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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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

Latitude

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 Millions</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>
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</tbody>
</table>

Warren, Hahn, London, Chervin, Jenne
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.
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).

Stubenrauch, Rossow, ... Ackerman, ... Chepfer, DiGirolamo, ... Winker et al., BAMS, 2013
Optical depth of cirrus layer estimated from lidar return as 0.003 to 0.004.
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).

<table>
<thead>
<tr>
<th></th>
<th>All-Sky</th>
<th>Cloud-Free</th>
<th>CRE</th>
<th>dCRE/dCF*</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>W m⁻²</td>
<td>W m⁻²</td>
<td>W m⁻²</td>
<td>W m⁻² %⁻¹</td>
</tr>
<tr>
<td>Shortwave absorbed</td>
<td>239.3</td>
<td>287.7</td>
<td>-48.4</td>
<td>-0.7</td>
</tr>
<tr>
<td>Longwave emitted</td>
<td>234.5</td>
<td>265.6</td>
<td>31.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Net</td>
<td>4.8</td>
<td>22.1</td>
<td>-17.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Uncertainties ~ 5 W m⁻².

*For global-average cloud cover 70%.
Different methods yield \textit{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.
MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION

Cloud Radars (FOV 0.2°; 3.5 mrad)

Cloud Lidars (FOV 80 µrad)

ARSCL (Active Remote Sensing of CLouds)

TSI (FOV 100°)
Total Sky Imager

Domain 55-140 km on a side

Ground

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

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

Dependence on shortwave optical depth and cloud-top temperature

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

Longwave CRE also initially linear; saturates; depends on cloud-top temp.
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?
High resolution, narrow field of view camera brings complementary perspective to study of cloud amount and properties.
Solar zenith angle and azimuth shown for July 15, 2014 from 6 am to 6 pm EDT

Sun, Angular Diameter
0.535° = 9.3 mrad

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

Both drawn 10 times
actual angular dimension
With increasing cloud optical thickness zenith radiance decreases as reflectance increases and transmittance decreases.
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!
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**

<table>
<thead>
<tr>
<th>Natural color</th>
<th>Expand</th>
<th>Expand</th>
<th>Expand</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Red</th>
<th>Red/(Red+Blue)</th>
<th>Pixelate</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5.png" alt="Image" /></td>
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<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>
DETERMINING CLOUD FRACTION

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

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

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

Natural color  |  Red  |  Red/(Red + Blue)
---|---|---

Results in indeterminate cloud fraction.
DETERMINING CLOUD FRACTION

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

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

Resolution artificially degraded from 6 μrad to 2 μrad 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 $20 \times 30$ mrad, as function of threshold.

As resolution is degraded, cloud fraction tends to increase if threshold is below mean, and vice versa.
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!
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.

\[
\frac{\langle \text{Red} \rangle}{\langle \text{Red} \rangle + \langle \text{Blue} \rangle} = 0.421 \\
\frac{\langle \text{Red} \rangle}{\langle \text{Red} \rangle + \langle \text{Blue} \rangle} = 0.295
\]

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).