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

Upton NY USA

December 5, 2014

www.ecd.bnl.gov/steve

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.

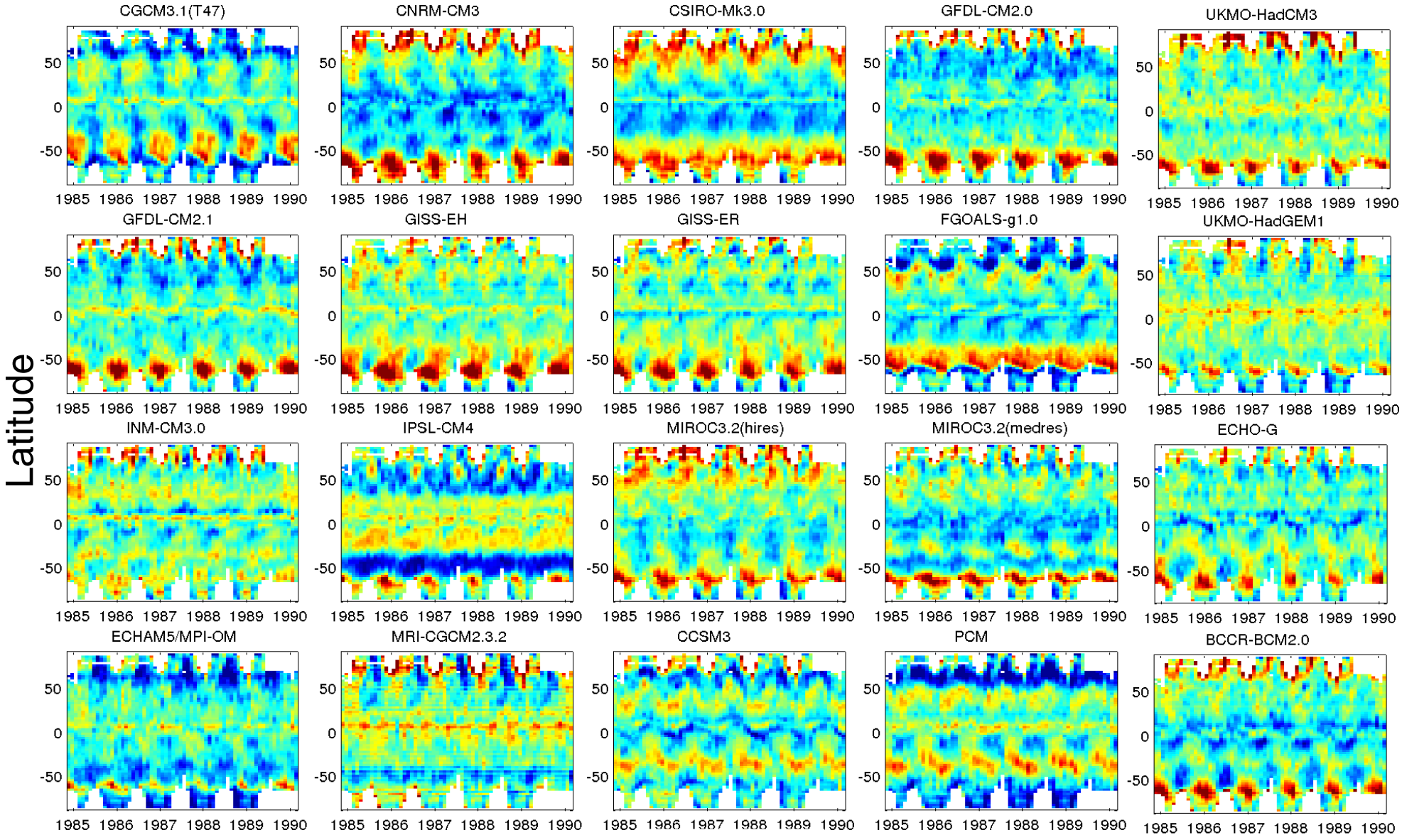
Slight change in cloud fraction could augment or offset greenhouse gas induced warming – cloud feedbacks.

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?

DOE/ER/60085-H1
NCAR/TN-273 + STR
NCAR Technical Notes

Prepared for:
United States Department of Energy
Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division

and

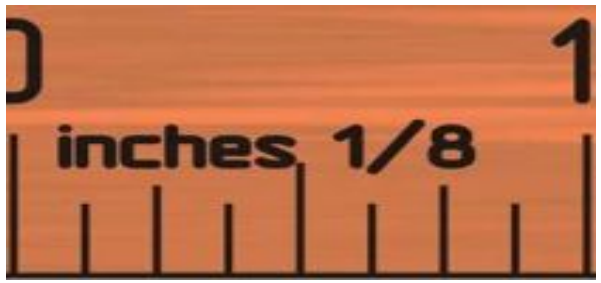
National Center for Atmospheric Research
Boulder, Colorado 80307

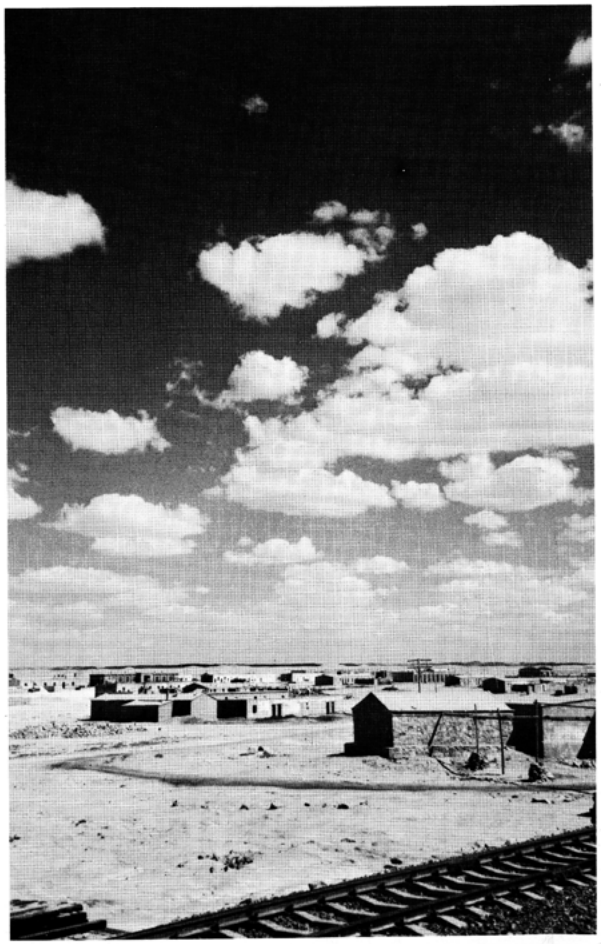
October 1986

Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land

Oktas – eighths of the sky

Domain	Observations Millions	Cloud cover %
Land	116	52.4
Ocean	43.3	64.8
Global	159	61.2



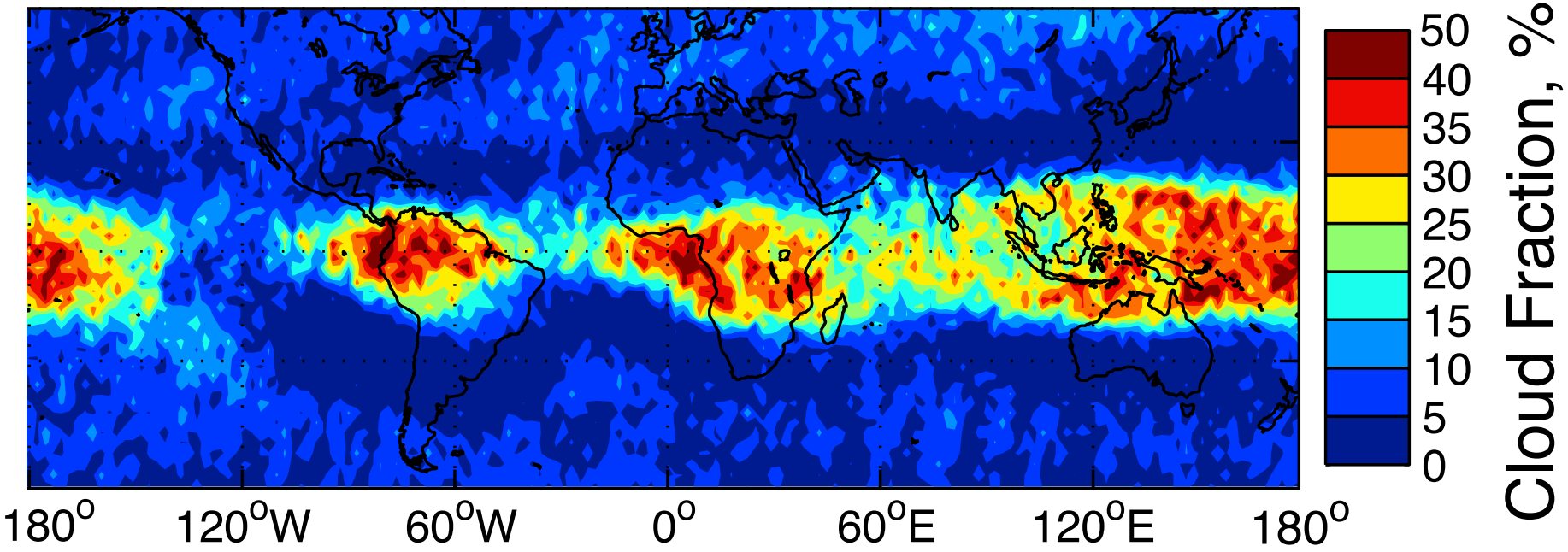


Warren, Hahn, London, Chervin, Jenne

OPTICALLY THIN CLOUDS CAN BE PREVALENT IN TROPICS

Subvisible cirrus detected by lidar from space, DJF

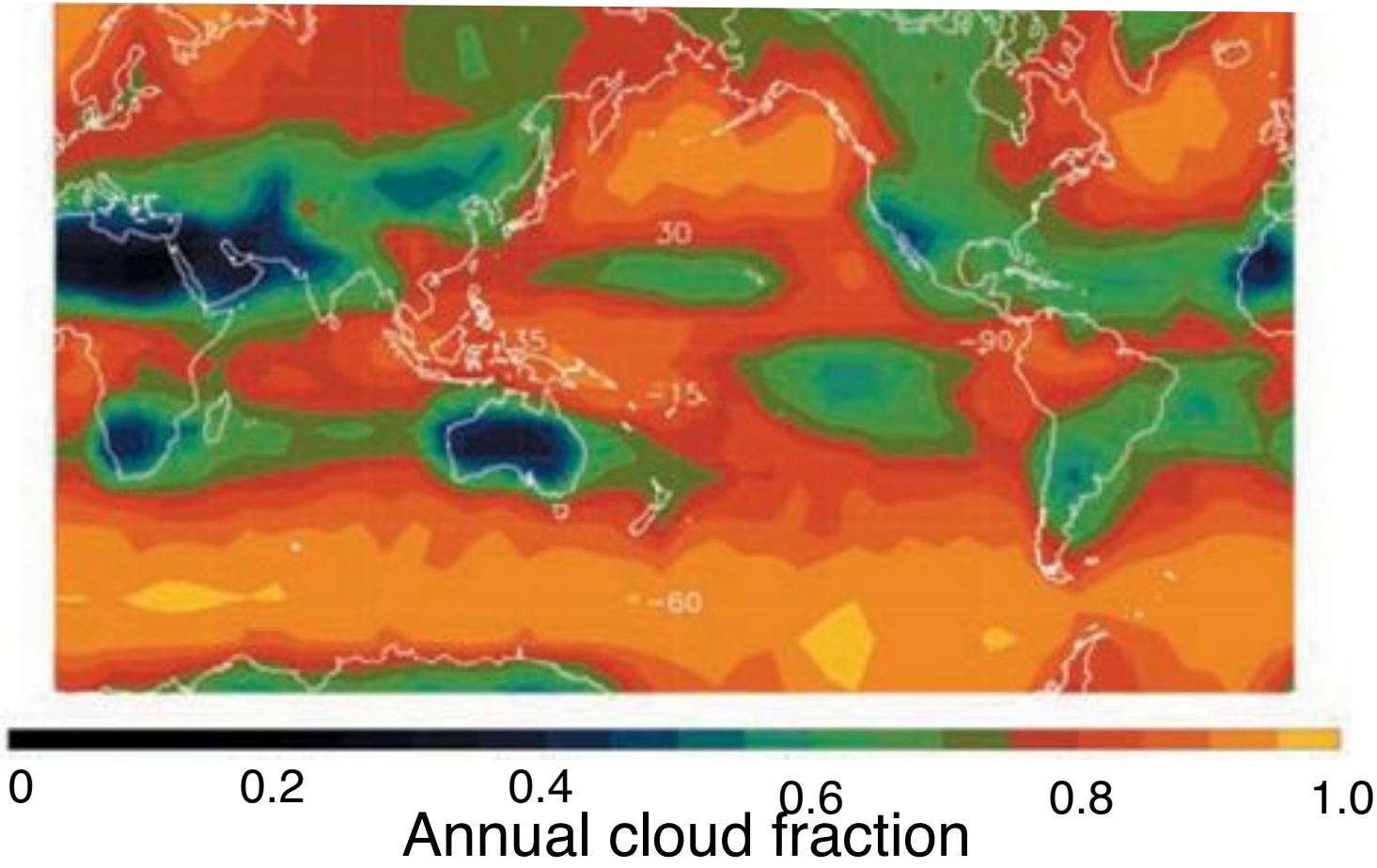
$0.01 \leq \tau \leq 0.03$



Martins Noel & Chepfer, JGR, 2011

GEOGRAPHICAL DISTRIBUTION OF CLOUD FRACTION

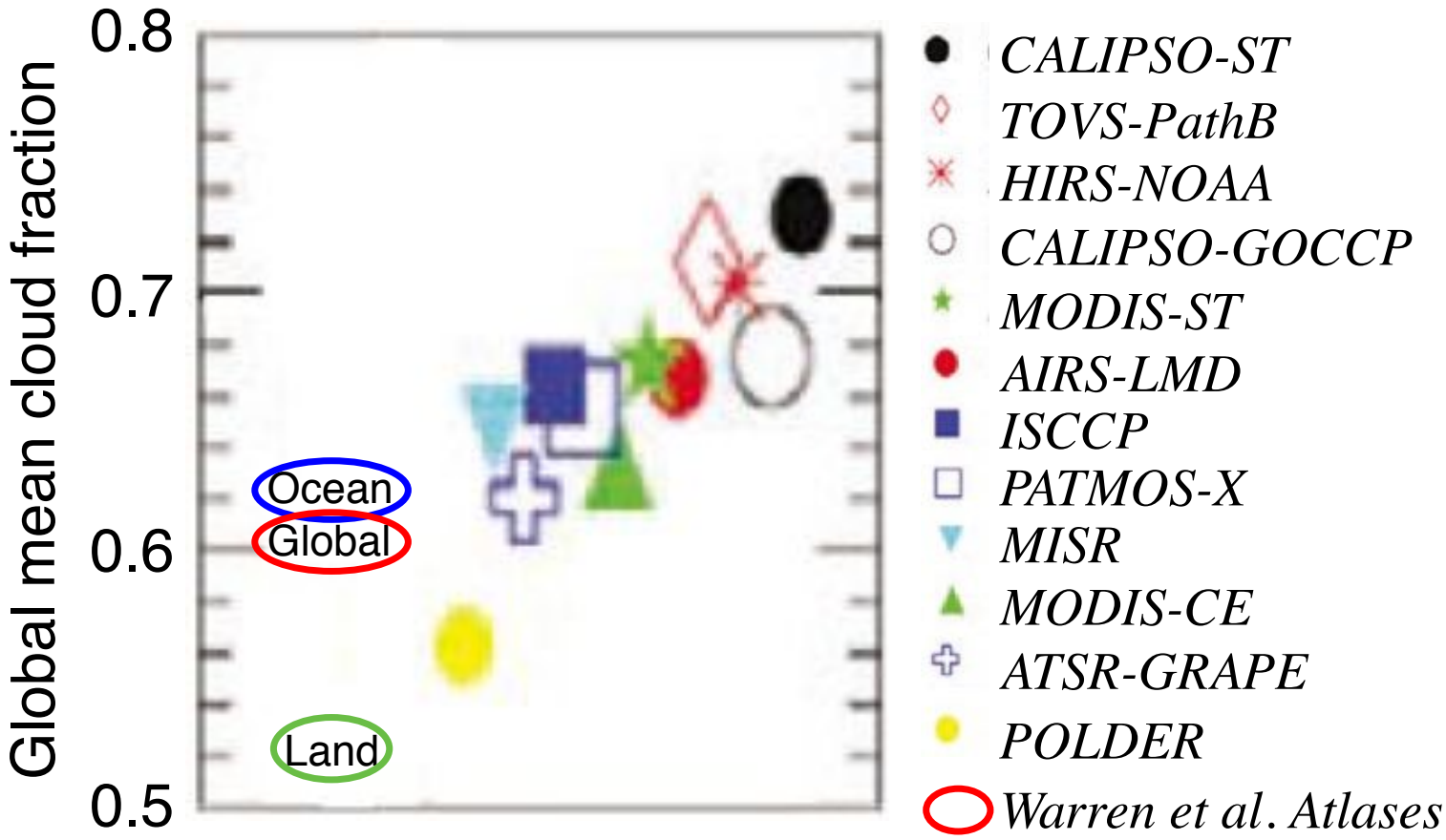
Cloudsat Calipso Product



Mace, ... Stephens, Trepte, Winker, JGR 2009

Annual cloud fraction varies widely as function of location.

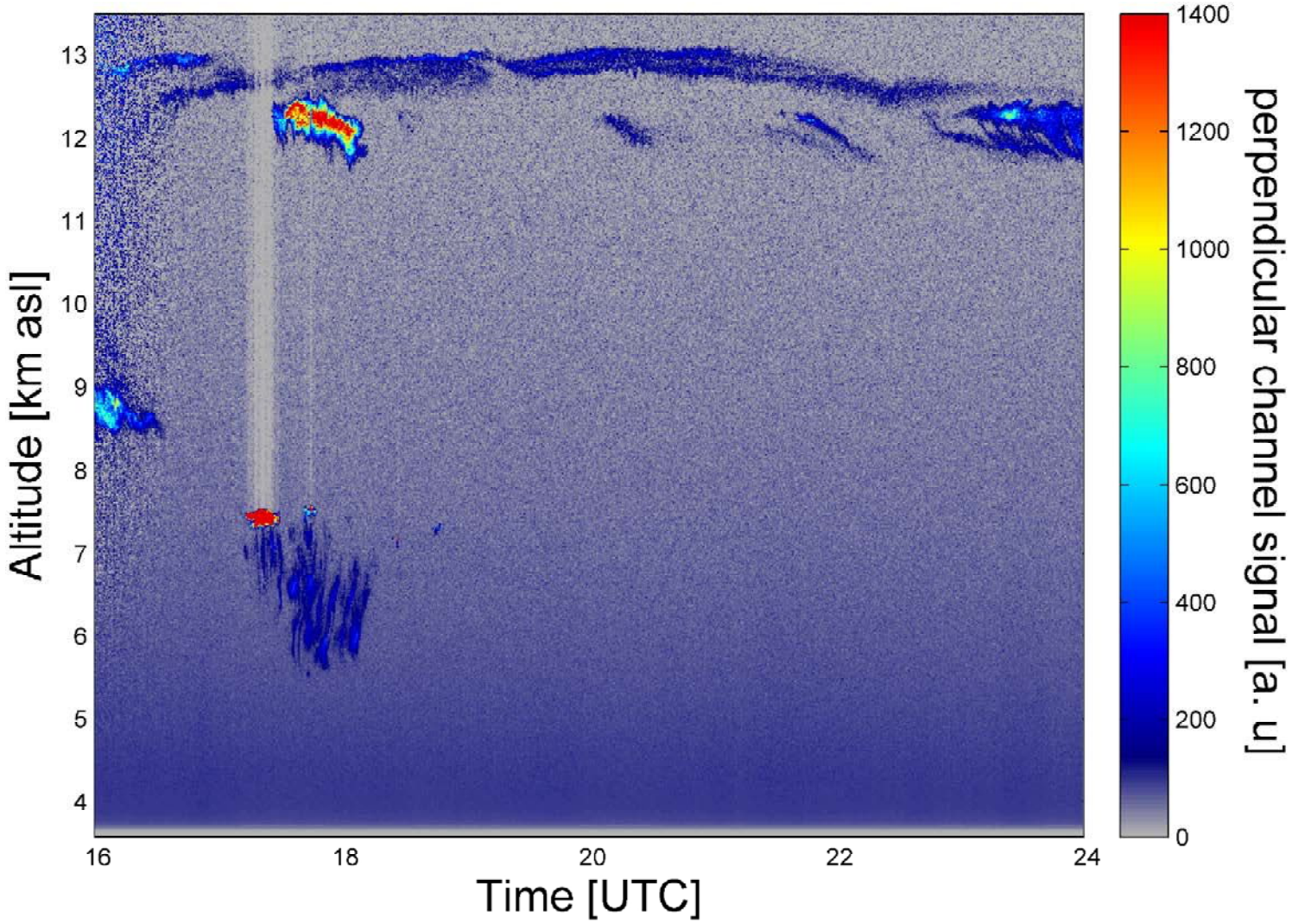
MEASUREMENTS OF GLOBAL CLOUD FRACTION



- 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 MIDLATITUDE SITE



Kienast-Sjögren et al., 9th Int. Symp. on Tropospheric Profiling, 2012

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

GLOBAL AND ANNUAL MEAN RADIATIVE FLUXES AND CLOUD RADIATIVE EFFECT FROM ERBE

JOURNAL OF GEOPHYSICAL RESEARCH, 1990

Seasonal Variation of Cloud Radiative Forcing Derived From the Earth Radiation Budget Experiment

E. F. HARRISON, P. MINNIS, B. R. BARKSTROM, V. RAMANATHAN, R. D. CESS, AND G. G. GIBSON

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).

	All-Sky	Cloud-Free	CRE
	W m^{-2}	W m^{-2}	W m^{-2}
Shortwave absorbed	239.3	287.7	-48.4
Longwave emitted	234.5	265.6	31.1
Net	4.8	22.1	-17.3

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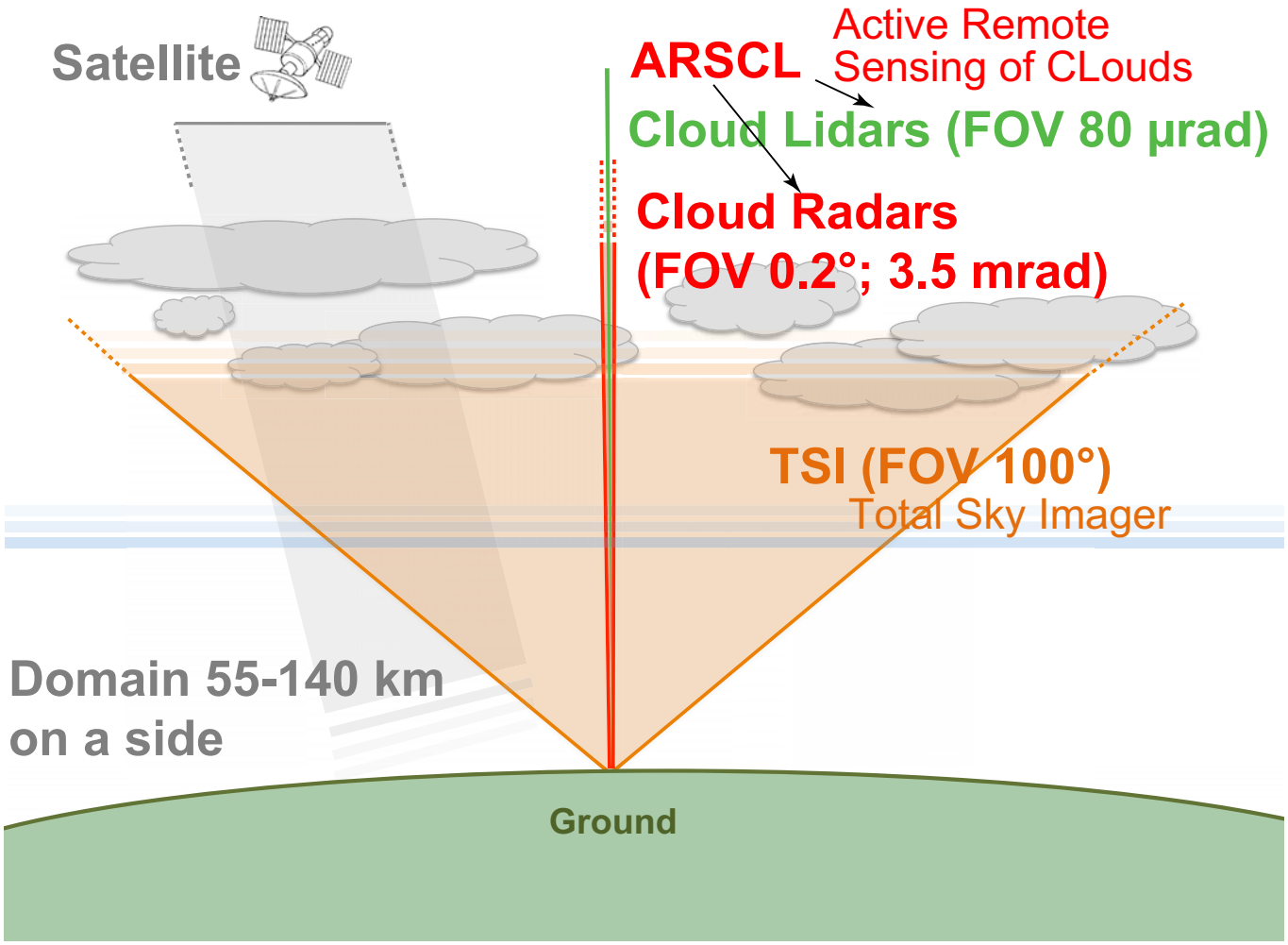
	All-Sky	Cloud-Free	CRE	*d*CRE/*d*CF*
	W m^{-2}	W m^{-2}	W m^{-2}	W m^{-2} $\%^{-1}$
Shortwave absorbed	239.3	287.7	-48.4	-0.7
Longwave emitted	234.5	265.6	31.1	0.4
Net	4.8	22.1	-17.3	-0.3

Uncertainties ~ 5 W m^{-2}.

*For global-average cloud cover 70%.

Two planets for the price of one – Cess

MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION

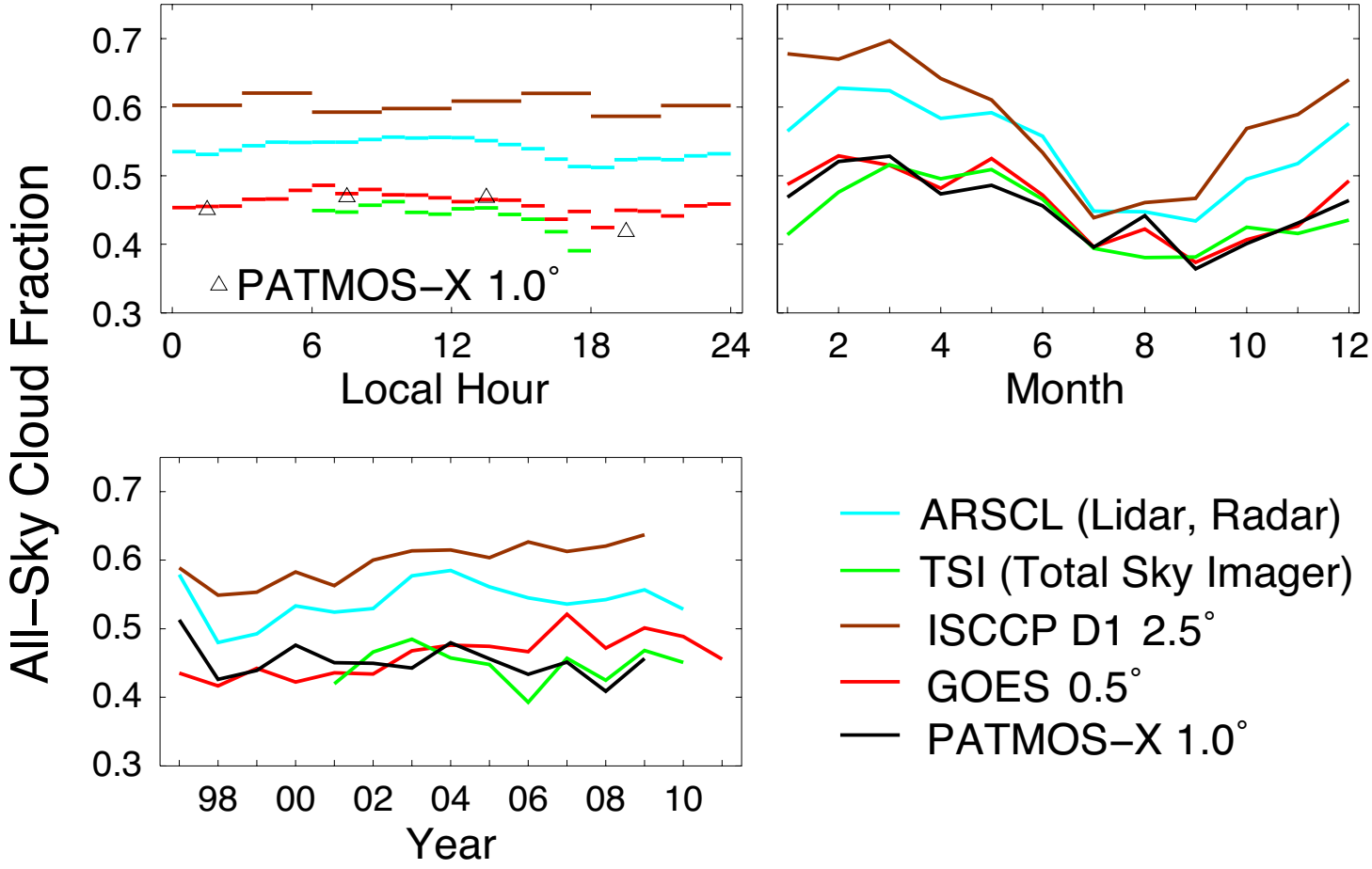


Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014

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

CLOUD FRACTION BY MULTIPLE METHODS

2 Surface, 3 satellite methods at U.S. Southern Great Plains; 10 years data



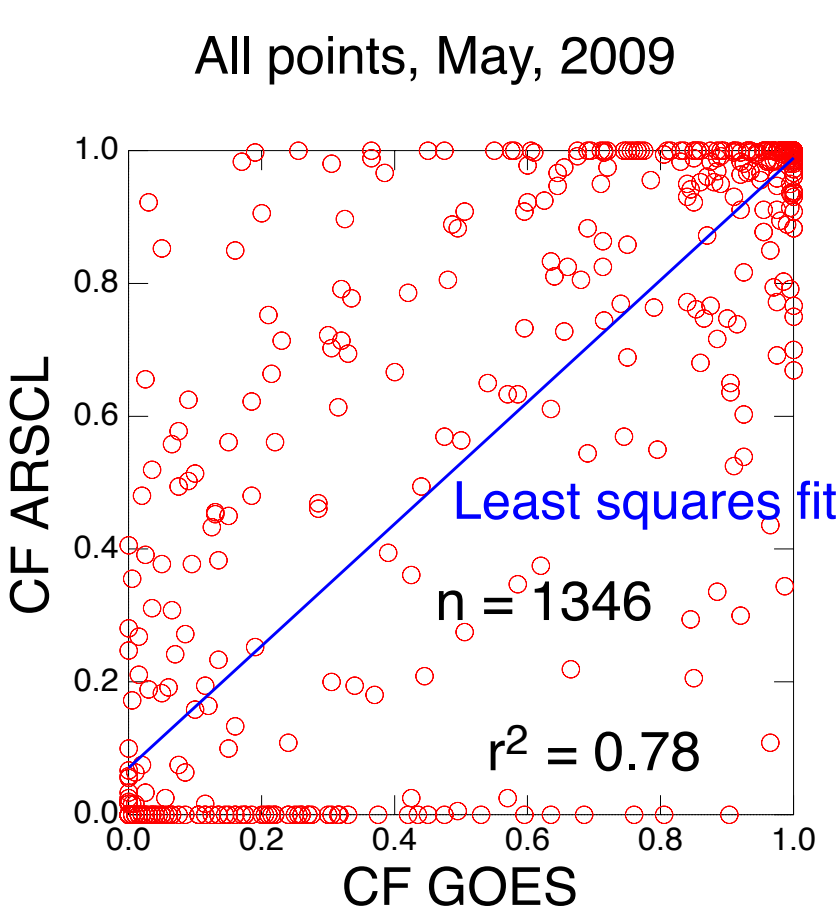
Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014

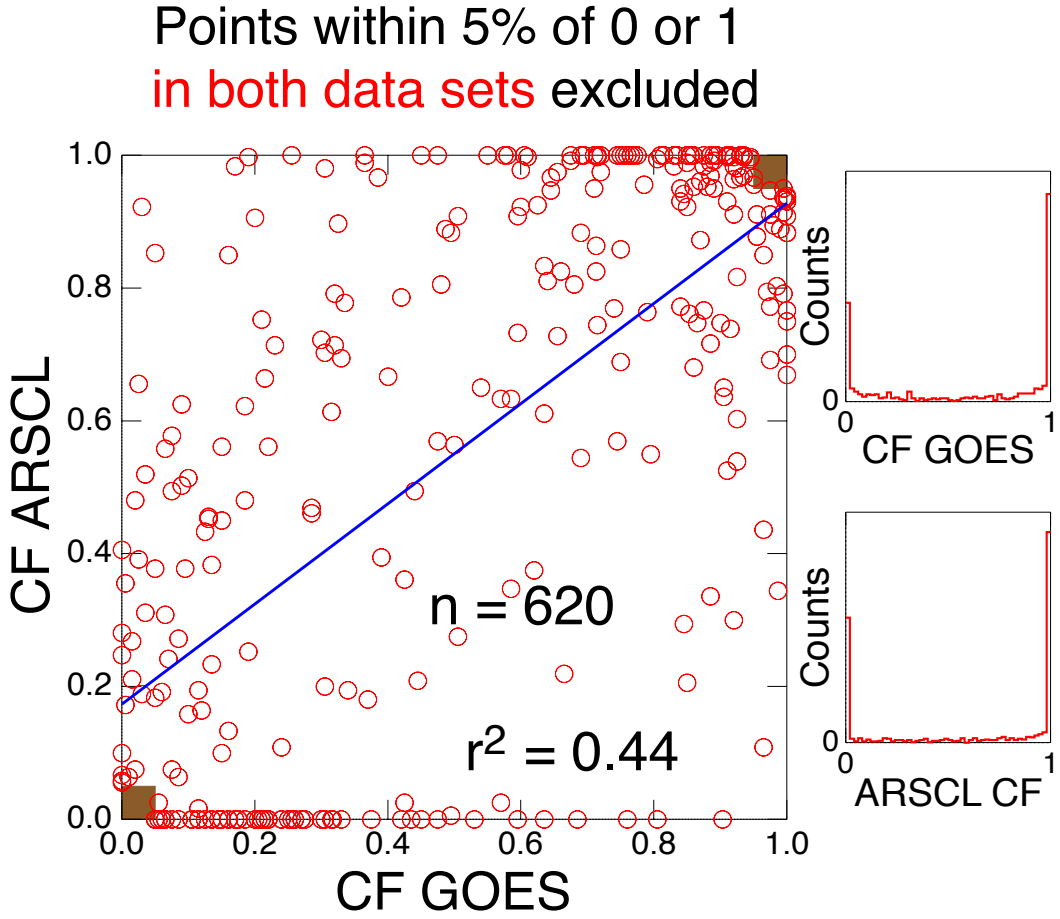
Different methods yield ***substantial systematic differences in the mean***.

Error of 0.1 in cloud fraction is ~ 7 W m^{-2} in shortwave, 4 W m^{-2} in longwave.

CORRELATION OF CLOUD FRACTION BY DIFFERENT METHODS

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

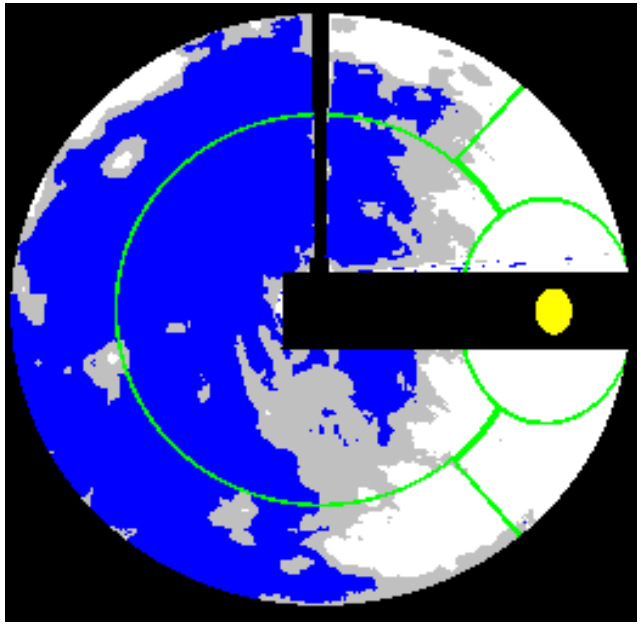




Excluding all-cloud and no-cloud scenes reduces variance accounted for by the regression from 78% to 44%.

TOTAL SKY IMAGER

Uplooking convex mirror; downlooking camera



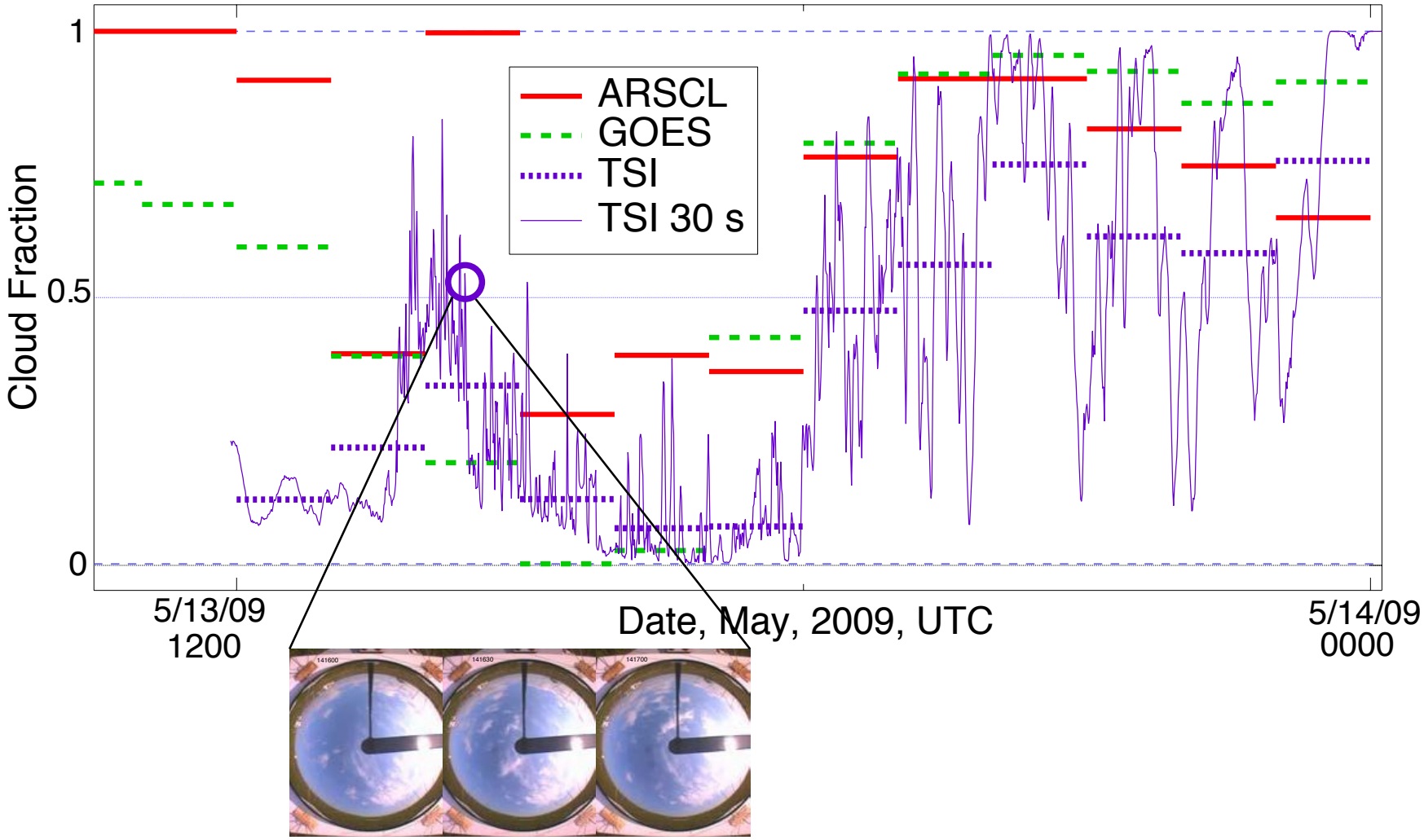
Opaque and thin cloud masks as fraction of pixels

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

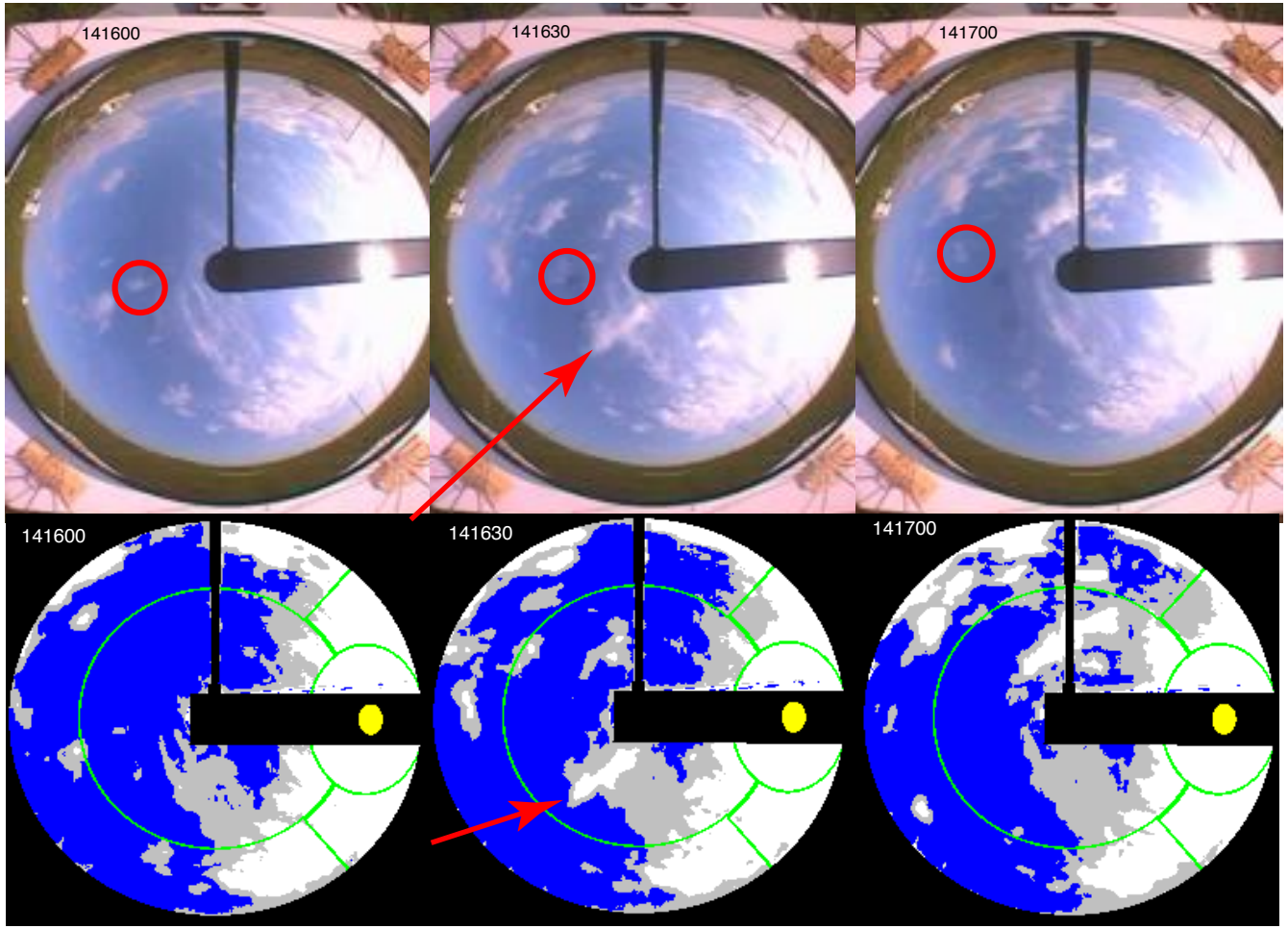


Substantial variation among methods.

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



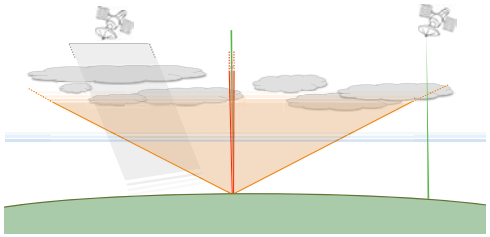
TSI threshold misses thin visible clouds

Substantial changes at 30-s intervals as clouds are blown by wind.

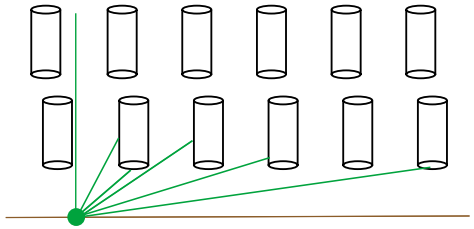
REASONS FOR DIFFERENCES IN MEASURED CLOUD FRACTION

Trivial

Mismatch of spatial and/or temporal domain.

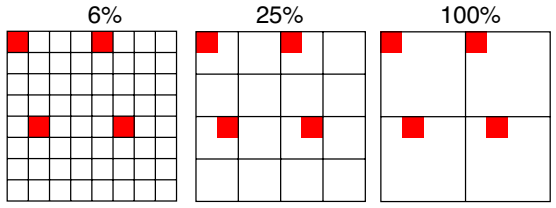


View angle – sidewall effect – cloud aspect ratio.

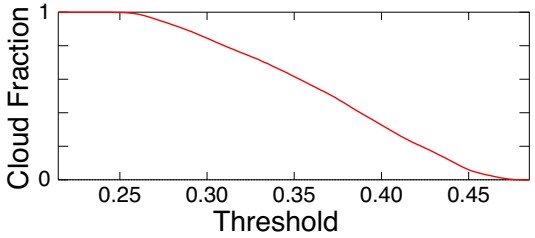


Intrinsic

Spatial resolution.



Threshold.

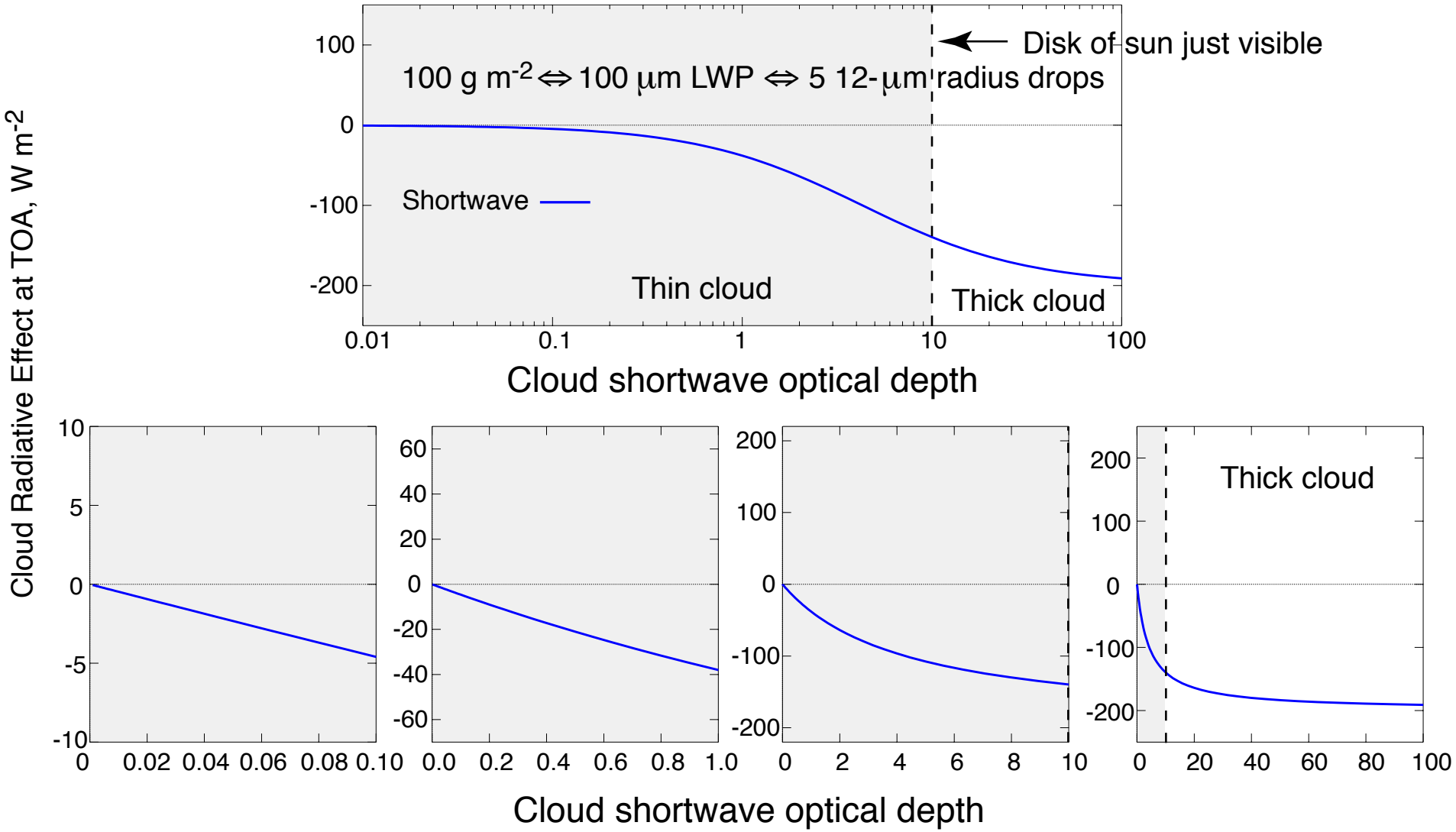


AND IF WE KNEW CLOUD FRACTION, WOULD IT BE OF ANY USE TO US?

CLOUD RADIATIVE EFFECT

Dependence on shortwave optical depth and cloud-top temperature

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

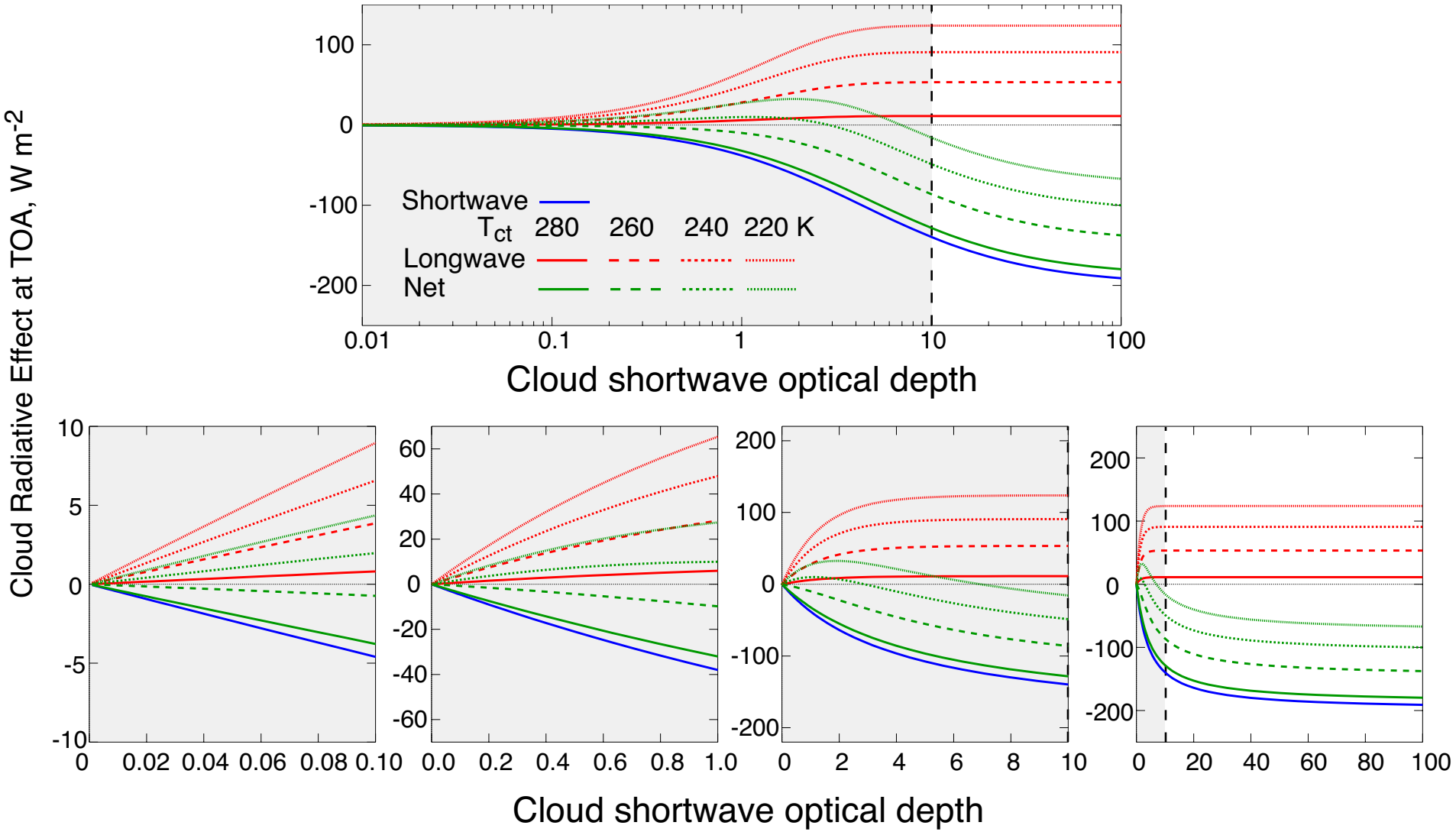


CRE is initially linear in optical depth, saturating at high optical depth.

CLOUD RADIATIVE EFFECT

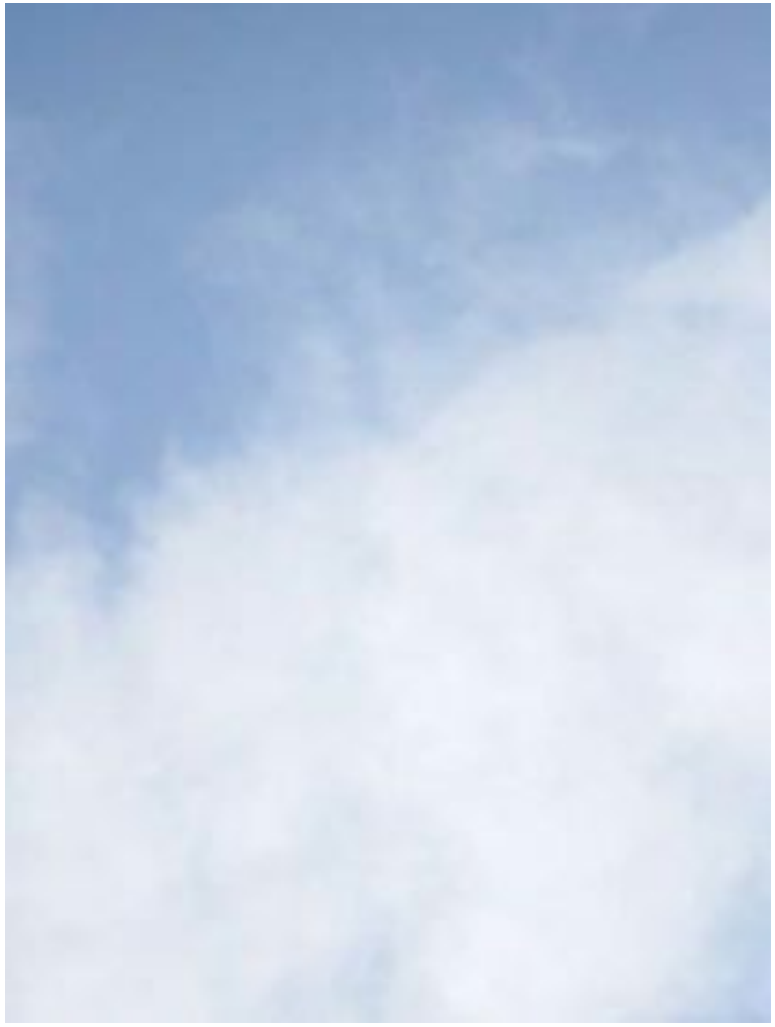
Dependence on shortwave optical depth and cloud-top temperature

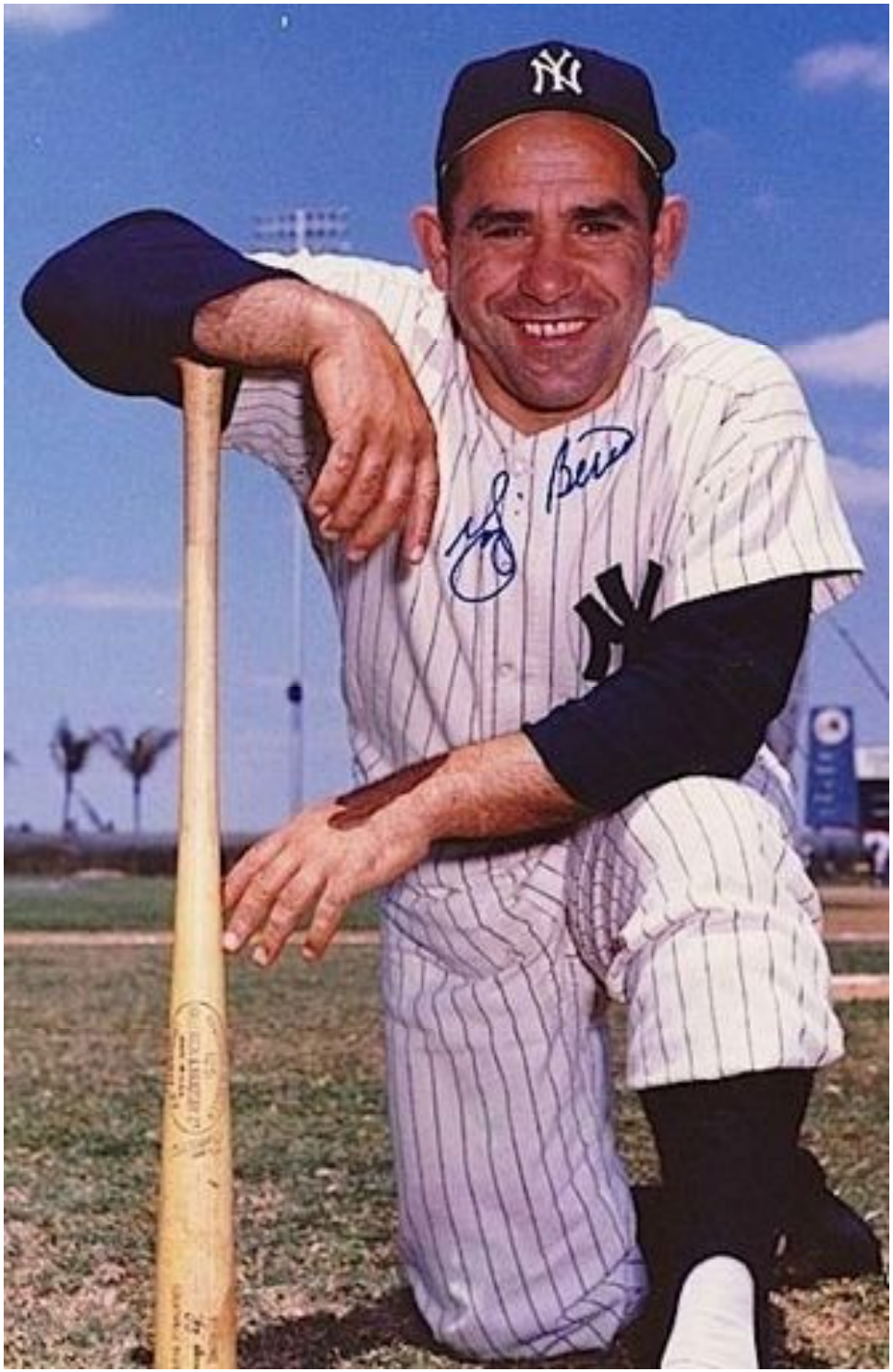
24-Hour average CRE, north central Oklahoma, at equinox



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?



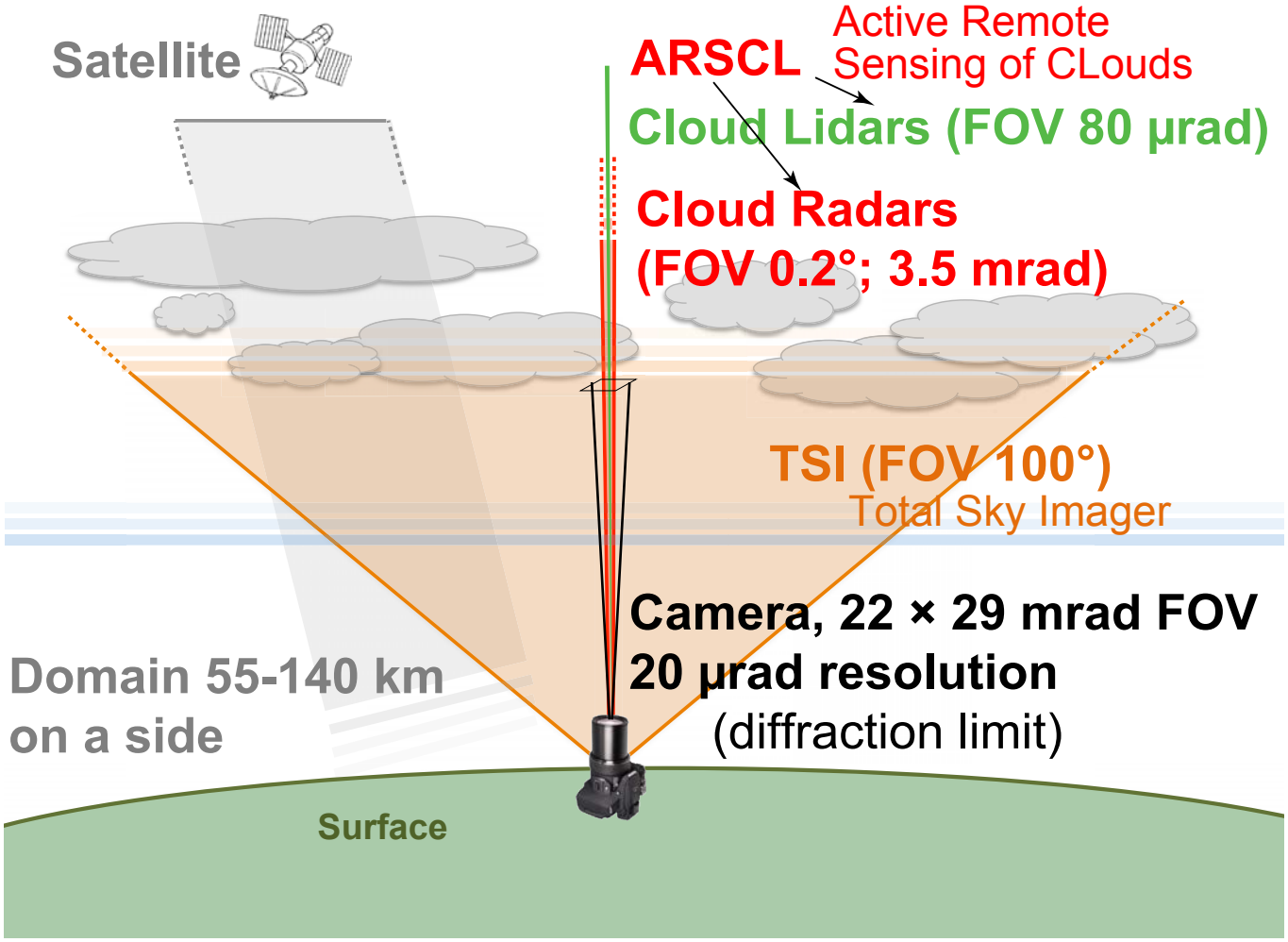


YOU CAN OBSERVE A LOT JUST BY LOOKING

-Yogi Berra

WHAT CAN WE LEARN FROM HIGH RESOLUTION SURFACE-BASED IMAGING OF CLOUDS?

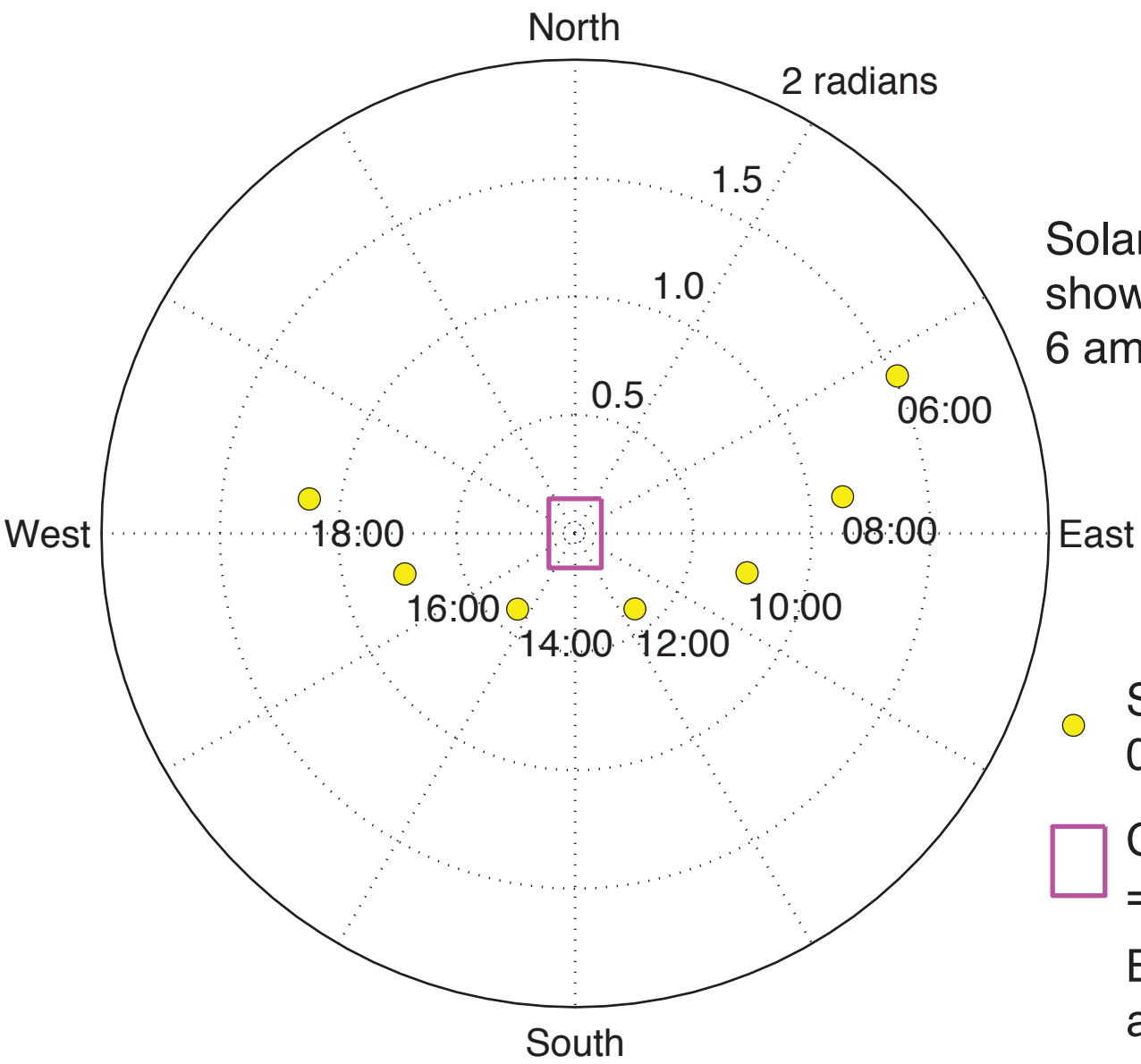
MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION



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

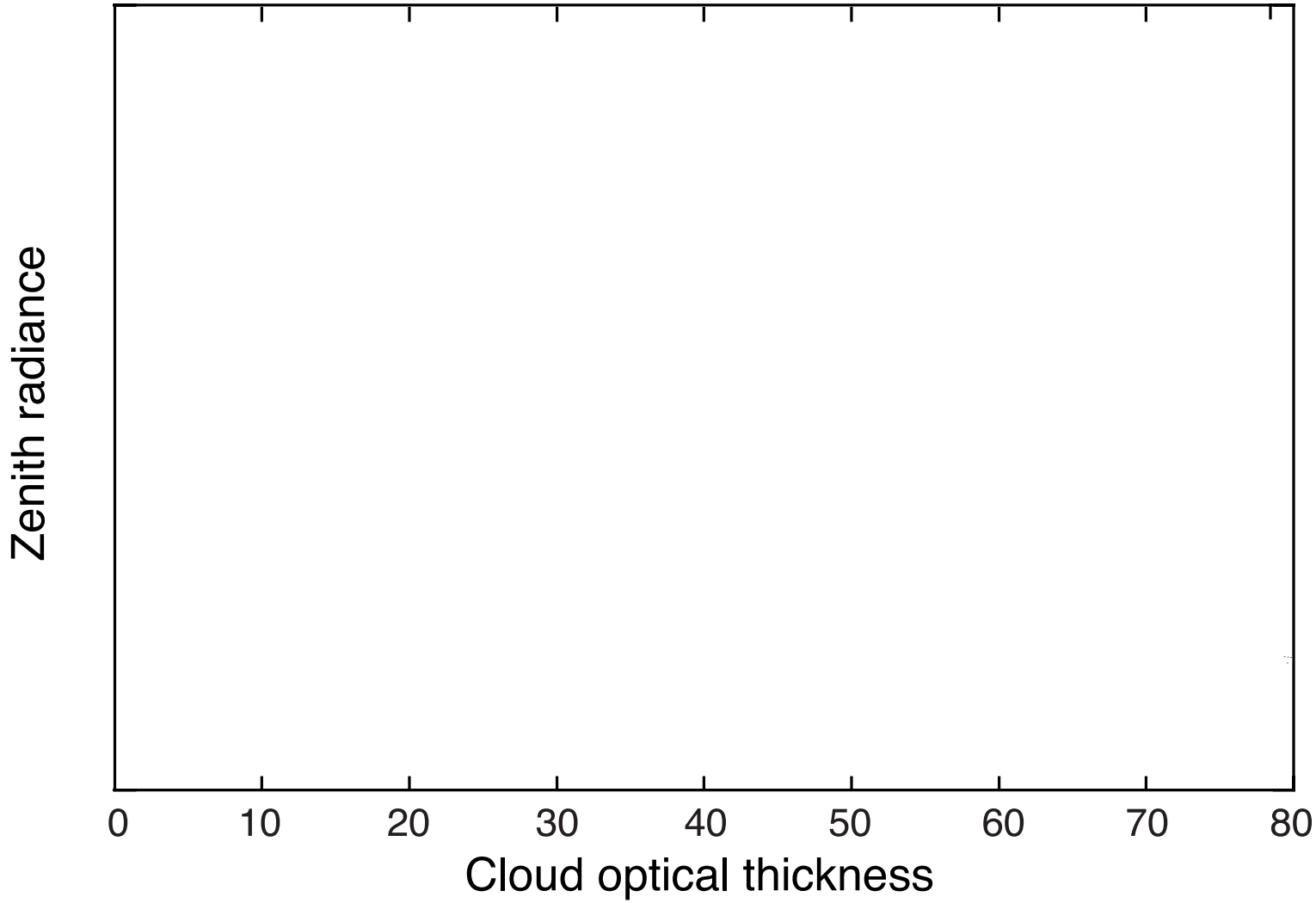
Sun, Angular Diameter 0.535° = 9.3 mrad

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

Both drawn 10 times actual angular dimension

ZENITH RADIANCE

How does it depend on cloud optical thickness??

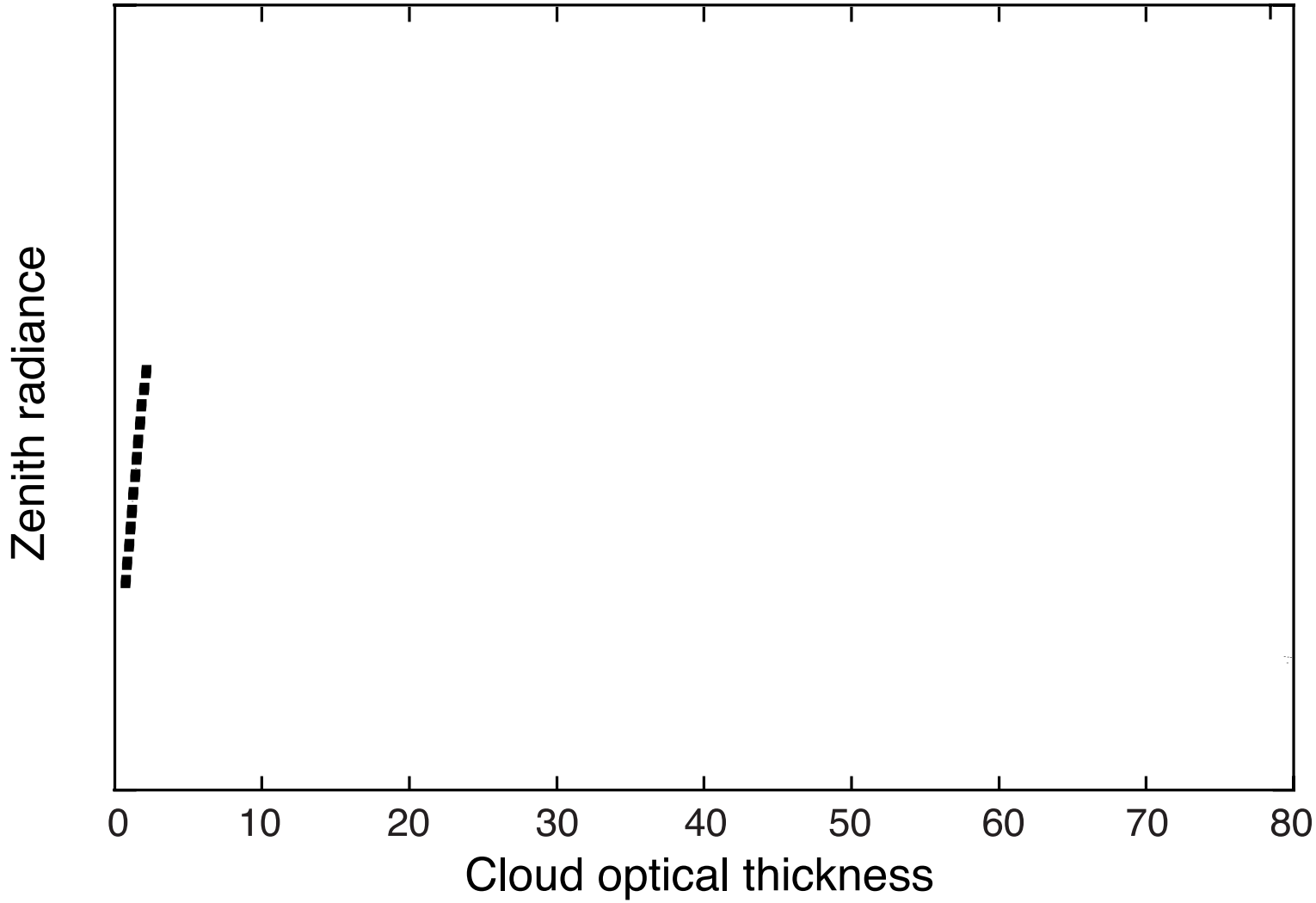


Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006

Simple question. But what is the answer?

ZENITH RADIANCE

How does it depend on cloud optical thickness??

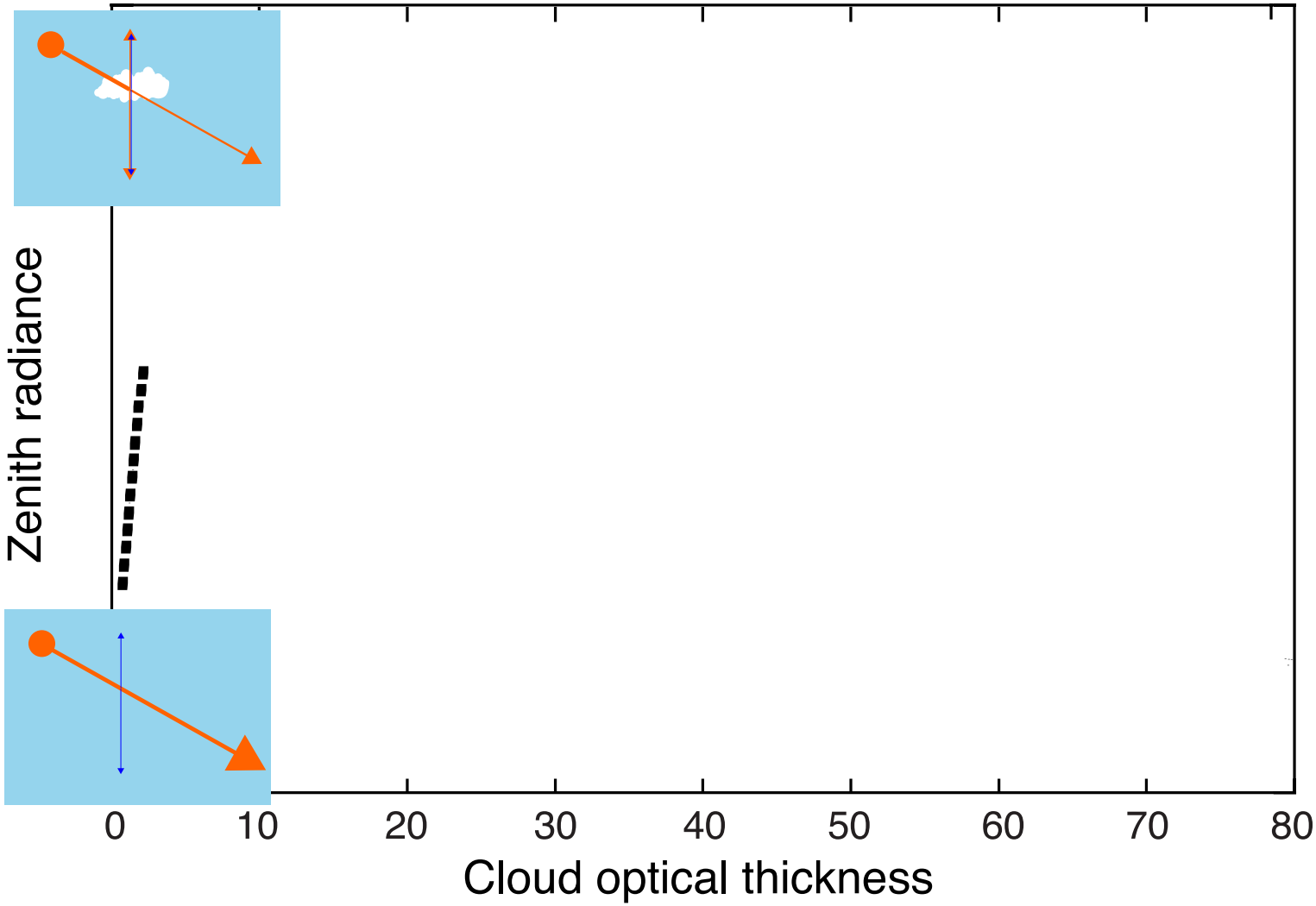


Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006

Initially, with thin cloud it increases. Why??

ZENITH RADIANCE

How does it depend on cloud optical thickness??

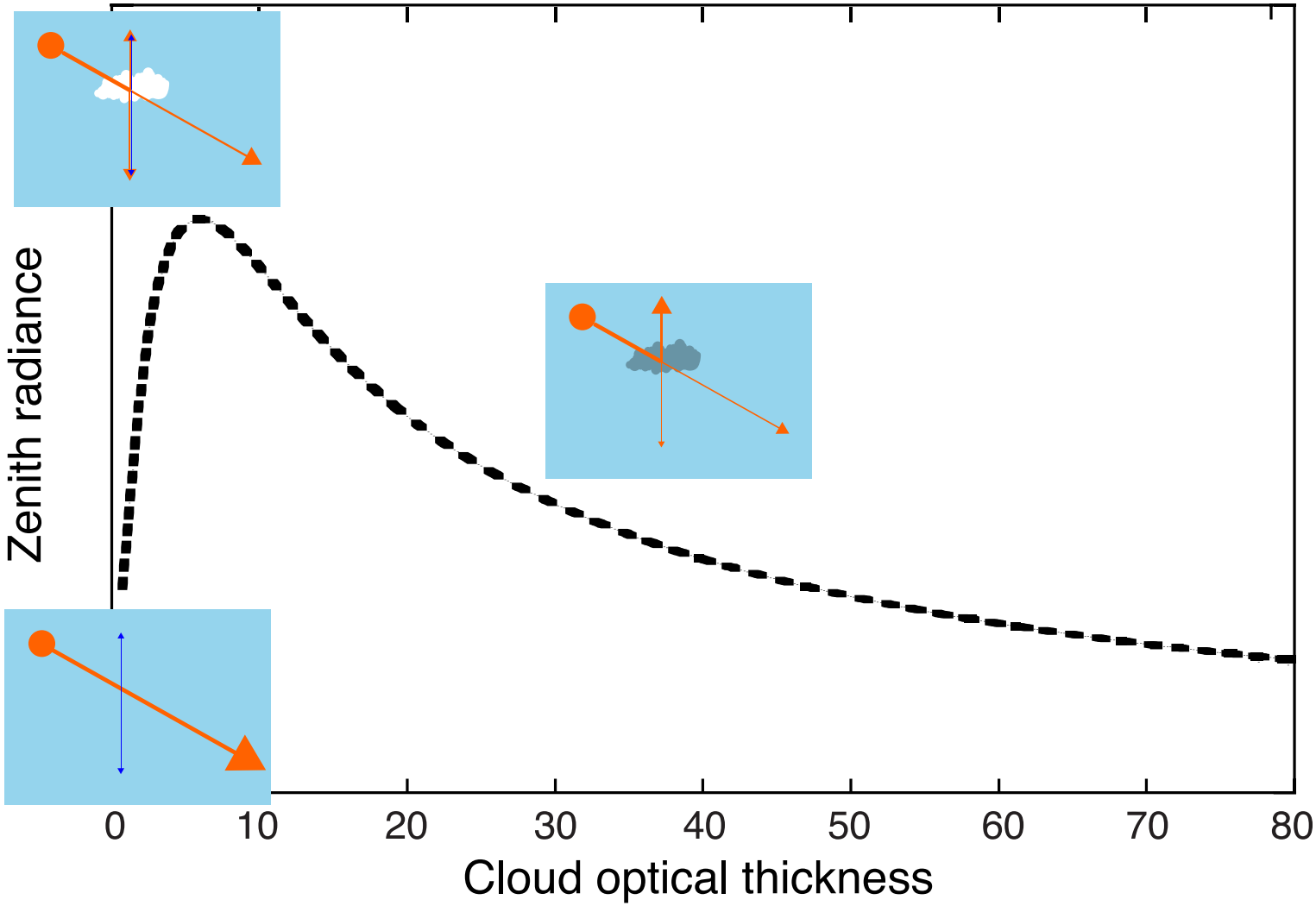


Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006

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

ZENITH RADIANCE

How does it depend on cloud optical thickness??

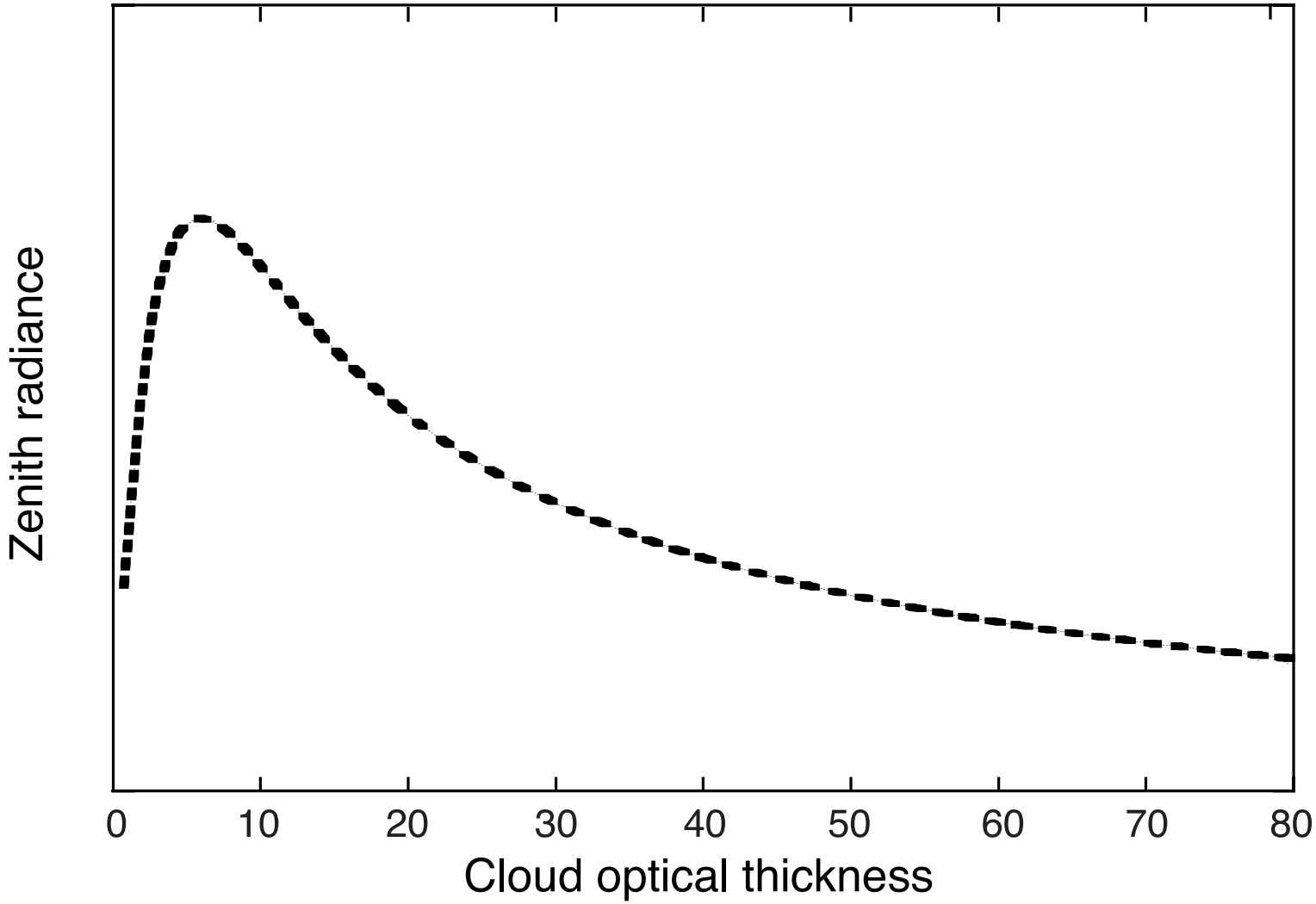


Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006

With increasing cloud optical thickness zenith radiance decreases as reflectance increases and transmittance decreases.

ZENITH RADIANCE

How does it depend on cloud optical thickness??



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

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

COMPUTER OPERATING SYSTEM AS CATALOG

S0012627.tif

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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.

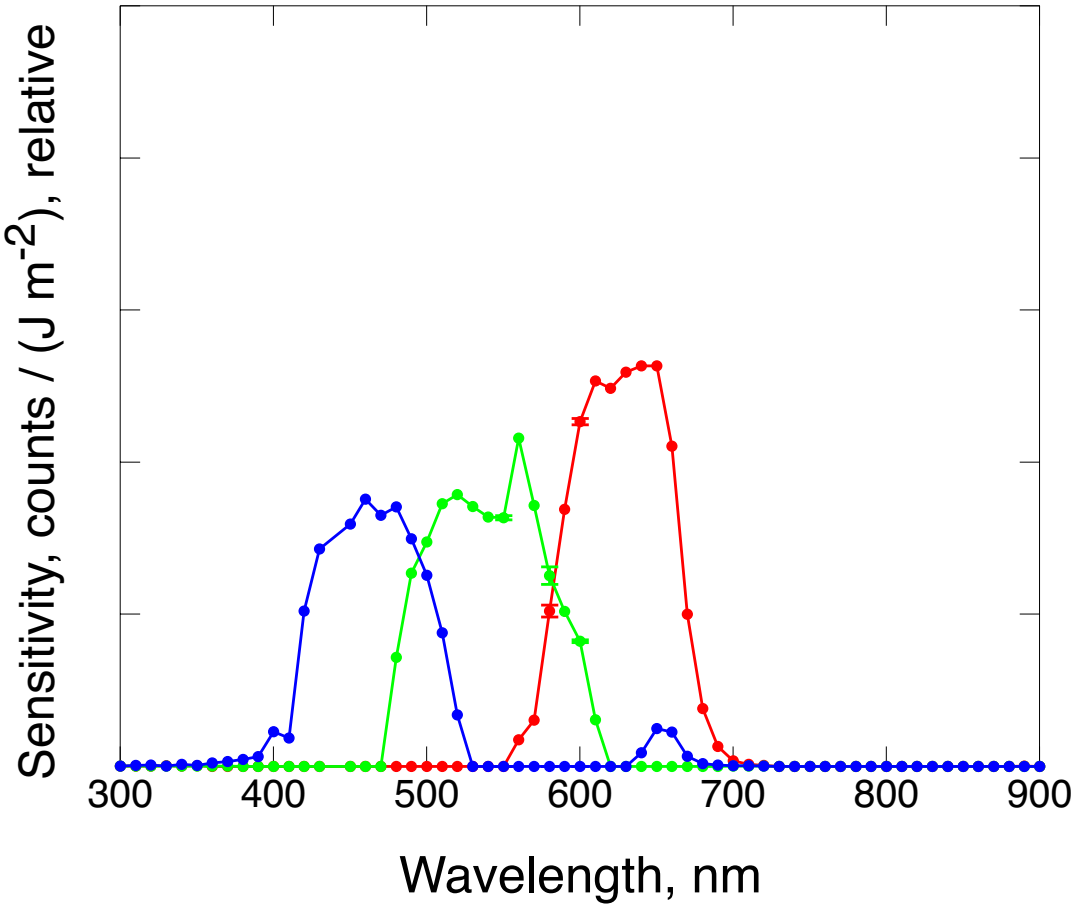
Extremely local.

Aerosol masquerades as cloud.

Lots of data!

CAMERA WAVELENGTH RESPONSE

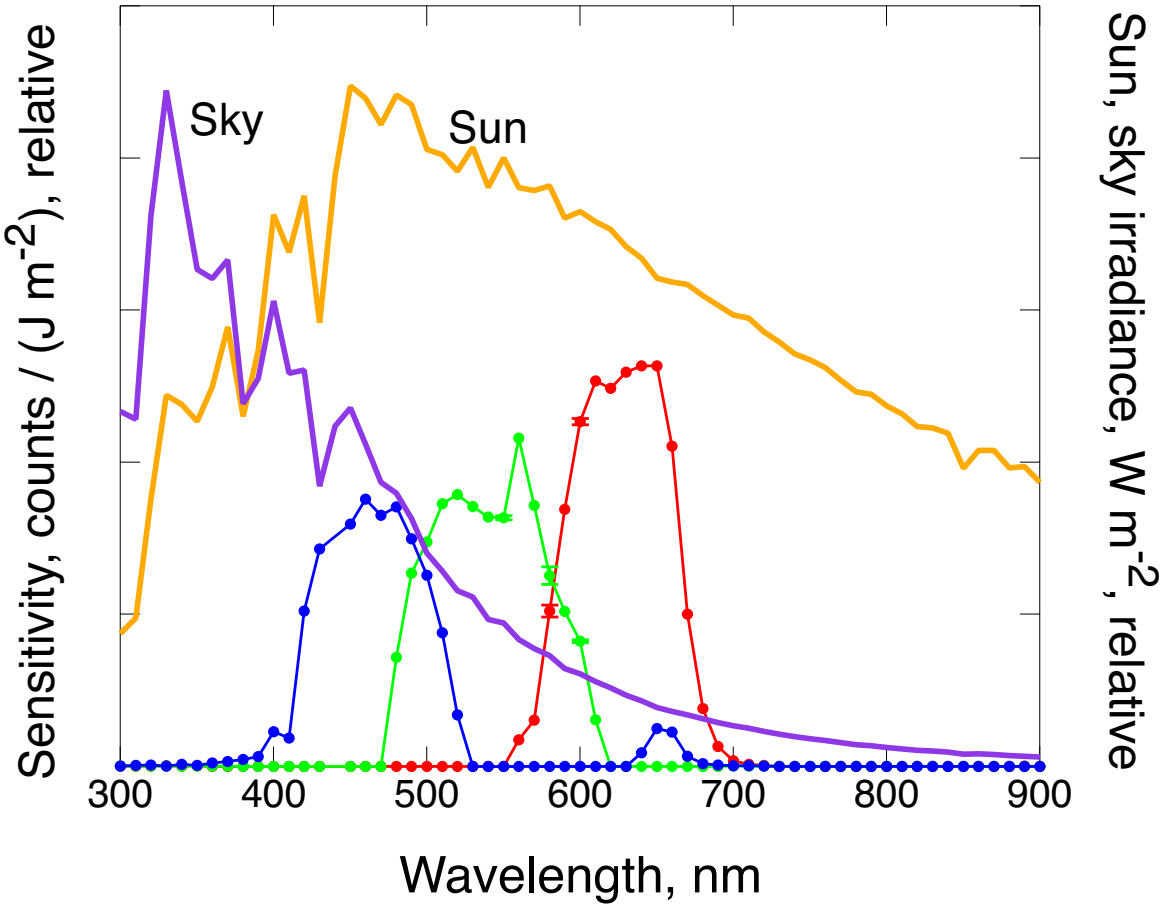
Integrating sphere with NIST traceable photodiode



Red and Blue are fairly well separated.

CAMERA WAVELENGTH RESPONSE

Comparison with Sun and Sky spectral irradiance

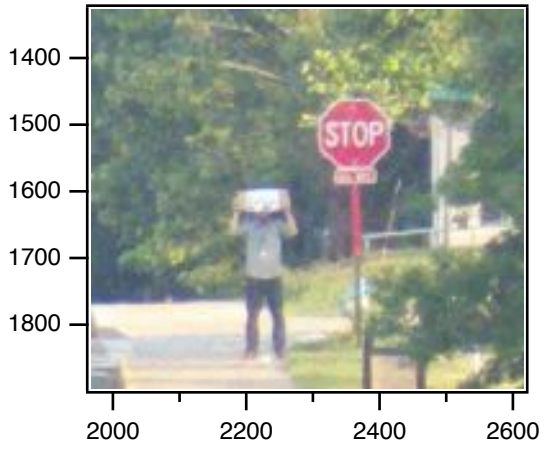


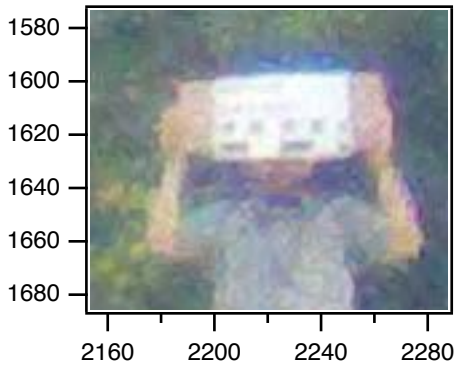
Red and Blue are fairly well separated.

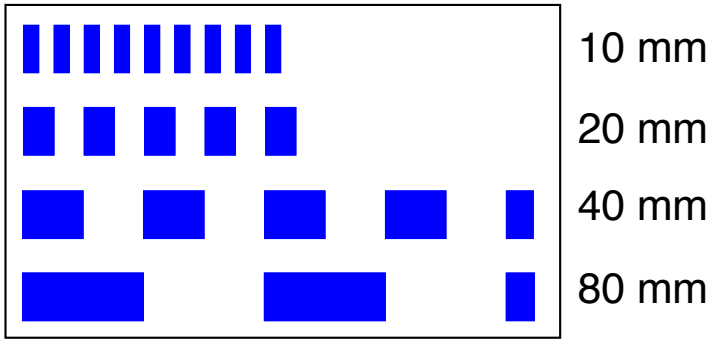
Sun and Sky spectra overlap both Red and Blue, but with different weights.

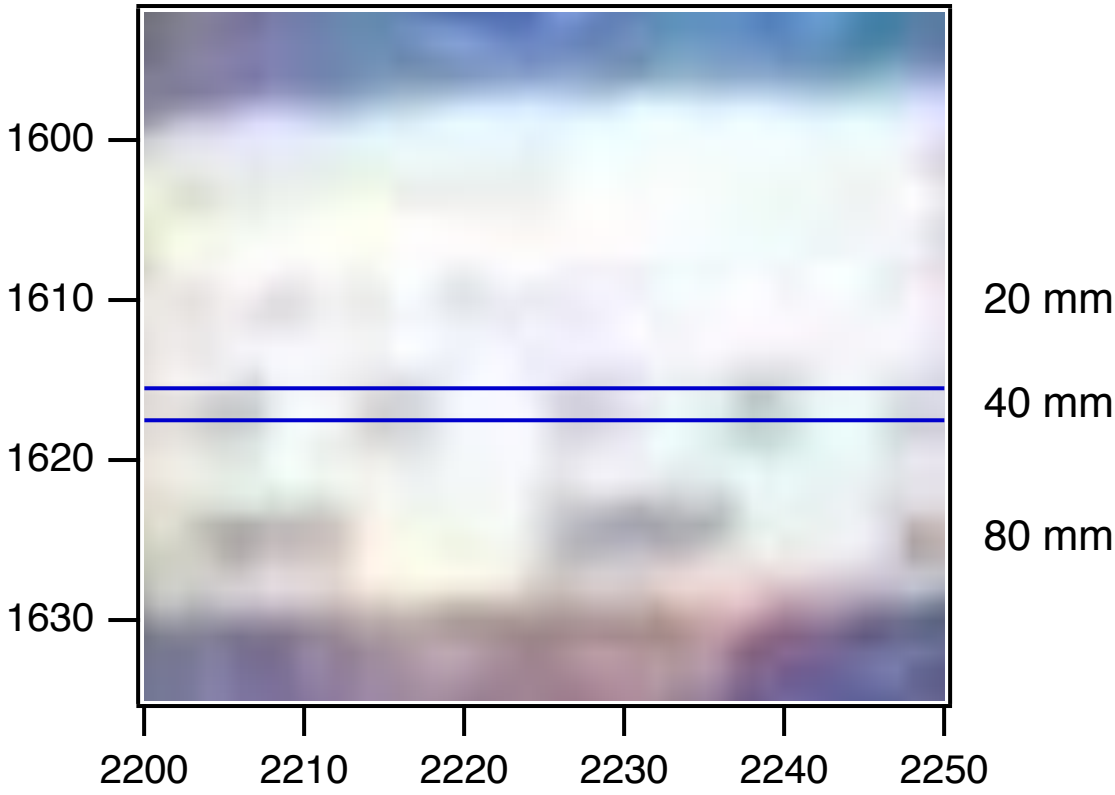
This can be exploited in distinguishing cloudy and cloud-free sky.

RESOLVING POWER TEST AT 1 km









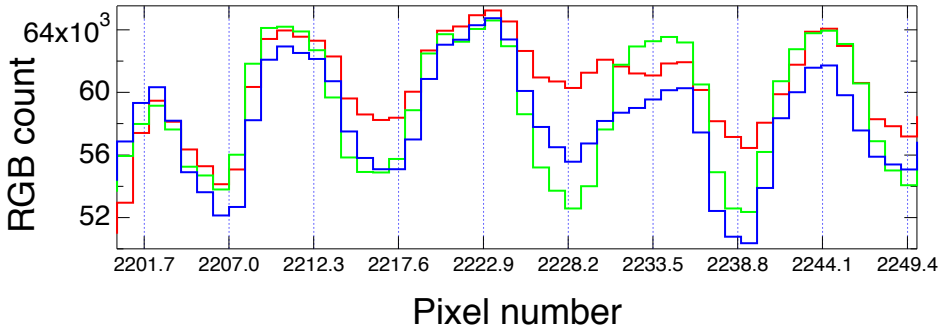
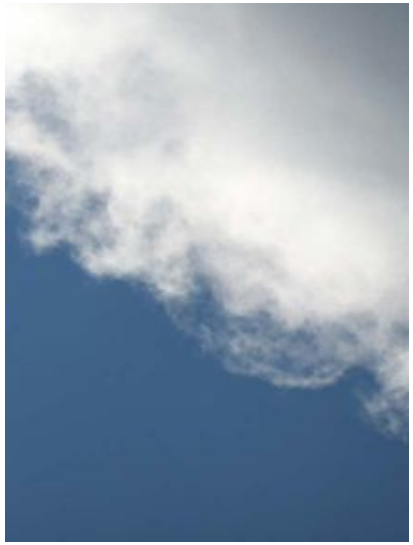
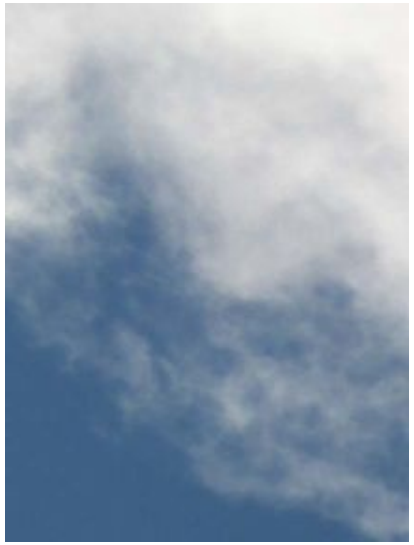


IMAGE PROCESSING AND ANALYSIS TOOLS

Natural color



Expand



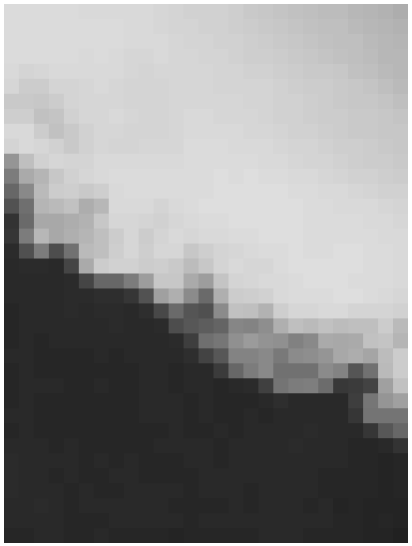
Expand

Expand

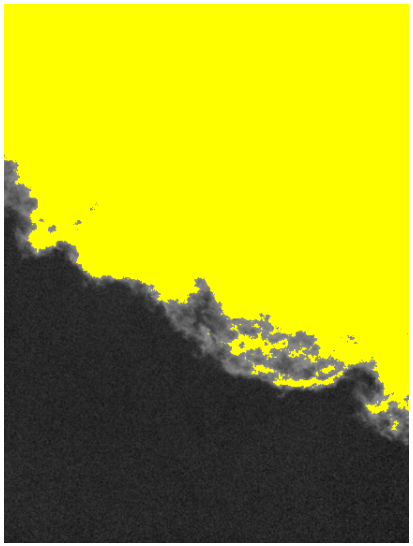
Red

Red/(Red+Blue)

Pixelate

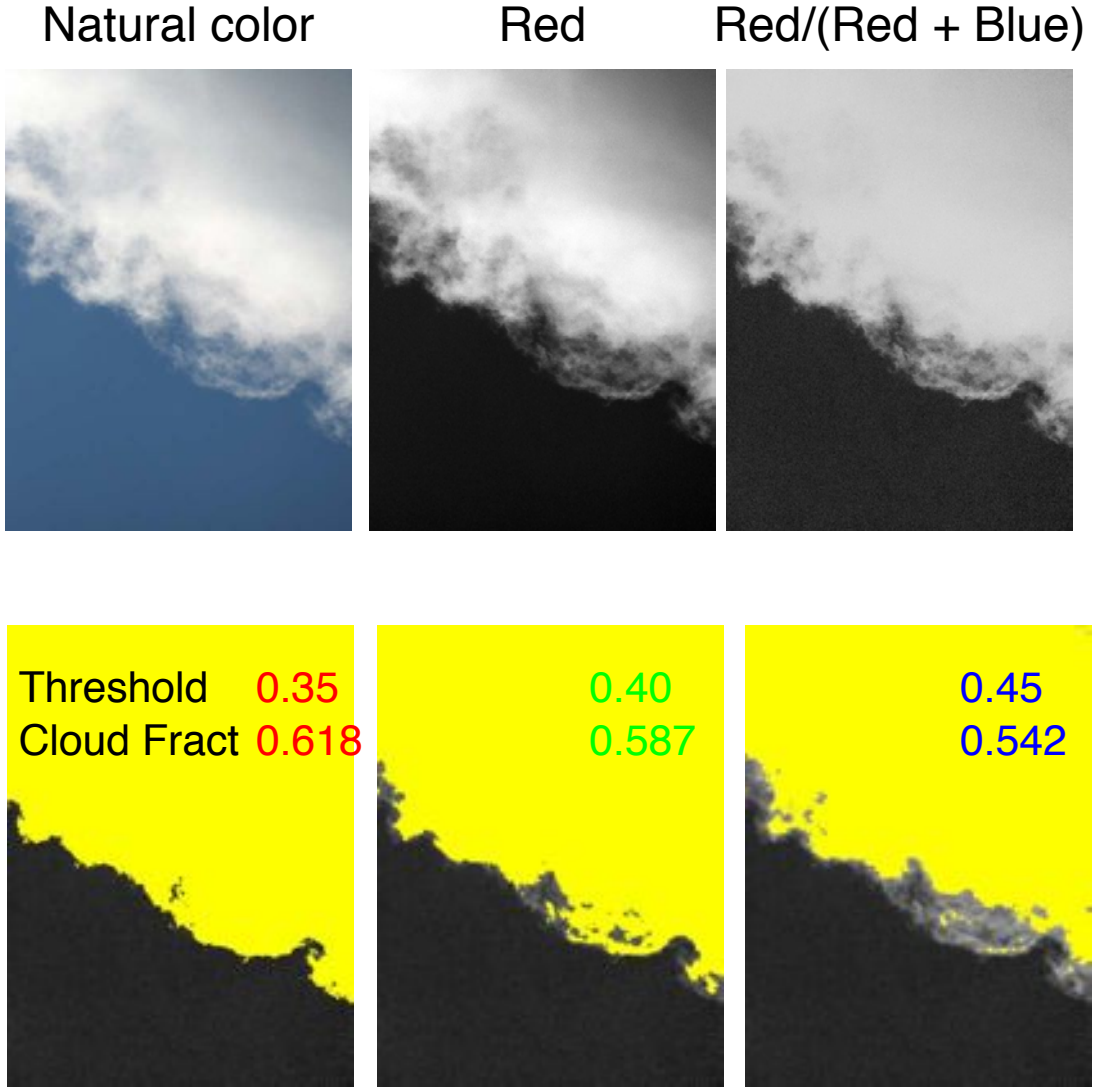


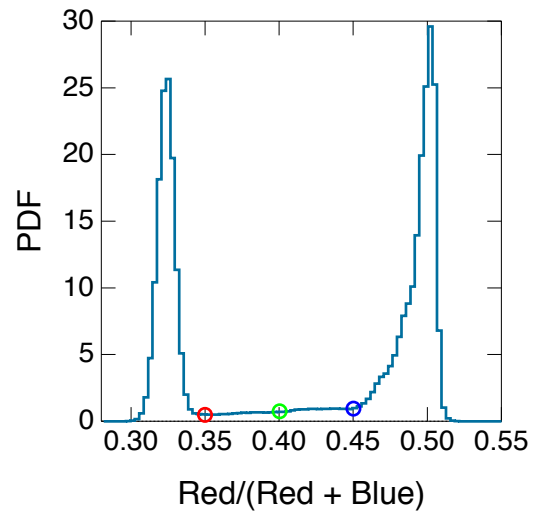
Threshold

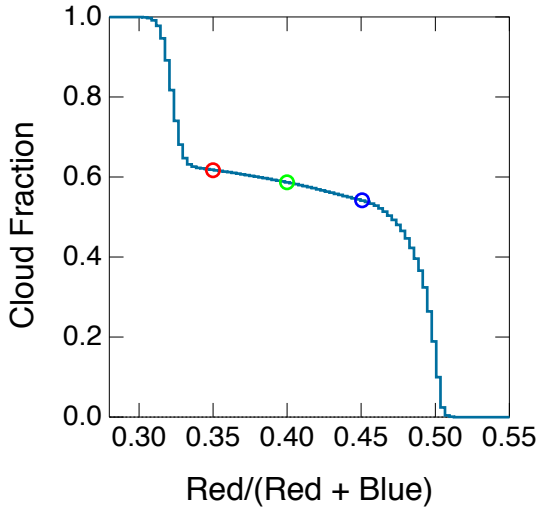


DETERMINING CLOUD FRACTION

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



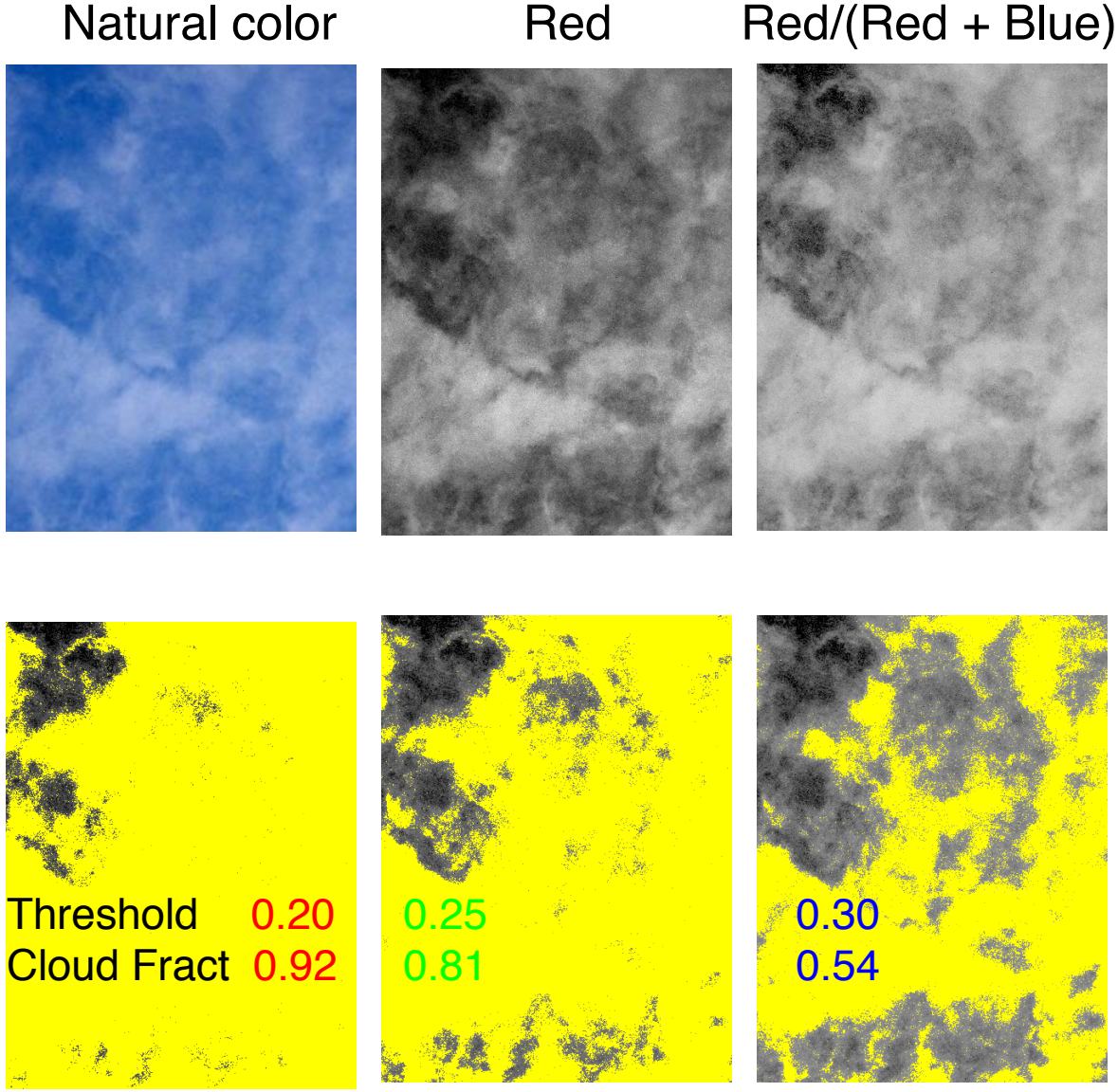


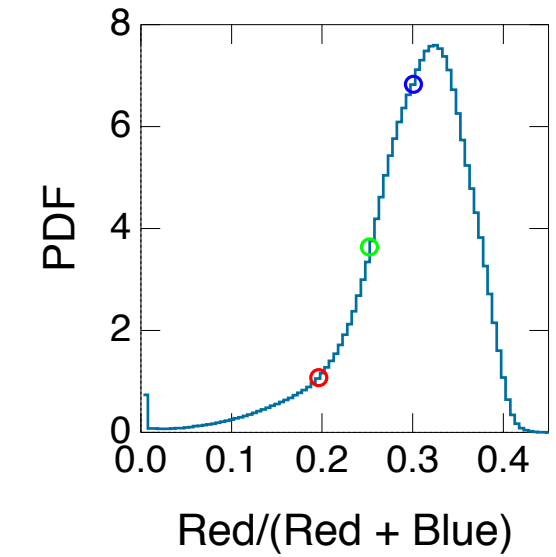


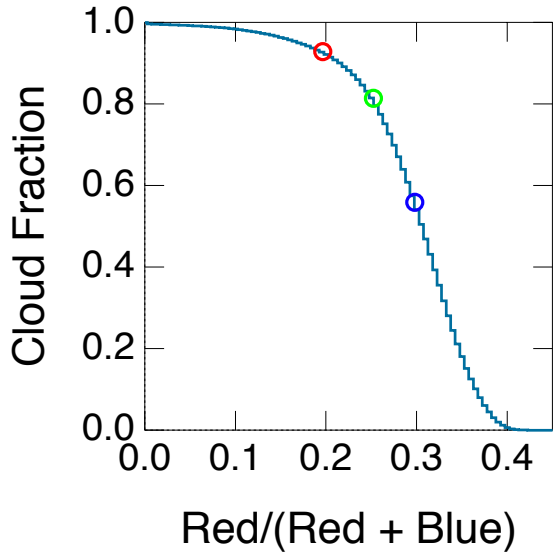
Cloud fraction is constrained between ~0.54 and ~0.62.

DETERMINING CLOUD FRACTION

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



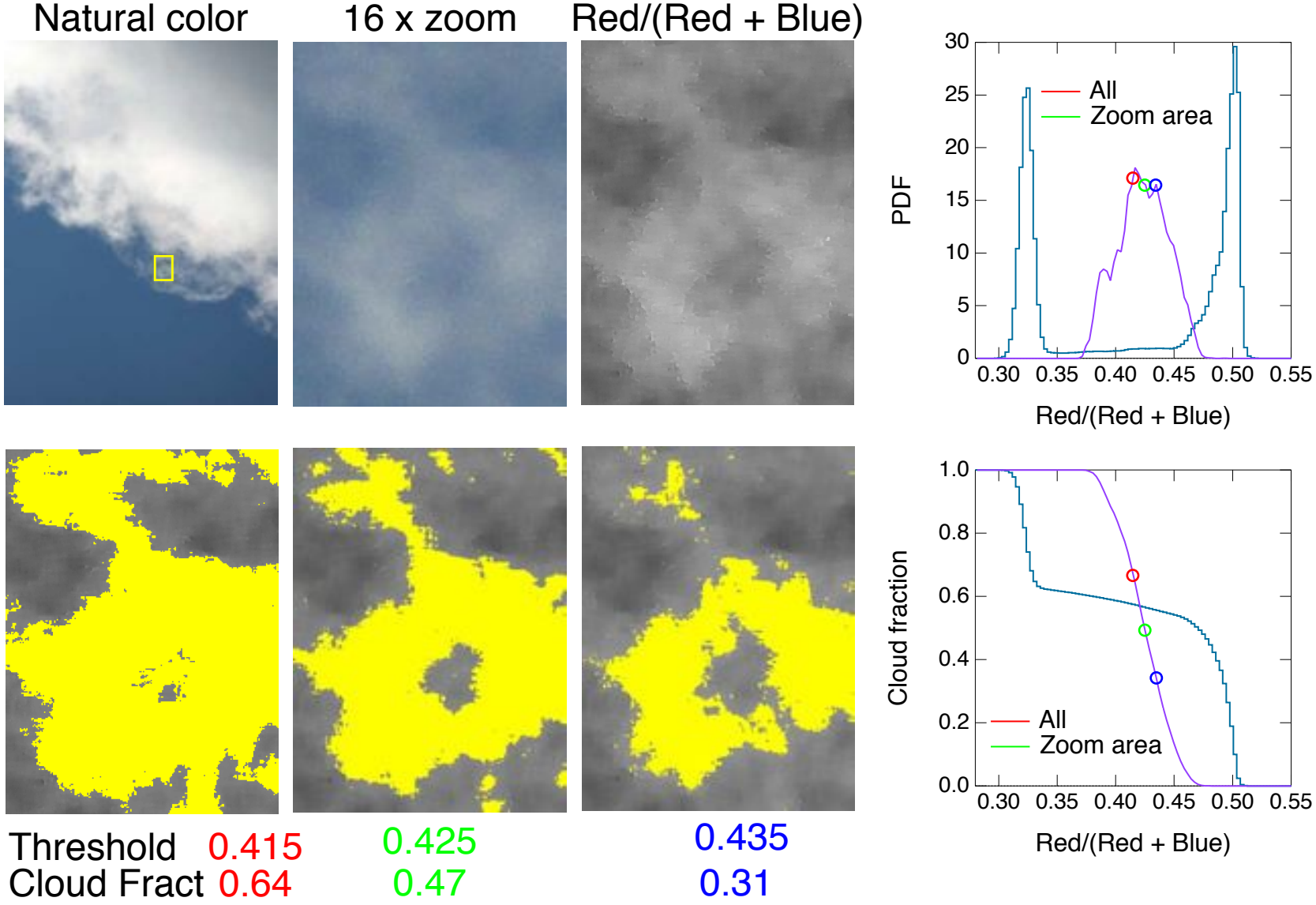




Cloud fraction is indeterminate.

DETERMINING CLOUD FRACTION

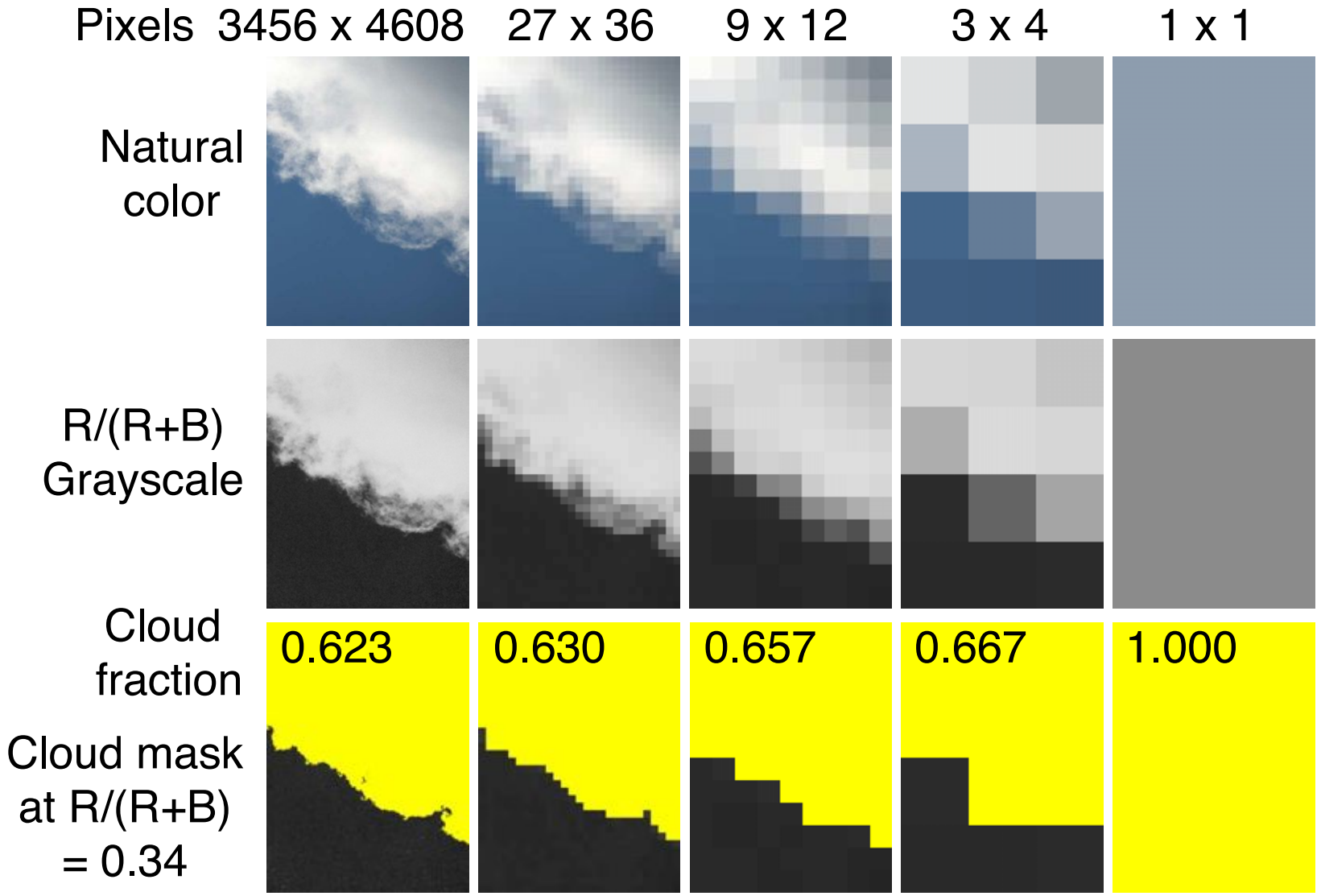
Cloud mask as function of threshold Red/(Red + Blue)



Cloud fraction in zoom area is indeterminate.

EFFECT OF RESOLUTION ON CLOUD FRACTION

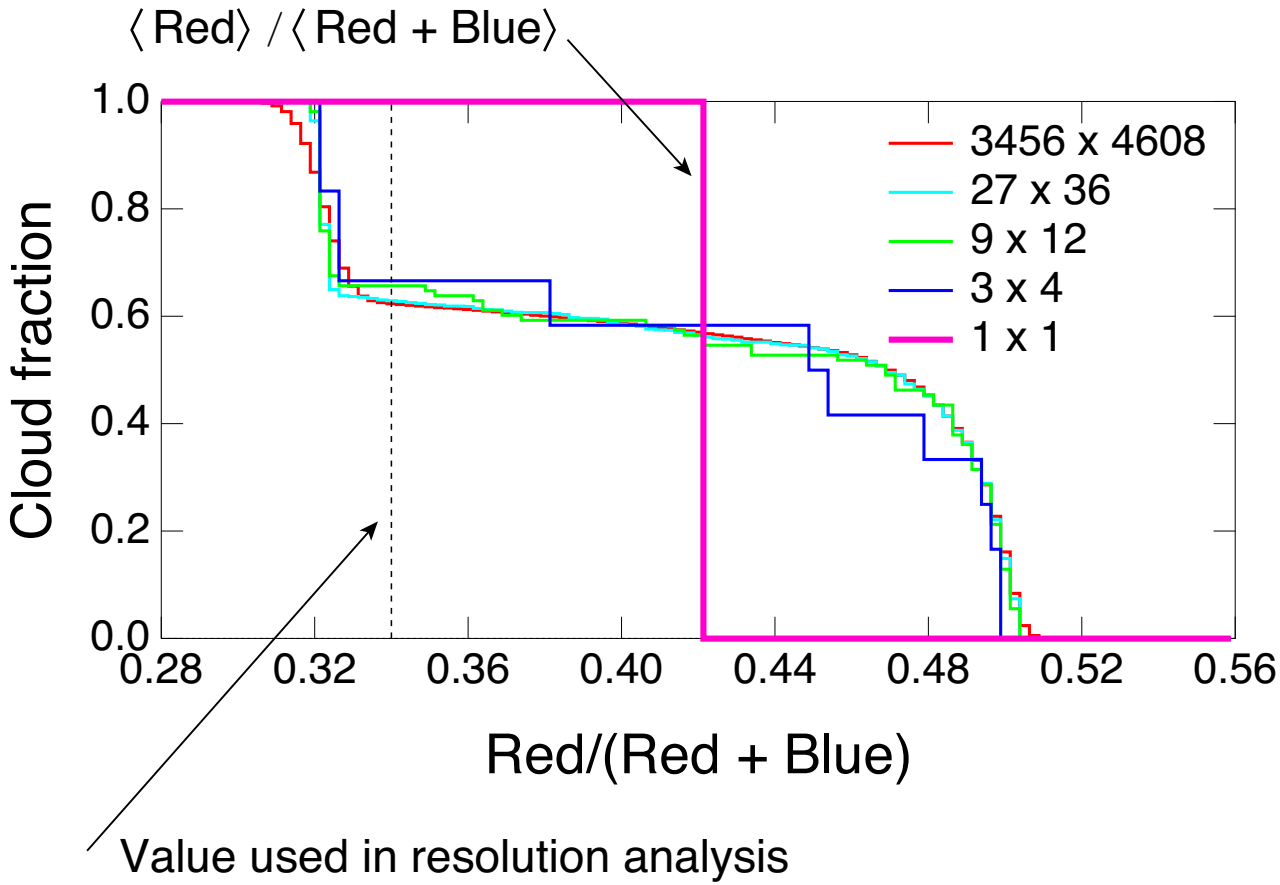
Resolution artificially degraded from 6 μrad to 2 × mrad
at constant threshold



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



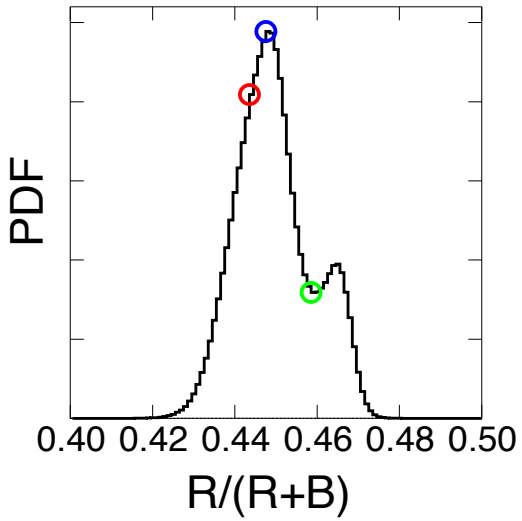
As resolution is degraded, cloud fraction tends to increase if threshold is below mean, and vice versa.

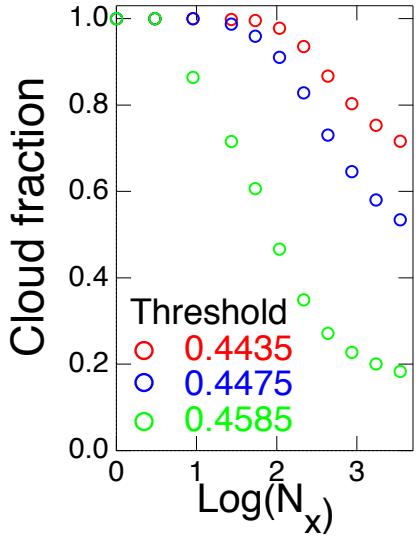
CLOUD FRACTION DEPENDENCE ON THRESHOLD AND RESOLUTION

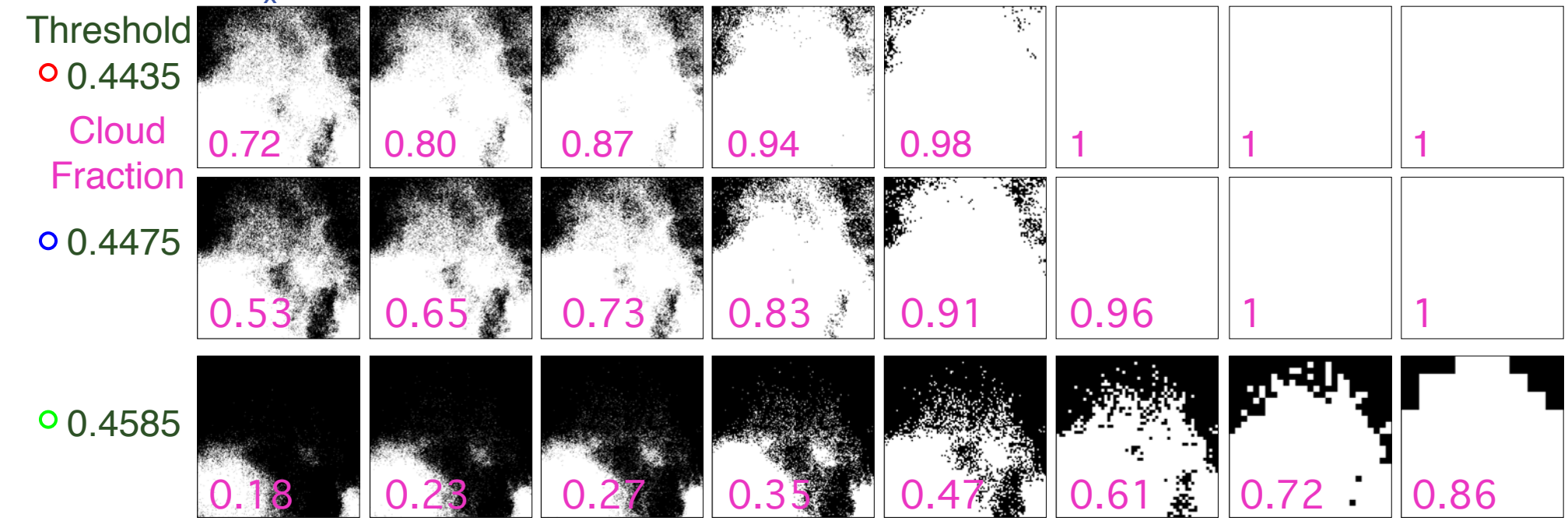
All pixels with ***any*** cloud are counted as cloud

Original Image

Red/(Red + Blue)







Cloud fraction depends strongly on on threshold and resolution.

SUMMARY ON CLOUD FRACTION

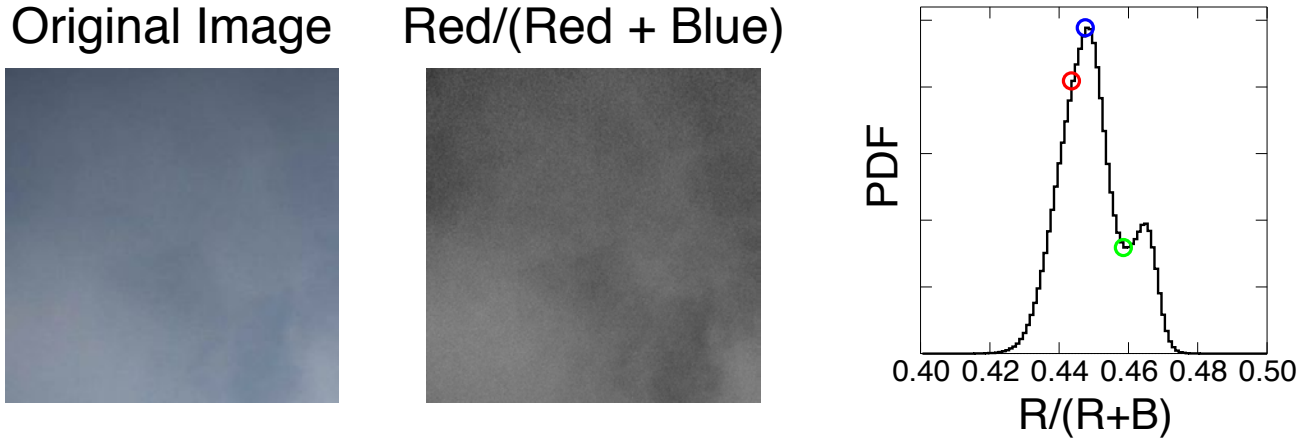
CAN IT BE DEFINED? NO!

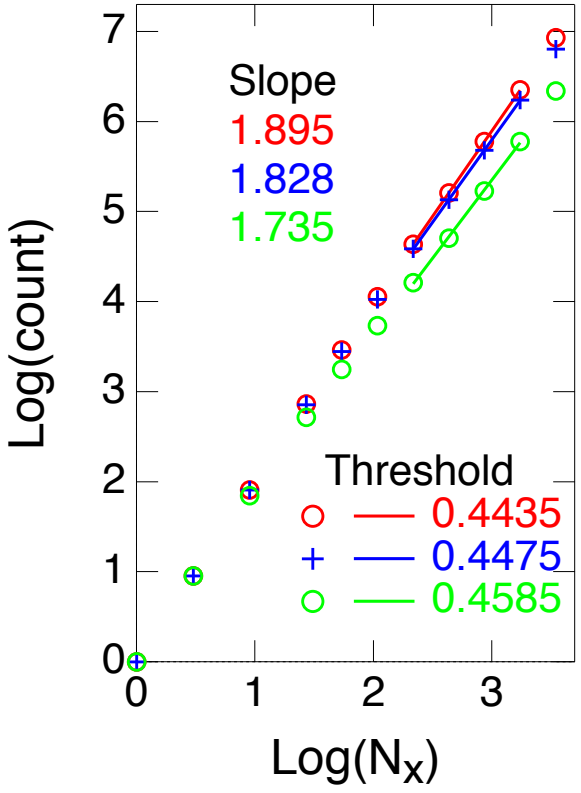
CAN IT BE MEASURED? NO!

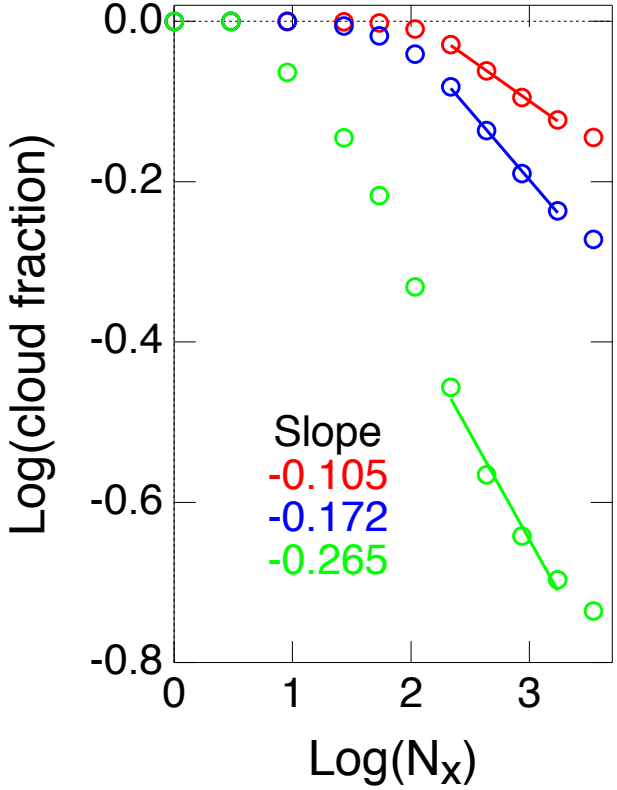
AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY? NO!

CLOUD FRACTAL DIMENSION DEPENDENCE ON THRESHOLD

All pixels with any cloud are counted as cloud – Box counting method



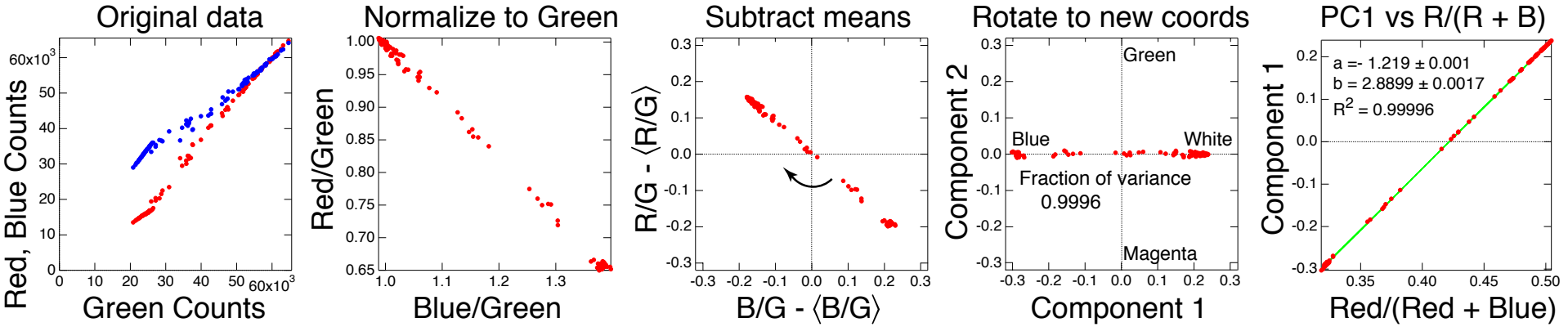


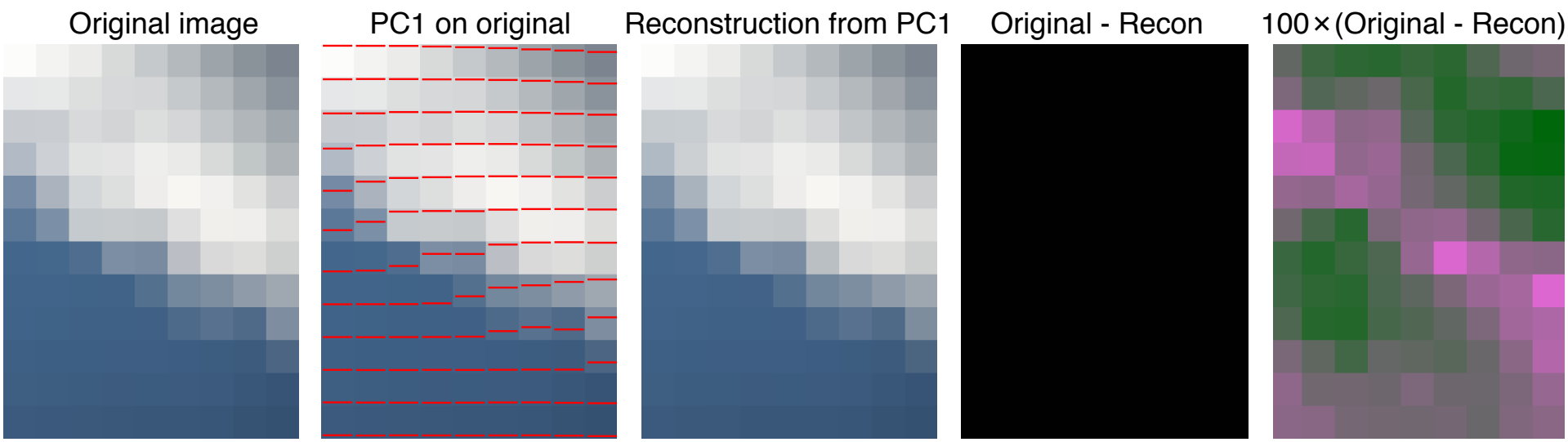


Cloud fractal dimension depends strongly on on threshold.

PRINCIPAL COMPONENT ANALYSIS

Five easy steps





The color of the original image is accurately reconstructed by a ***single component***.

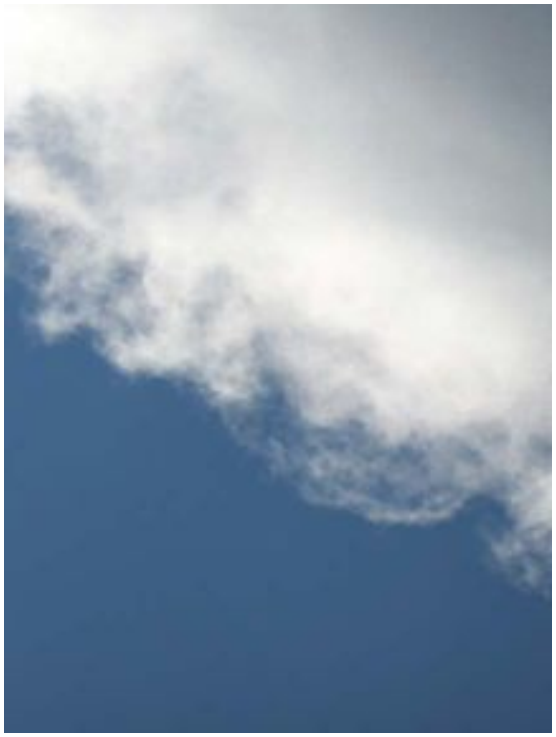
The first principal component is linearly related to Red/(Red + Blue), which thus serves as a ***quantitative measure of cloud contribution to zenith radiance***.

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).