Detecting Super-thin Clouds with Polarized Sunlight (NASA Technology GSC-17392-1)

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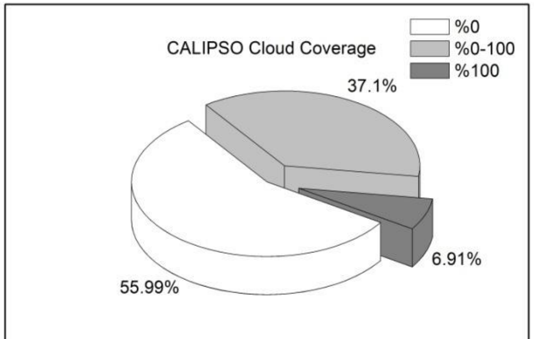
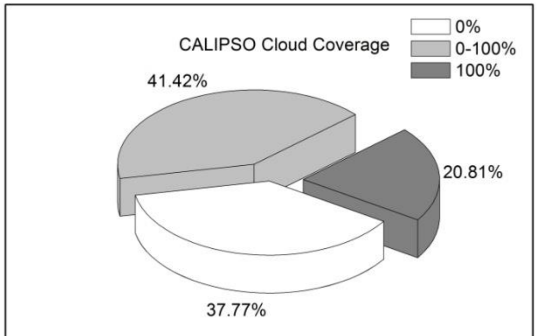
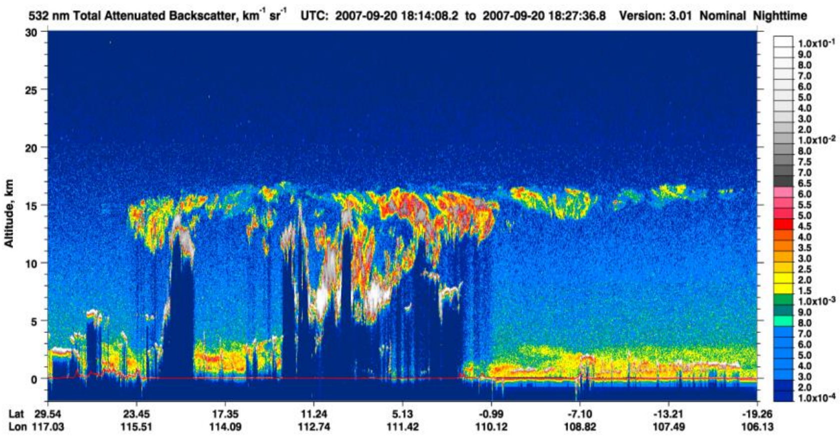


For daytime clear CERES footprints



For nighttime clear CERES footprints

CALIPSO-derived cloudy percentage in MODIS-clear CERES FOVs



Total attenuated backscatter at 532nm from CALIPSO lidar

Historically, super-thin clouds cannot be detected by any passive instruments, including the 1.38 µm channel technique.

Space-borne lidar can detect some of them, but still issues involved.

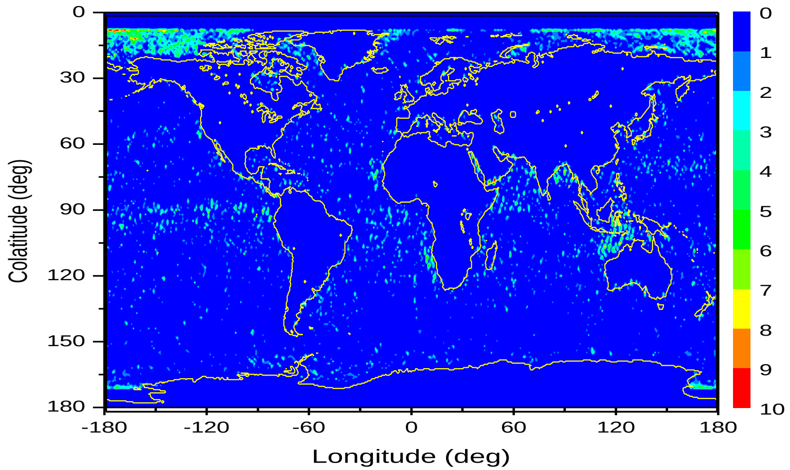
Passively detecting super-thin clouds is an impossible mission?

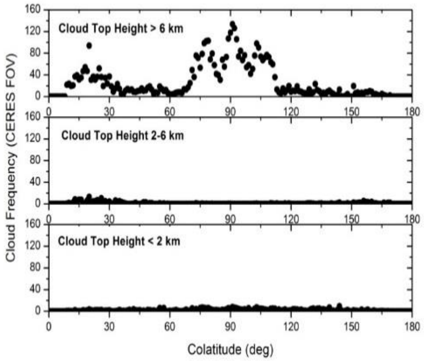
- **CERES (MODIS) misses most of the super-thin clouds with OD < 0.3.**
- **25% of missing clouds are ice clouds with OD < 0.3.**
- **75% of missing clouds are water clouds with OD < 0.3.**

  - not much chance for reliable detection.
  - difficult to make a retrieval**.**

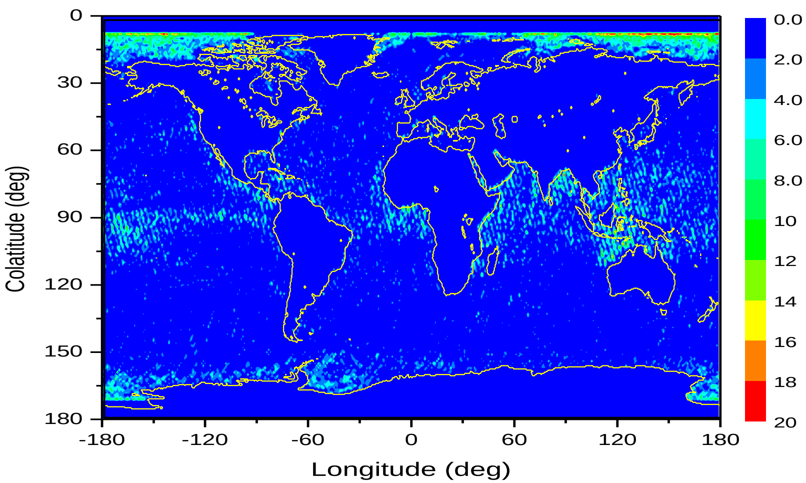
(**Minnis et al**., "Improvement of Passive Sensor Retrievals of Cloud Properties Using Surface and Satellite Lidar-Radar Datasets", 4th Pan-GCSS Meeting, Toulouse, France 2-6 June 2008.)

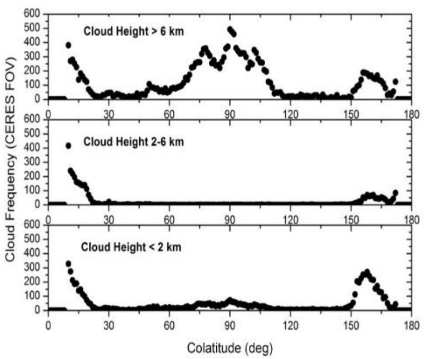
12-month Super-Thin-Cloudy CERES FOVs Distribution



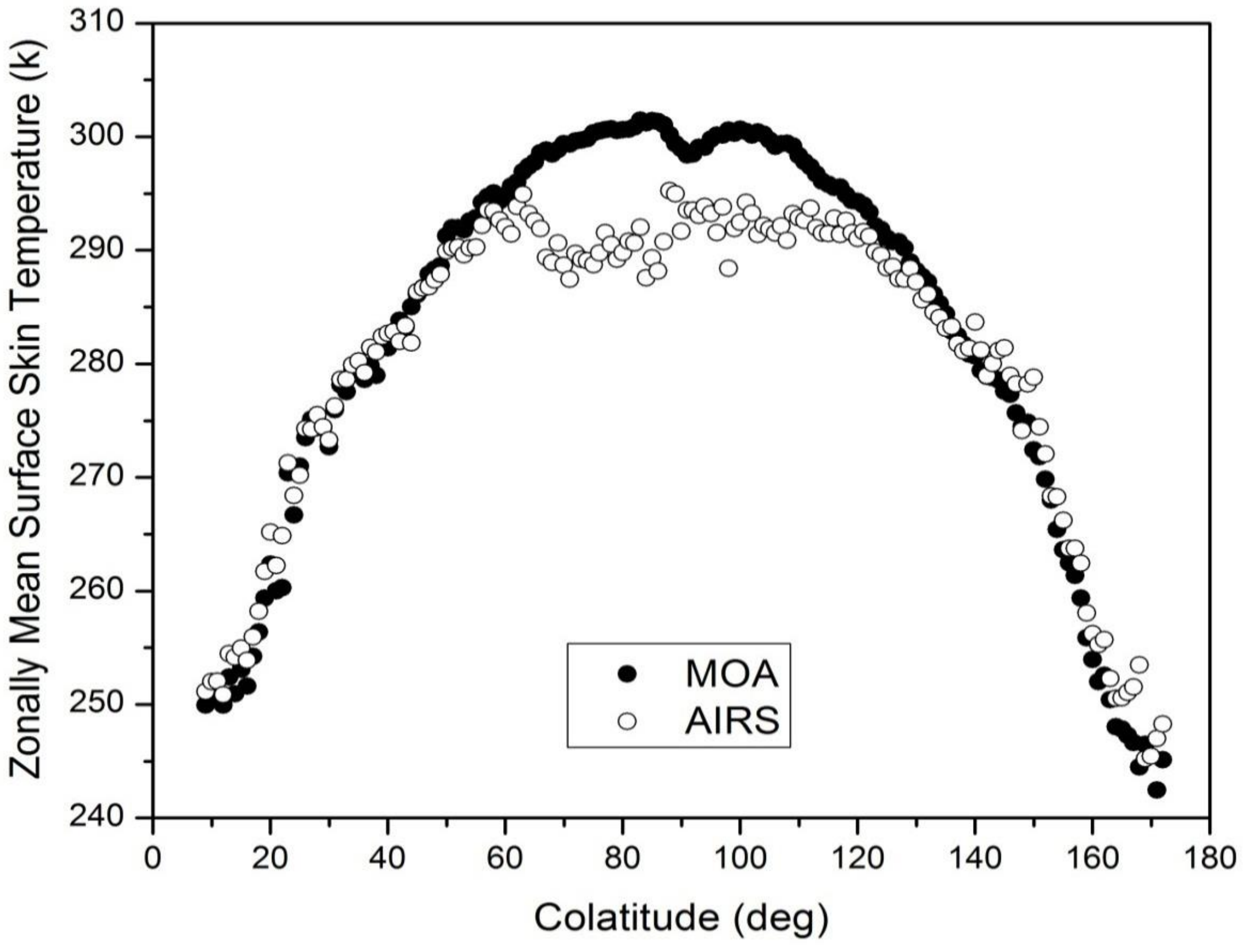


Daytime



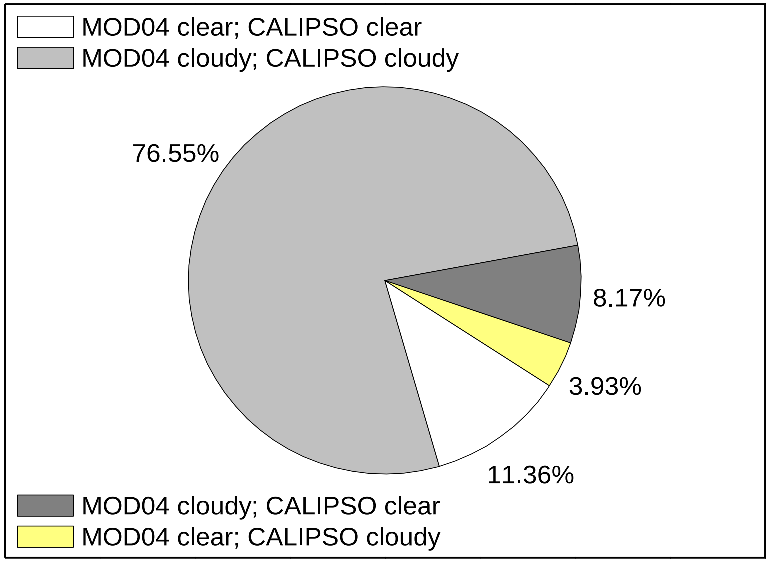


Nighttime

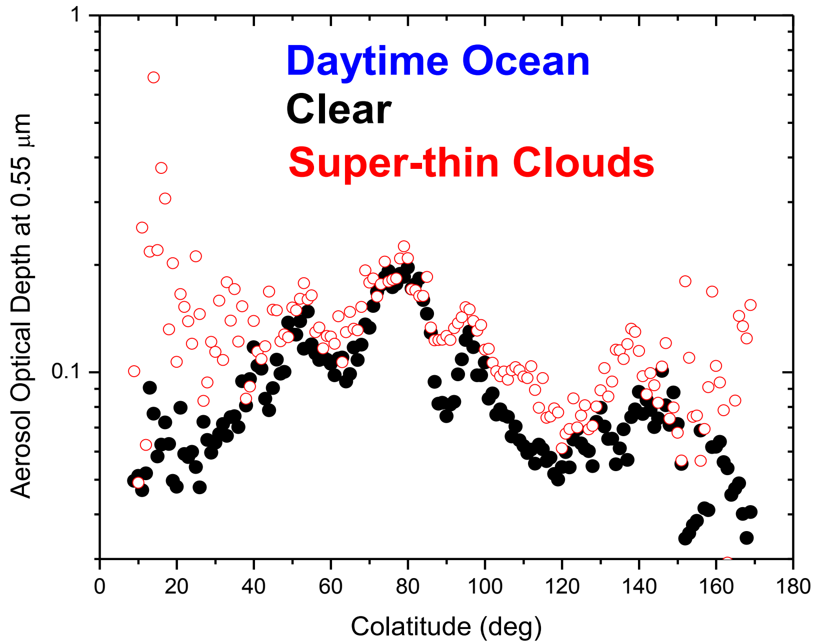


Failed to detect super-thin clouds, NASA AIRS satellite measured SST is ~10K lower than actual values.

Effect of Super-thin Clouds on MODIS Aerosol Product



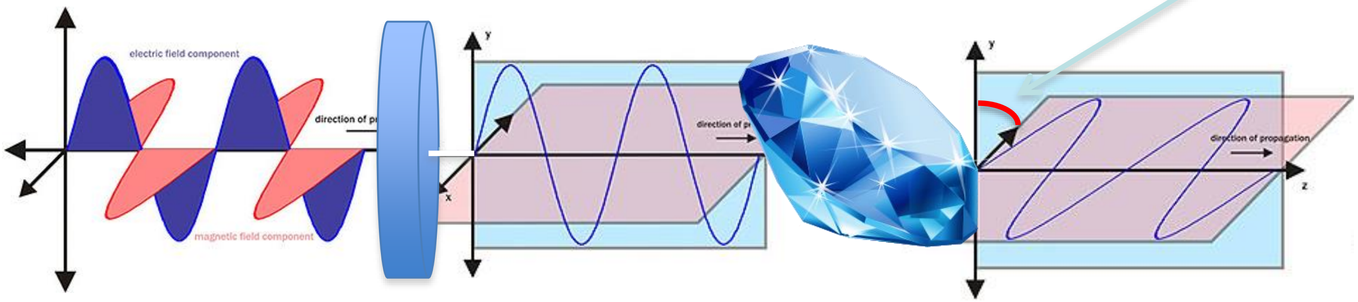
Statistics of 1km x 1km areas with matched and unmatched cloud masks from CALIPSO and MOD04



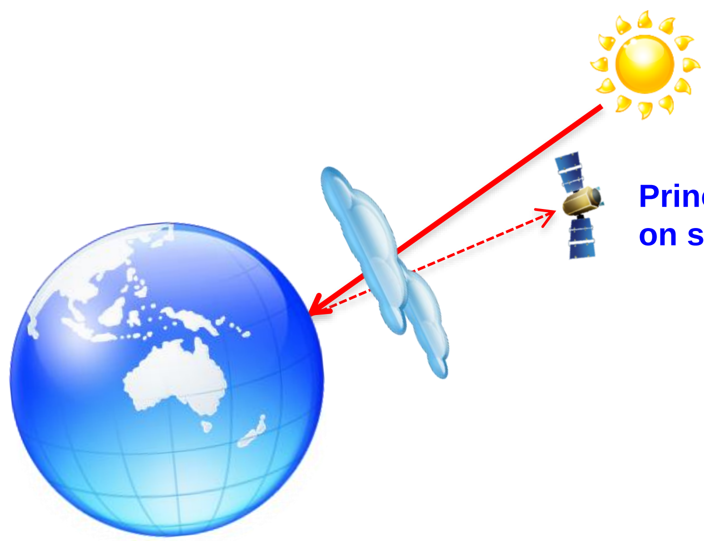
Zonal mean MOD04 aerosol optical depth at 0.55 µm for daytime ocean

A new concept to detect super-thin clouds

Transmitted light's angle of linear polarization (AOLP) tells the target is quartz or diamond

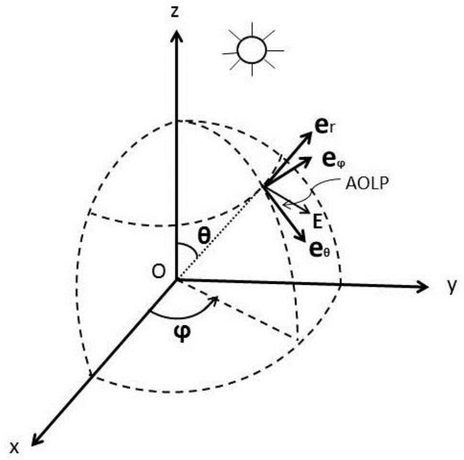


To detect super-thin clouds, we use a similar principle, except that our polarizer is Earth surface and atmosphere, our target is atmosphere.



Principal Plane Polarimetric Scanner (PPPS) on small satellite

Observation and modeling of reflected solar polarization



Any arbitrarily polarized incoherent radiation can be represented by the linear sum of an unpolarized part and a 100% polarized part as

$$I_{pol} = \sqrt{Q^2 + U^2 + V^2} = DOP \cdot I$$

$$I_{unpol} = I - \sqrt{Q^2 + U^2 + V^2} = (1 - DOP) \cdot I$$

$$DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} = I_{pol} / I$$

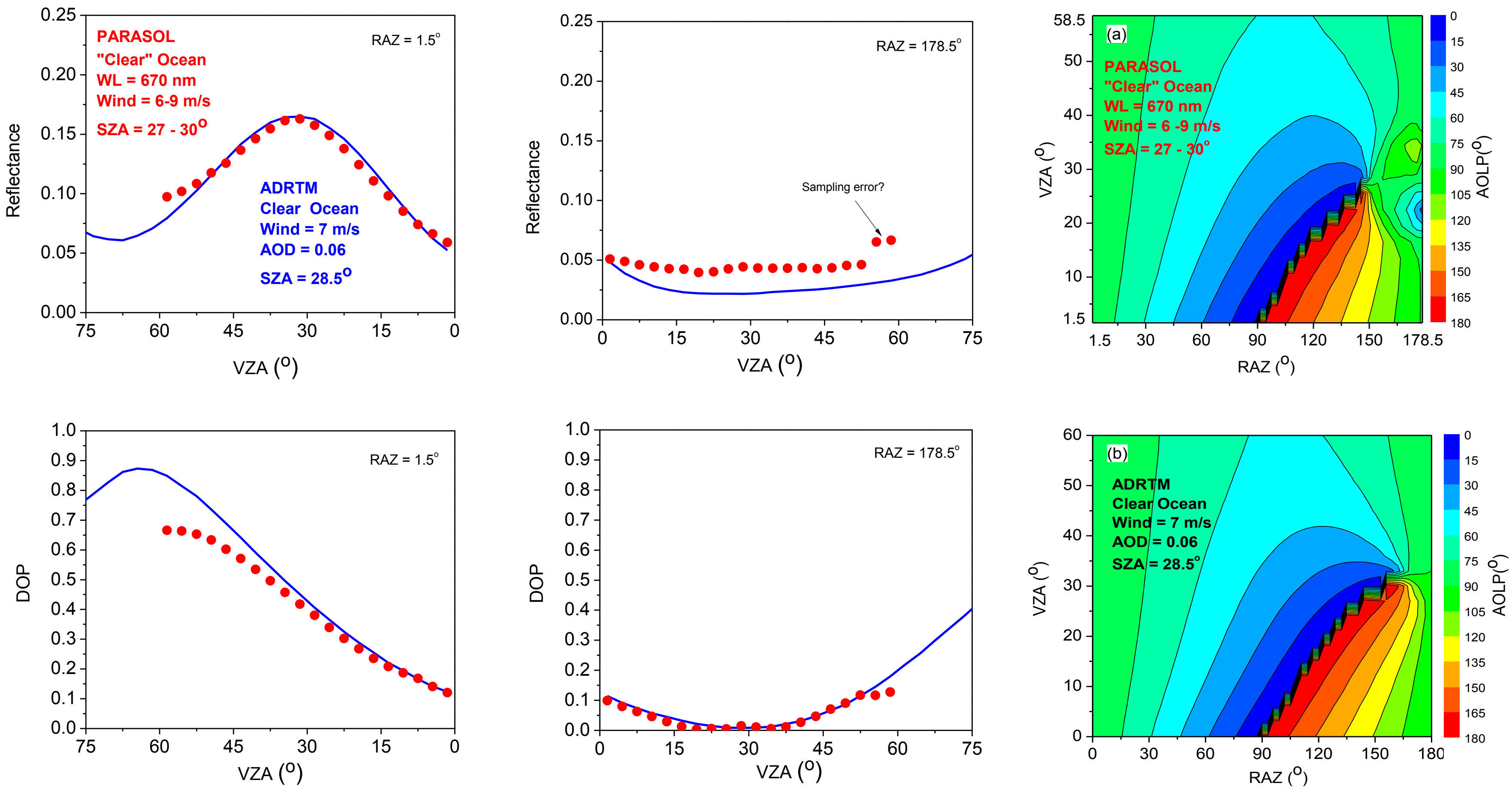
$$\tan(2AOLP) = \frac{U}{Q}$$

An airborne or space-borne polarimeter can measure Stokes parameters I, Q, U, and V.

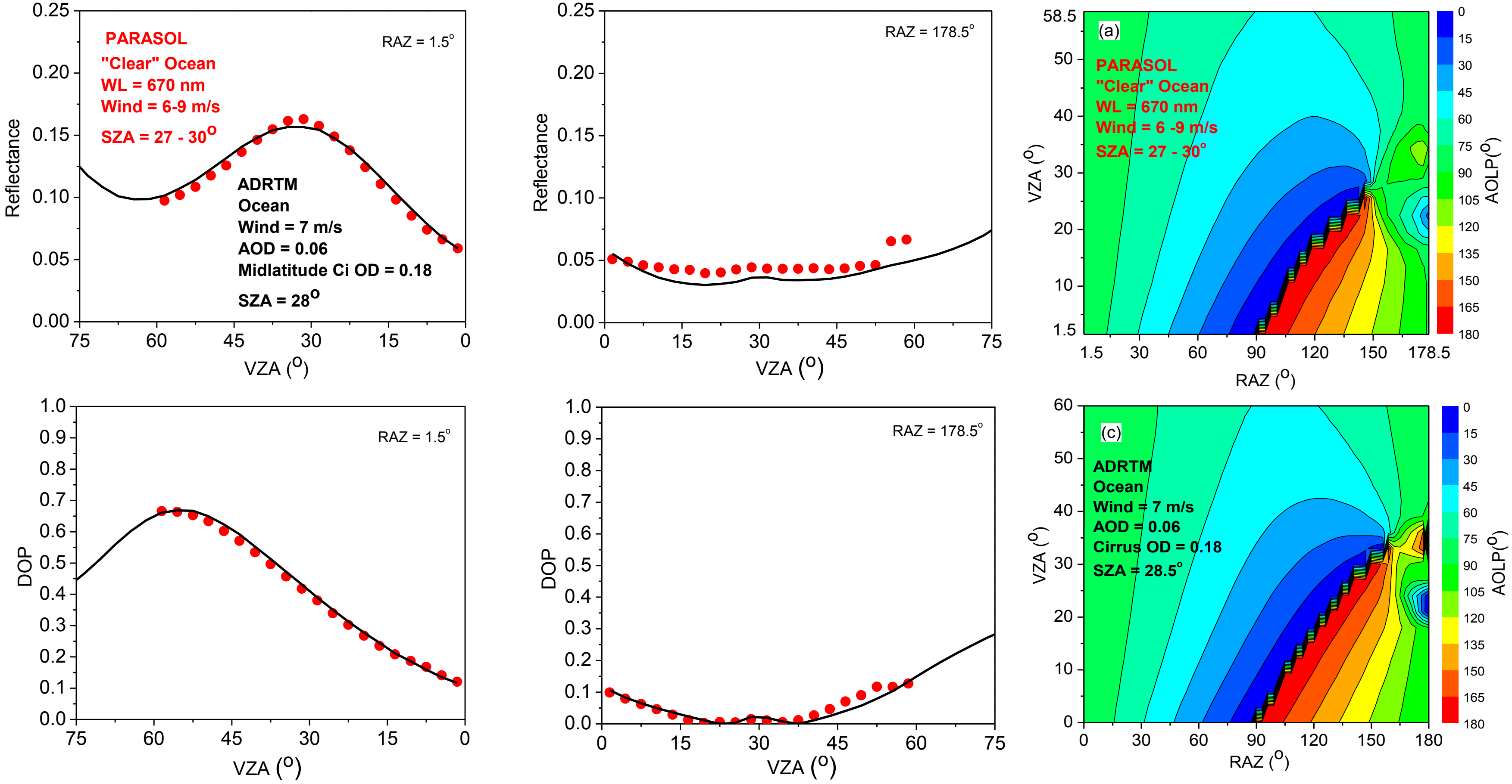
The adding-doubling radiative transfer model (ADRTM) can model I, Q, U, and V.

Comparison of ADRTM results with PARASOL data

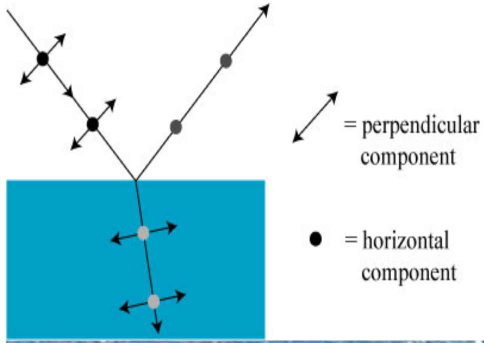
No cloud in the ADRTM

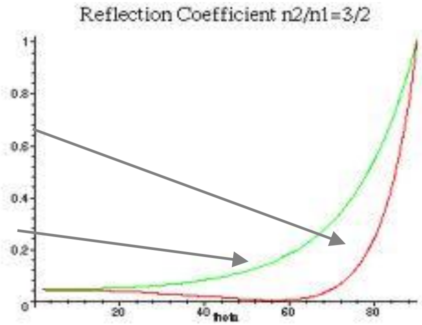


A layer of super-thin cirrus added in the ADRTM



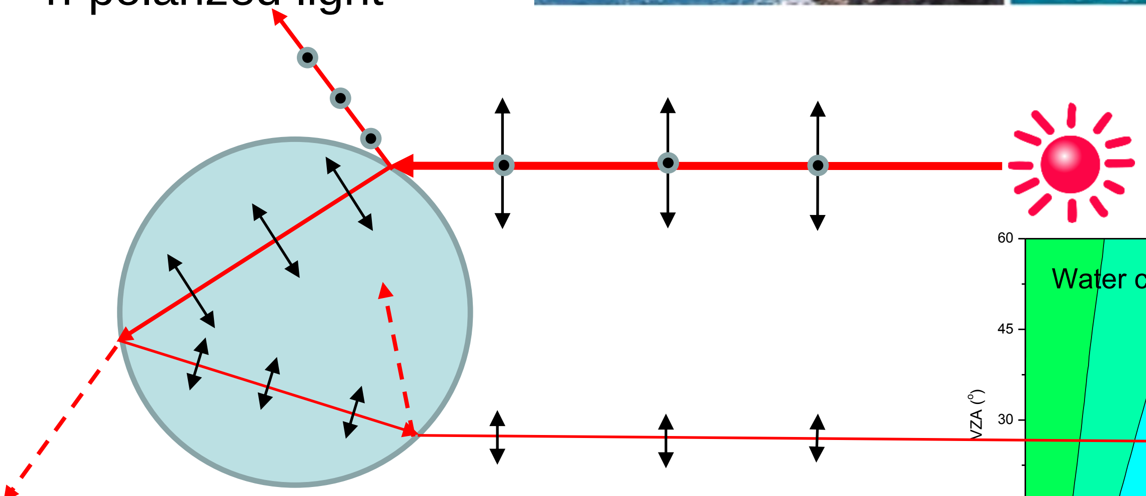
Plausible explanation of clouds' AOLP pattern

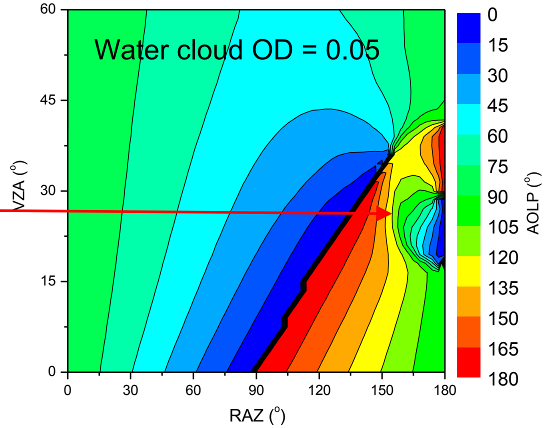




Light reflected by a dielectric surface?

h-polarized light

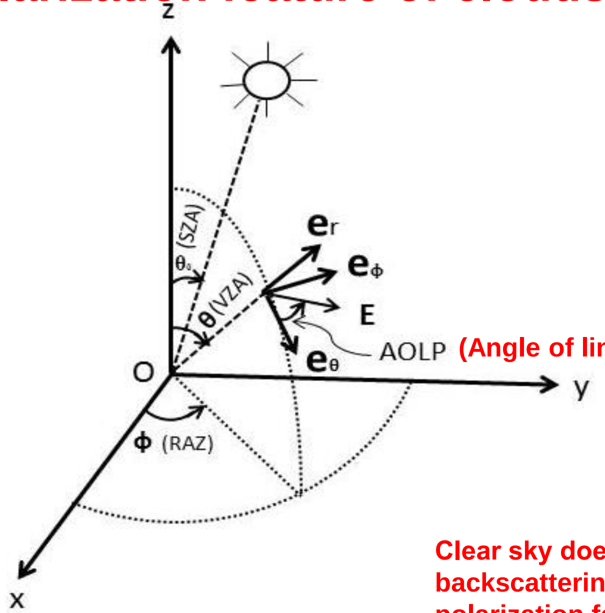




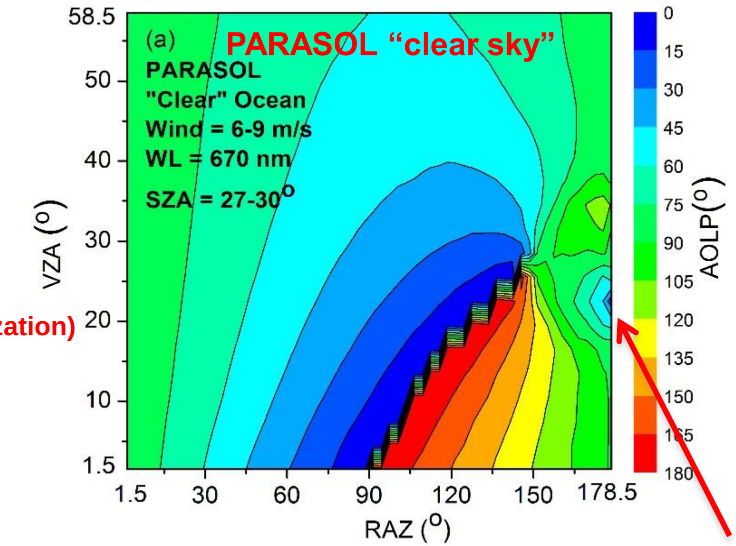
p-polarized light

A novel technique for detecting super-thin clouds

P-polarization feature of clouds (ice)

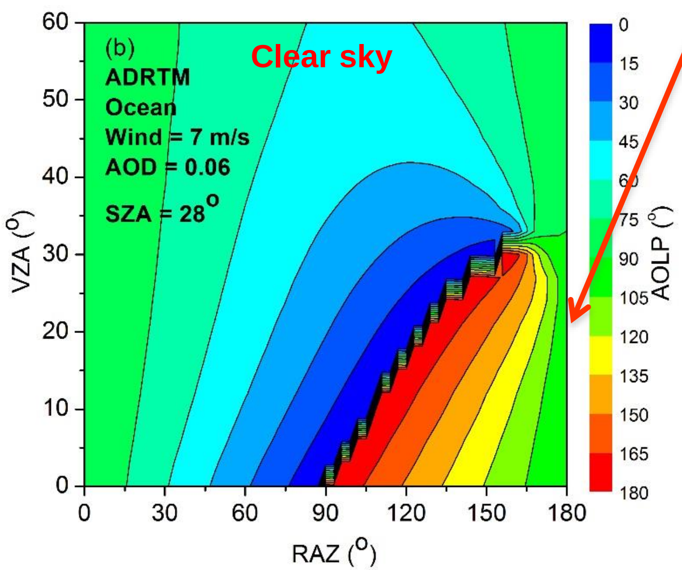


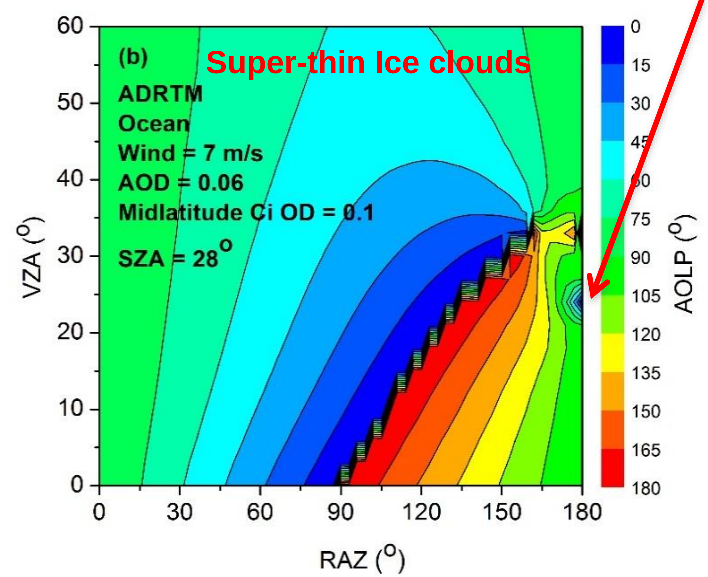
(Angle of linear polarization)



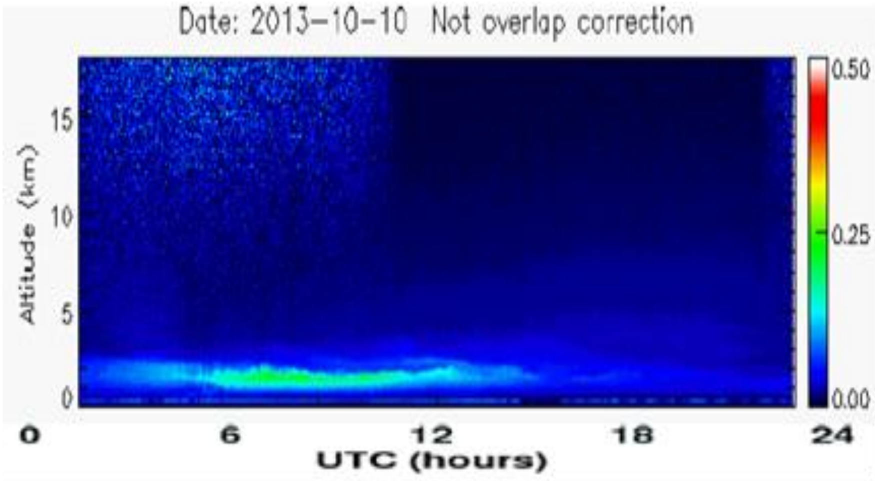
Backscattering *p*-polarization feature

Clear sky doesn't have backscattering *p*-polarization feature

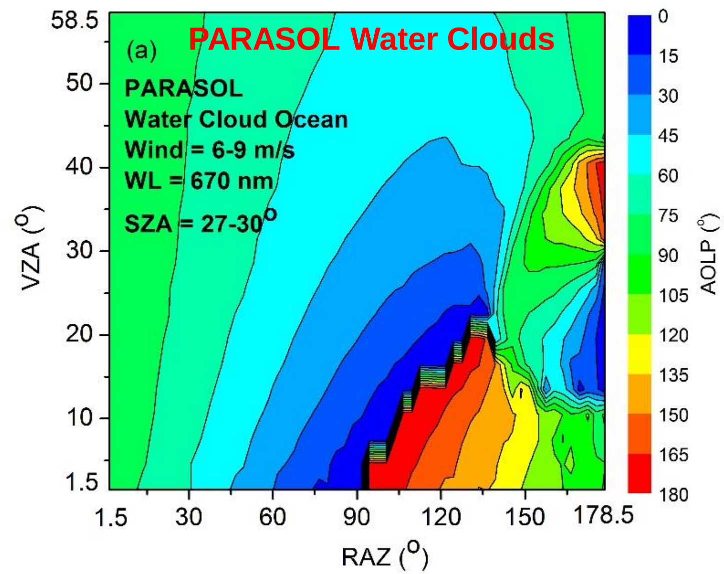


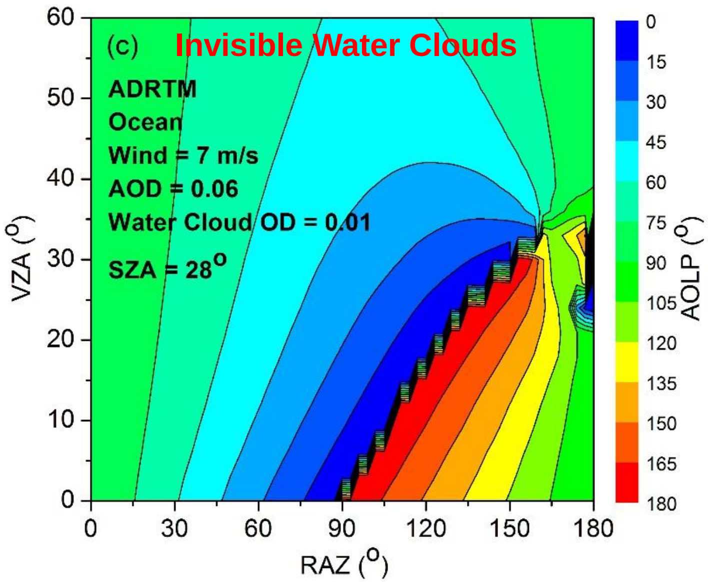


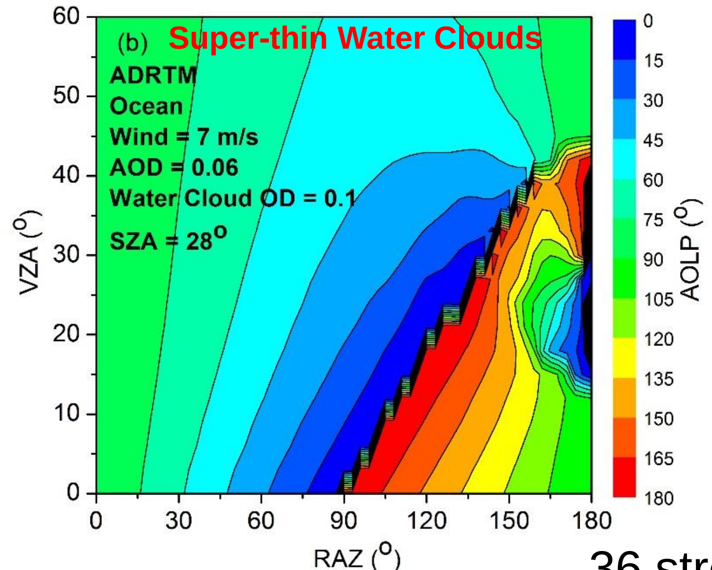
P-polarization feature of clouds (liquid water)



Ground-lidar detects invisible water clouds at 1 to 2 km in Lanzhou, China (Qiang Fu). These cannot be detected by 1.38 micron channel.

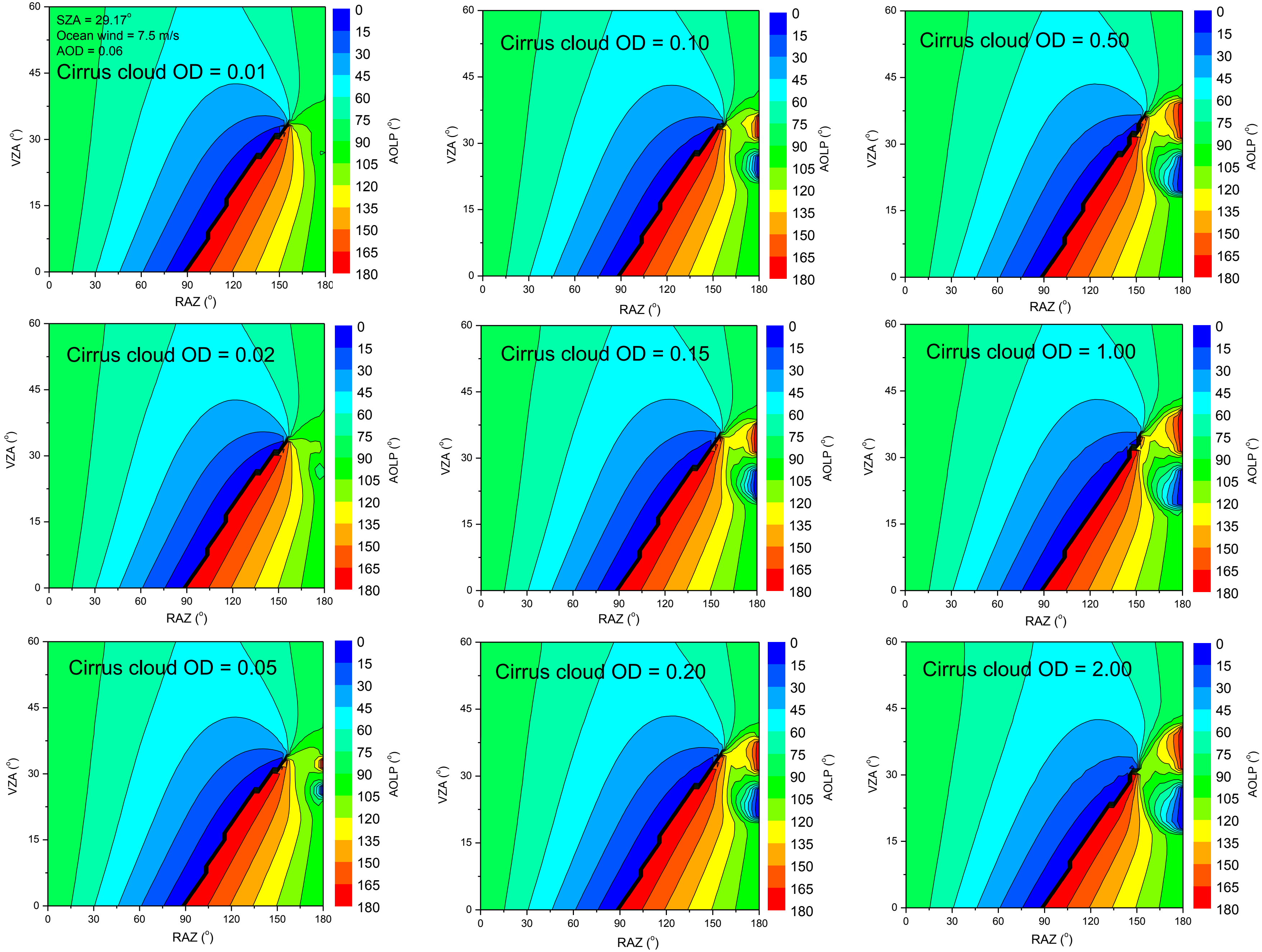




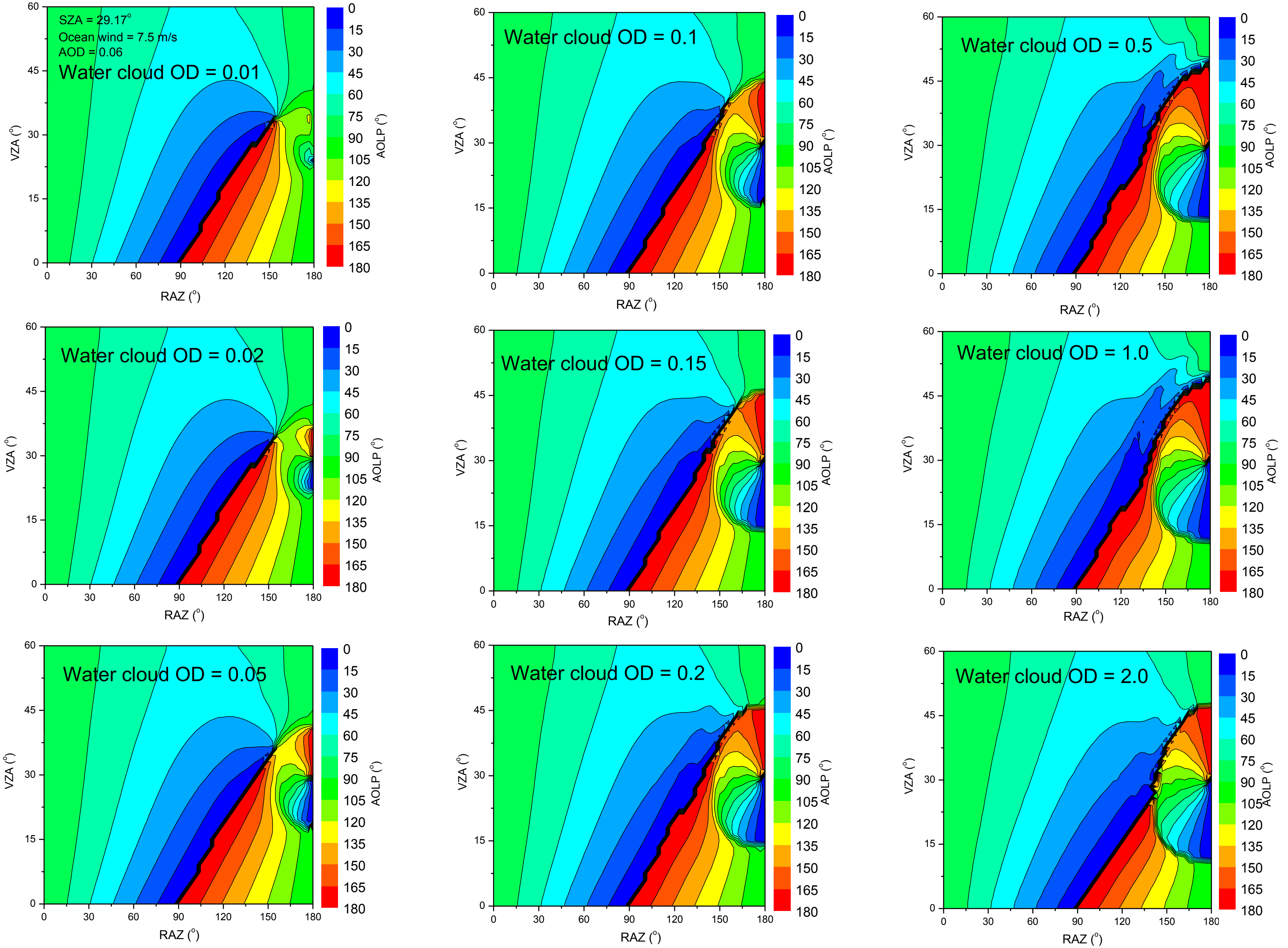


36 streams

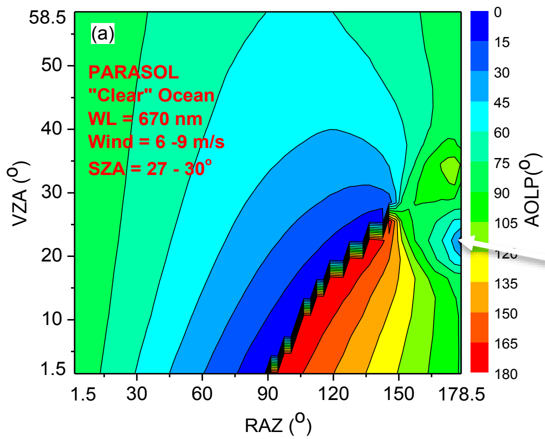
P-polarization feature of ice clouds (Tropics ice cloud particle shapes)



P-polarization feature of water clouds as a function of optical depth



How to retrieve the optical depth (OD) of the super-thin clouds?

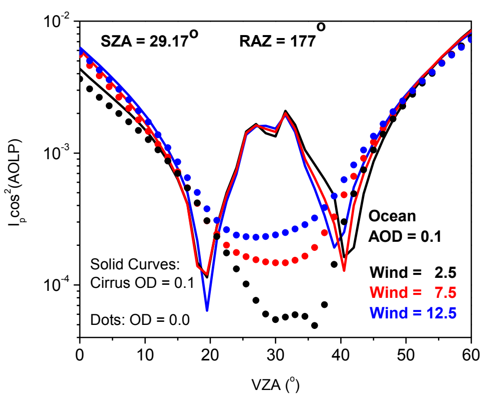


$$OD = f^{-1}[I_p \cos^2(AOLP)]$$

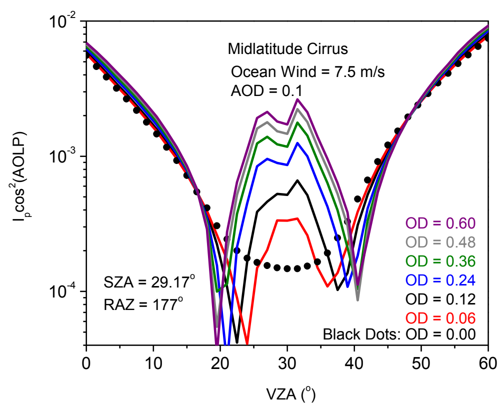
I_p is polarized reflectance

The retrieval is done at "blue spot"

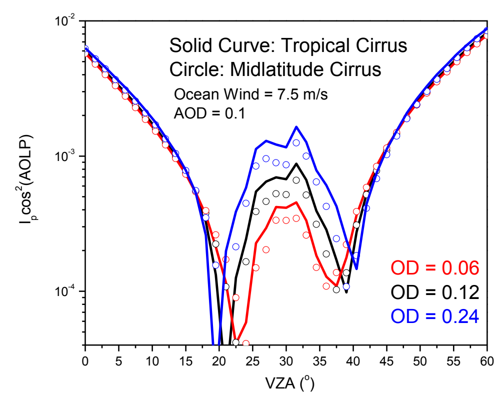
At the "blue spot":



$I_p \cos^2(AOLP)$
has little dependence on ocean surface when clouds' OD > ~0.1.



$I_p \cos^2(AOLP)$
nearly linearly correlates with OD, but it saturates when OD ~0.6.



Uncertainty in particle shapes can cause a difference in OD of ~0.05.

Conclusion

- Up to 50% of MODIS-derived clear-sky scenes are actually covered by super-thin clouds.
- **The angle of linear polarization (AOLP) of reflected sunlight is a robust indicator of any clouds, even if they are super-thin and at low altitude.**
- This method could tremendously impact the remote sensing of ocean surface temperature, aerosol, gases, and the modeling for climate change.
- **This concept could lead to a small satellite mission for ocean/atmosphere remote sensing.**

References:

1.Wenbo Sun, Constantine Lukashin, Rosemary R. Baize, and Daniel Goldin, "Modeling polarized solar radiation for CLARREO inter-calibration applications: Validation with PARASOL data," *J. Quant. Spectrosc. Radiat. Transfer,* doi:10.1016/j.jqsrt.2014.05.013 (2015).

2.Wenbo Sun, Gorden Videen, and Michael I. Mishchenko, "Detecting super-thin clouds with polarized sunlight," *Geophy. Res. Lett.* 41, doi: 10.1002/2013GL058840 (2014).

3.Wenbo Sun and Constantine Lukashin, "Modeling polarized solar radiation from ocean-atmosphere system for CLARREO inter-calibration applications," *Atmos. Chem. Phys.* 13, 10303-10324, doi: 10.5194/acp-13-10303-2013 (2013).

4.Wenbo Sun, Gorden Videen, Seiji Kato, Bing Lin, Constantine Lukashin, and Yongxiang Hu, "A study of subvisual clouds and their radiation effect with a synergy of CERES, MODIS, CALIPSO and AIRS data," *J. Geophy. Res.,* 116, doi: 10.1029/2011JD016422 (2011).

5.Wenbo Sun, Bing Lin, Yongxiang Hu, Constantine Lukashin, Seiji Kato, and Zhaoyan Liu, "On the consistency of CERES longwave flux and AIRS temperature and humidity profiles," *J. Geophy. Res.*, 116, D17101, doi:10.1029/2011JD016153 (2011).