a single component.

The first principal component is linearly related to Red/(Red + Blue), which thus serves as a quantitative measure of cloud contribution to zenith radiance.
A POSSIBLE PATH FORWARD

Use first principal component, PC1, or Red/(Red + Blue), RRB, as metric of cloud effect on zenith radiance, rather than as a discriminant of cloud fraction.

\[
\frac{\langle \text{Red} \rangle}{\langle \text{Red} \rangle + \langle \text{Blue} \rangle} = 0.421
\]

\[
0.295
\]

PC1 and RRB are independent properties of each pixel.

PC1 and RRB are continuously variable quantities, not a binary property (0 or 1) of each pixel.

PC1 and RRB are conserved when decreasing resolution.
FUTURE DIRECTIONS

Principal component analysis (PCA) allows attribution of *downwelling radiance* to blue (sky) and white (cloud) contributions.

As Rayleigh radiance is exactly calculable, determination of PC1 or RRB should allow determination of the decrease in blue (sky) radiance and increase in white (cloud) irradiance due to clouds, on a pixel-by-pixel basis.

Perhaps this can lead to a quantitative determination of Cloud Radiative Effect.

Evaluation of climate models on their ability to represent Cloud Radiative Effect (rather than cloud fraction).