Improvements in cloud climatology with CALIPSO and CloudSat missions

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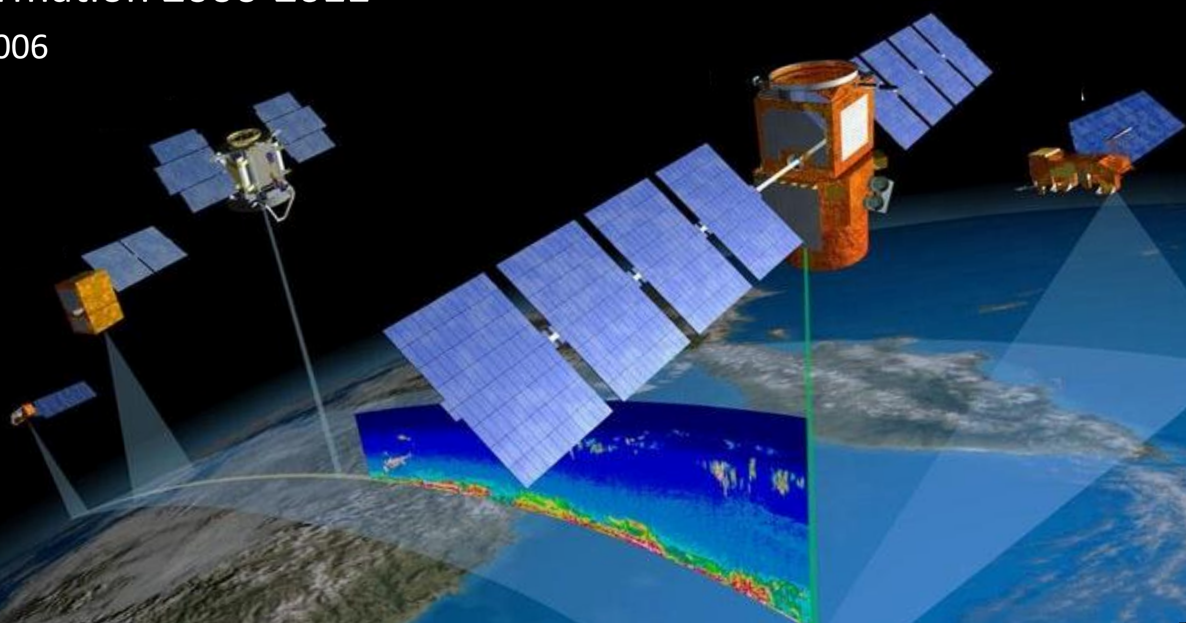
Outline

CLOUDSAT and CALIPSO two-slide intro

1. **CALIPSO helps MODIS**
   - How the CALIPSO profiles collocated with MODIS cloud detections allowed for a calibration of MODIS cloud climatology
2. **CALIPSO validates SYNOP**
   - How the CALIPSO data on cirrus validated the only pre-satellite climate records on cirrus, originating from surface-based, manual observations
3. **CALIPSO joins CloudSat**
   - How the unique, joint CloudSat-CALIPSO vertically-resoled cloud climatology was impacted by a mission-specific sampling scheme

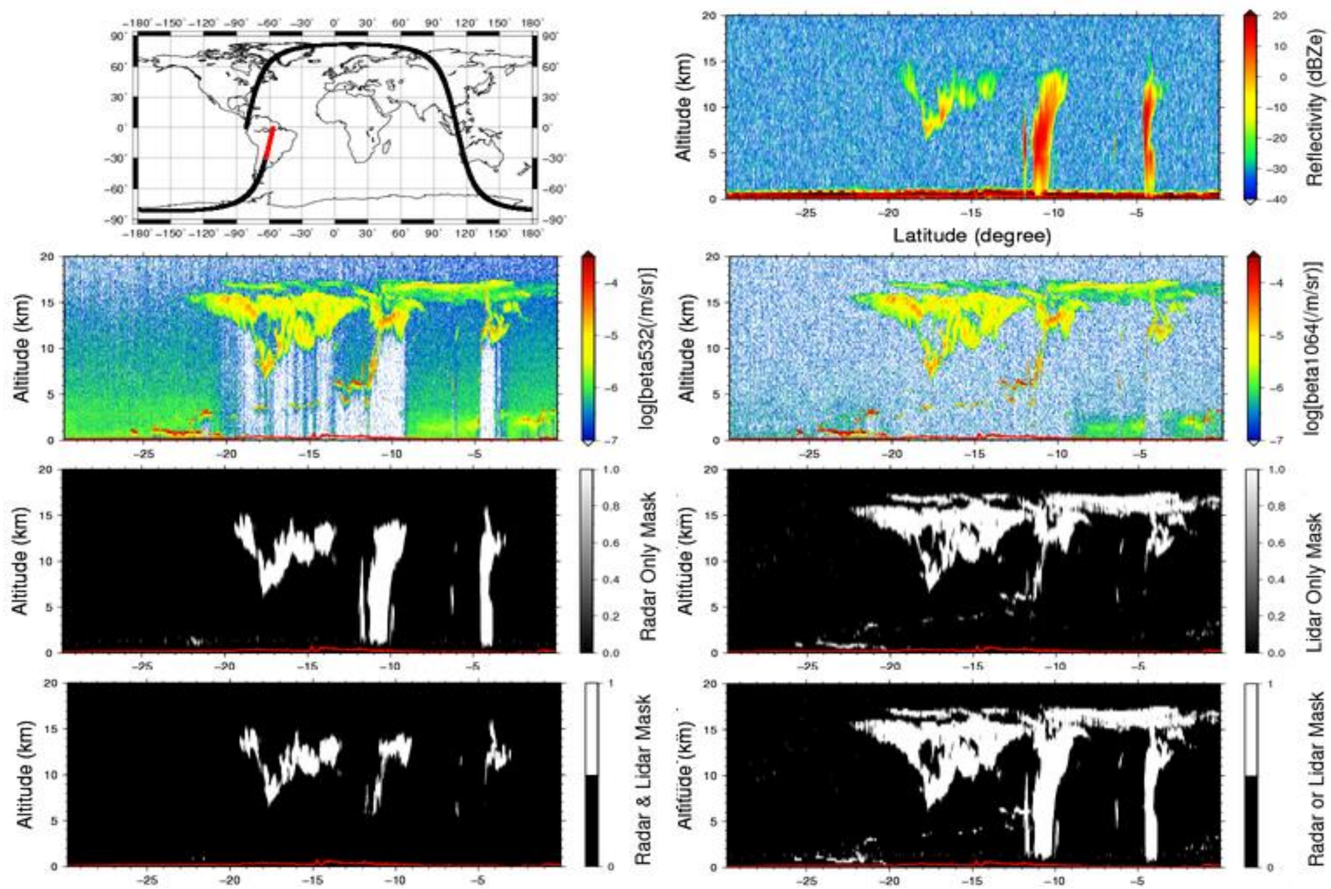
- **CALIPSO**: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
  - CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarisation; 0.532 µm and 1.064 µm
  - Footprint: 100 m, sampling every 333 m (also averaged into 1 km and 5 km)
  - Vertical resolution: 30 m (below 8.2 km), and 60 m (8.2-20.2 km); up to 40 km
  - Sensitive to optically thin clouds (COD <0.01), signal totally attenuated at COD ~5
- **CloudSat**
  - Cloud Profiling Radar (CPR) at 94 GHz
  - Footprint: 1.4 km (cross-track) × 1.7 km (along-track); vertical resolution 480 m, up to 25 km
  - Sensitive to optically thick clouds / hydrometeors
- Orbited in a close orbital formation **2006-2011**
  - Launched together in April 2006
  - Joined A-Train constellation
  - Temporal separation 15 sec
  - 60 sec after Aqua (MODIS)

705 km orbit
sun-synchronous
EQT 13:30 LST



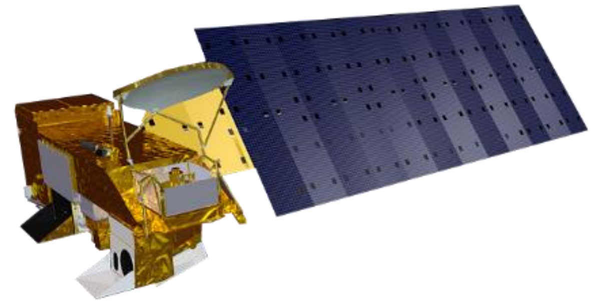
CALIPSO and CloudSat

→ Complementary mission of lidar and radar



1

CALIPSO helps MODIS



- MODIS: Moderate Resolution Imaging Spectroradiometer
  - state-of-the-art cloud imager on board Terra (1999+) and Aqua (2002+) polar orbiting satellites
  - 36 spectra bands (0.4 µm – 14.4 µm), some dedicated for clouds
  - very stable in terms of radiometry, and orbit = best qality data for climate studies
  - sensitive to clouds with optical depth >0.4 (Ackerman et al., 2008)

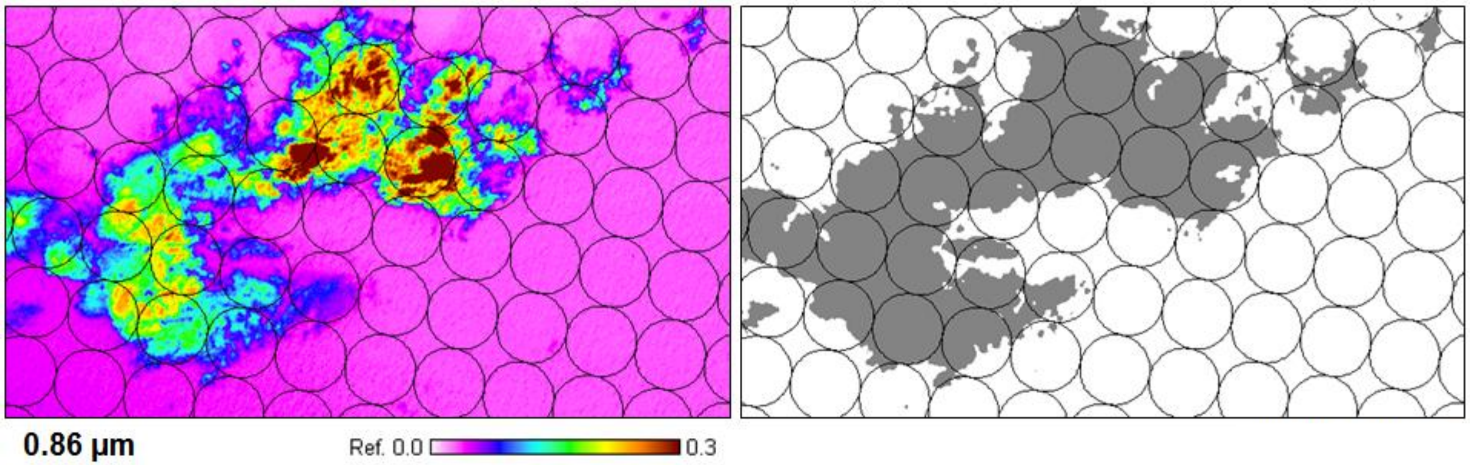
- Why MODIS needs help?
  - MODIS does not inform on cloud amount, but only report four classes for cloud detection: *confident clear*, *probably clear*, *probably cloudy*, *confident cloudy*.
    - 87% for MODIS Collection 005 (Holz et al. 2008)
    - 77.8% for Collection 006 (Wang et al. 2016)
    - 86.7% for Collection 061 (Kotarba 2020)
  - **Big question is**: How those classes translate into a quantitative measure? What is the fractional cloud cover that should be assigned to those classes?

    Assumption by NASA is

    - confident clear, probably clear = fractional cloud cover of 0%
    - probably cloudy, confident cloudy = fractional cloud cover of 100%

CALIPSO helps MODIS

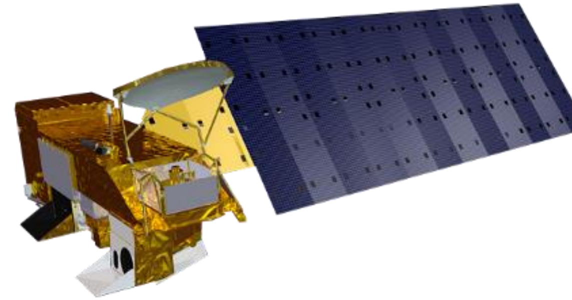
- NASA assumption can be validated by looking inside a MODIS 1 km FOV...



e.g. ASTER 30 m vs MODIS 1 km (Kotarba 2010; 10.1029/2009JD013520), but it works only on a limited scale.

- …or alternatively use CALIPSO data to test.

CALIPSO helps MODIS



- Match CALIPSO profiles with MODIS IFOVS
- **pros**: collocated observations MODIS Aqua + CALIPSO (A-Train constellation)
- **cons**: not exactly the same FOV (but it's better than pure guessing)

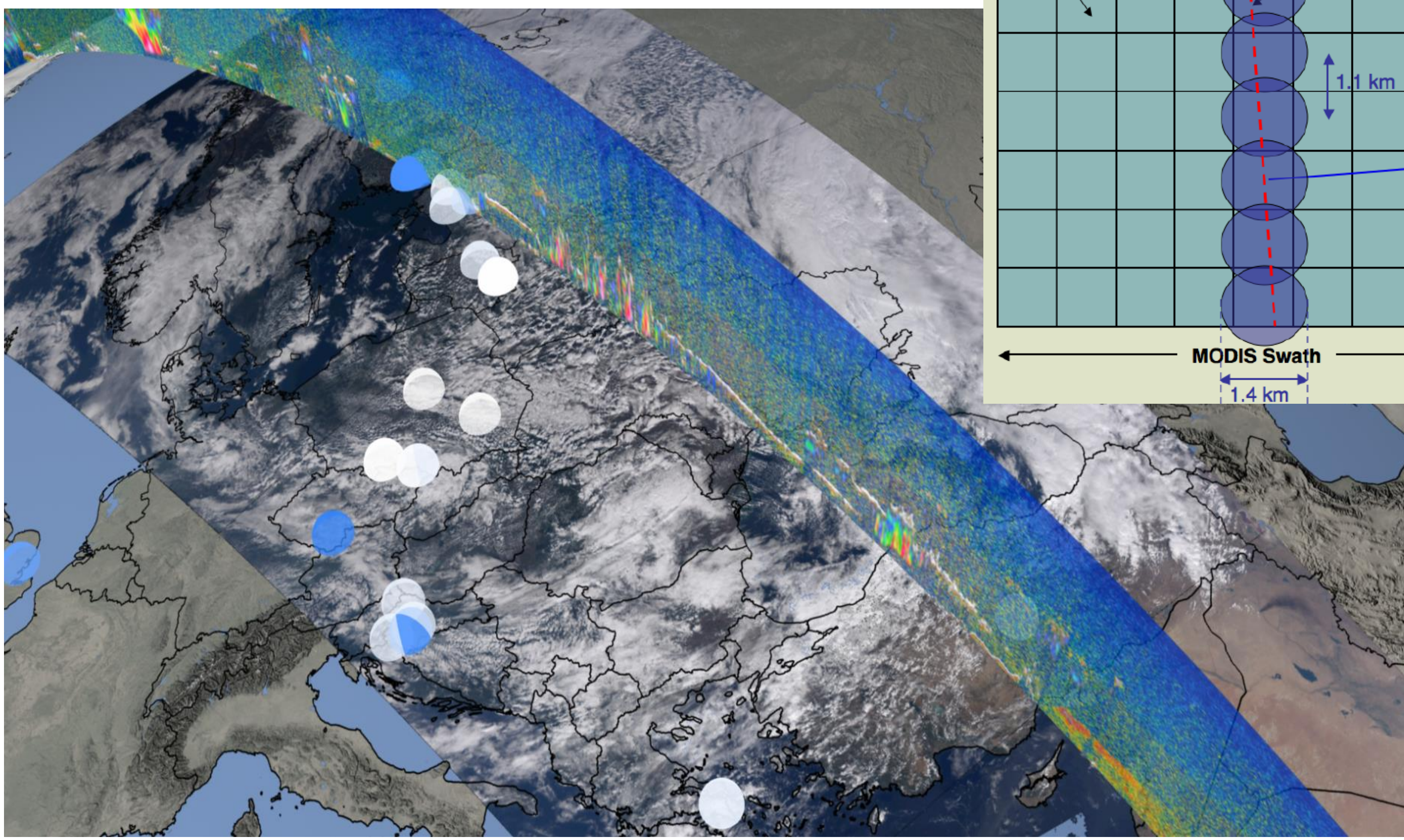
Experiment

- MODIS MYD35 Collection 061 + CALIPSO CloudLayer L2 1 km ver. 4.20
- January and July 2005, 33 793 648 MODIS-CALIPSO pairs, dt = 81 s (avr.)
- Assumption: cloud detected by CALIOP fills whole MODIS IFOV (100% cloudy)

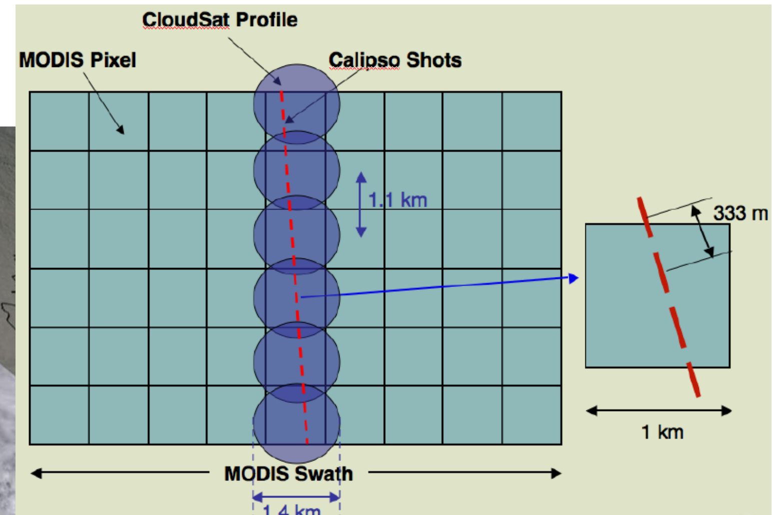
Full results in: Kotarba A.Z., (2020) *Calibration of global MODIS cloud amount using CALIOP cloud profiles*. Atmospheric Measurement Techniques, 13, 4995-5012, doi:10.5194/amt-13-4995-2020.

CALIPSO helps MODIS

→ Imager vs lidar's profiles



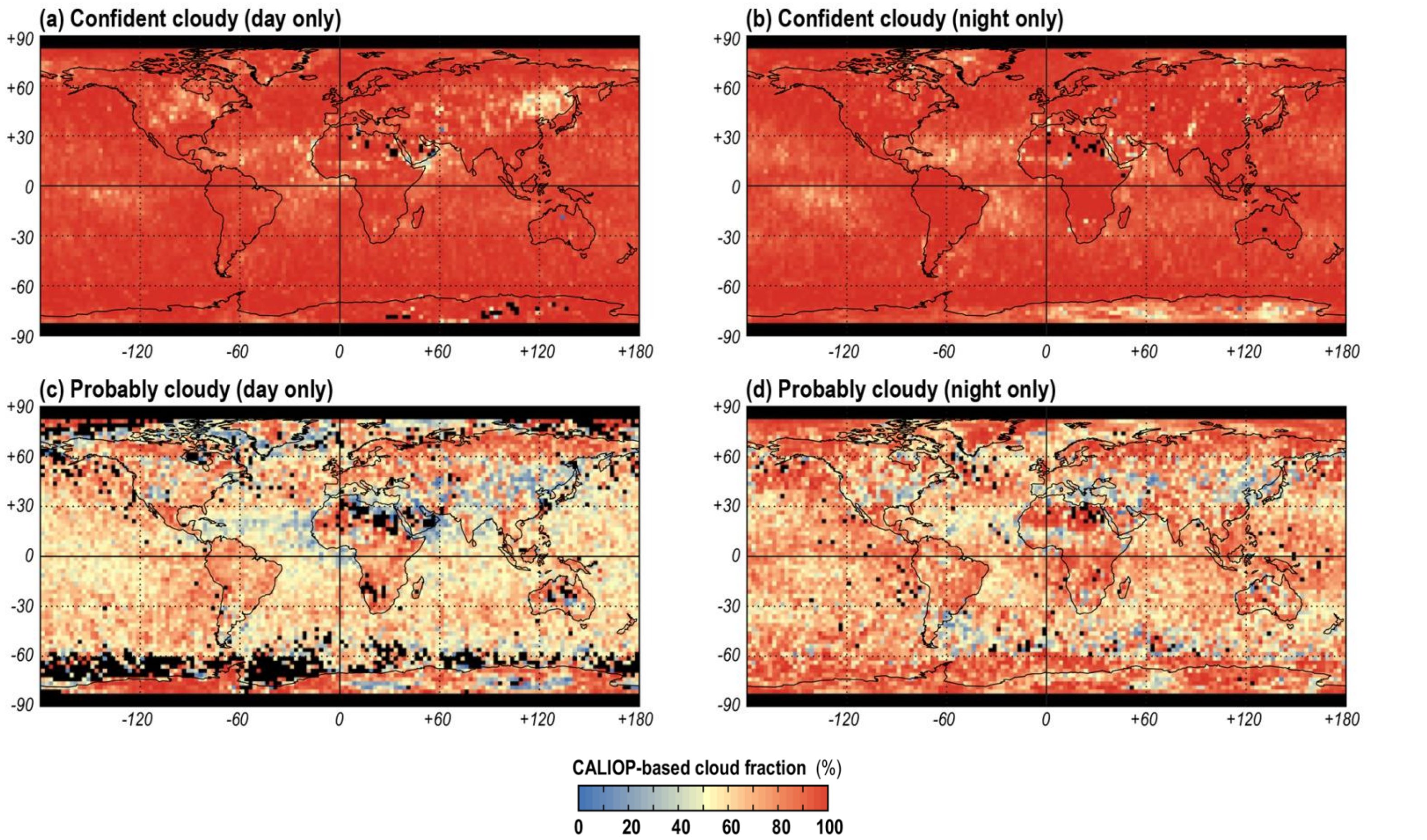
Sun-Mack et al. (2007)



333 m aggregated into 1 km footprint

CALIPSO helps MODIS

→ The actual cloud fraction for CM classes is...



CALIPSO helps MODIS

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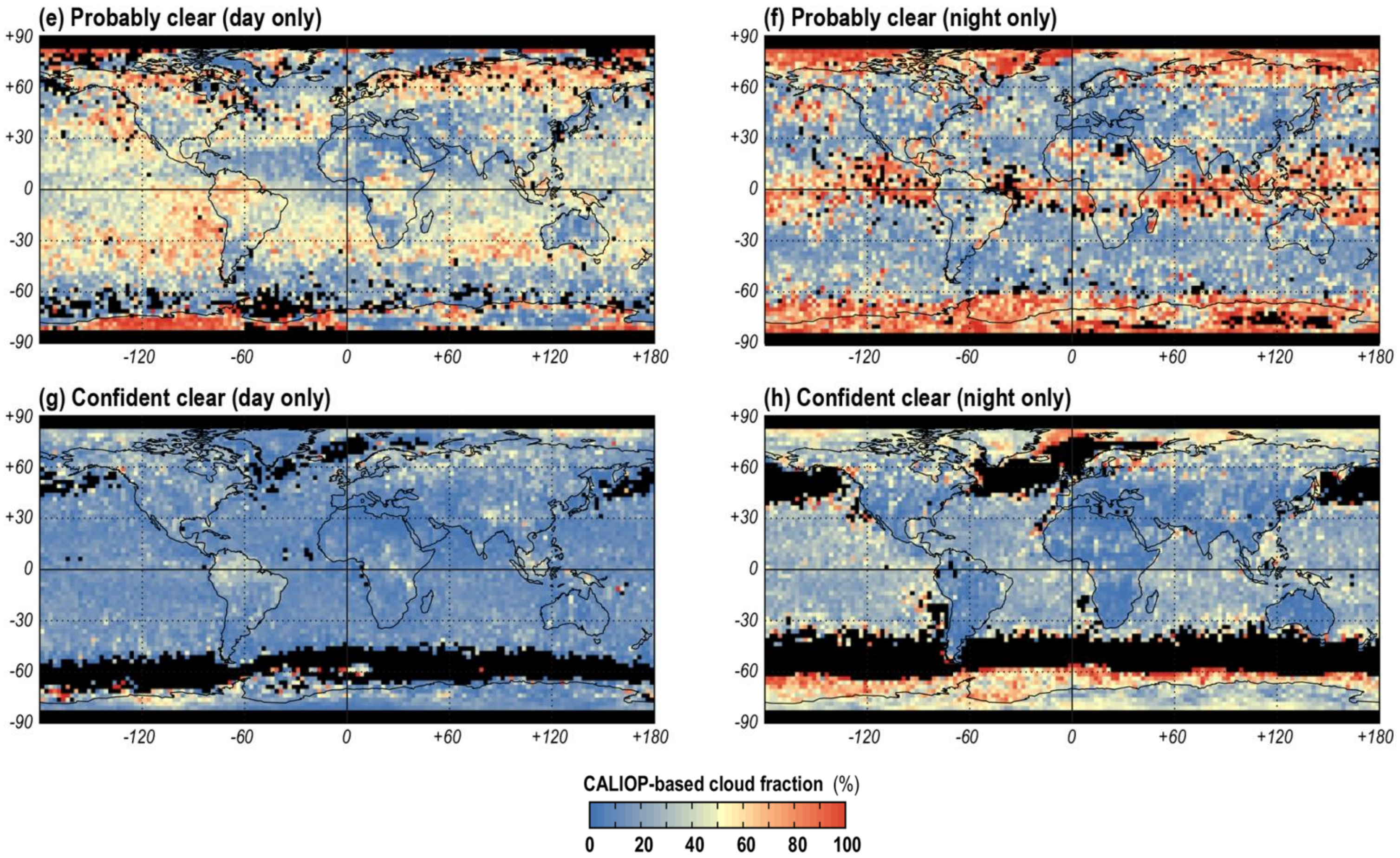


CALIPSO helps MODIS

→ The actual cloud fraction for CM classes is...

Source of cloud fractions for cloud mask classes		Cloud fractions (%) for MODIS cloud mask class (class frequency, % of n)			
		Confident clear (28.9 %)	Probably clear (7.5 %)	Probably cloudy (5.8 %)	Confident cloudy (57.8 %)
Operational	Day+night	0.0	0.0	100.0	100.0
This study	Day+night	21.5	27.7	66.6	94.7
	Day only	12.7	28.4	58.4	94.7
	Night only	29.5	27.1	70.7	94.7

CALIPSO helps MODIS

→ Fractions for algorithm paths...

Table 3. MODIS Cloud Mask Tests Executed (✓) for a Given Processing Path

	MODIS Cloud Mask Test Layout for a Given Processing Path									
	Daytime Ocean	Nighttime Ocean	Daytime Land	Nighttime Land	Polar Day (snow)	Polar Night (snow)	Coastline Day	Coastline Night	Desert Day	Desert Night
BT_{11} (bit 13)	✓	✓								
$BT_{13.9}$ (bit 14)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$BT_{6.7}$ (bit 15)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$R_{1.38}$ (bit 16)	✓		✓		✓		✓		✓	
$BT_{3.7} - BT_{12}$ (bit 17)				✓		✓				✓
BT_{8-11} & BT_{11-12} (bit 18)	✓	✓	✓	✓			✓	✓	✓	✓
$BT_{3.7} - BT_{11}$ (bit 19)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$R_{.66}$ or $R_{.87}$ (bit 20)	✓		✓				✓			
$R_{.87}/R_{0.66}$ (bit 21)	✓		✓							
$R_{.935}/R_{.87}$ (bit 22)	✓		✓		✓		✓			
$BT_{3.7} - BT_{3.9}$ (bit 23)	✓		✓				✓		✓	
Temporal consistency (bit 25)	✓	✓								✓
Spatial variability (bit 25)	✓	✓								

Ackerman et al. 1998

– 13+ „sub-algorithms” = possible **inhomogeneity** in cloud detection

CALIPSO helps MODIS

→ Fractions for algorithm paths...

Cloud masking algorithm path				CALIOP-based cloud fractions (%) for MODIS cloud mask class			
				Confident clear	Probably clear	Probably cloudy	Confident cloudy
Day (47.2)	Snow-covered (5.5)	Land	(0.2)	13.8	67.0	56.0	97.6
		Desert	(3.9)	12.6	32.6	71.8	96.6
		Coast	(0.2)	15.3	55.5	61.8	93.8
		Ocean	(1.1)	20.5	76.3	69.7	88.6
	Snow-free (41.7)	Land	(6.7)	15.6	32.3	63.9	93.4
		Desert	(3.4)	9.1	19.1	45.5	90.0
		Coast	(1.6)	19.0	33.8	59.8	93.0
		Ocean	(30.1)	10.5	28.4	54.5	95.2
Night (52.8)	Snow-covered (15.8)	Land	(2.6)	31.4	65.0	80.9	93.9
		Desert	(4.7)	34.3	65.3	75.9	86.4
		Coast	(0.9)	29.8	60.8	75.0	93.7
		Ocean	(7.6)	49.7	73.7	82.5	96.8
	Snow-free (37.0)	Land	(5.4)	8.0	25.6	68.5	97.7
		Desert	(2.6)	8.2	23.5	55.8	95.4
		Coast	(0.9)	10.9	23.0	60.9	96.4
		Ocean	(28.1)	22.9	22.4	61.8	94.6

0% **100%**

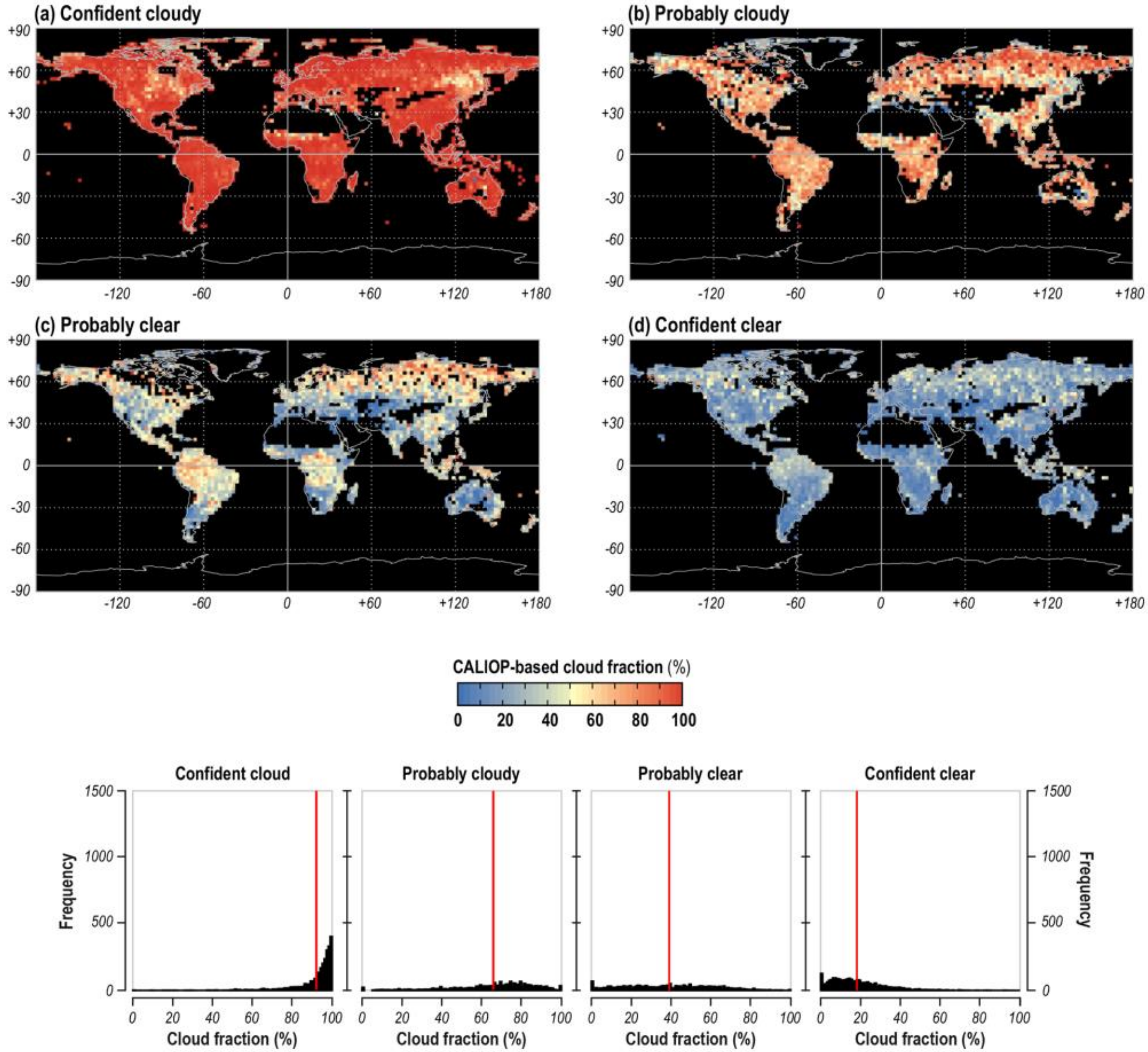


Figure 6. CALIOP-based cloud fraction for MODIS cloud mask classes for the "daytime, snow-free land" algorithm path and corresponding histograms (red vertical line indicates the mean value).

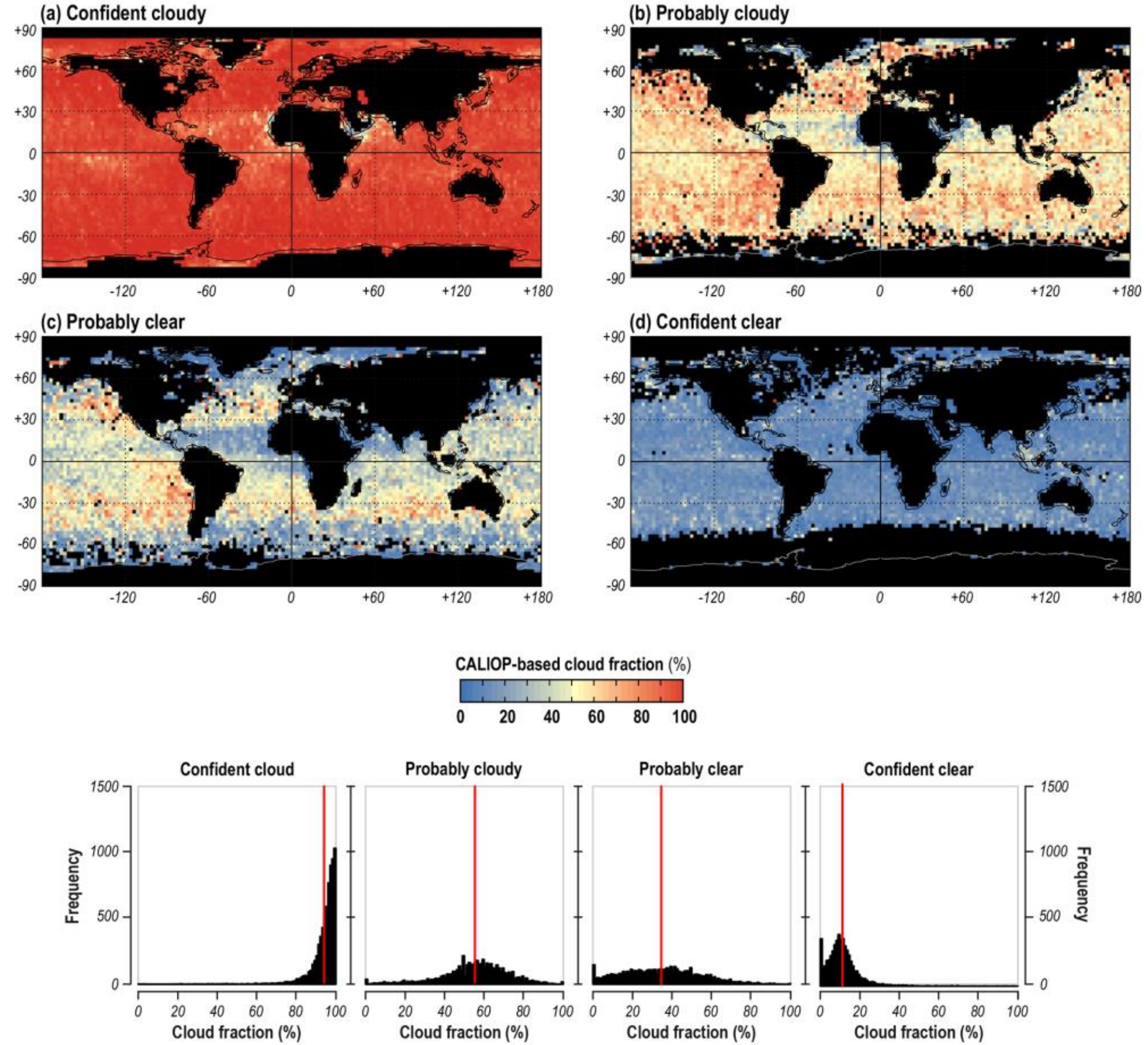


Figure 7. CALIOP-based cloud fraction for MODIS cloud mask classes for the "daytime, snow-free ocean" algorithm path and corresponding histograms (red vertical line indicates the mean value).

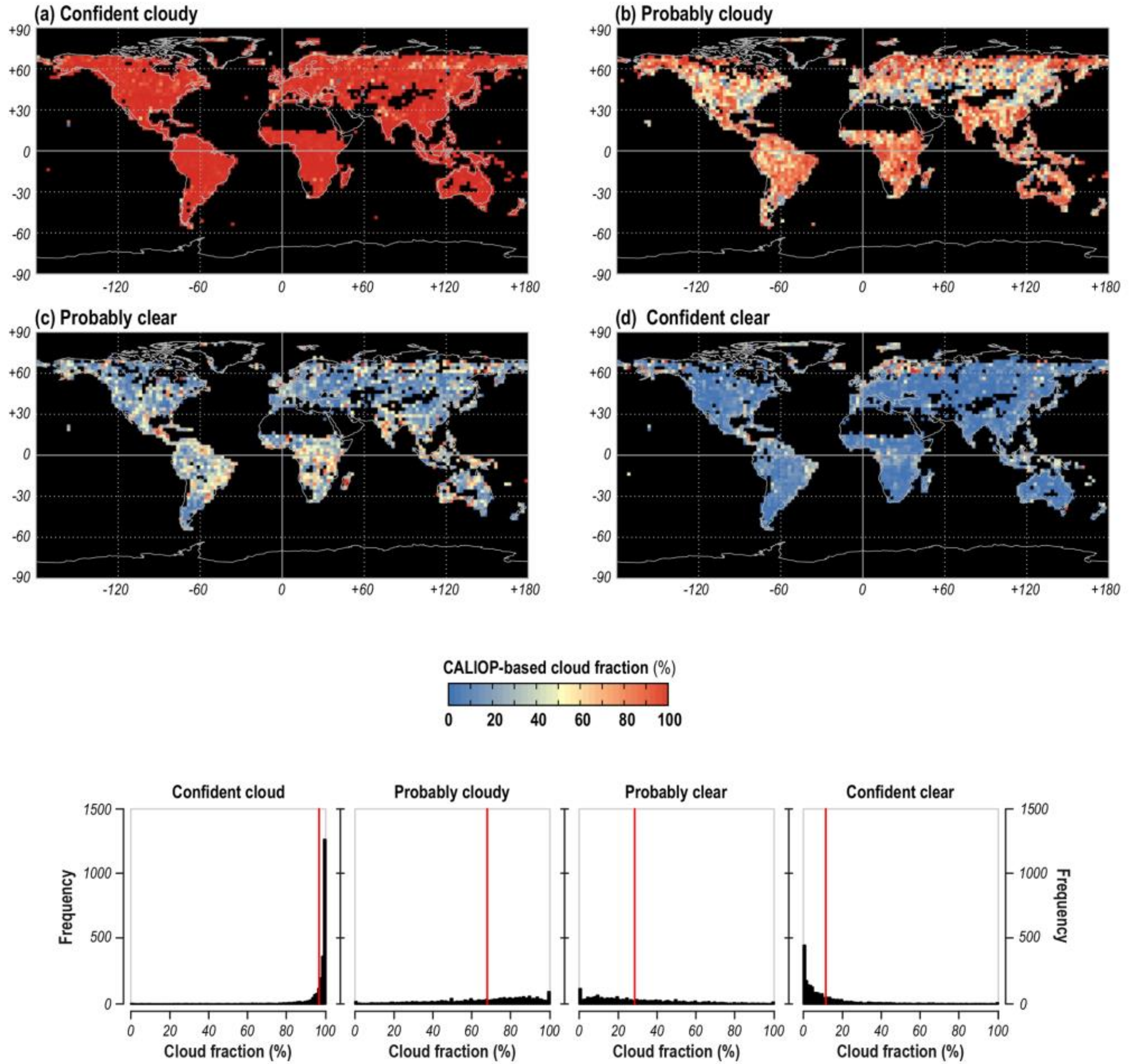


Figure 5. CALIOP-based cloud fraction for MODIS cloud mask classes for the "nighttime snow-free land" algorithm path and corresponding histograms (red vertical line indicates the mean value).

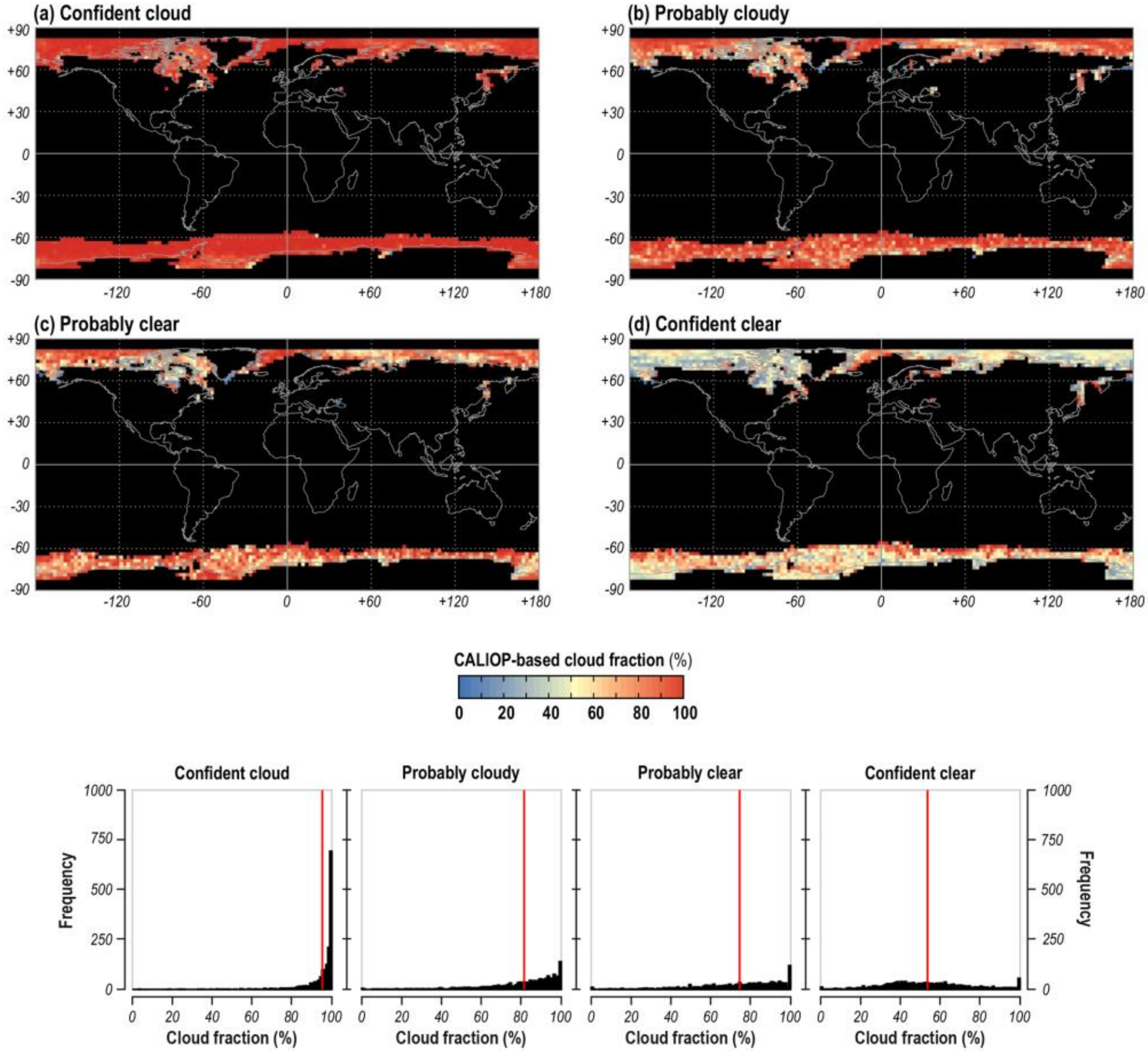
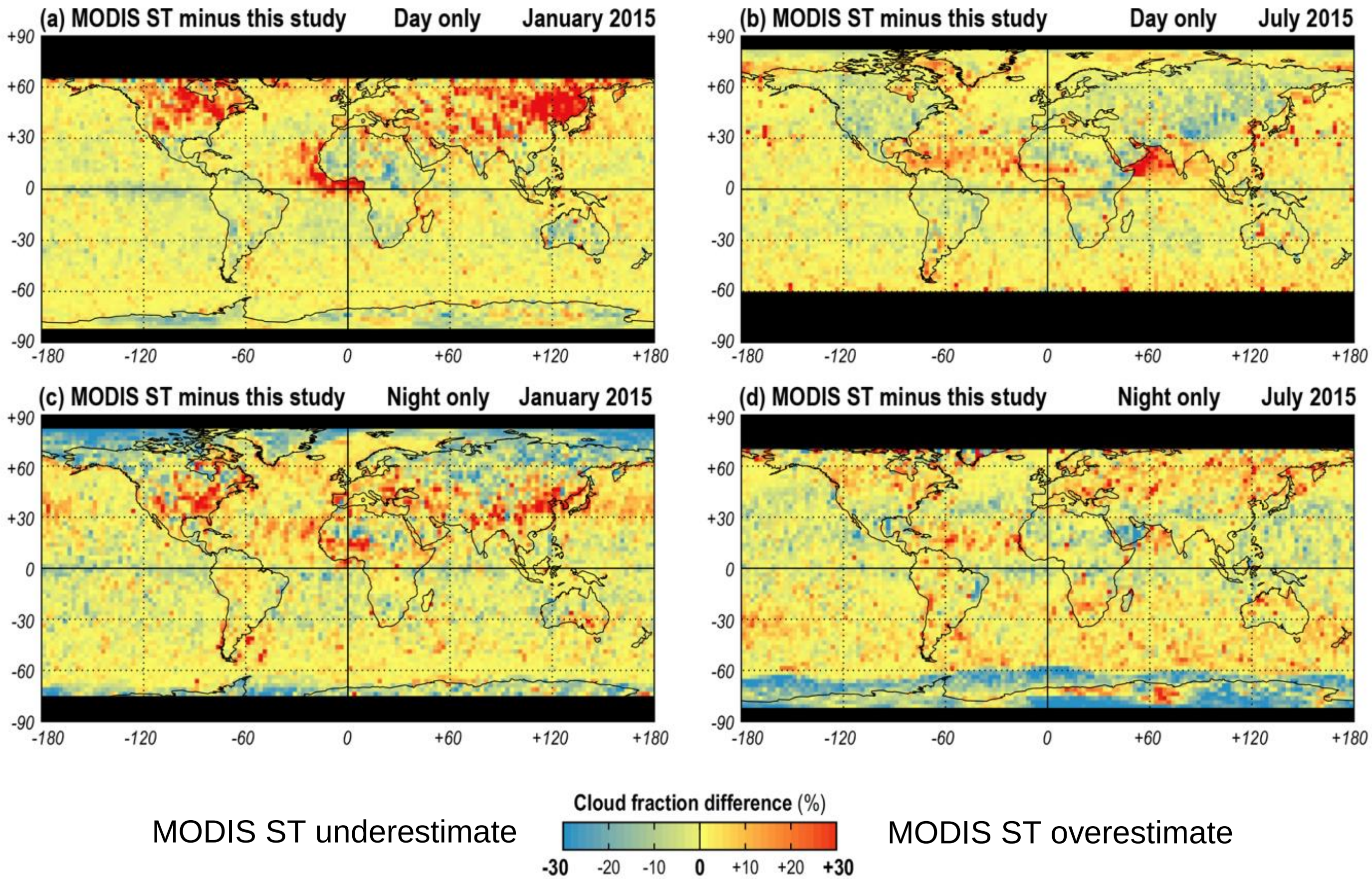


Figure 4. CALIOP-based cloud fraction for MODIS cloud mask classes for the "nighttime, snow(ice)-covered ocean" algorithm path and corresponding histograms (red vertical line indicates the mean value).

CALIPSO helps MODIS

→ Practical implications: Calibration of MODIS climatology



CALIPSO helps MODIS

→ Conclusions

- Method for deriving empirical cloud fraction for thematically cloud detection classes; applicable to MODIS, AVHRR, VIIRS, and geostationary imagers.
- MODIS ST assumption is inaccurate; the actual cloud fractions for MODIS are: 21.5 %, 27.7 %, 66.6 %, and 94.7 %, instead of 0%, 0%, 100%, 100%.
- Cloud fractions vary among algorithm paths, and regionally – within a single path (region specific cloud detection errors).
- Calibrated climatology indicate over/under estimation of as much as 30% in polar regions, and „aerosol regions".

2

CALIPSO validates SYNOP

- Surface-based detection of cirrus (SYNOP)
  - Cirrus, Cirostratus, Cirrocumulus as defined by WMO - hereinafter „cirrus"
  - Detected visually, by a human observers at meteo stations over land (and oceans)
  - The only pre-satellite data on cirrus, the longest existing climate records on cirrus
    United States, 1948-1994, and the former Soviet Union, 1936-1990 (Sun et al. 2001), Canada, 1953–2003 (Milewska 2008), China, 1971-1996 (Endo and Yasunari 2006), the Arctic, 1954-2008 (Eastman and Warren 2010), the northern Chilean coast, 1969-2013 (Muñoz et al. 2016), the north–east of Spain, 1910-2006 (Curto et al. 2009), or Poland, 1971-2000 (Filipiak and Miętus 2009).
  - Challenging geometry: cloud overlap; unknown sensitivity of human eye to cirrus

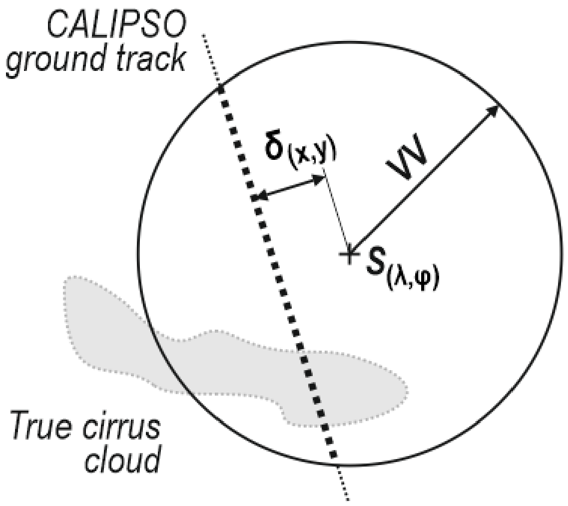
Experiment

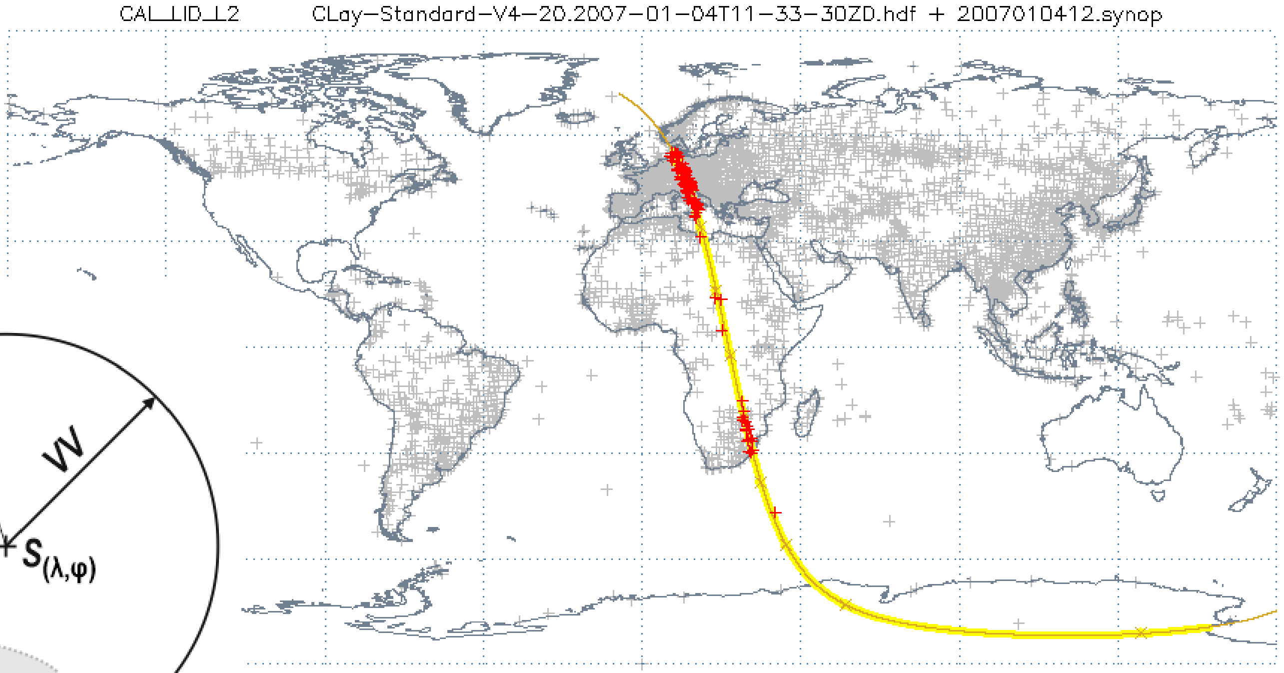
- Quality-checked SYNOP FM-12 reports for 2006-2020, globally
- CALIPSO: CloudLayer L2 5 km ver. 4.20 (the most sensitive product for cirrus)
- Confusion matrix for binary classification, and related measures of agreement

Full results in: [1] Kotarba A.Z., Nguyen Huu, Ż., *Accuracy of visual cirrus detection by a surface-based human observers*. *(about to be submitted);* [2] Nguyen Huu, Ż., Kotarba, A.Z., (2021) Reliability of visual detections of cirrus over Poland. Theoretical and Applied Climatology, 144, 1–11, doi:10.1007/s00704-020-03494-9.

CALIPSO validates SYNOP

→ Data base of paired observations

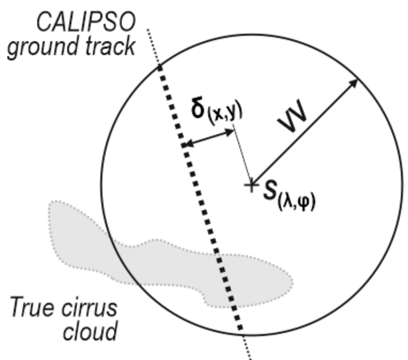


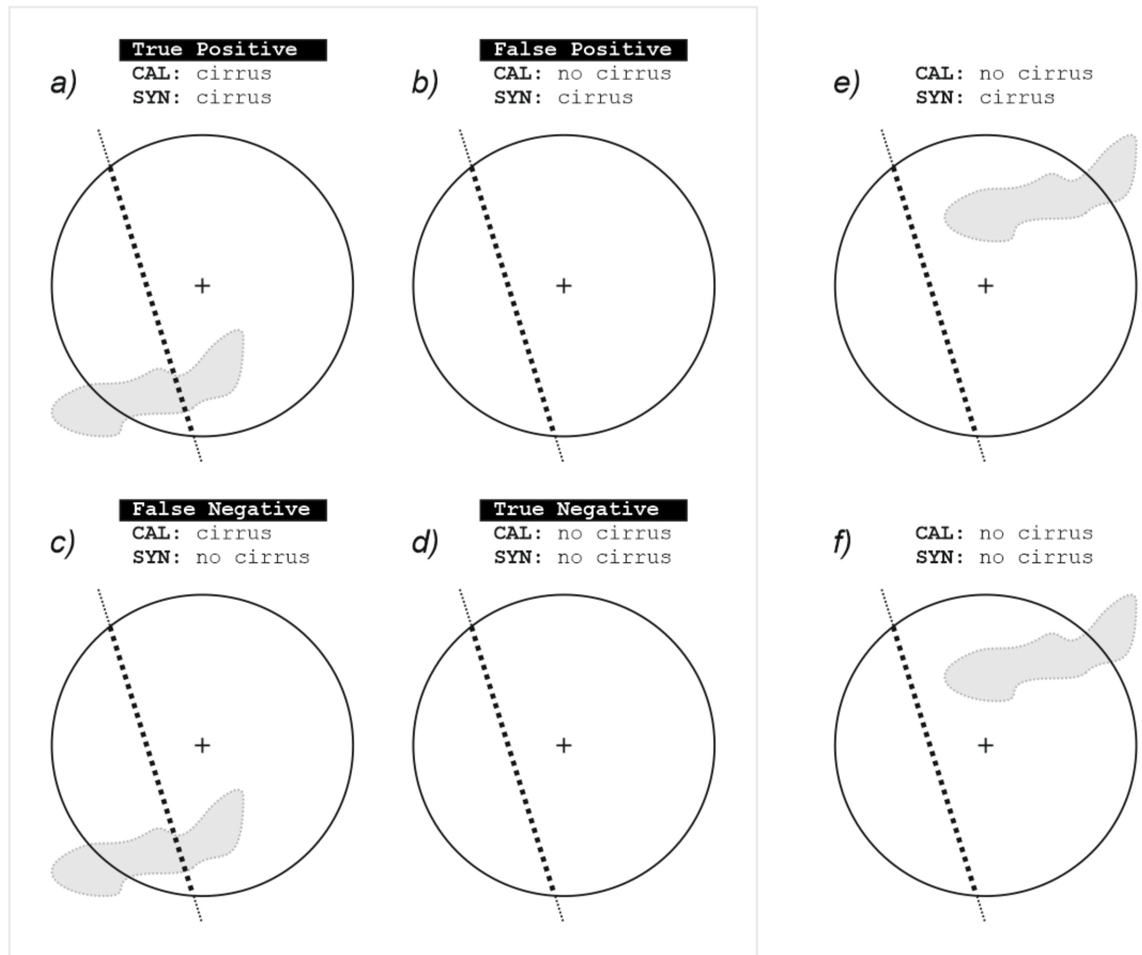


- Time-frame: 2006-2020 (232,680,353 reports initialy)
- 64,390 SYNOP-CALIPSO pairs considered
- dt = 4.9 min (avr.), 10.0 (max)
- dxy = 11 km (avr.), VV=33 km (avr.)

CALIPSO validates SYNOP

→ Field of view issue (inconsistency)

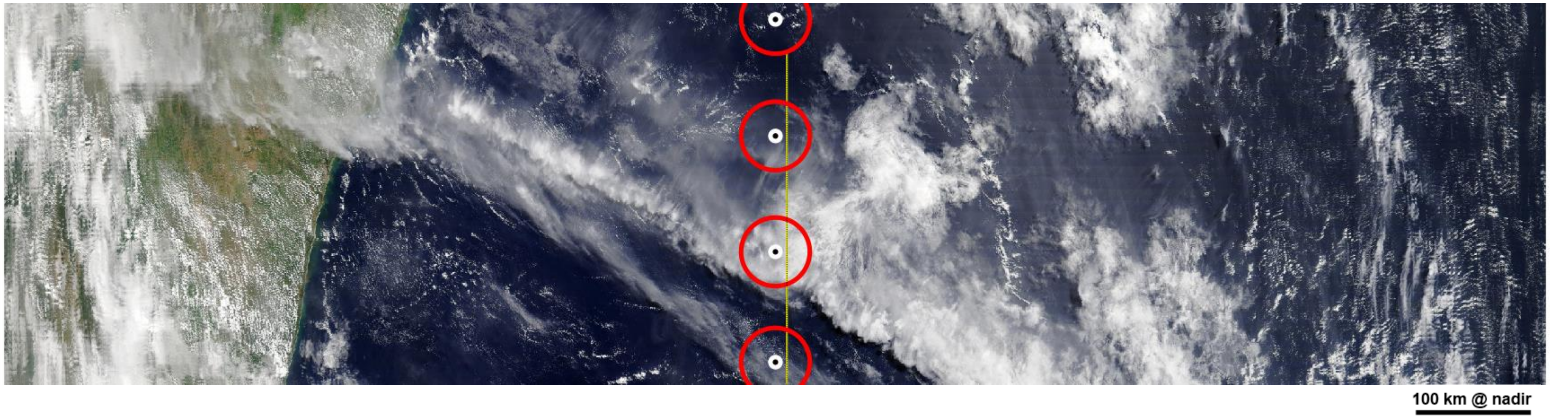




CALIPSO validates SYNOP

→ Field of view issue (inconsistency) – correction factor

- How frequently CAIPSO passes over a station, and report no cirrus just because of a ground track misalignment?
- **Simlulation**
  - MODIS data: Aqua, full day of observations, every 10 days in 2017 = 10,368 MODIS granules
  - International Satellite Cloud Climatology Project (ISCCP) definition of cirrus:
    cloud with optical thickness less than 23, and top pressure less than 440 hPa
  - virtual meteo station every 100 km along the MODIS ground track
  - simulated CALIPSO pass 11 km to the station (i.e. average dxy in SYNOP-CALIPSO database)
  - SYNOP-like cirrus reported within 33 km buffer (i.e. average visibility range in our database)



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- **Results**
  - 13% of observations: cirrus missed by CALIPSO because of ground track mislocation
  - 32% of observations: cirrus presence confirmed by both techniques
  - 55% of observations: cirrus absence confirmed by both techniques
  - Correction factor: **19%** of FP → TP, TN → FN
  - + Sensitivity study (now the corr. factor ipmacts the results)

CALIPSO validates SYNOP

→ Overall agreement

Conditions	Accuracy measures				
	POD	FAR	OA	F-score	κ
All, day	48%	22%	60%	0,58	0,24
All, night	28%	12%	53%	0,40	0,14
Perfect, day	67%	24%	72%	0,69	0,43
Perfect, night	35%	13%	61%	0,47	0,22

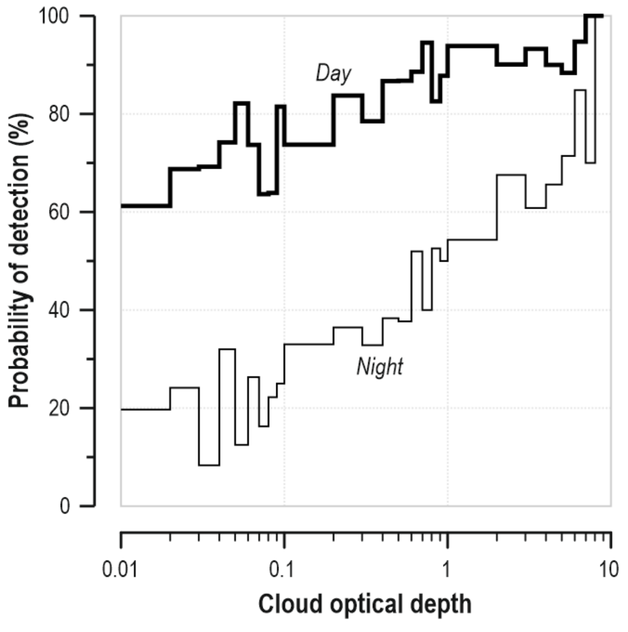
method's performance (All, day / All, night)

observer's performance (Perfect, day / Perfect, night)

- Probability of cirrus detection (**POD**), false alarm rate (**FAR**), overal accuracy (**OA**)
- F-score + Cohen's Kappa (evaluation of binary clasification; range 0 to 1)

CALIPSO validates SYNOP

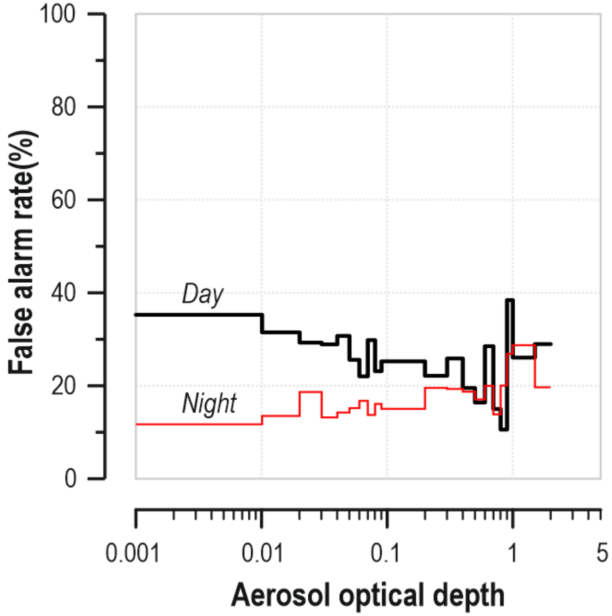
→ Perfect conditions: cirrus optical depth



- Very strong dependance, both day-time and night-time
- Interestingly: sub-visual cirrus (τ_{cir}<0.03) also detected by human observers

CALIPSO validates SYNOP

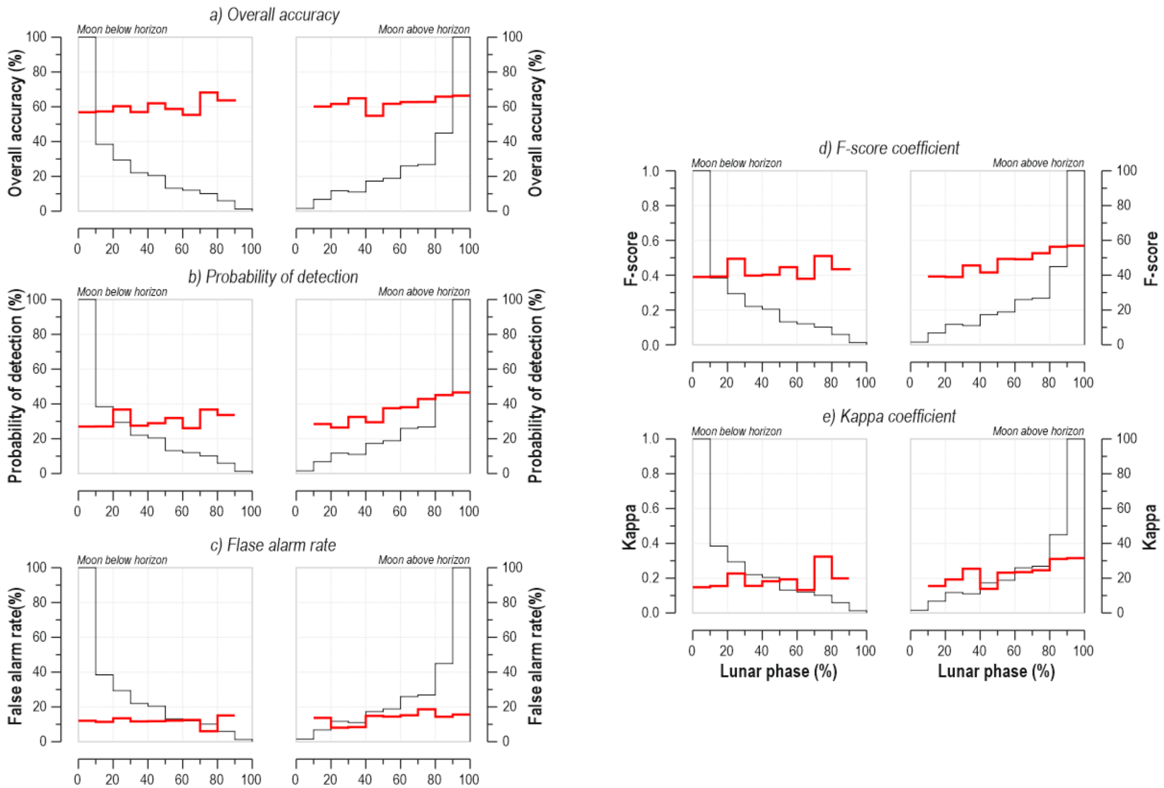
→ Perfect conditions: aerosol misclassified as cirrus?



- Possibly during the night time, but relations is weak
- Day-time conditions are inconclusive

CALIPSO validates SYNOP

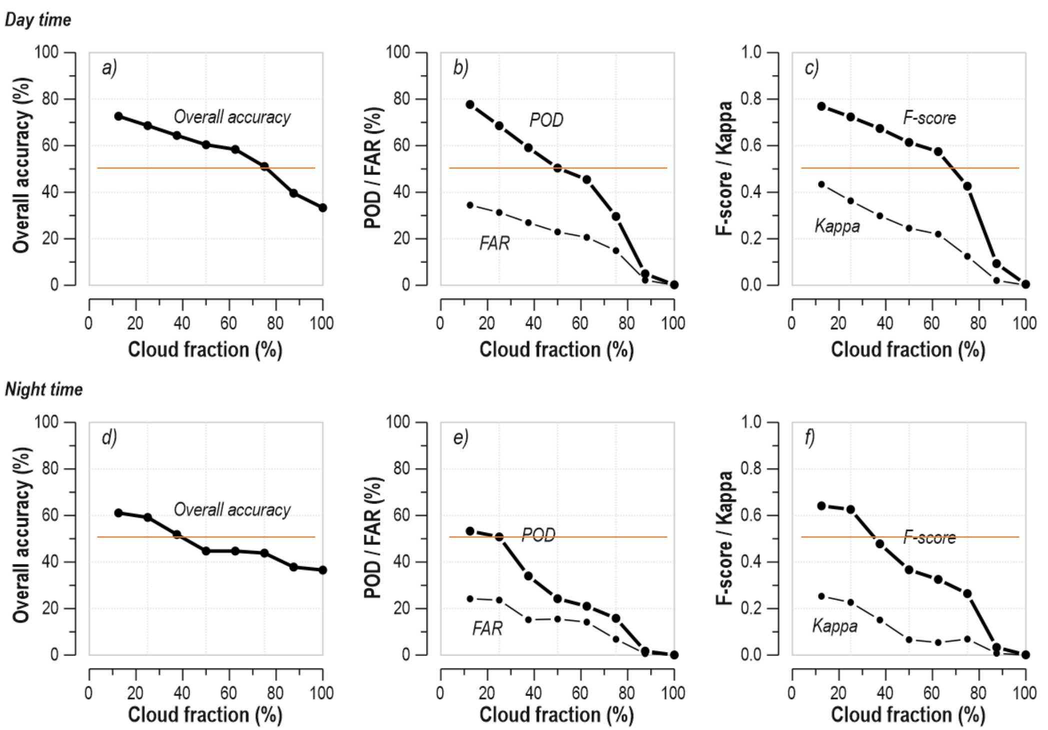
→ Perfect conditions: any hope from lunar illumination?



- Probability of detction slightly higher when lunar pahse >50%, no impact on FAR and OA

CALIPSO validates SYNOP

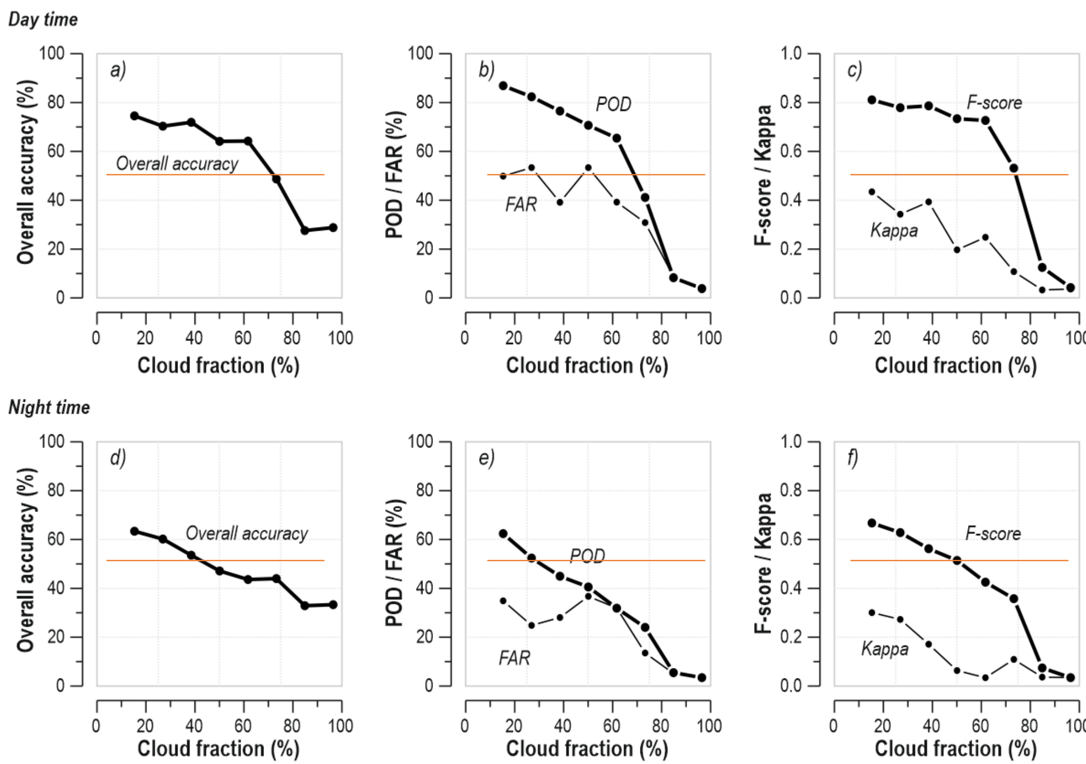
→ Real conditions: clouds at middle and/or low levels



- Performance systematically decreases as the cloud fraction increase
- Rapid drop in POD after 60% day time, and 25% night time.
- Kappa always very low (almost random agreement between SYNOP and CALIPSO)

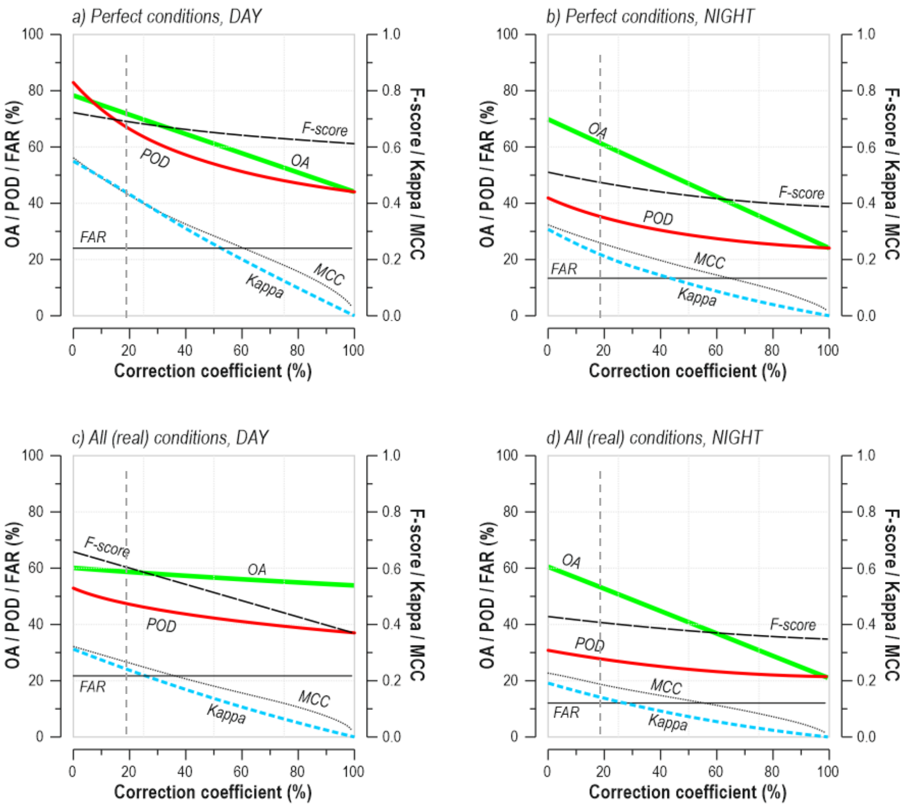
CALIPSO validates SYNOP

→ Real conditions: clouds at middle level only



CALIPSO validates SYNOP

→ Correction factor – sensitivity study



- Corr. factor = 19% is close to the best of what can be achieved with SYNOP
- Even with any other corr. factor (0-100%) the performance still would be moderate to low

CALIPSO validates SYNOP

→ Conclusions

- First quantitative assessment of visual detection of cirrus; method that allows for matching SYNOP and CALIPSO transects + method's uncertainty analysis.
- SYNOP moderately reliable (PoO>60%) for cirrus only daytime, only during perfect condition or under real conditions but with few middle/low-level clouds
- In other cases detections unreliable (PoD<50%) → agreement with CALIPSO can be purely random (very low Kappa coincident, <0.2).
- Lunar illumination is not much helpful for cirrus detection.

- The results can be also a benchmark for camera-based detections
  (does your algorithm perform better than a human observer?)

3

CALIPSO joins CloudSat

- The only avaliable lidar–radar cloud profile data, globally (2006-2011)
  (Follow on: EarthCARE 2021+, or Aerosol Cloud Convection and Precipitation ?)
- Complementary observations: CALIOP (thin clouds) + CloudSat (thick clouds)
- Profiling instruments + 16-day revisit = 22/23 obs. per year
- Uncertanity of climate data resulting from the infrequent revisit… ?

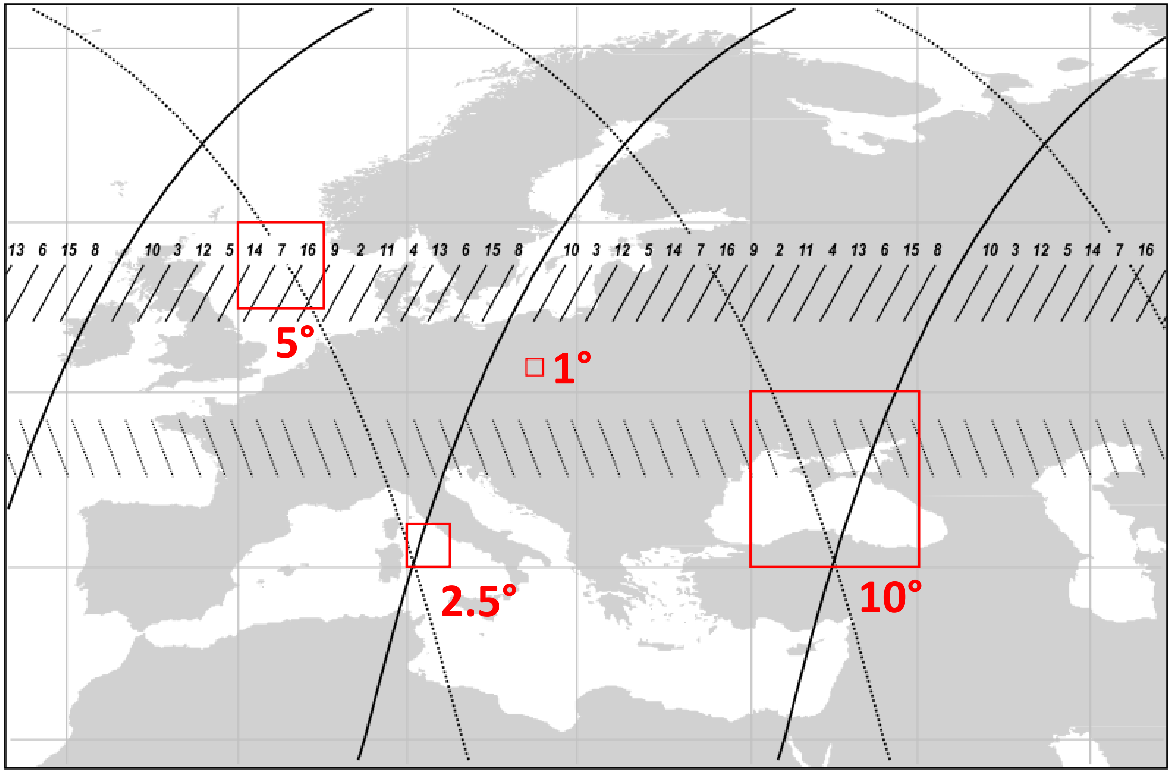
Experiment

- 2B-GEOPROF-LIDAR (ver. P2_R05), Layer Base and Layer Top altitude (m)
- Epoch 00 to Epoch 04 (2 June 2006 - 17 April 2011), dt = 10-15 s
- Mean cloud amount at 40 levels (480 m) + bootstrap confidence interval at: 4 spatial resolutions, 4 confidence levels, and 3 time scales.

Full results in: Kotarba, A.Z.; Solecki, M. (2021) *Uncertainty Assessment of the Vertically-Resolved Cloud Amount for Joint CloudSat–CALIPSO Radar–Lidar Observations*. Remote Sensing, 13, 807. doi: 10.3390/rs13040807.

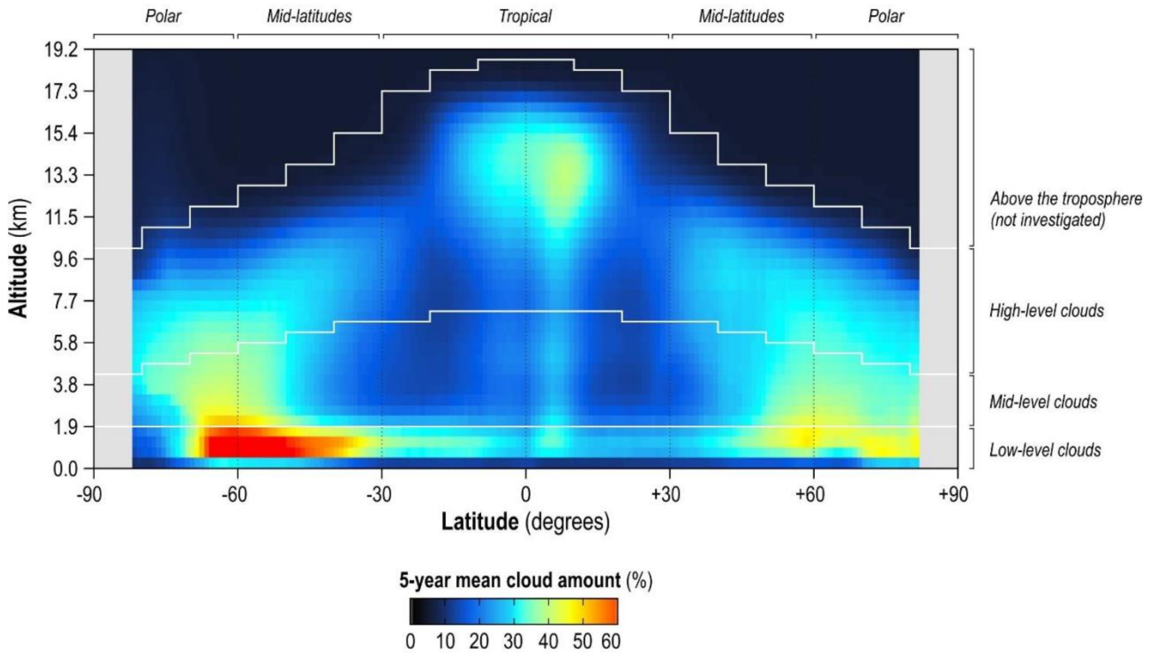
CALIPSO joins CloudSat

→ Orbit and sampling



CALIPSO joins CloudSat

→ 3D climatology + uncertanity analysis



- Only the troposphere has been considered in this study

CALIPSO joins CloudSat

→ Average width of confidence interval

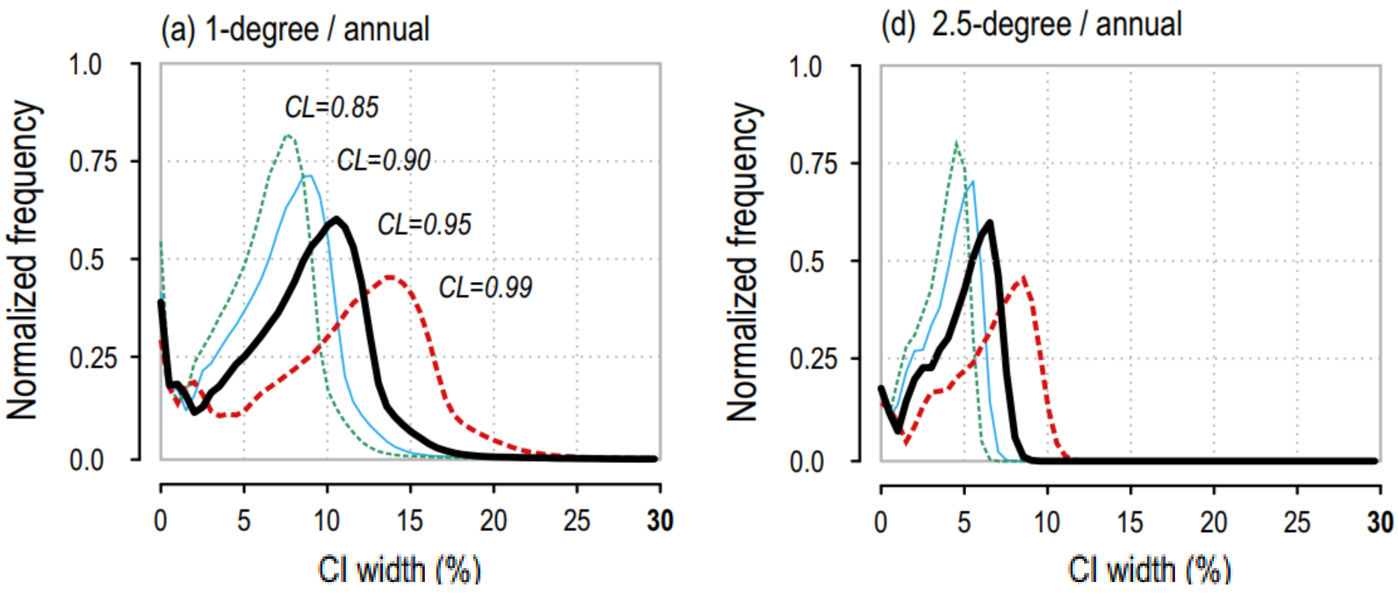
Table 2. Average width of the Confidence Interval (CI) for assumed Confidence Levels (CL), and grid box sizes.

Confidence Level (CL)	Width of Confidence Interval (%) 0.85	0.90	0.95	0.99
		Annual mean		
1.0°	6.10	6.96	8.27	10.81
2.5°	3.42	3.91	4.66	6.12
5.0°	2.19	2.50	2.98	3.91
10.0°	1.38	1.58	1.88	2.47
		Seasonal mean (autumn)		
1.0°	10.71	12.19	14.44	18.67
2.5°	6.20	7.08	8.43	11.04
5.0°	3.98	4.55	5.42	7.12
10.0°	2.53	2.89	3.45	4.53
		Monthly mean (September)		
1.0°	16.48	18.66	21.87	27.59
2.5°	10.14	11.56	13.72	17.83
5.0°	6.61	7.55	8.98	11.75
10.0°	4.26	4.86	5.79	7.60

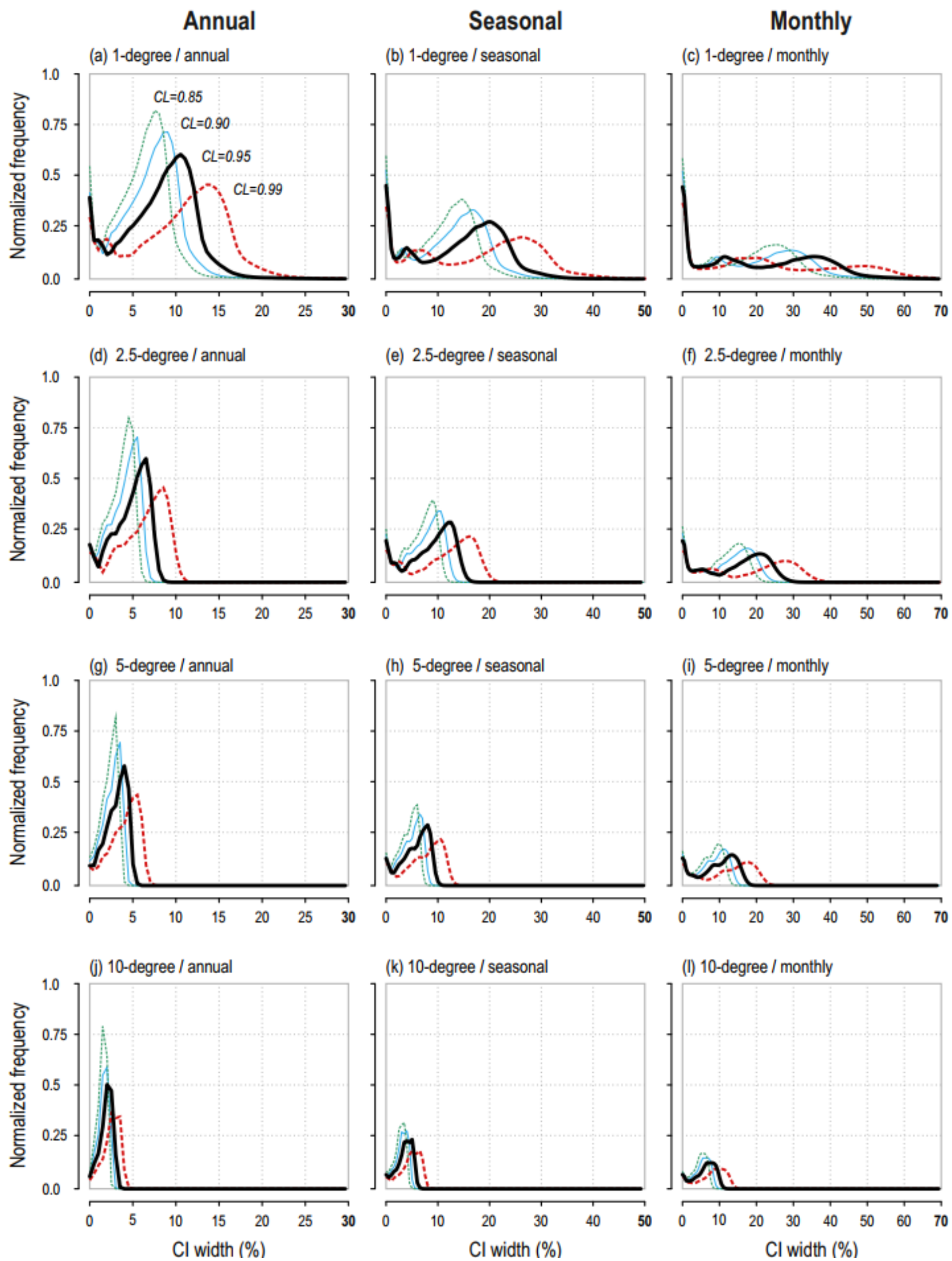
5-year data (2006-2011)

CALIPSO joins CloudSat

→ Average width of confidence interval



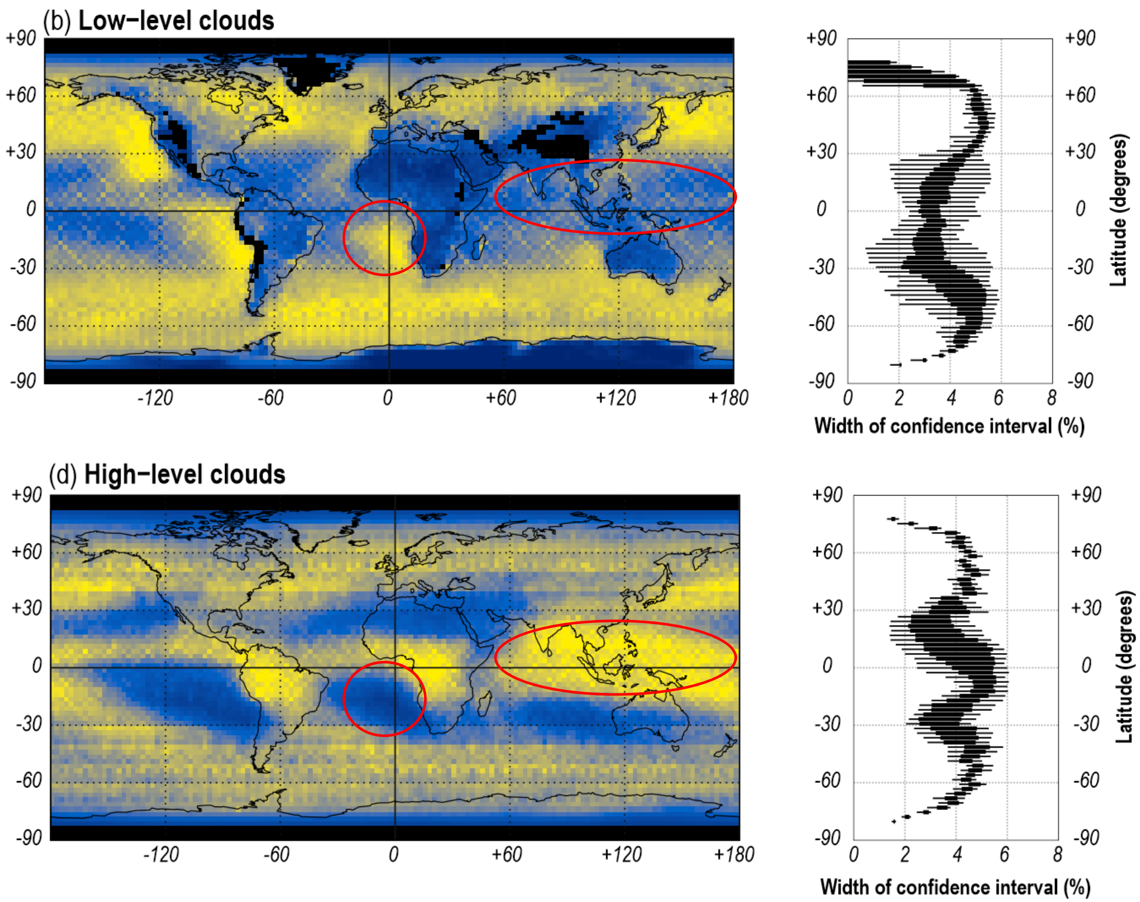
- **4× increase** ← resolution of a grid increases from 10° to 1°
- **3× increase** ← number of months considered decrease from 12 (annual) to 1 (monthly)
- **2× increase** ← confidence level increases from 0.85 to 0.99

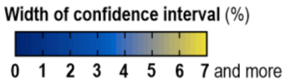


Annual
Seasonal
Monthly
(a) 1-degree / annual
(b) 1-degree / seasonal
(c) 1-degree / monthly
CL=0.85
CL=0.90
CL=0.95
CL=0.99
(d) 2.5-degree / annual
(e) 2.5-degree / seasonal
(f) 2.5-degree / monthly
(g) 5-degree / annual
(h) 5-degree / seasonal
(i) 5-degree / monthly
(j) 10-degree / annual
(k) 10-degree / seasonal
(l) 10-degree / monthly
Normalized frequency
CI width (%)

CALIPSO joins CloudSat

→ Vertical structure of confidence interval





5-year annual / 2.5 deg / conf. lev. 0.95

CALIPSO joins CloudSat

→ Expected accuracy

- **Global Climate Observing System (GCOS)** (WMO 2011)

  1% (optically thin clouds) to 5% (optically thick clouds)

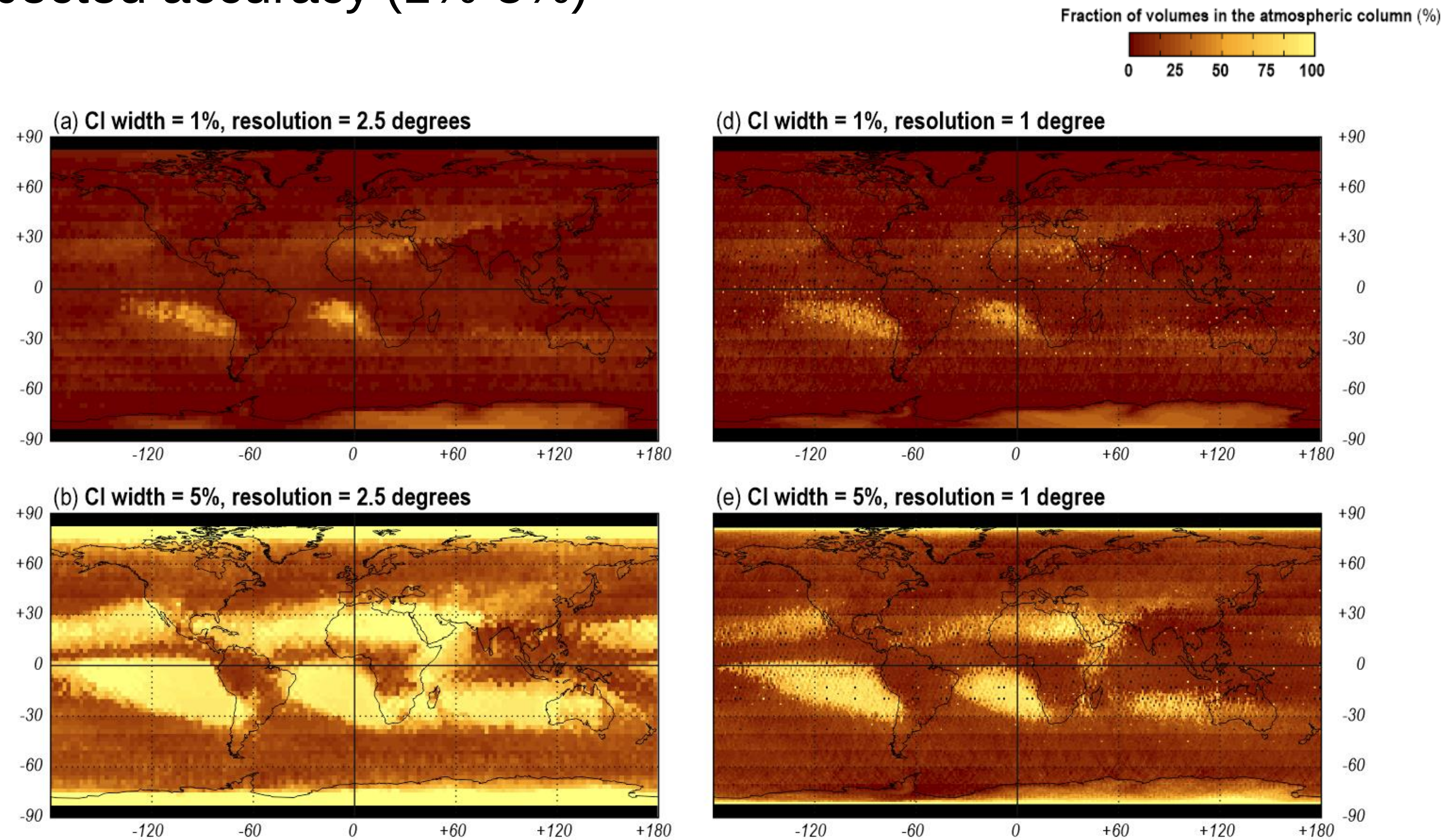
  + cloud data to be available globally, every three hours, at a spatial resolution of 50 km (0.5° at the equator)

- **US National Institute of Standards and Technology** (**NIST**) (Ohring et al., 2005)

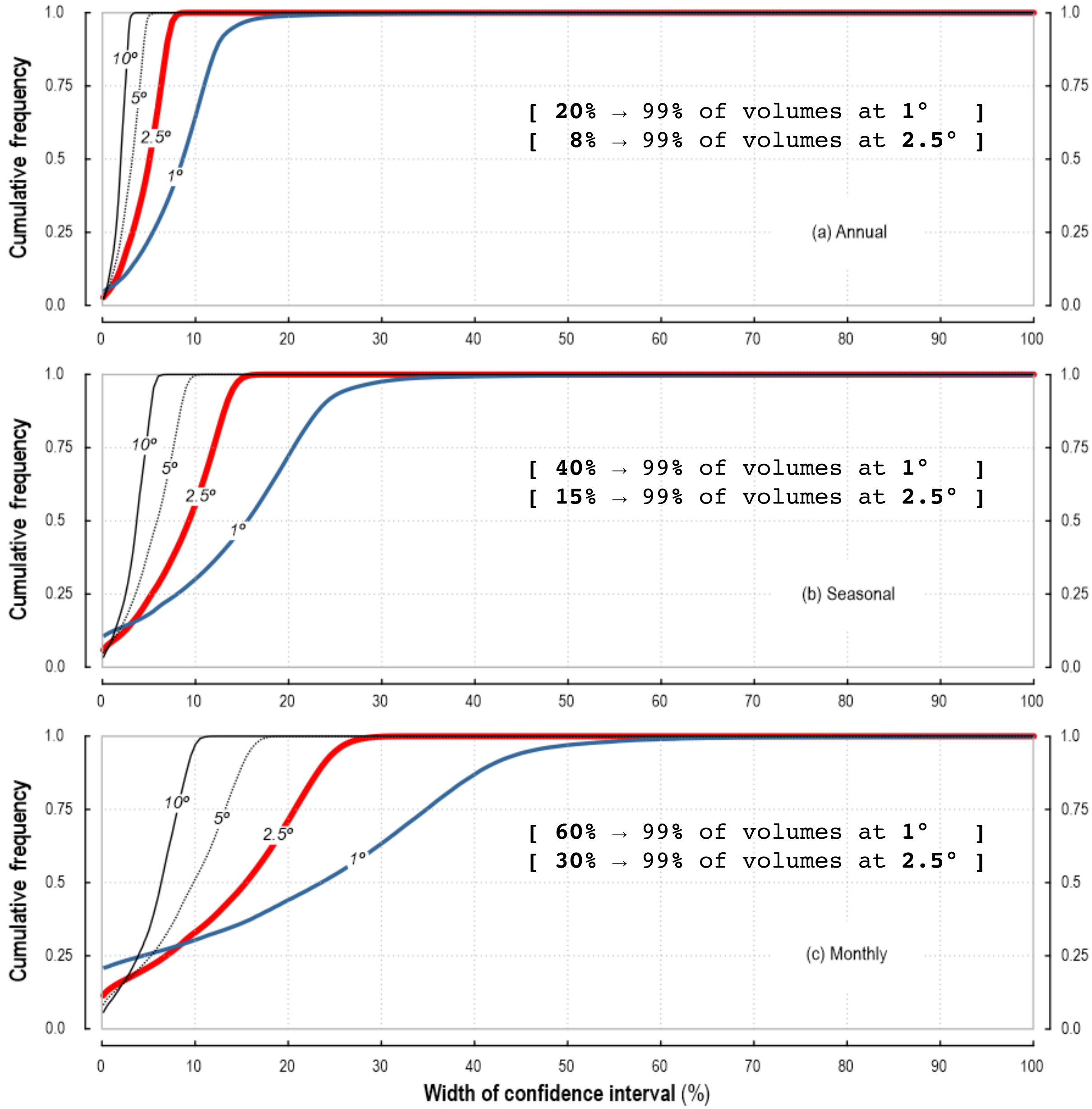
  1% accuracy for global mean cloud cover

CALIPSO joins CloudSat

→ Expected accuracy (1%-5%)



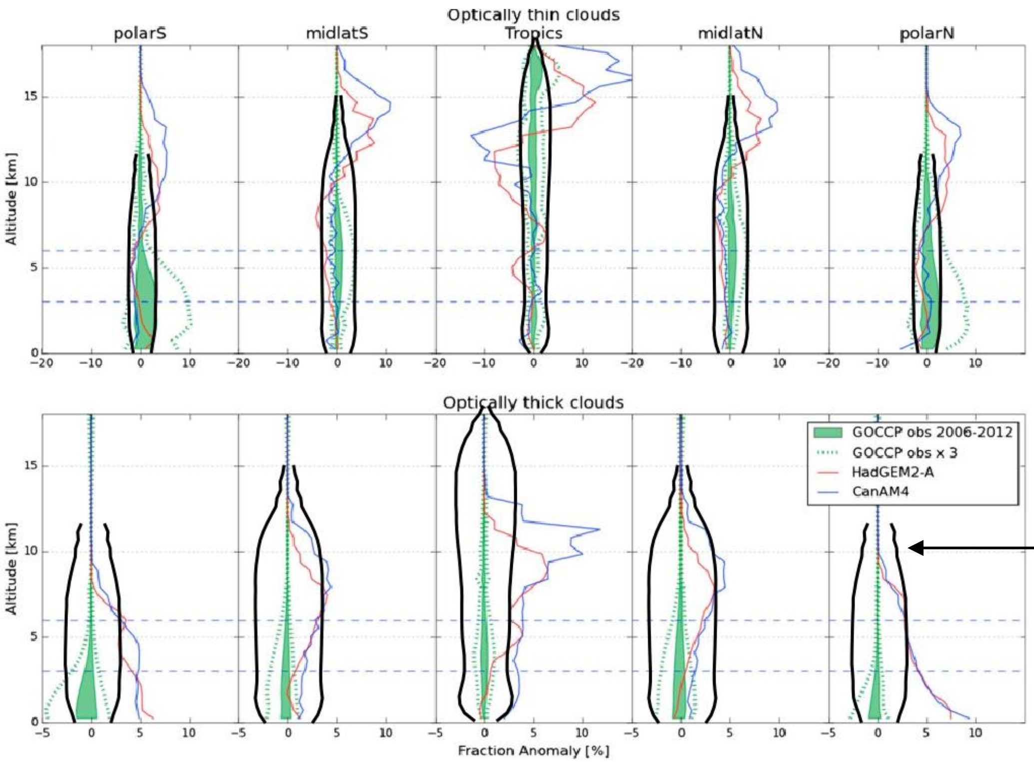

```
1% →  6.5% of volumes at 1° and 2.5°
5% → 22.5% of volumes at 1°
     48.9% of volumes at 2.5°
```



Cumulative frequency
1.0
0.75
0.5
0.25
0.0
10°
5°
2.5°
1°
[20% → 99% of volumes at 1°]
[8% → 99% of volumes at 2.5°]
(a) Annual
0
10
20
30
40
50
60
70
80
90
100
[40% → 99% of volumes at 1°]
[15% → 99% of volumes at 2.5°]
(b) Seasonal
[60% → 99% of volumes at 1°]
[30% → 99% of volumes at 2.5°]
(c) Monthly
Width of confidence interval (%)

CALIPSO joins CloudSat

→ Detectable change in cloud structure → Chepfer et al. (2014)



Lidar + Radar
.95 conf. interval
@ 2.5 deg

- „Current climate" minus „+4K climate", two models (**CanAM4**, **HadGEM2**)
- Simulated lidar data for model (lidar only)
- + real variability of CALIPSO (**GOCCP 2006-2012**)

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→ What matters most?

Table 3. Partial contribution of variables to the model's determination coefficient (R^2). Partial coefficients are not scaled, i.e., they sum up to the overall value of R^2. Results refer to cloud amount analyzed in the annual timeframe.

	Partial Contribution to R2			
Grid size:	**1°**	**2.5°**	**5°**	**10°**
Model's overall R^2:	65.3	87.6	89.8	91.1
Cloud regime				
mean cloud amount	14.7	20.2	21.0	21.4
std. dev. of cloud amount	30.9	37.5	37.5	36.4
Geography				
latitude	<0.1	<0.1	<0.1	<0.1
longitude	0.1	0.1	0.1	0.1
altitude	1.9	2.6	2.0	2.3
Statistical				
no. of observations	6.6	8.8	10.5	9.5
Confidence Level	11.1	18.4	18.7	21.4

- Some variable are not 100% independent…
- Still: a general insight into factors that controll the conf. interval width

CALIPSO joins CloudSat

→ Conclusions

- First uncertainty assessment for the joint CloudSat-CALIPSO vertically-resolved cloud amounts: confidence intervals at common conf. levels and grid sizes.
- Quantitative information on how the conf. interval width is determined by: grid size, time frame for data averaging, and confidence level.
- Not possible to get the cloud amounts at high (1-5%) accuracy, while maintaining a high spatio-temporal resolution
  (it still may be possible locally – use our 3D data to test it for your area of interest!)
- CloudSat-CALIPSO-like configuration will most likely allow for detecting trends in optically thin clouds globally, and thick clouds in tropics and polar regions.

Summary / **take-away message**

- [CALIOP helps MODIS] Use CALIOP detections to calibrate MODIS (AVHRR, VIIRS) cloud data → you will avoid ±30% error in cloud amount regionally.

- [CALIOP vlidates SYNOP] Use surface-based data on cirrus frequency with extreme caution → only trust the data taken under perfect conditions, and daytime.

- [CALIOP joins CloudSat] Consider uncertanity budget for joint CloudSat-CALIPSO cloud climatology (may by very large for you 3D location) → do not expect high accuracy at fine spatio-temporal resolution.

  CBK PAN is open for collaboration on MODIS/CALIPSO/CloudSat/and other imagers/souders → MSc/PhD interns are welcome too!

Thank you for attention!

Acknowledgement

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