MODIS Cloud MASK MOD35

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Outline

- Introduction
- Description of the Cloud Mask
- Assessment and Validation
- Some Applications
- Summary
- Some Useful References

What is a cloud?

Depends on detection objective….

What are three ways that we detect objects using our visual sensors (eyes and brain)?

Our philosophy

Restrictions in the 1990s

MODIS

- The MODIS (Moderate Resolution Imaging Spectroradiometer) measures radiances at 36 wavelengths including infrared and visible bands with spatial resolution 250 m to 1 km.
- MODIS "cloud mask" algorithm uses conceptual domains according to surface type and solar illumination including land, water, snow/ice, desert, and coast for both day and night.
- A series of threshold tests attempts to detect instrument field-of-view scenes with unobstructed views of surface.

Table 2 in MODIS Cloud Mask ATBD

Table 2. MODIS bands used in the MODIS cloud mask algorithm.

Band	Wavelength (µm)		Comment
1 (250 m)	0.659	Y	250-m and 1-km cloud detection
2 (250 m)	0.865	Y	250-m and 1-km cloud detection
3 (500 m)	0.470	Y	Smoke, dust detection
4 (500 m)	0.555	Y	Snow/ice detection (NDSI)
5 (500 m)	1.240	Y	Smoke, dust detection
6 (500 m)	1.640	Y	Terra snow/ice detection (NDSI)
7 (500 m)	2.130	Y	Aqua snow/ice detection (NDSI)
8	0.415	Y	Desert cloud detection
9	0.443	Y	Sun-glint clear-sky restoral tests
10	0.490	N	
11	0.531	N	
12	0.565	N	
13	0.653	N	
14	0.681	N	
15	0.750	N	
16	0.865	N	
17	0.905	Y	Sun-glint clear-sky restoral tests
18	0.936	Y	Sun-glint clear-sky restoral tests
19	0.940	N	
26	1.375	Y	Thin cirrus, high cloud detection
20	3.750	Y	Land, sun-glint clear-sky restoral tests Snow/ice, dust detection
21/22	3.959	Y(21)/Y(22)	smoke detection (21)/Cloud detection (22)
23	4.050	N	
24	4.465	N	
25	4.515	N	
27	6.715	Y	High cloud, inversion detection
28	7.325	Y	Cloud, inversion detection
29	8.550	Y	Cloud, dust, snow detection
30	9.730	N	
31	11.030	Y	Cloud, dust, snow detection, Land, sun-glint clear-sky restoral tests Inversion detection Thin cirrus detection
32	12.020	Y	Cloud, dust detection
33	13.335	Y	Inversion detection
34	13.635	N	
35	13.935	Y	High cloud detection
36	14.235	N	

Table 4. MODIS cloud mask tests executed for a given processing path.

Test/Bit #		Day Ocean	Night Ocean	Day Land	Night Land	Day Snow/ice	Night Snow/ice	Day Coast	Day Desert	Polar Day	Polar Night
BT_{11}	13	✓	✓								
$BT_{13.9}$	14	✓	✓	✓	✓	✓	✓	✓	✓		
$BT_{6.7}$	15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$R_{1.38}$	16	✓		✓		✓		✓	✓	✓	
$BT_{3.9}$-BT_{12}	17				✓		✓				✓
BT_{11}-BT_{12}	18	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
BT_{11}-$BT_{3.9}$	19	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$R_{0.66}$, $R_{0.87}$	20	✓		✓				✓	✓		
$R_{0.48}$	20								✓		
$R_{0.87}/R_{0.66}$	21	✓							✓		
$BT_{7.3}$-BT_{11}	23				✓		✓			✓	✓
$BT_{8.6}$-BT_{11}	24	✓	✓								
Sfc. Temp.	27	✓	✓		✓						
$BT_{8.6}$-$BT_{7.3}$	29		✓								
BT_{11} Var.	30		✓								

Table 4 in MODIS Cloud Mask ATBD

Cloud Mask output

Bits 1&2 most popular

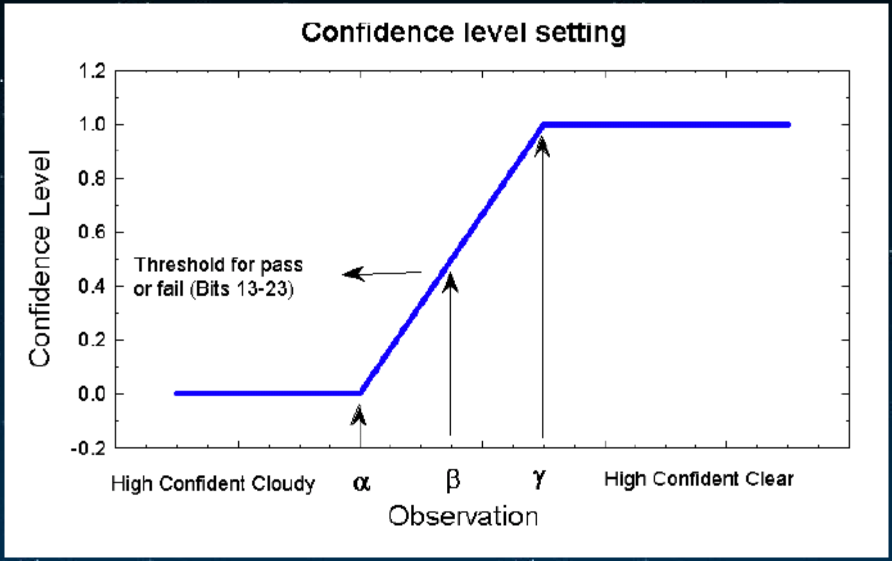
48 bits

Table 3 in MODIS Cloud Mask ATBD

Table 3. File specification for the 48-bit MODIS cloud mask. A '0' for tests 13-47 may mean the test was not run.

BIT FIELD	DESCRIPTION KEY	RESULT
0	Cloud Mask Flag	0 = not determined 1 = determined
1-2	Unobstructed FOV Confidence Flag	00 = cloudy 01 = uncertain 10 = probably clear 11 = confident clear
PROCESSING PATH FLAGS		
3	Day / Night Flag	0 = Night / 1 = Day
4	Sun glint Flag	0 = Yes / 1 = No
5	Snow / Ice Background Flag	0 = Yes/ 1 = No
6-7	Land / Water Flag	00 = Water 01 = Coastal 10 = Desert 11 = Land
ADDITIONAL INFORMATION		
8	Non-cloud obstruction Flag (heavy aerosol)	0 = Yes / 1 = No
9	Thin Cirrus Detected (solar)	0 = Yes / 1 = No
BIT FIELD	DESCRIPTION KEY	RESULT
10	Shadow Found	0 = Yes / 1 = No
11	Thin Cirrus Detected (infrared)	0 = Yes / 1 = No
12	Spare (Cloud adjacency)	(post launch)
	1-km CLOUD FLAGS	
13	Cloud Flag - simple IR Threshold Test	0 = Yes / 1 = No
14	High Cloud Flag - CO_2 Threshold Test	0 = Yes / 1 = No
15	High Cloud Flag - 6.7 μm Test	0 = Yes / 1 = No
16	High Cloud Flag - 1.38 μm Test	0 = Yes / 1 = No
17	High Cloud Flag - 3.7-12 μm Test	0 = Yes / 1 = No
18	Cloud Flag - IR Temperature Difference	0 = Yes / 1 = No
19	Cloud Flag - 3.9-11 μm Test	0 = Yes / 1 = No
20	Cloud Flag - Visible Reflectance Test	0 = Yes / 1 = No
21	Cloud Flag - Visible Ratio Test	0 = Yes / 1 = No
22	Clear-sky Restoral Test- NDVI in Coastal Areas	0 = Yes / 1 = No
23	Cloud Flag - 7.3-11 μm Test	0 = Yes / 1 = No
ADDITIONAL TESTS		
24	Cloud Flag - Temporal Consistency	0 = Yes / 1 = No
25	Cloud Flag - Spatial Consistency	0 = Yes / 1 = No
26	Clear-sky Restoral Tests	0 = Yes / 1 = No
27	Cloud Test - Night Ocean Variability Test	0 = Yes / 1 = No
28	Suspended Dust Flag	0 = Yes / 1 = No
29-31	Spares	
	250-m CLOUD FLAG - AISIBLE TESTS	
32	Element (1,1)	0 = Yes / 1 = No
33	Element (1,2)	0 = Yes / 1 = No
34	Element (1,3)	0 = Yes / 1 = No
35	Element (1,4)	0 = Yes / 1 = No
36	Element (2,1)	0 = Yes / 1 = No
37	Element (2,2)	0 = Yes / 1 = No
38	Element (2,3)	0 = Yes / 1 = No
39	Element (2,4)	0 = Yes / 1 = No
40	Element (3,1)	0 = Yes / 1 = No
41	Element (3,2)	0 = Yes / 1 = No
42	Element (3,3)	0 = Yes / 1 = No
43	Element (3,4)	0 = Yes / 1 = No
44	Element (4,1)	0 = Yes / 1 = No
45	Element (4,2)	0 = Yes / 1 = No
46	Element (4,3)	0 = Yes / 1 = No
47	Element (4,4)	0 = Yes / 1 = No

Cloud detection Threshold approach



- Each test returns a confidence (F) ranging from 0 to 1.
- Similar tests are grouped and minimum confidence selected [min (F_i)]
- Quality Flag is

$$Q = \sqrt[N]{\prod_{i=1}^{N} \min(F_i)}$$

- Four values; , >.66, >.95 and >.99

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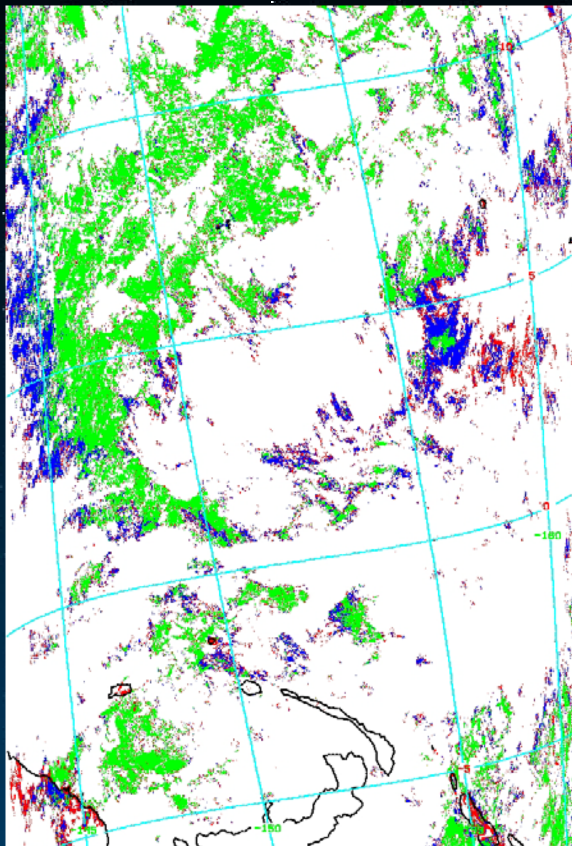
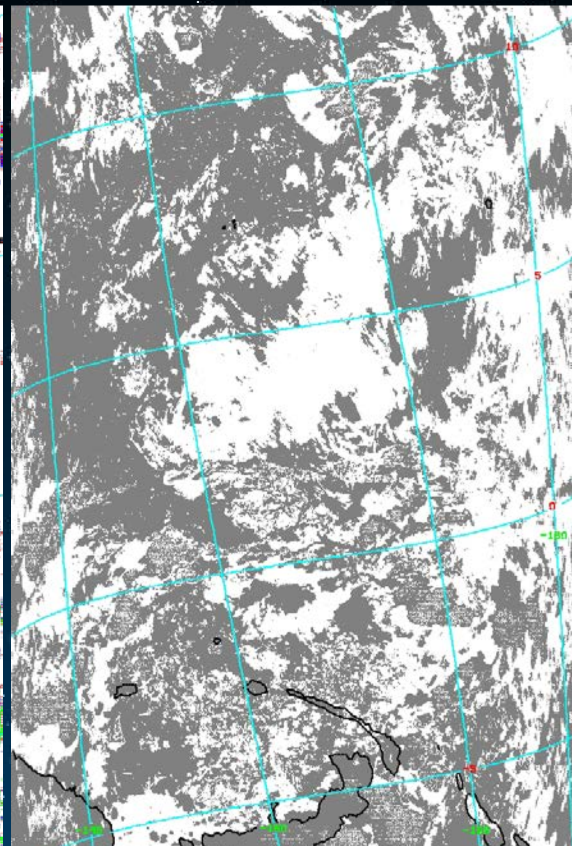
Example: Collection 6 MOD35 Cloud Test Results

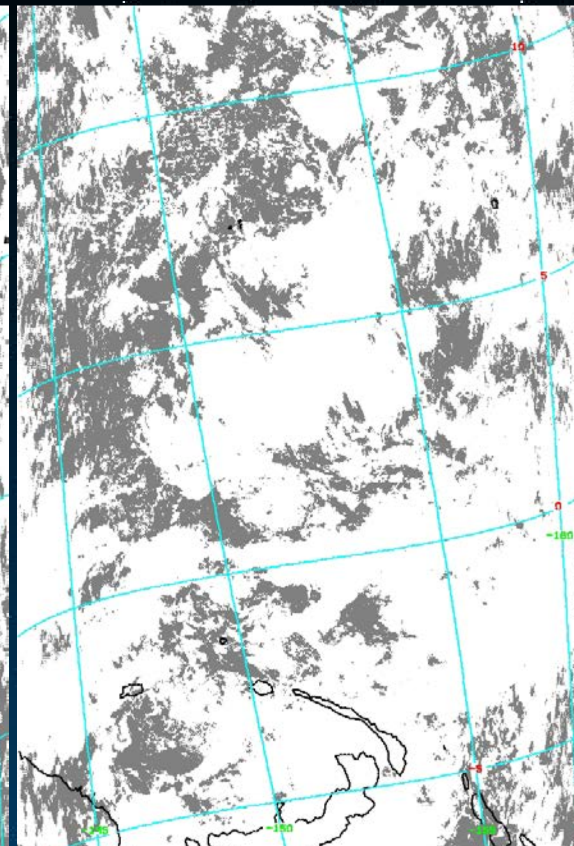


Final Confidence of Clear Sky

Green confident clear
Blue probably clear
Red probably cloudy
White confident cloudy



11-3.9 μm Cloud Test



IR “SST” Cloud Test

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Validation…. Assume a truth

How do we validate our cloud detection algorithm?

Compare with visual observations, lidar ground based observations, CALIOP, other satellites.

Comparison with Ground and Satellite -based Lidars/Radars

Systems are non-scanning, small fov

ARM site in central region of the USA

	ARCL clear	ARCL cloudy
MODIS clear	Terra: 146 Aqua: 117	Terra: 45 Aqua: 58
MODIS cloudy	Terra: 38 Aqua: 12	Terra: 298 Aqua: 185

Ackerman et al 2008

MODIS and radar/lidar detection agree 85% of the time.

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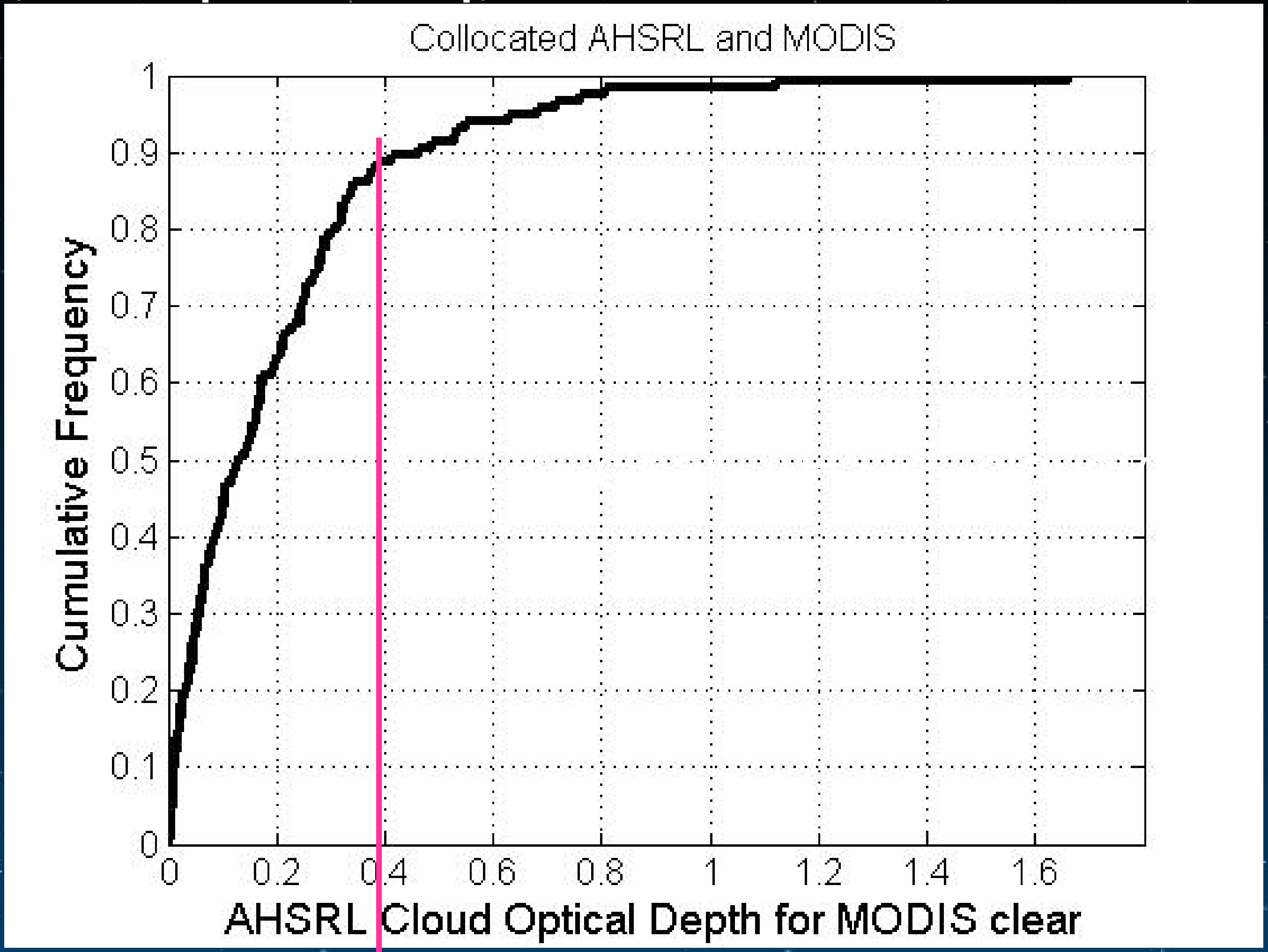
What is the optical depth threshold for detection by MODIS algorithm?

AHSRL measures optical depth directly.

MODIS optical depth threshold: over Wisconsin



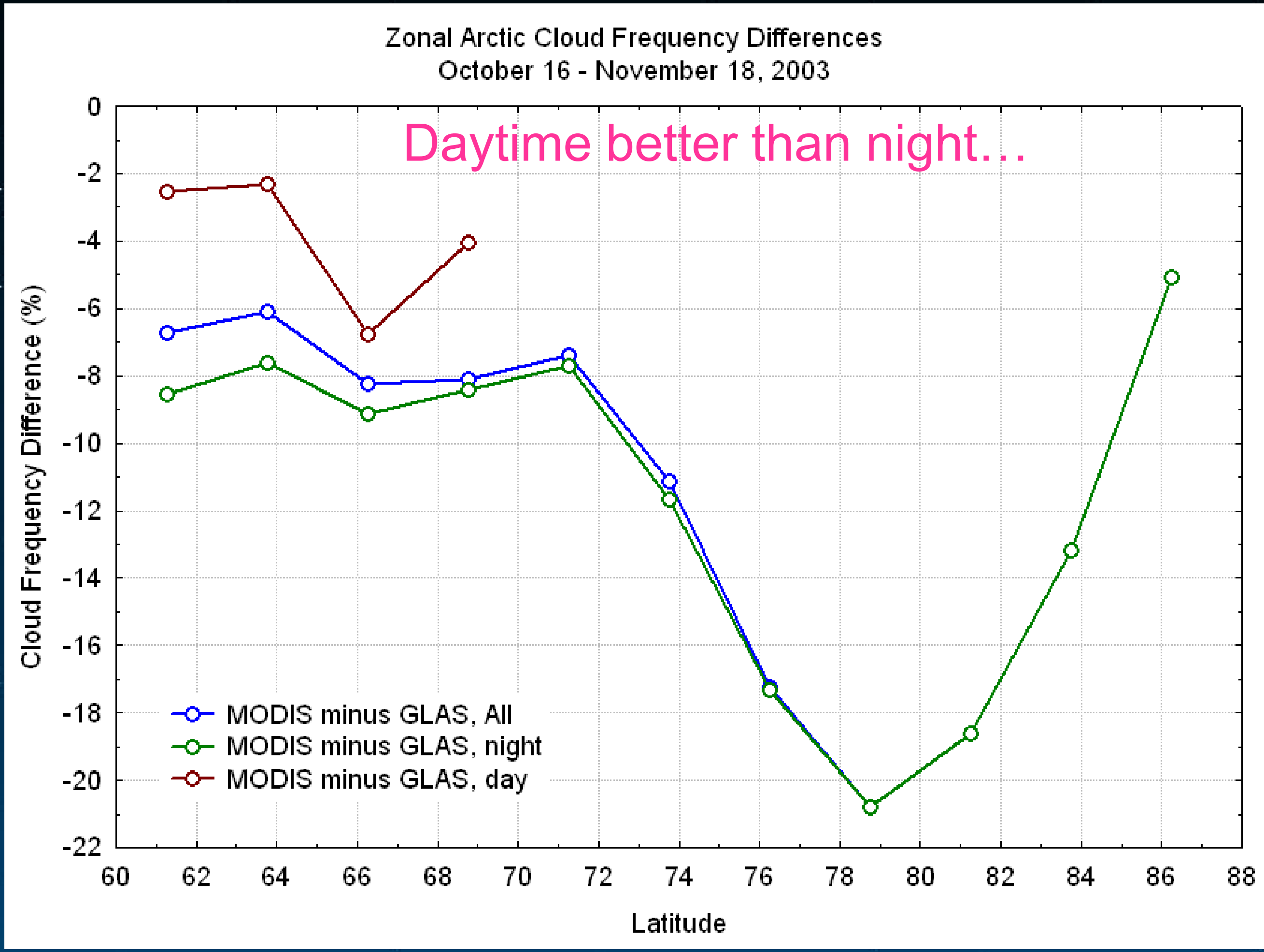
Ackerman et al 2008

MODIS optical depth threshold ~ 0.4

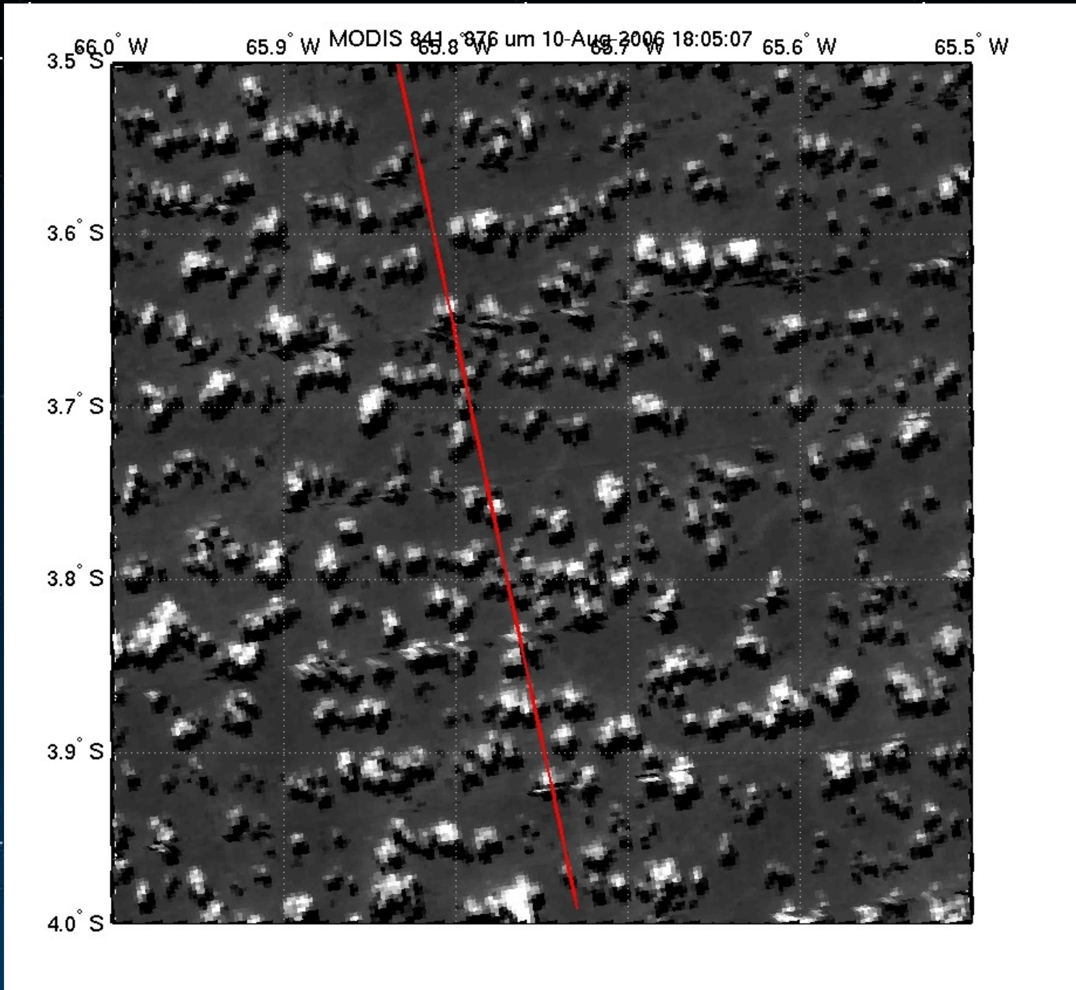
Comparison with GLAS

Difference, MODIS minus GLAS cloud amount

Frey et al 2008

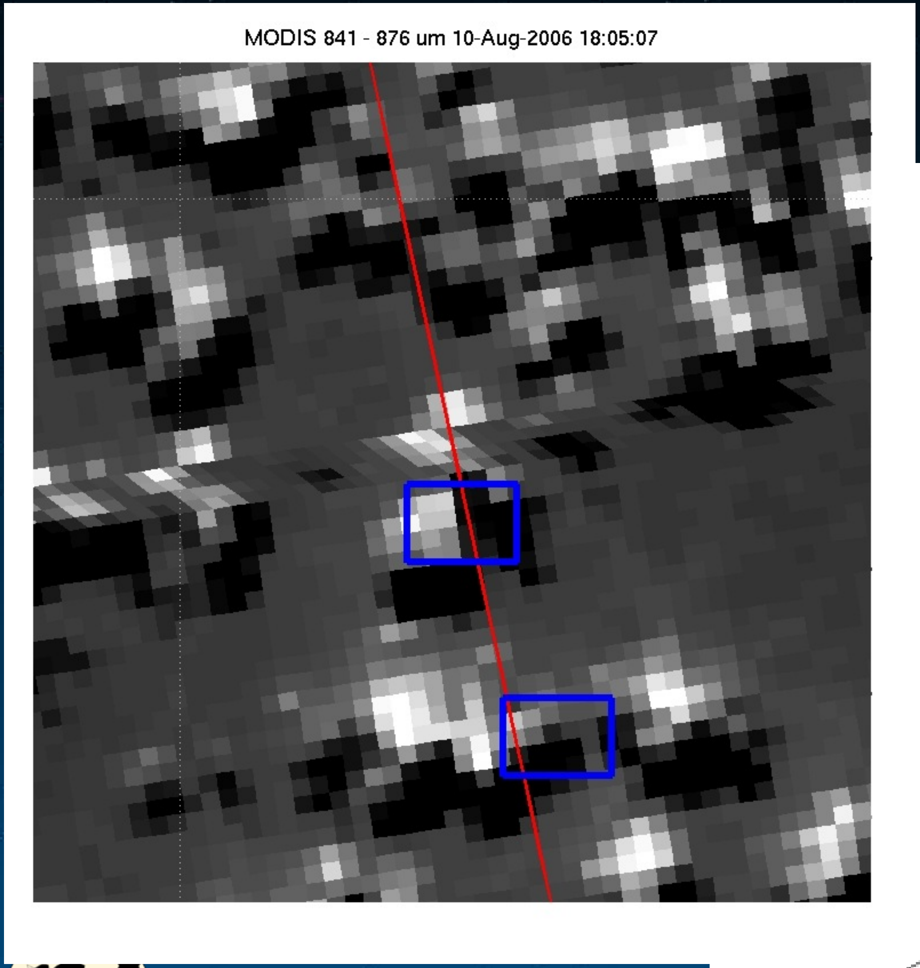


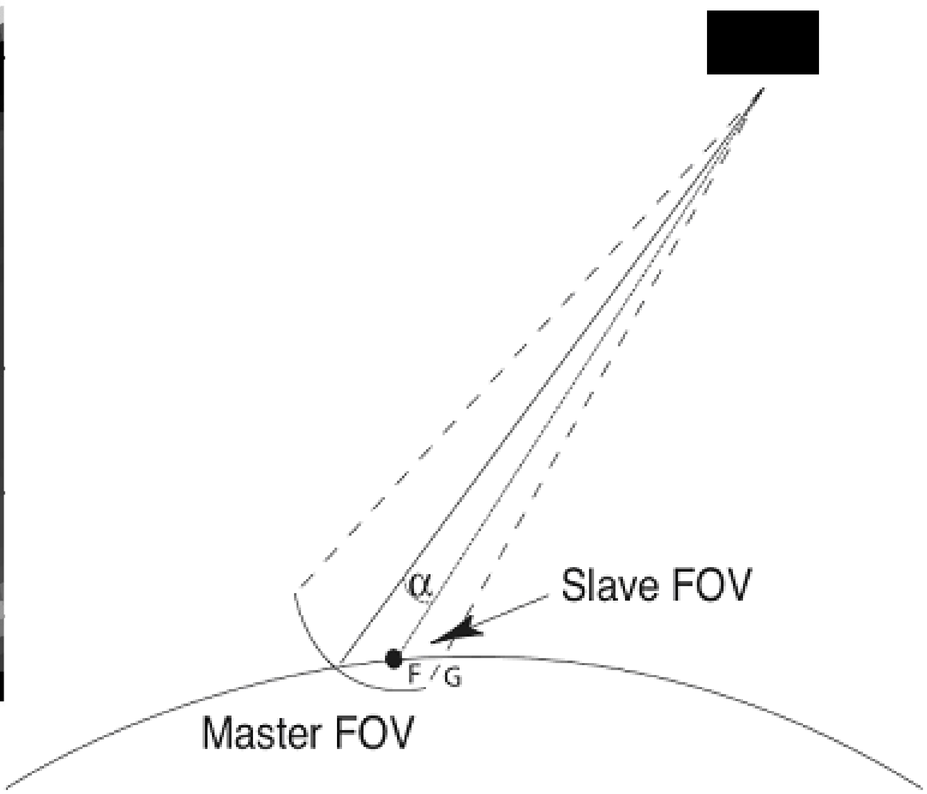
CALIOP and MODIS make very different measurements with different sampling characteristics. To correctly compare, collocation must be done carefully!



MODIS 250 m resolution image with the CALIOP sampling represented by the red line. The finer resolution of CALIOP makes careful collocation important in an analysis of combined data streams.

Careful Collocation



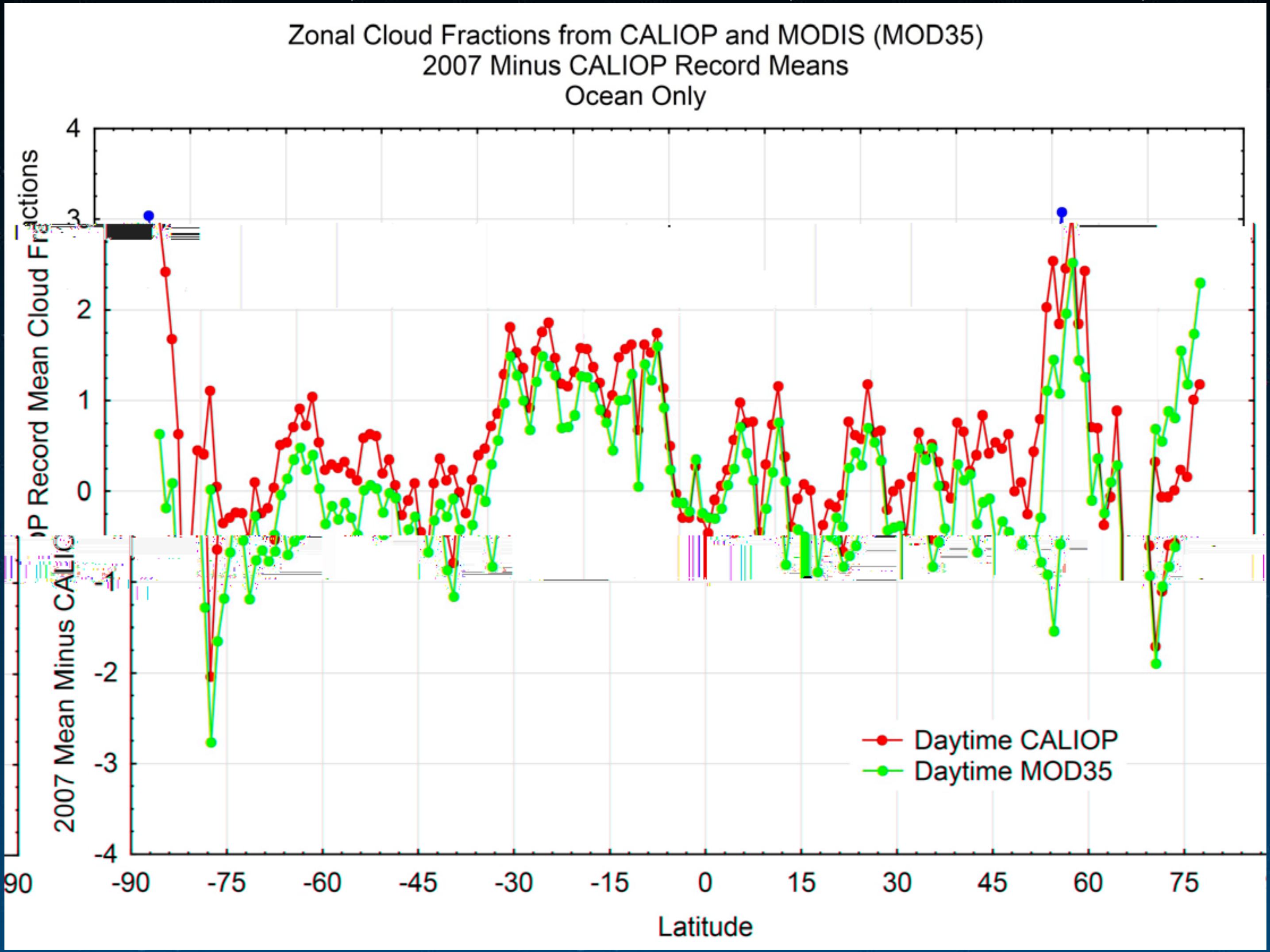


Global Comparison

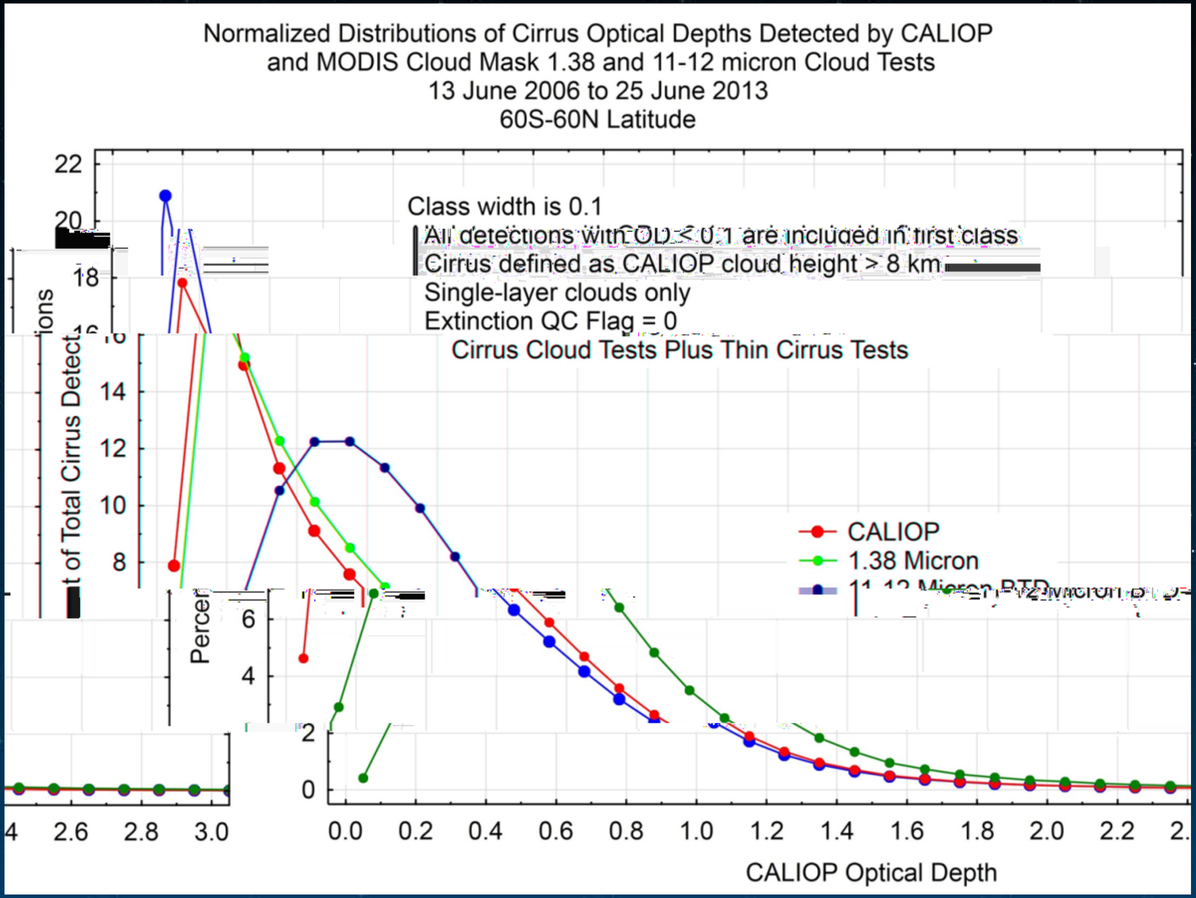
	CALIPSO clear	CALIPSO cloudy
MODIS clear	27.5%	6.2%
MODIS cloudy	6.3%	60.0%

Comparison of MODIS cloud detection with collocated observations from CALIPSO for the entire month of August 2006. Over 5 million observations went into the analysis. The results are expressed as a percentage.

Overall cloud detection by MODIS (1st byte) has been shown to be excellent (e.g. 90% agreement with lidar)



Validation of MODIS Cloud Mask Bits



Bit structure demonstrates increased sensitivity to optically thin cirrus clouds

Ackerman, Frey, MODIS team
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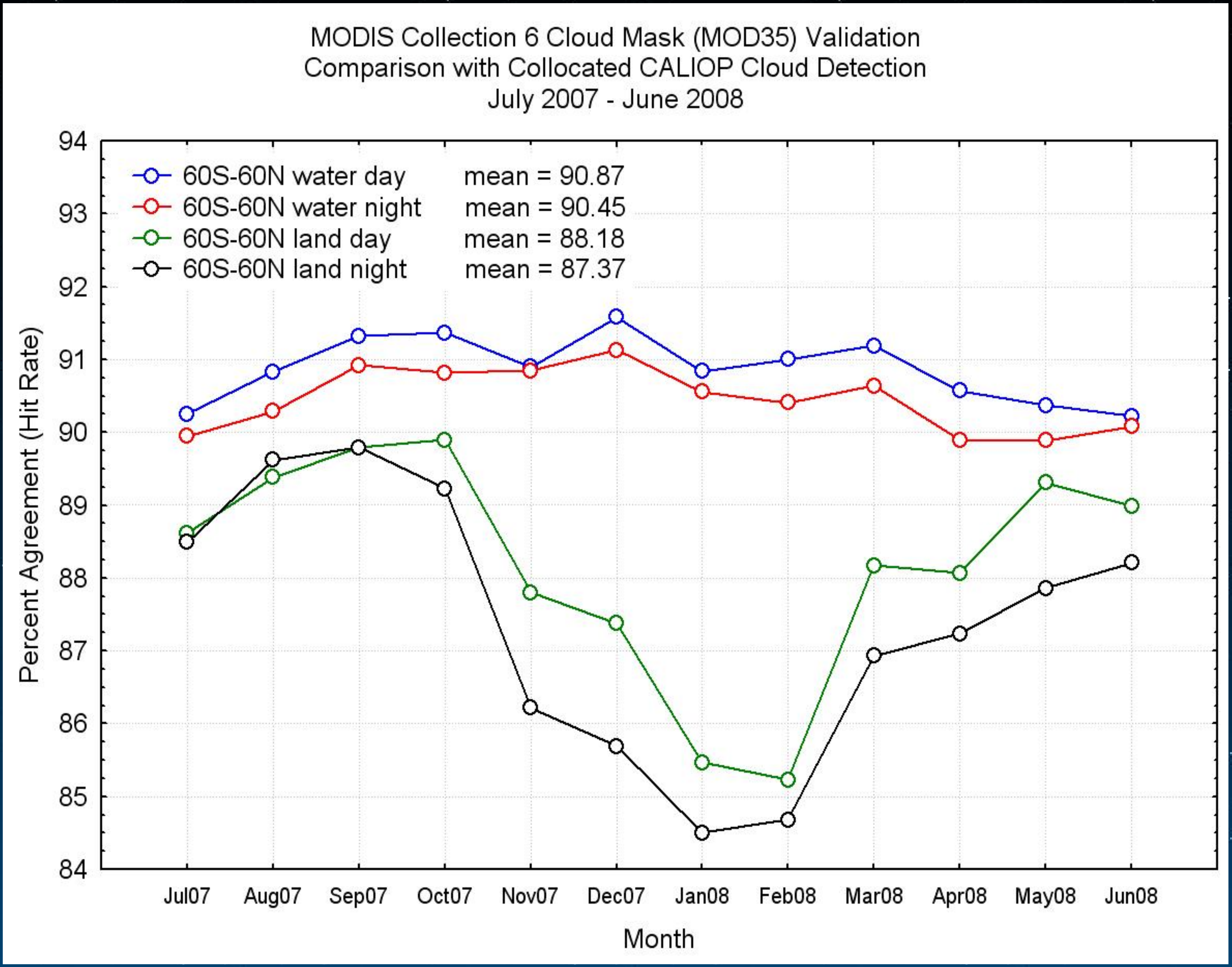

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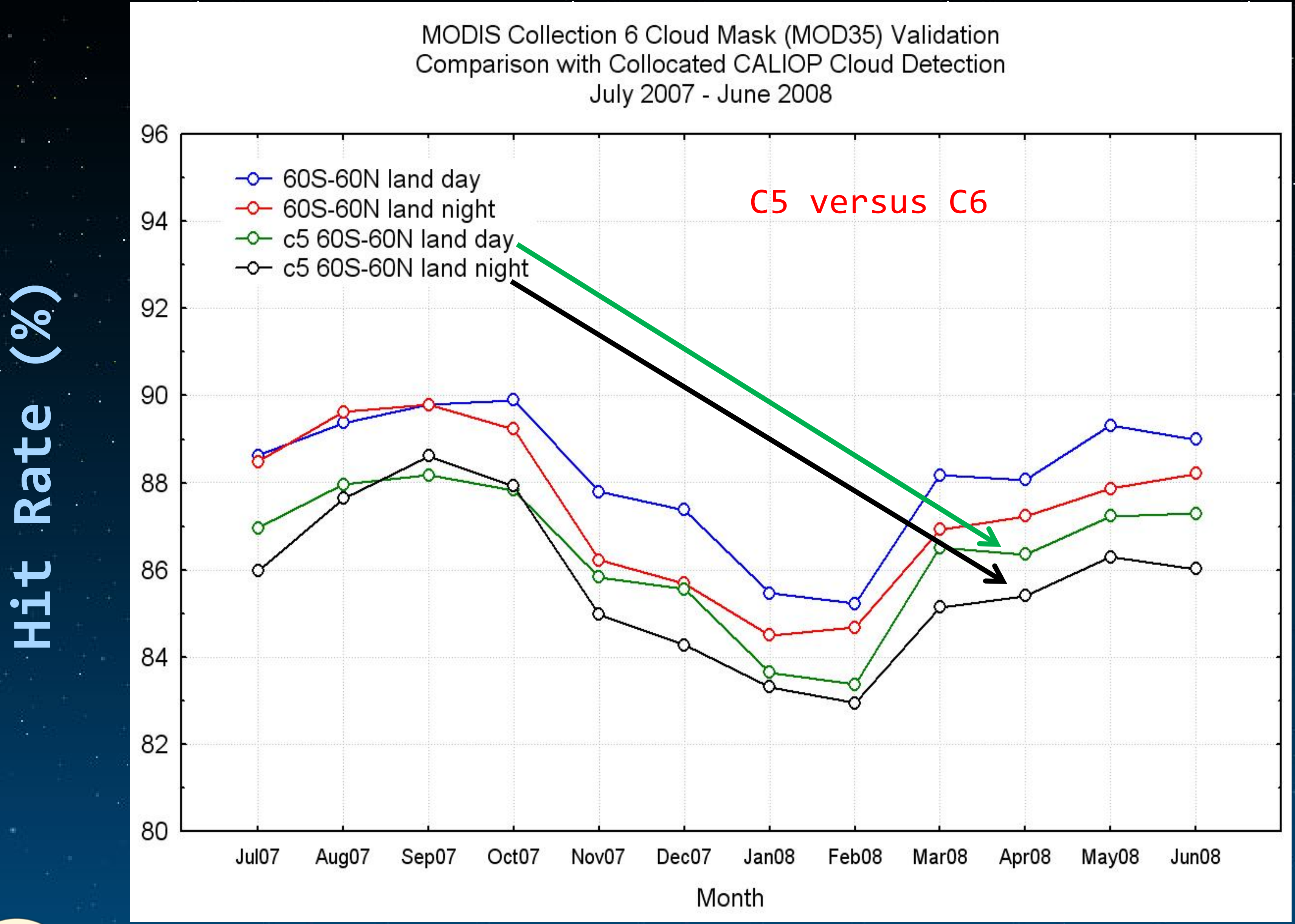

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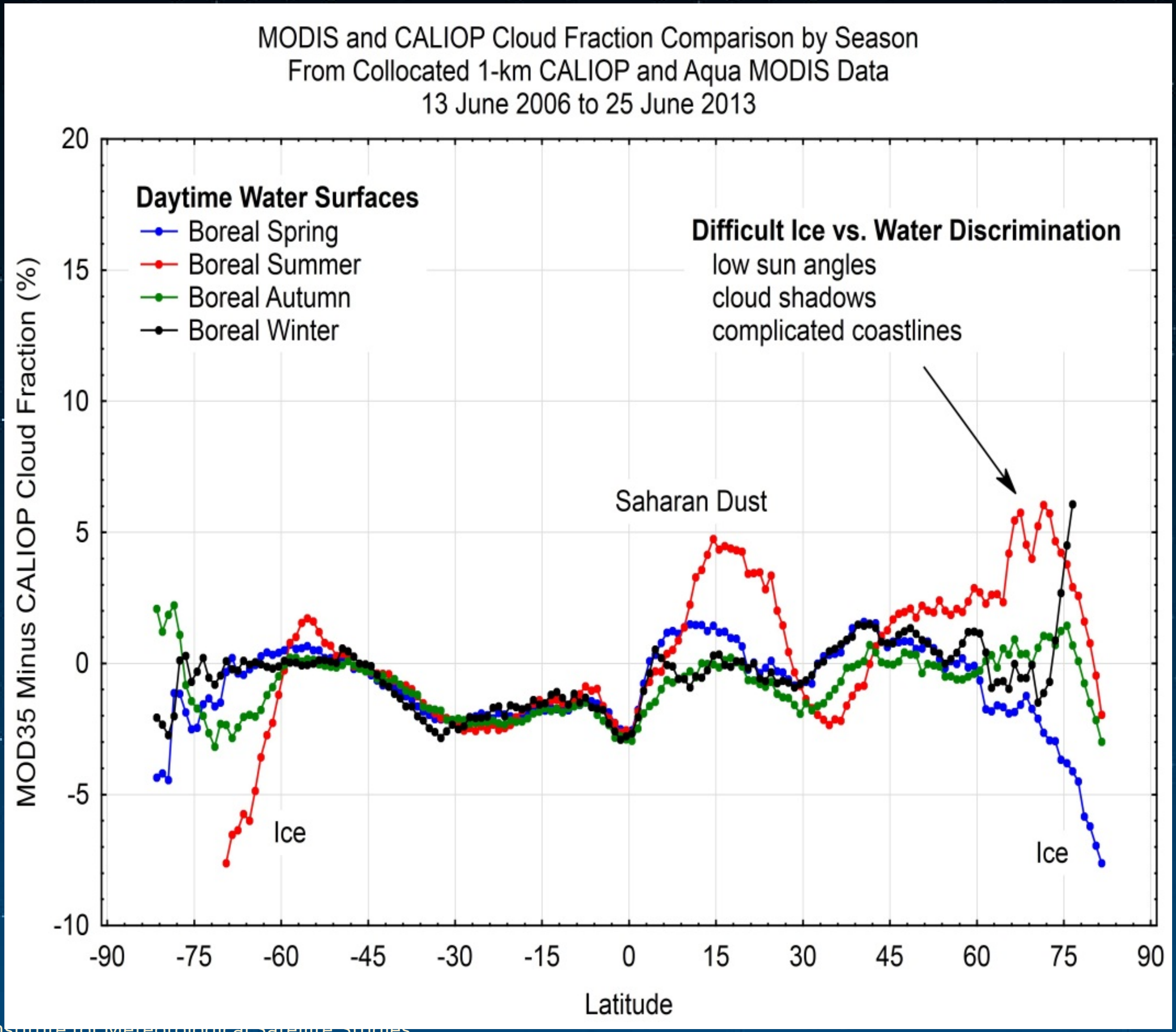
	August 2006 Clear	August 2006 Cloudy	February 2006 Clear	February 2006 Cloudy
Global Day/Night CALIOP 1-km (5-km)	0.84 (0.73)	0.88 (0.87)	0.85 (0.75)	0.88 (0.87)
Non-Polar Day/Night CALIOP 1-km (5-km)	0.87 (0.76)	0.91 (0.88)	0.85 (0.76)	0.90 (0.89)
Non-Polar Day CALIOP 1-km (5-km)	0.89 (0.85)	0.90 (0.88)	0.87 (0.78)	0.91 (0.89)
Non-Polar Night CALIOP 1-km (5-km)	0.85 (0.76)	0.91 (0.88)	0.84 (0.74)	0.90 (0.88)
Non-Polar Land CALIOP 1-km (5-km)	0.90 (0.85)	0.84 (0.80)	0.82 (0.74)	0.85 (0.84)
Non-Polar Ocean CALIOP 1-km (5-km)	0.86 (0.78)	0.93 (0.91)	0.86 (0.79)	0.93 (0.90)
Arctic > 60 deg Latitude	0.74 (0.62)	0.90 (0.93)	0.82 (0.62)	0.73 (0.79)
Antarctic < -60 Latitude	0.77 (0.55)	0.73 (0.76)	0.91 (0.85)	0.88 (0.88)

The global fractional agreement of cloud detection between MODIS and CALIOP for August 2006 and February 2007. The results are separated by CALIOP averaging amount, with the 5 km averaging results in parenthesis, as well as day, night and surface type. From Holz et al 2008.

CALIOP lidar vs. MODIS Imager Cloud Mask Comparisons 2006 – 2013 (Daytime Water)



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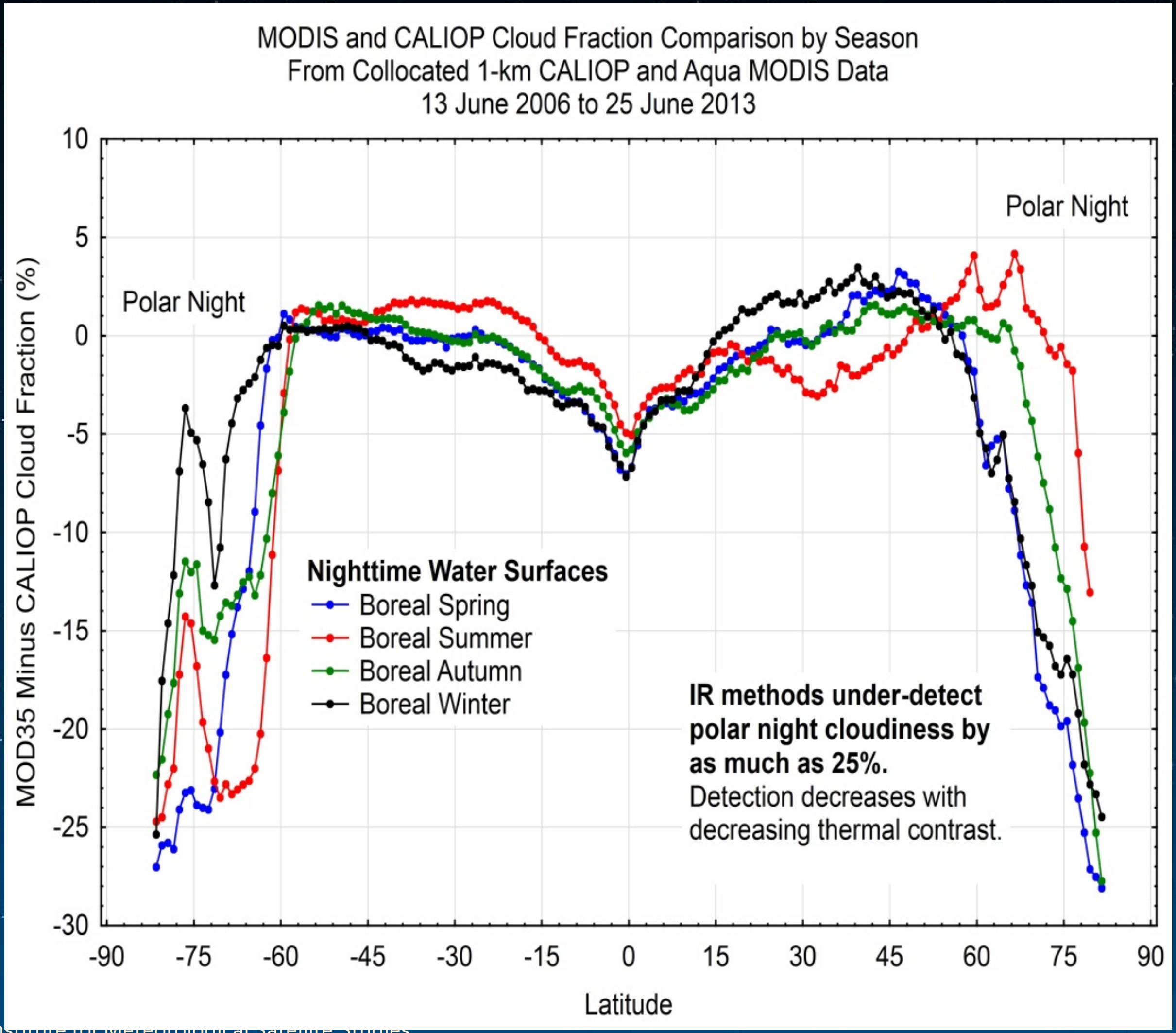
CALIOP lidar vs. MODIS Imager Cloud Mask Comparisons 2006 – 2013 (Nighttime Water)



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Comparison with active systems…

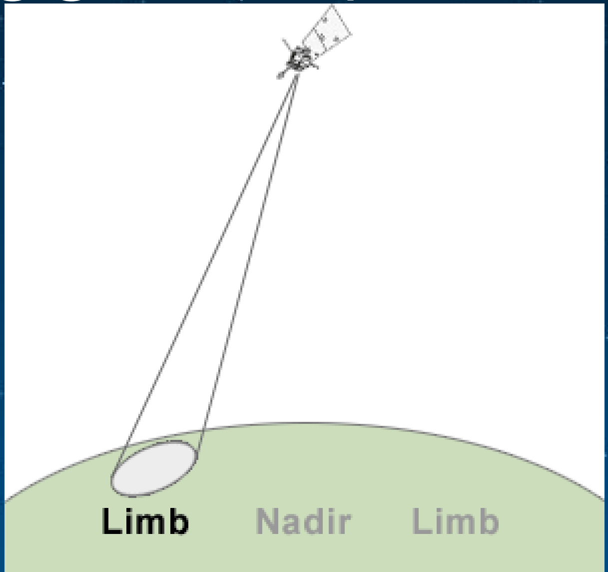
- Generally good agreement.
- Optical depth threshold of ~0.3-0.4 over land (not including thin cirrus alone bit)
- Detection a function of scene
- Polar regions at night still a problem for passive systems.

Understanding strengths and weakness makes for a good data set!

MODIS view angle dependence…

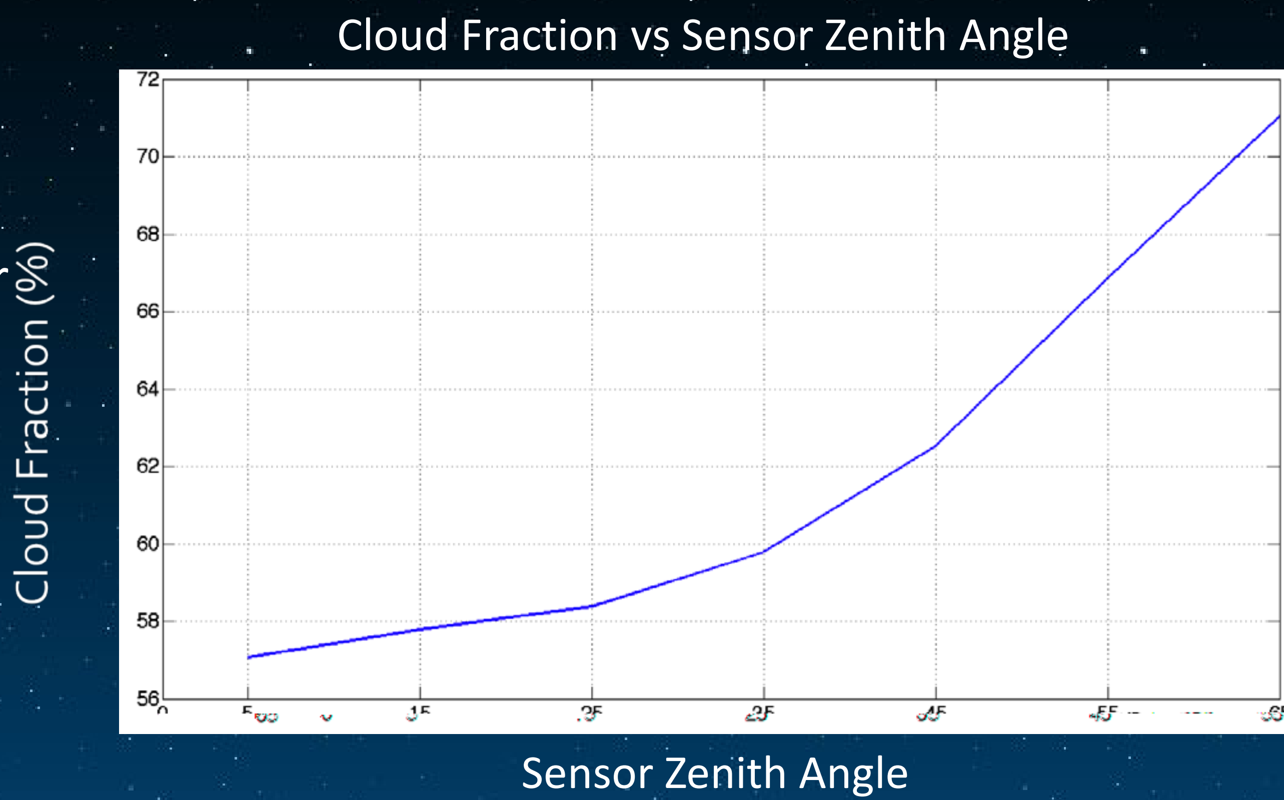
- View angle dependence is a issue will all sensors.
  - FOV size
  - Optical depth
- In some cases, as large as 25%.
- One option is to restrict viewing geometry.

How does viewing on the limb impact cloud detection?

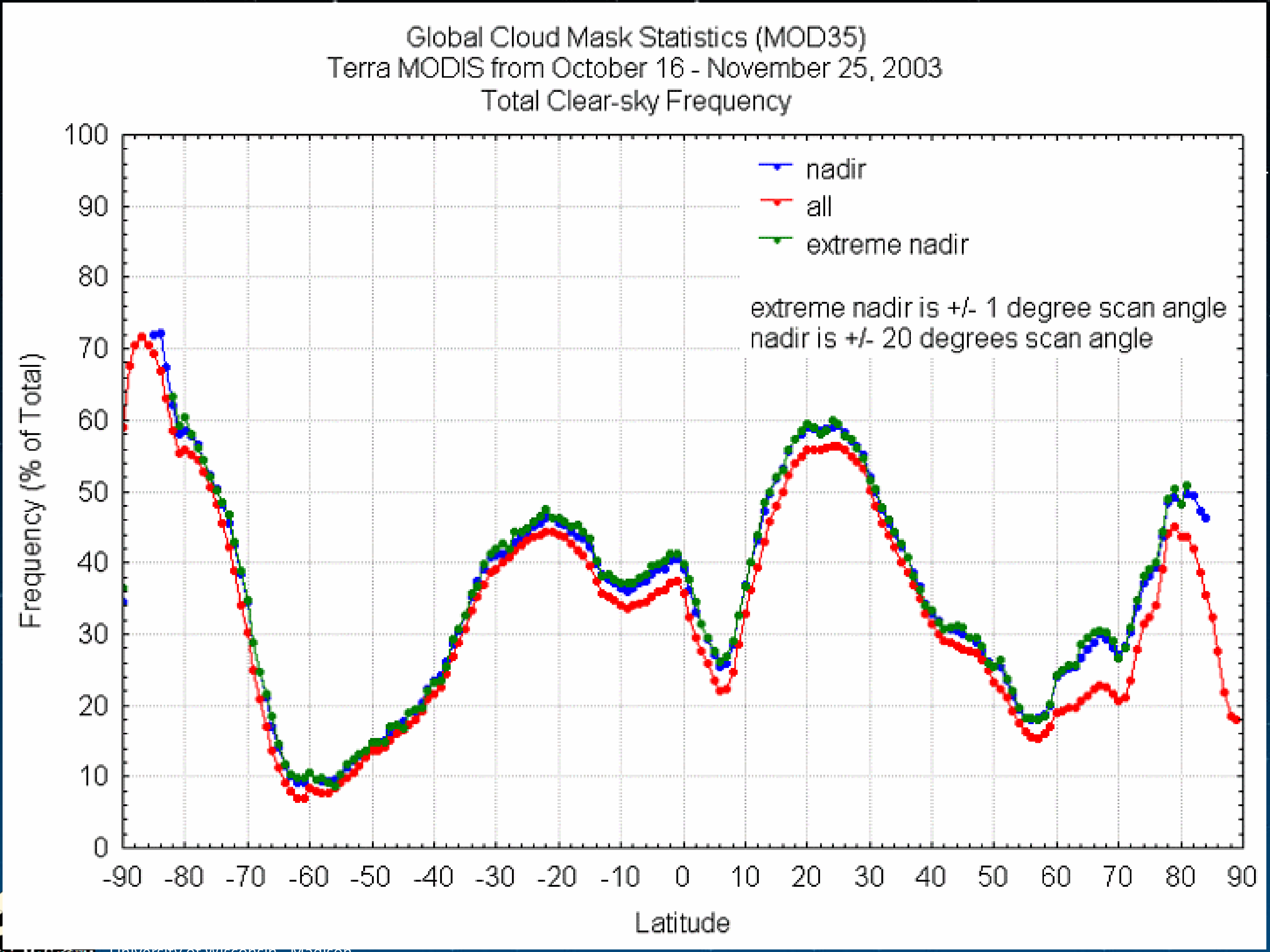


Cloud Fraction vs Viewing Angle

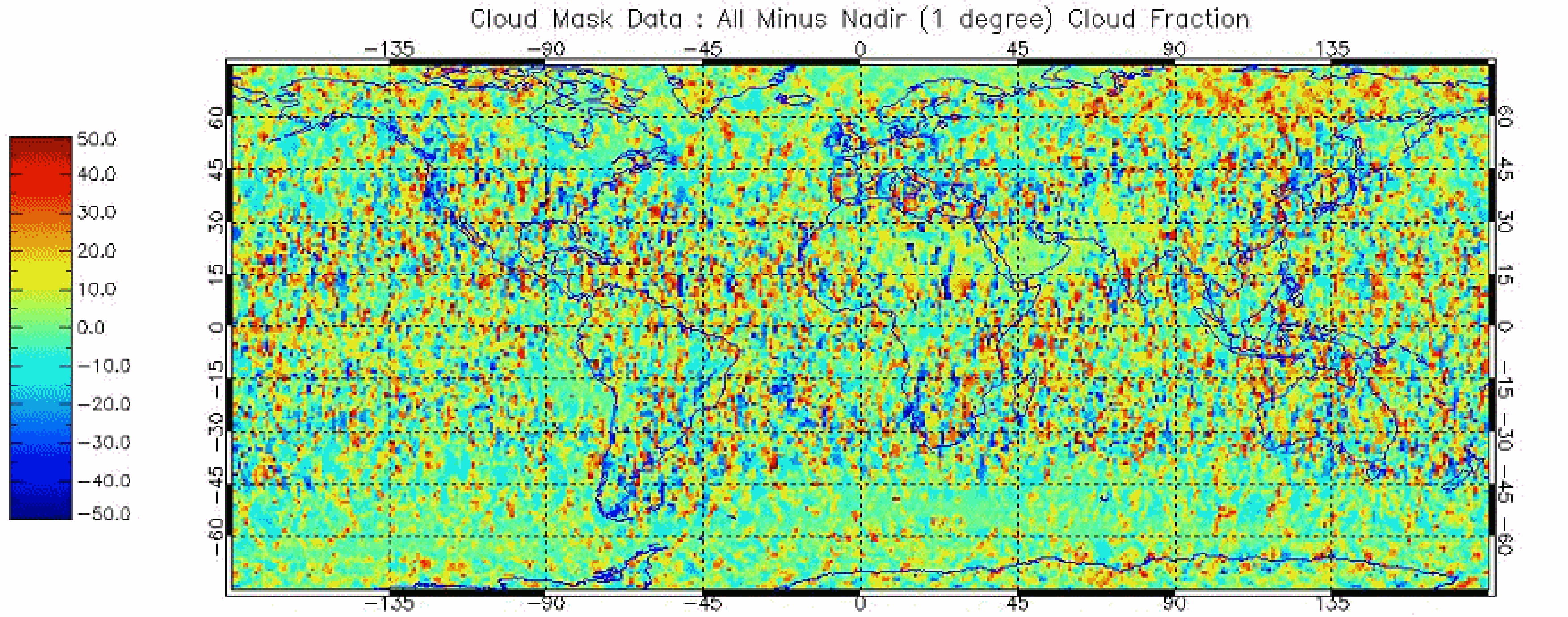
- 7 years of Aqua and Terra
- 16% increase from near nadir to edge of scan
- View angle effect not constant for all cloud types



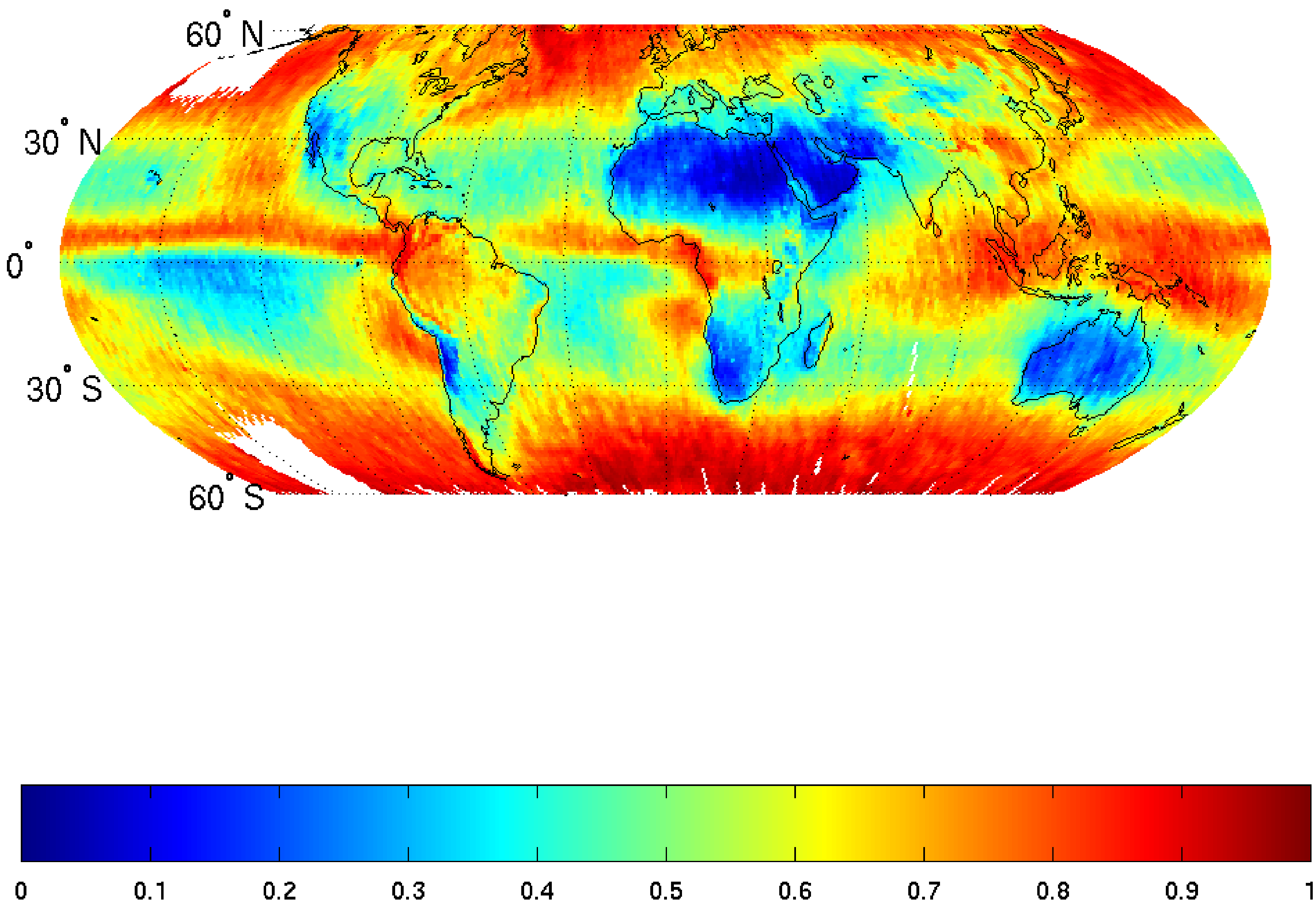
Maddux et al


Global Cloud Mask Statistics (MOD35)
Terra MODIS from October 16 - November 25, 2003
Total Clear-sky Frequency
nadir
all
extreme nadir
extreme nadir is +/- 1 degree scan angle
nadir is +/- 20 degrees scan angle
Frequency (% of Total)
Latitude
100
90
80
70
60
50
40
30
20
10
0
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90

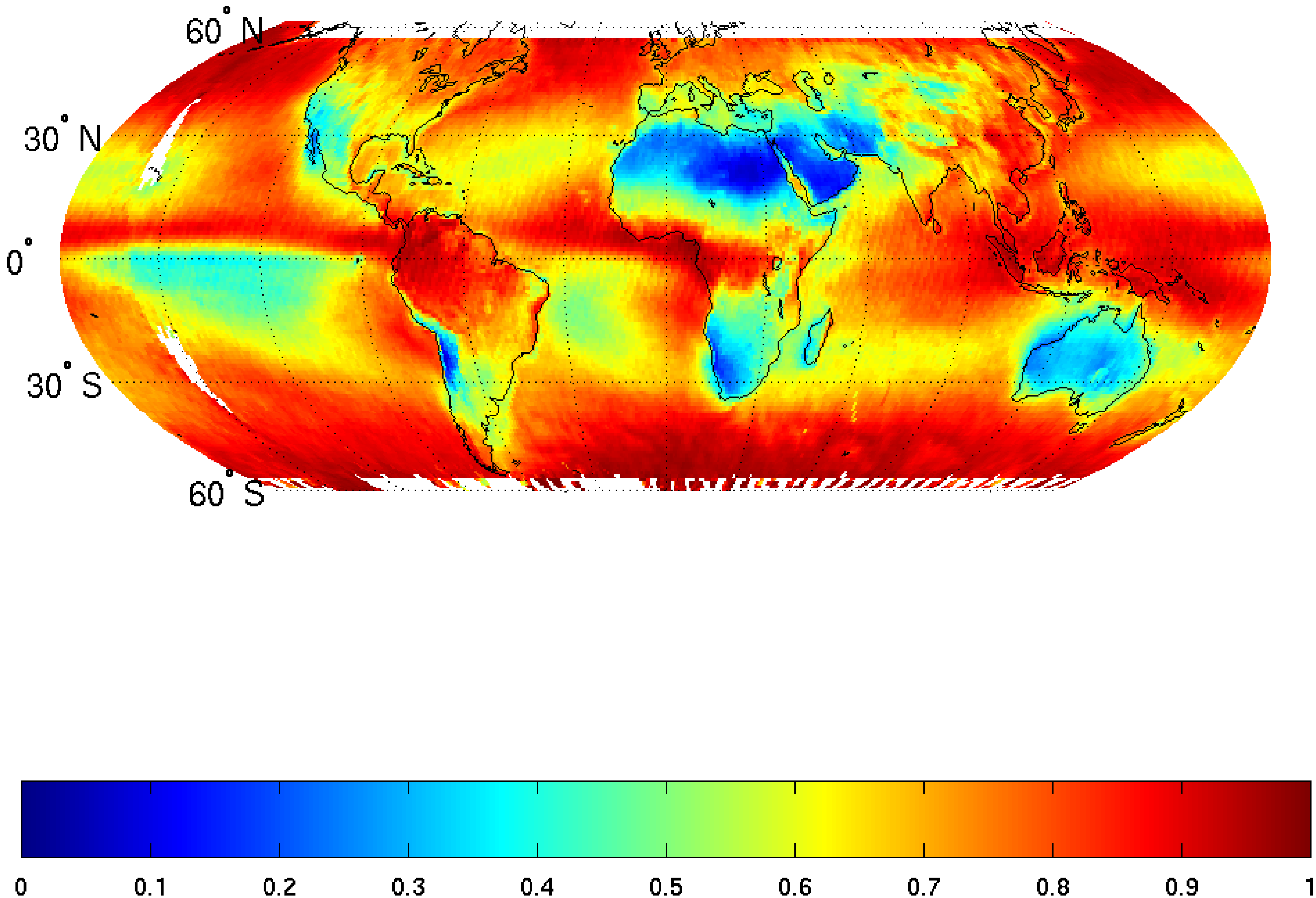
Cloud Fraction in %: Difference between All angles – Nadir (1 degree) for one month



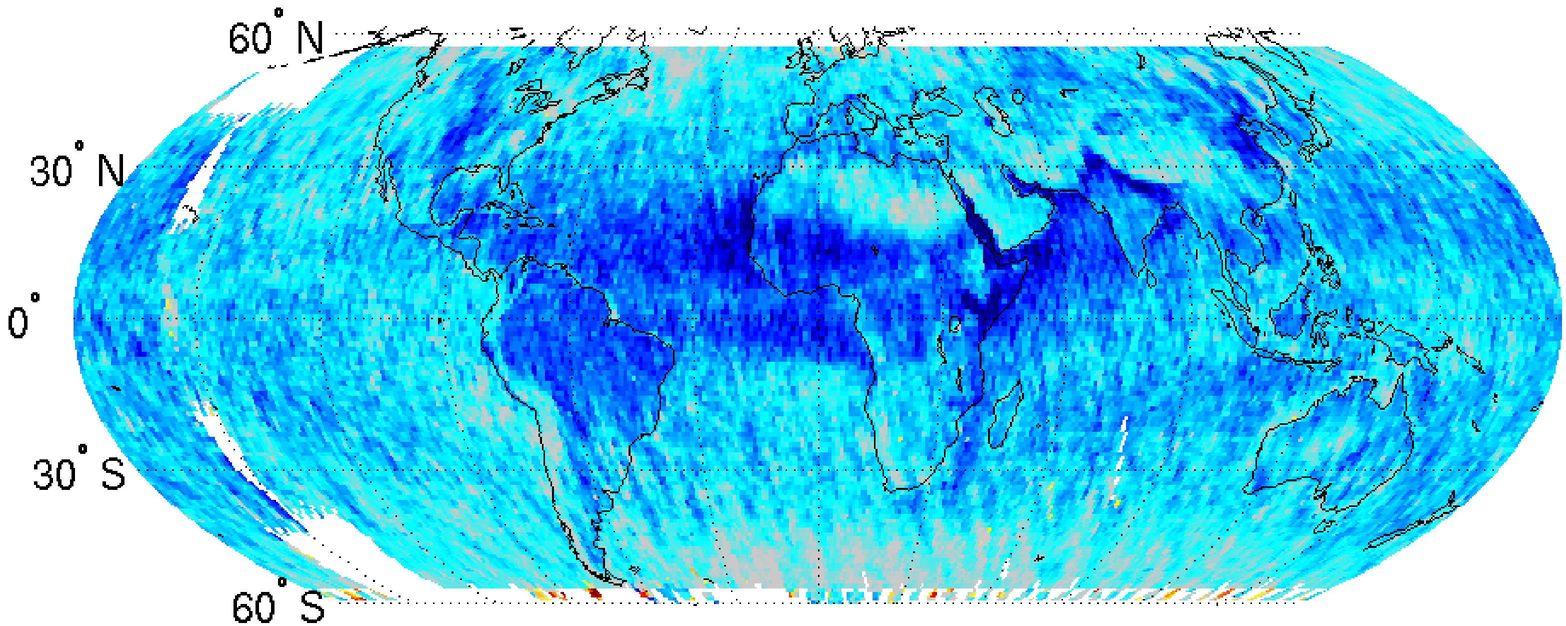
Mean Cloud Fraction for view < 10 degree



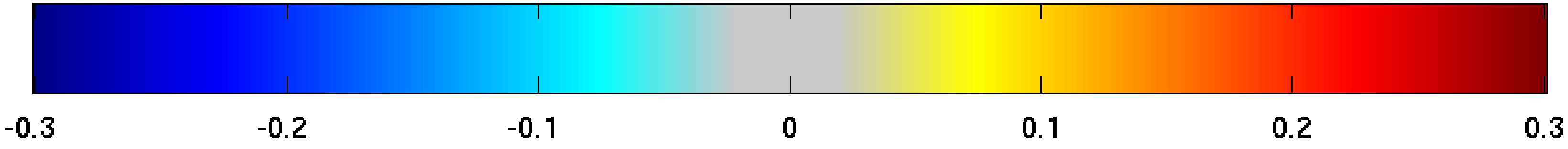
Mean Cloud Fraction for view > 70 degree



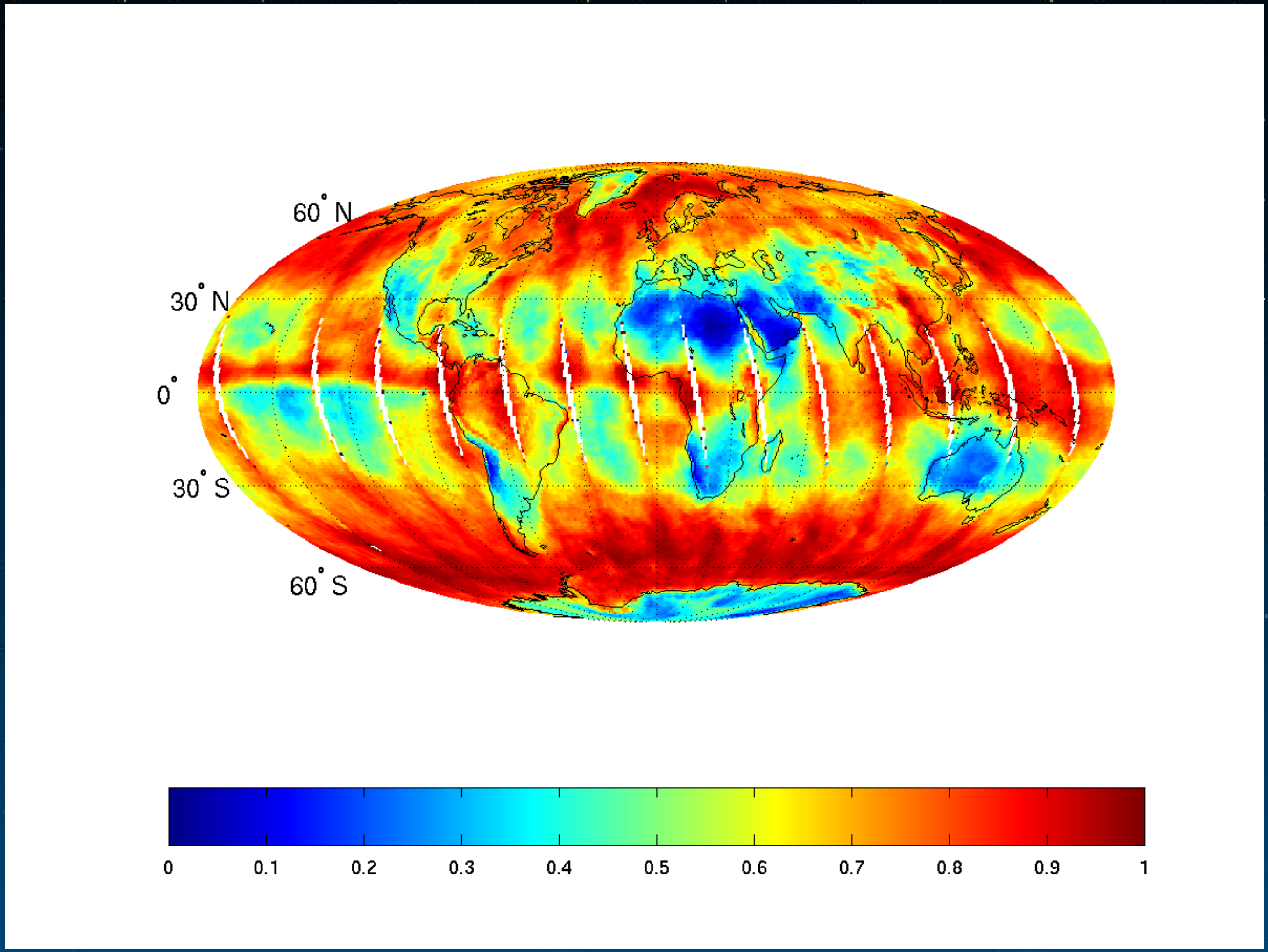
Mean Cloud Fraction difference



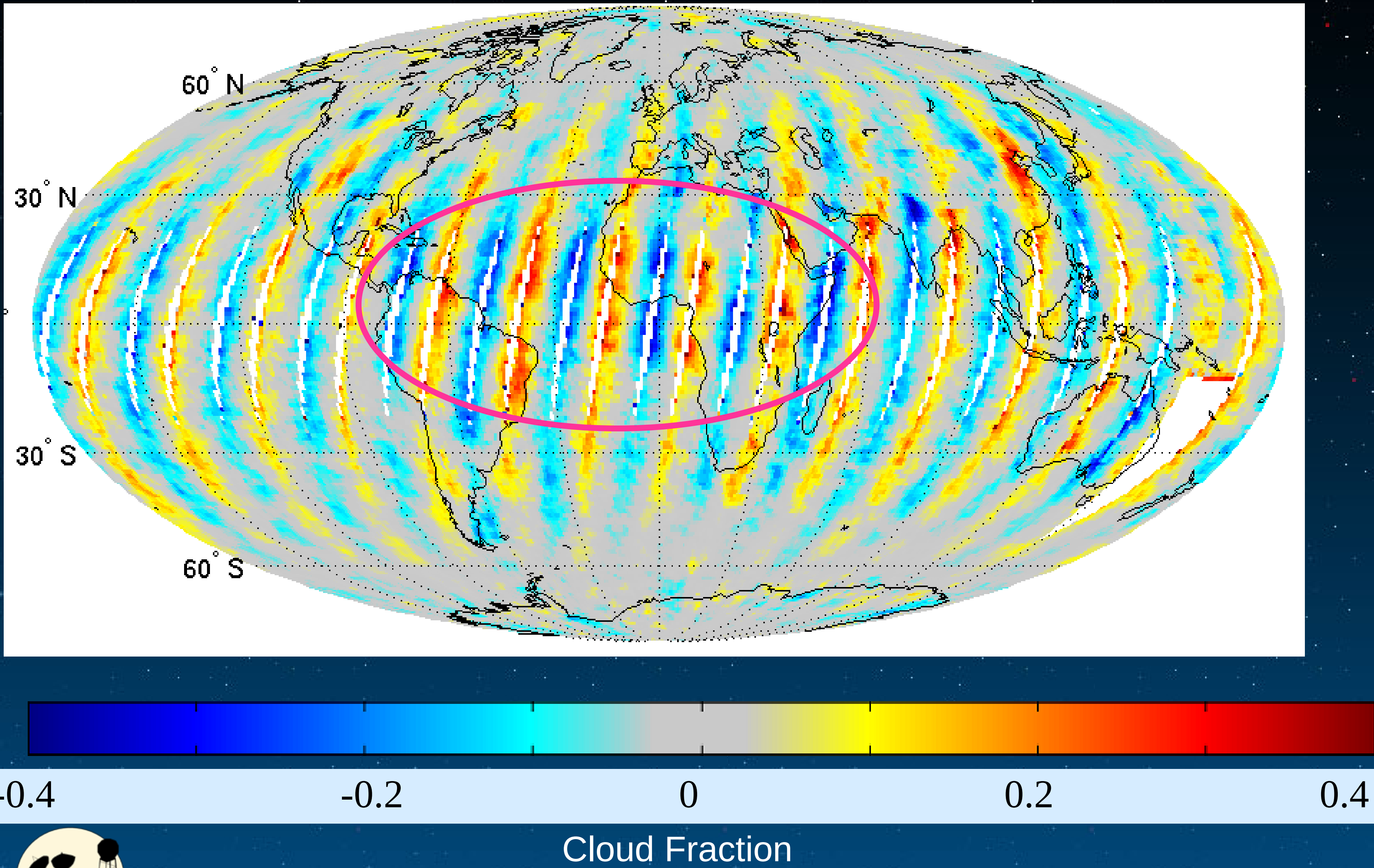
Impact is just perspective, projected a 3-D field on a 2-D plane, and increased detection of thin cloud or aerosol.



Day 1 cloud amount – one year and 1x1 degree



Orbit Day 1 – Orbit Day 2



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MODIS view angle dependence…

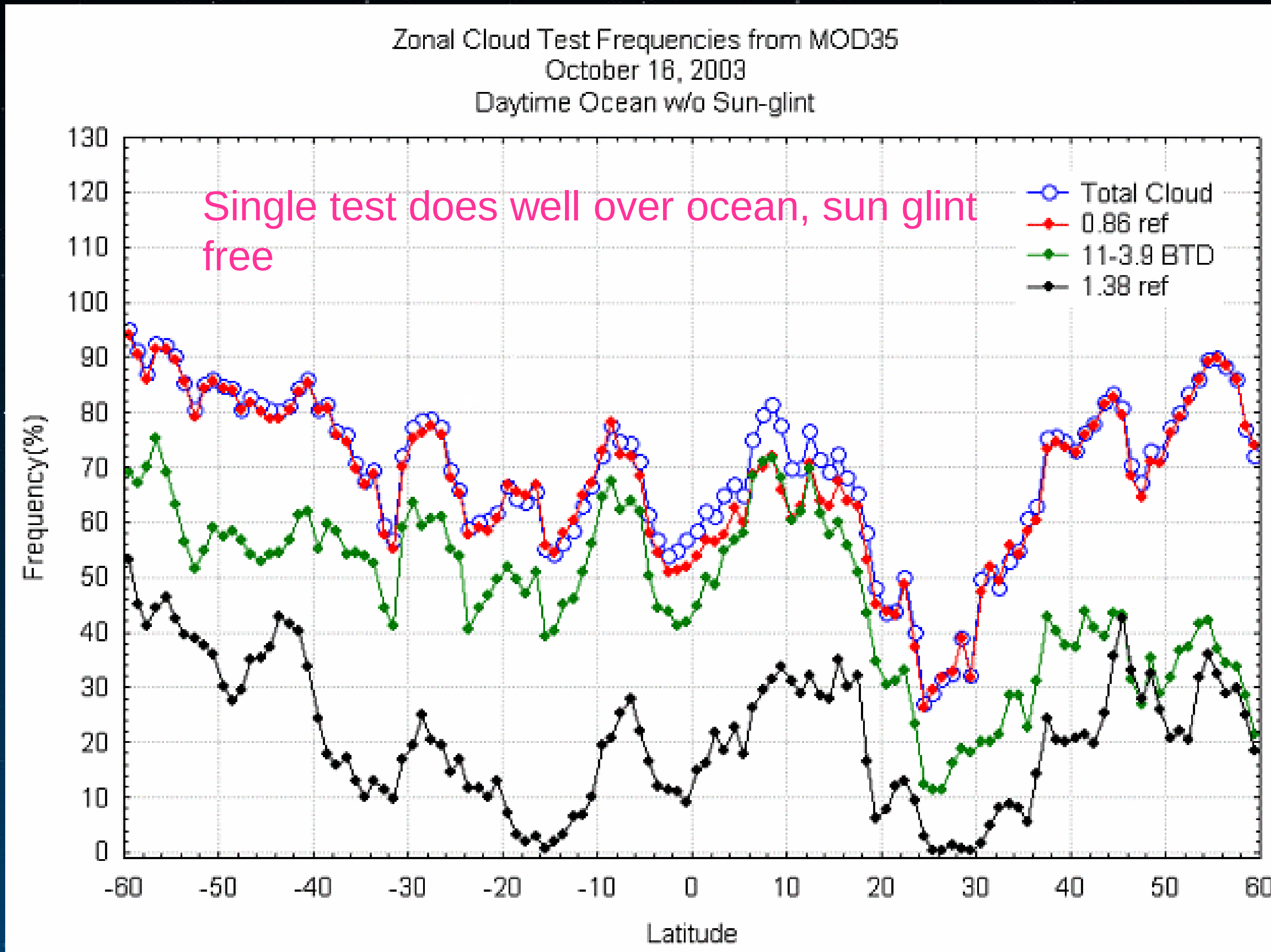
- View angle dependence is a issue will all sensors.
- In some cases, as large as 25%.
- One option is to restrict viewing geometry in compositing.

Spectral tests

- MODIS – number and thresholds vary with scene type.

Sensitivity to Input Reflectance Biases and Reflectance Thresholds; Daytime Terra MODIS Data
April 1, 2003 60N to 60S

		Cloud Amount
Collection 5 Cloud Mask	Water Land	72.7% 54.1%
Increase All B1, B2 Reflectances by 5% of Original	Water Land	73.3% (+0.6%) 54.6% (+0.5%)
Decrease All B1, B2 Reflectances by 5% of Original	Water Land	72.2% (-0.5%) 53.6% (-0.5%)
Increase VIS/NIR Reflectance Test Thresholds by 1%	Water Land	70.7% (-2.0%) 53.6% (-0.5%)
Decrease VIS/NIR Reflectance Test Thresholds by 1%	Water Land	75.5% (+2.8%) 54.7% (+0.6%)



Zonal mean – total and for particular tests

MODIS spectral tests…

- No one test dominates…
- Global means can differ by 2%…
- Random shifting is less 10ths of a percent
- Reflectance at 0.86 micron over oceans and out of sun-glint holds potential for comparison with other satellite cloud records…

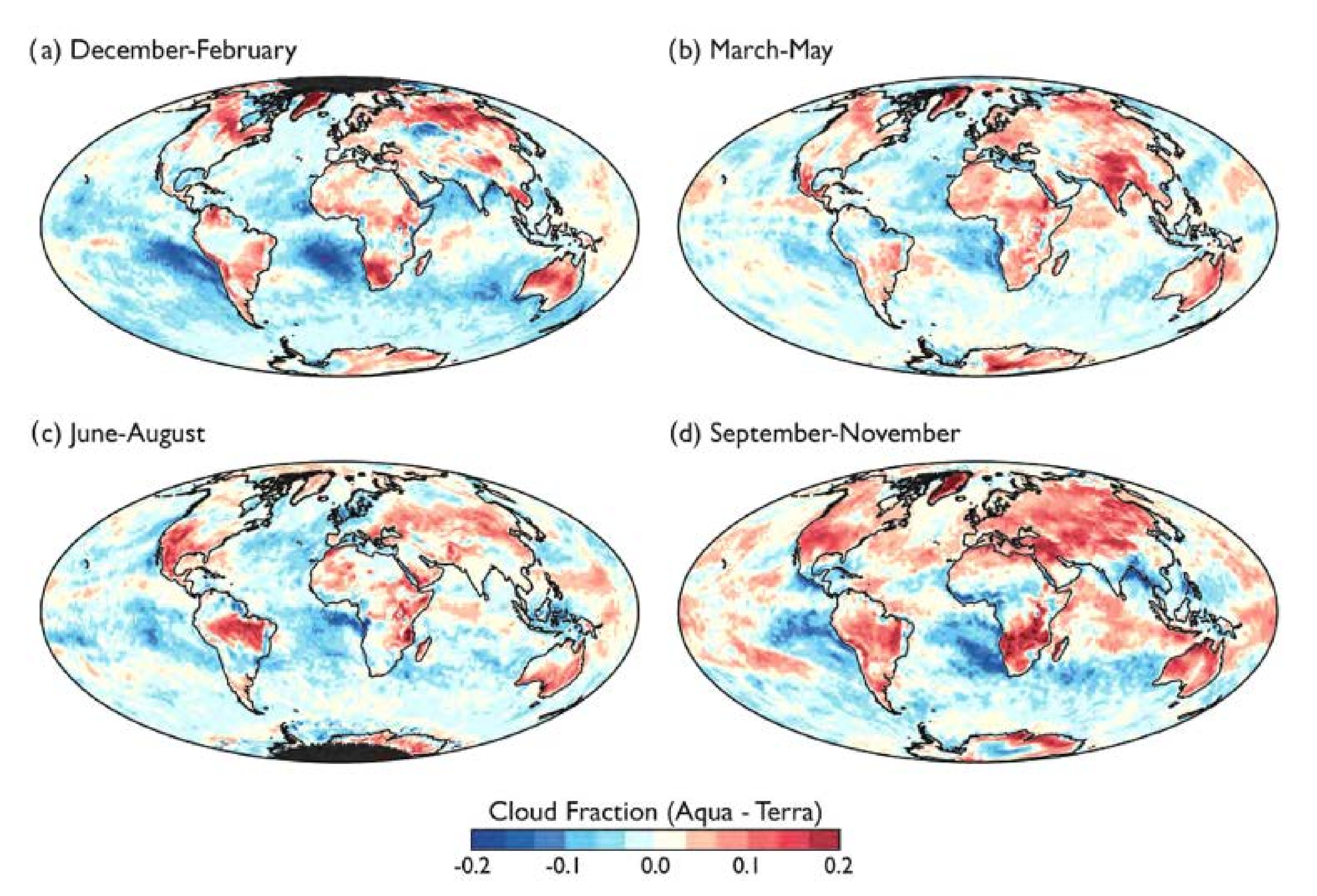
Applications…

Global Cloud Cover

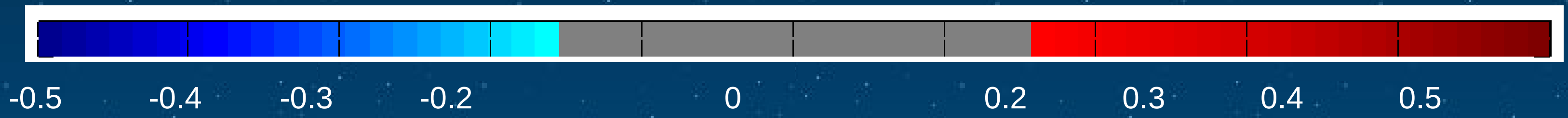
Global Cloud cover from the two MODIS instruments.

King et al 2013

Aqua – Terra cloud fraction…



Correlations with indices (ENSO)



Correlation is significant >± .15 for a p-value of .05

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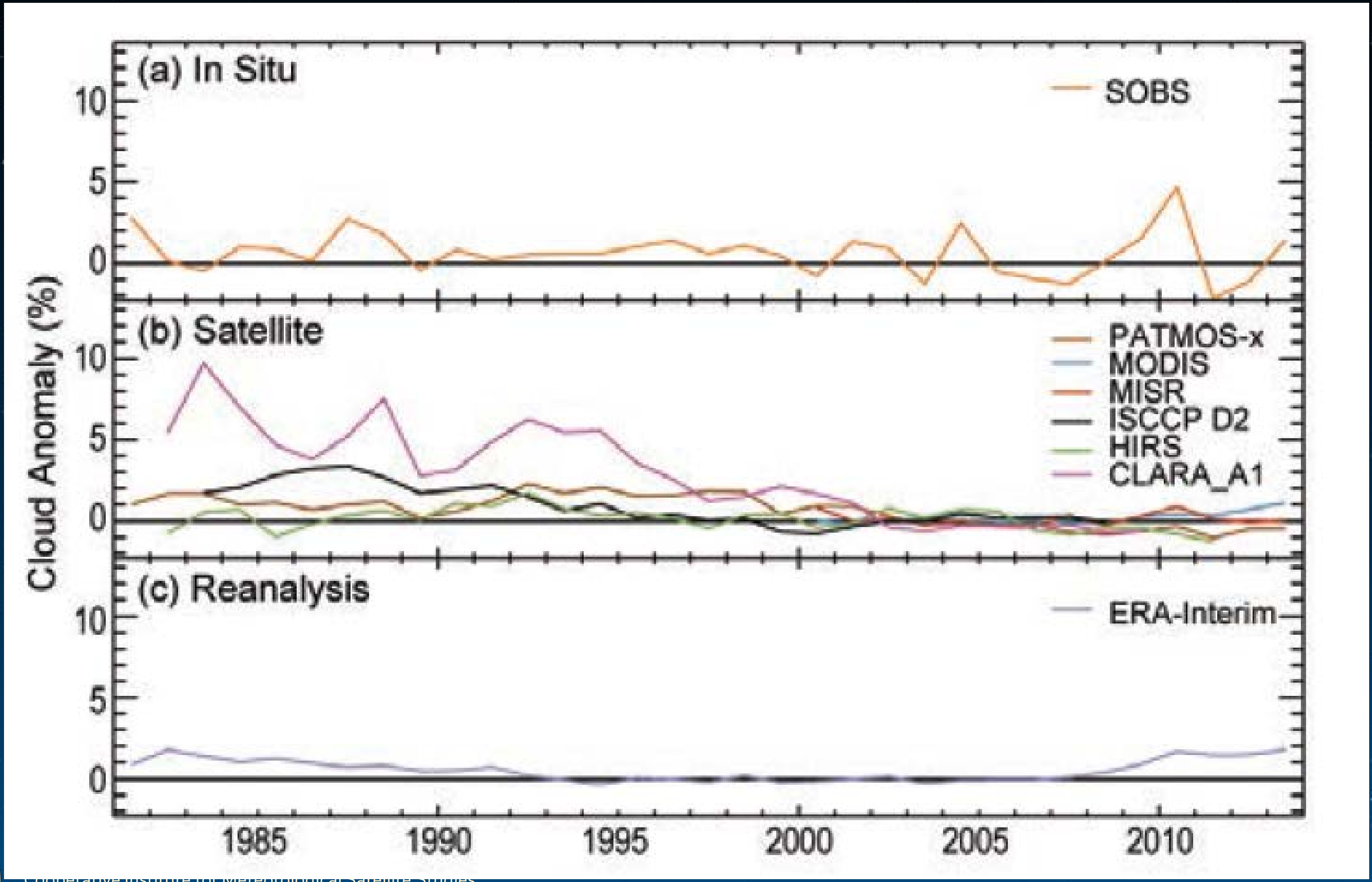
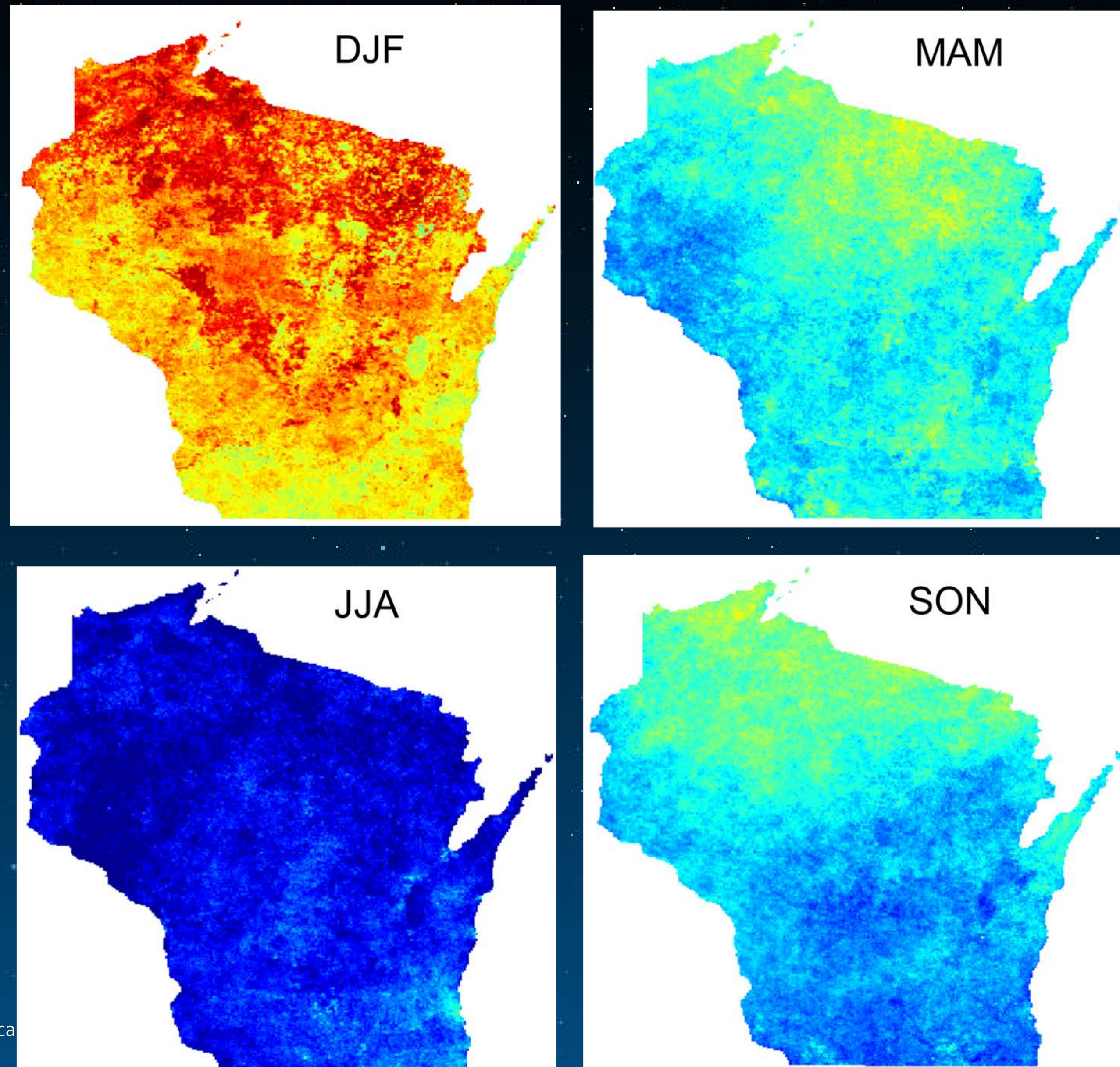
BAMS – State of Climate 2013



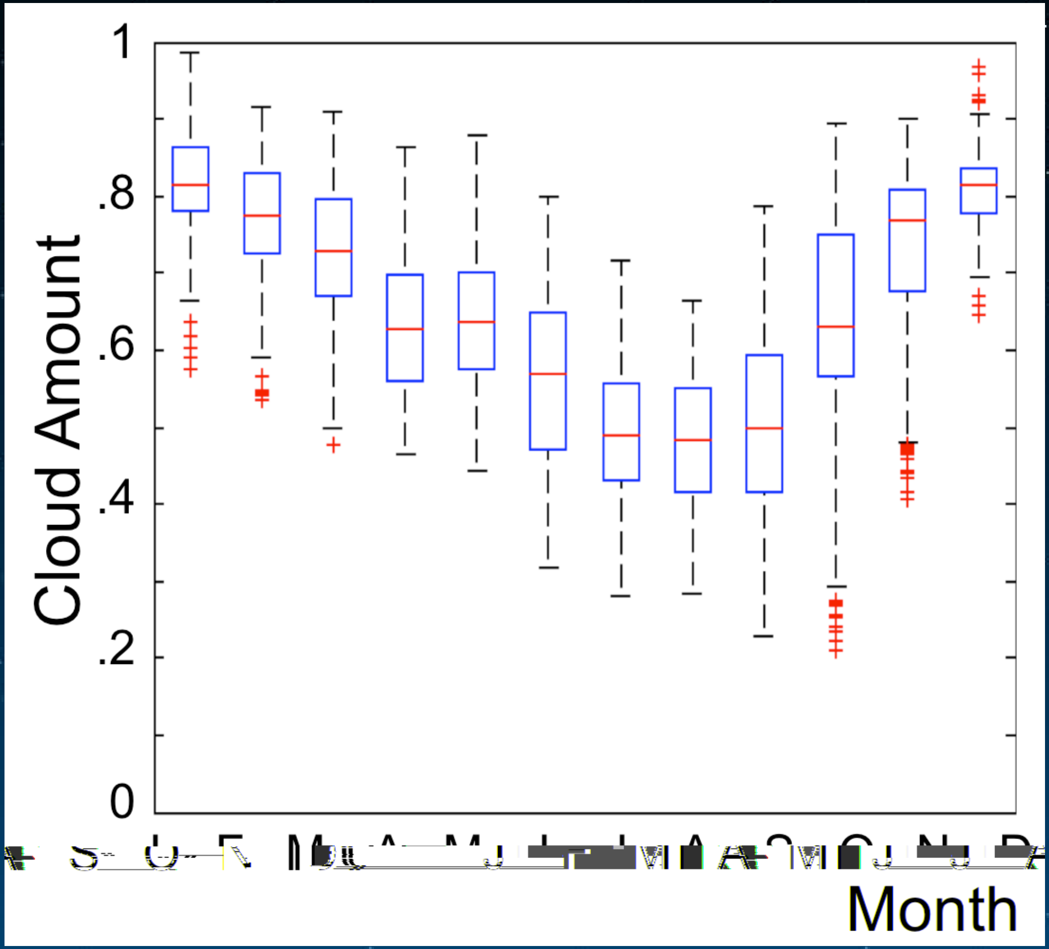
Regional Scale Analysis

The seasonal mean cloud amount at high spatial resolution enable regional studies.

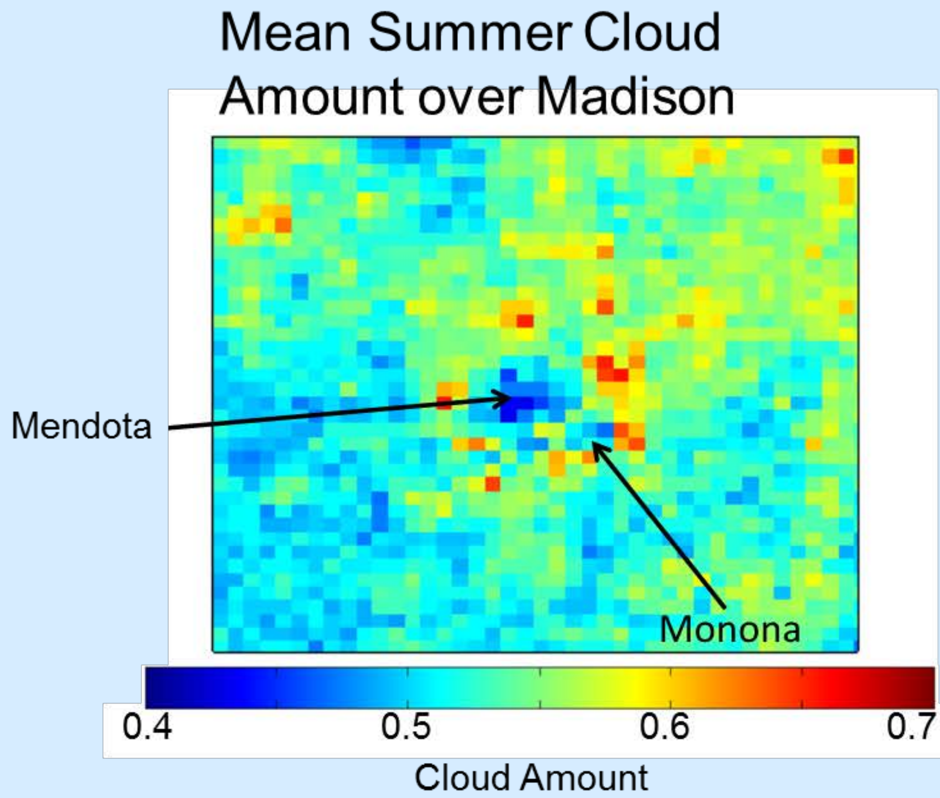


Regional Scale Analysis

Seasonal variation of cloud amount over Wisconsin (Box Plot.)

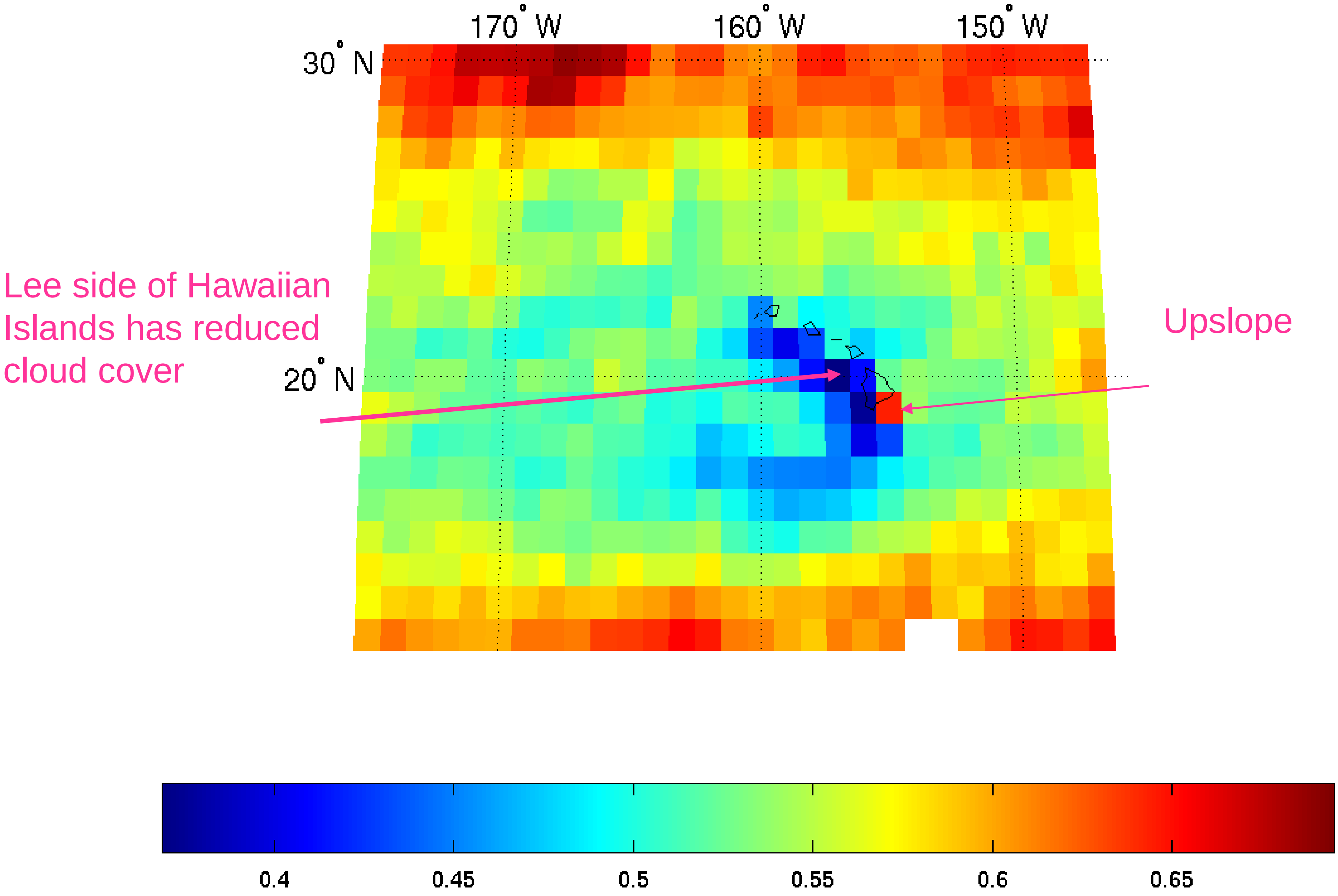


Regional Satellite Climate Studies



Extremely high resolution data shows the suppression of clouds over the lakes during the summer in Madison. The increase in summer cloud cover over other developed areas is also evident in the MODIS data record

Annual Cloud amount around Hawaiian Islands



Summary

i. Cloud coverage varies with:
   1. the spatial resolution of the instrument
   2. spectral resolution of the instrument
   3. viewing geometry and scene illumination.

ii. MODIS, AVHRR dependencies have be quantified

iii. The dependence of cloud detection on calibration and improvements requires a need to monitor changing instruments and satellites. Needed for long-term monitoring of cloud amount.

iv. MODIS cloud detection optical depth threshold ~ 0.4

v. Level-3 properties are accurately capturing small spatiotemporal scale variability. Be careful in your averaging choices!

Thank you – Questions?

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