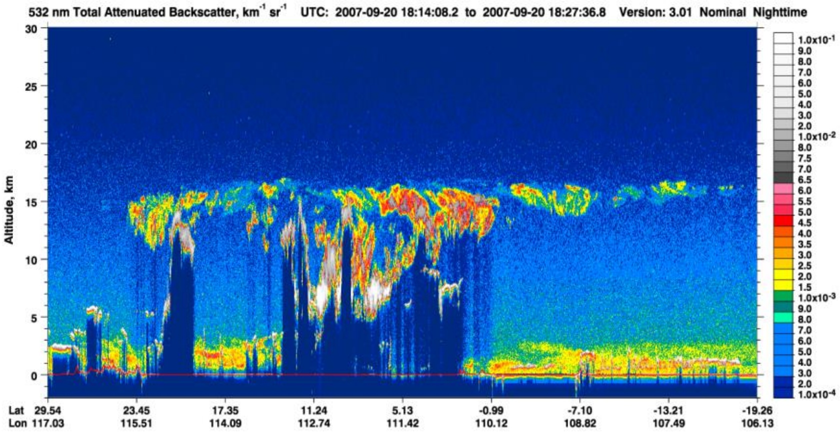
Detecting Super-thin Clouds with Polarized Sunlight (NASA Technology GSC-17392-1)

Wenbo Sun

Science Systems and Applications, Inc.
Mail Stop 420, NASA Langley Research Center, Hampton, VA23693, USA
wenbo.sun-1@nasa.gov

Introduction

- Super-thin clouds from current satellite data.
- Why it is necessary to detect super-thin clouds.
- A novel algorithm to detect super-thin clouds.



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**.**

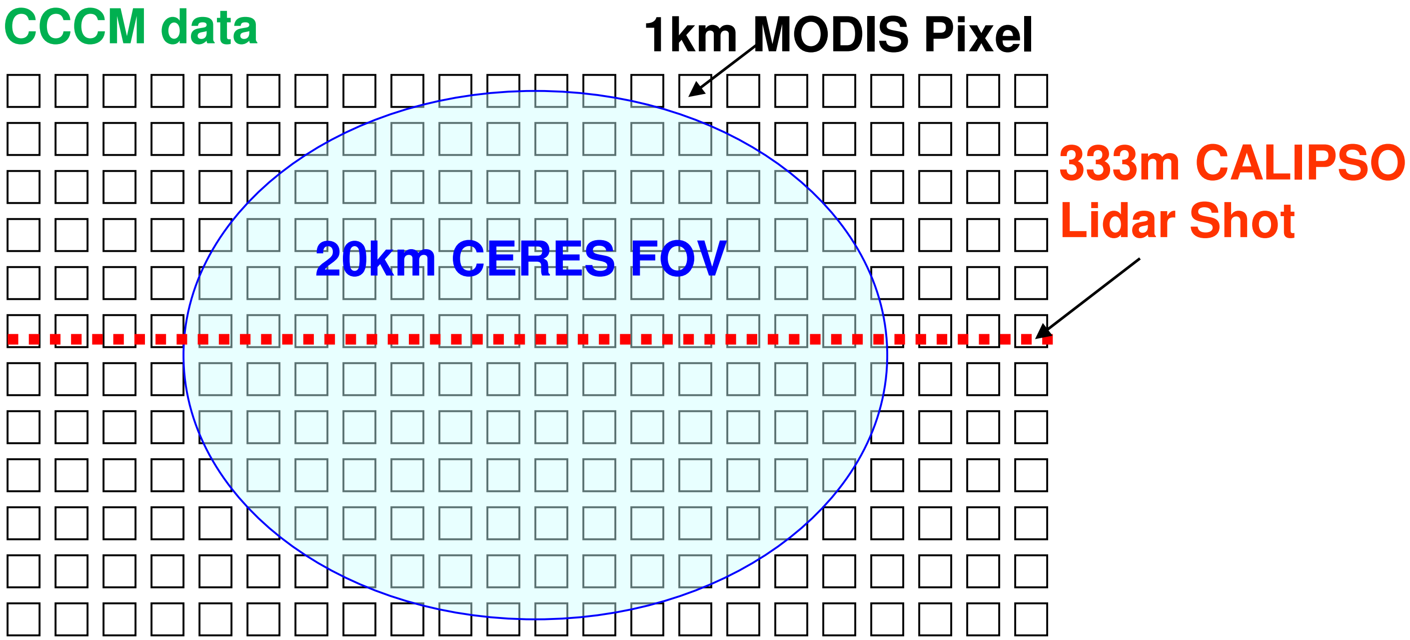
(**Minnis et al**., “Improvement of Passive Sensor Retrievals of Cloud Properties Using Surface and Satellite Lidar-Radar Datasets”, 4th Pan-GCSS Meeting, Toulouse, France 2-6 June 2008.)

Are things really so discouraged?

Original Data Lead to Our Finding Super-thin Clouds

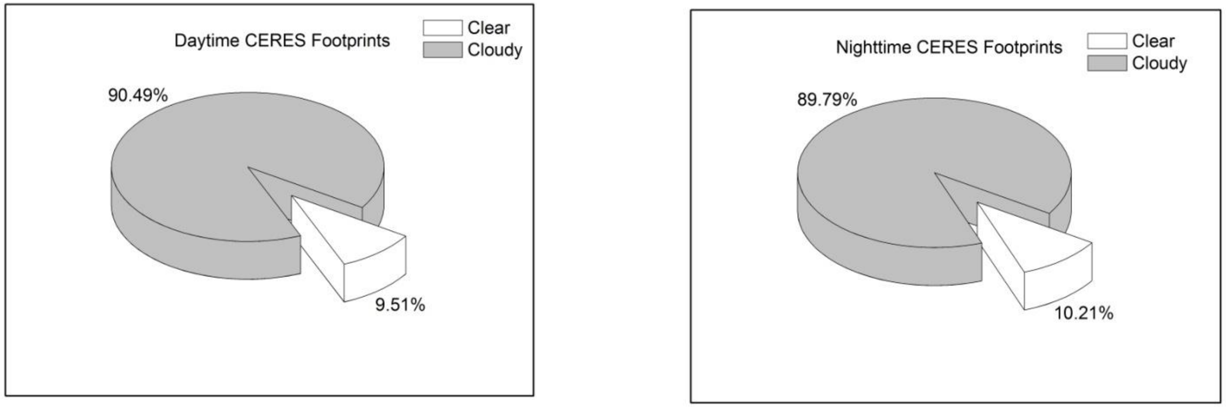
AIRS data – L3 daily 1°x1° gridded standard retrieval product V5

CCCM data – CERES, CALIPSO, MODIS, and MOA

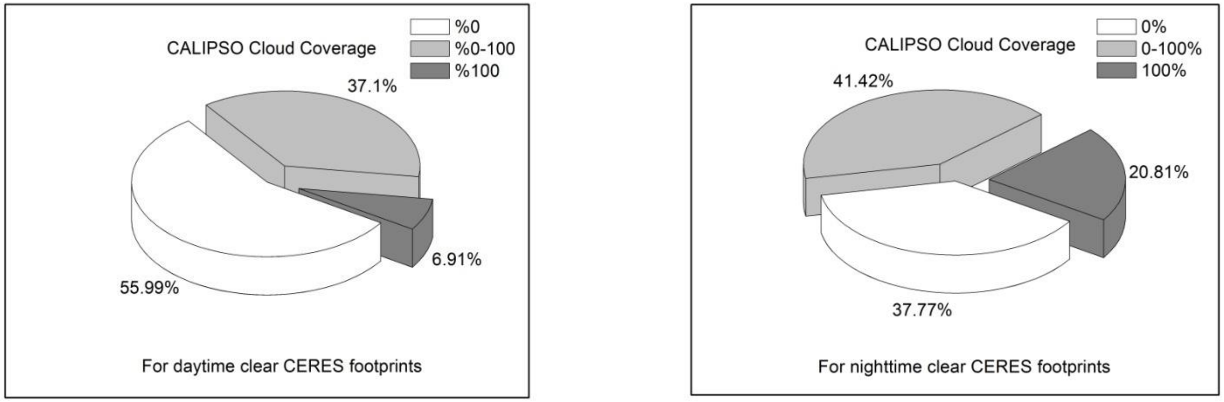


. Cloud coverage percentage is calculated using along-CALIPSO-track CALIPSO and MODIS data.

. Radiation energy budget effect of super-thin clouds is estimated on CERES FOVs of MODIS clear and CALIPSO cloudy.

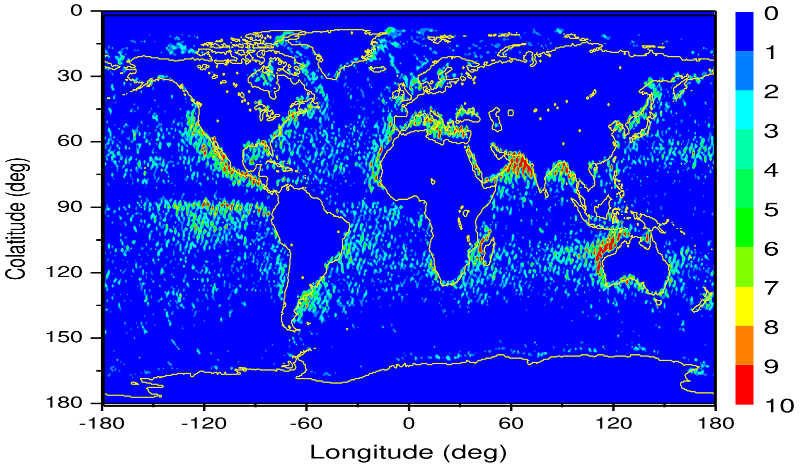


MODIS-derived 12-month clear percentage of CERES FOVs

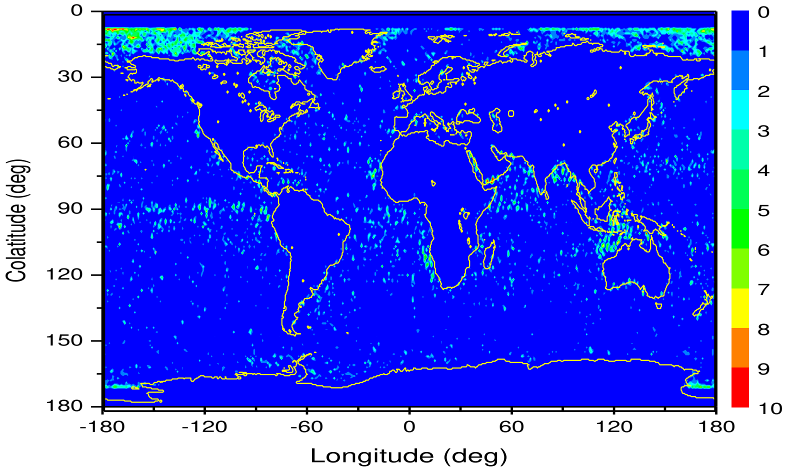


CALIPSO-derived cloudy percentage in MODIS-clear CERES FOVs

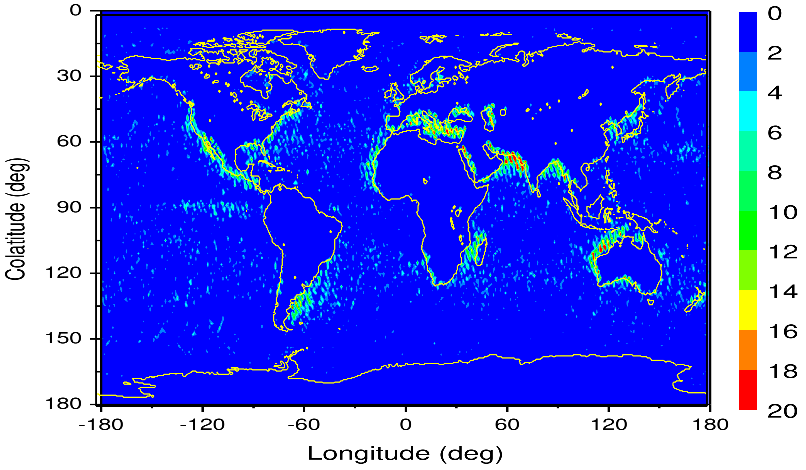
12-month CERES FOVs Sampling Distribution



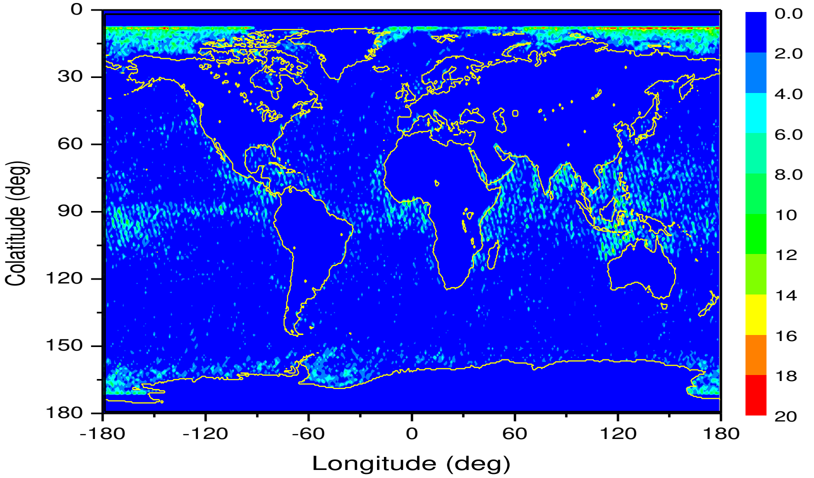
Daytime Purely Clear



Daytime Super-thin Clouds

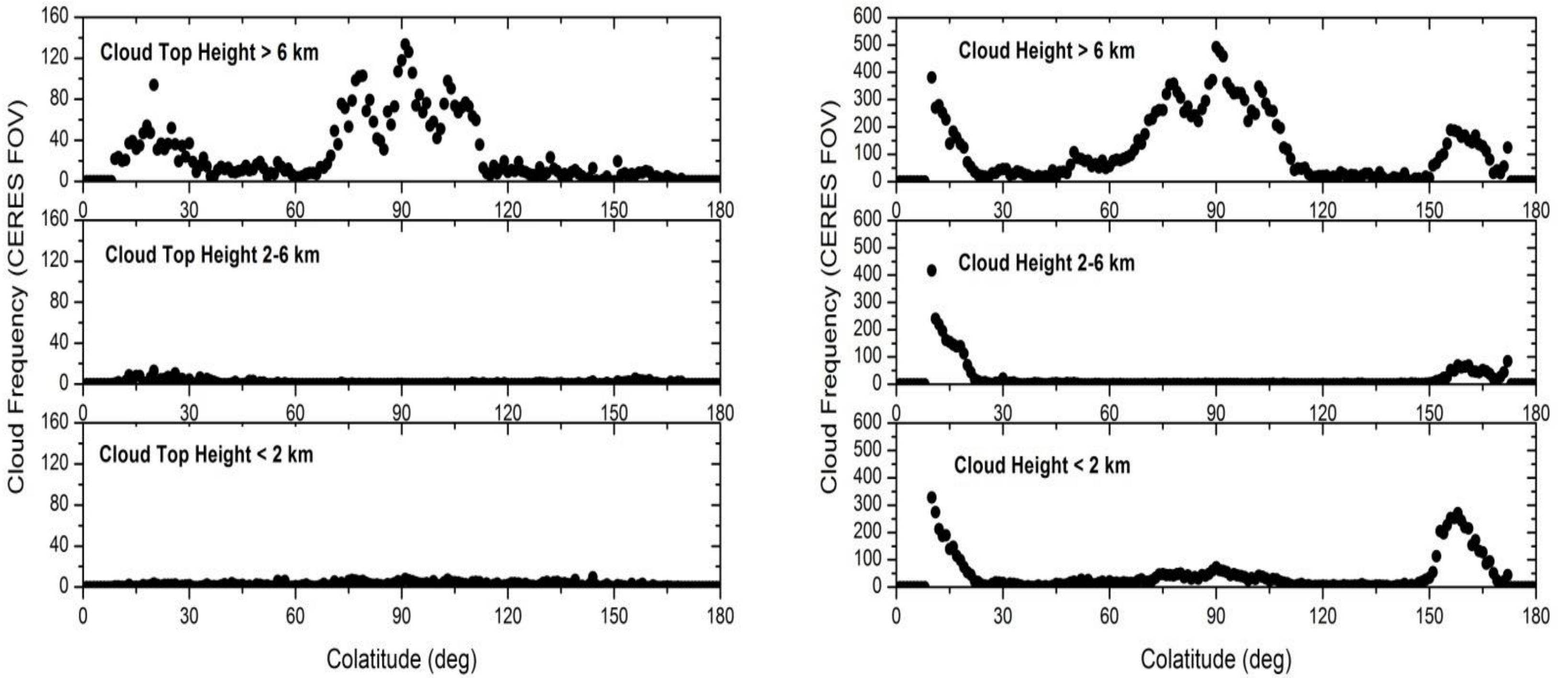


Nighttime Purely Clear



Nighttime Super-thin Clouds

Zonal and Altitude Distribution of Super-thin Clouds

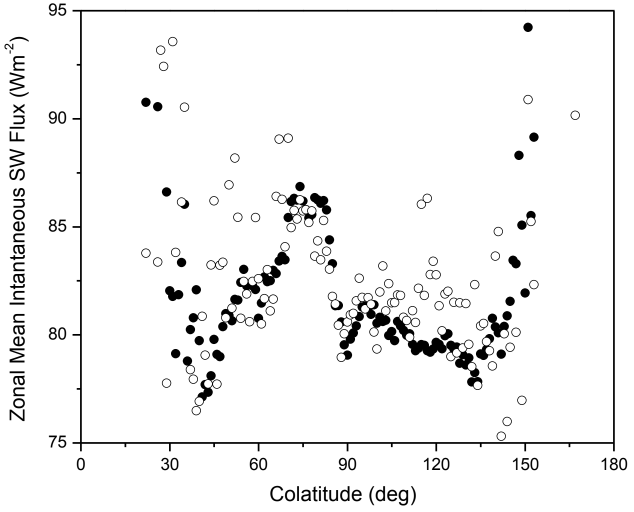


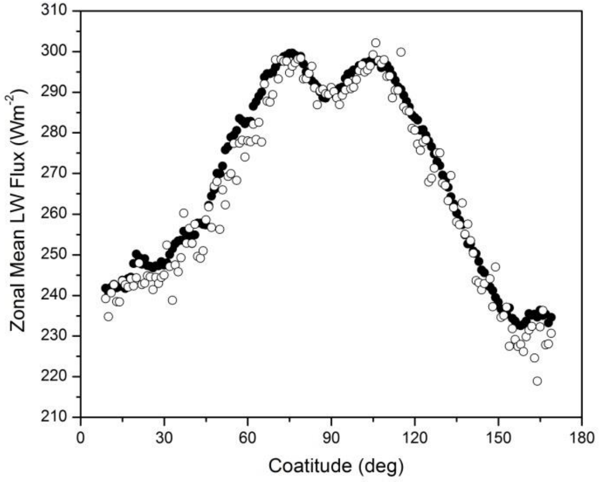
Daytime

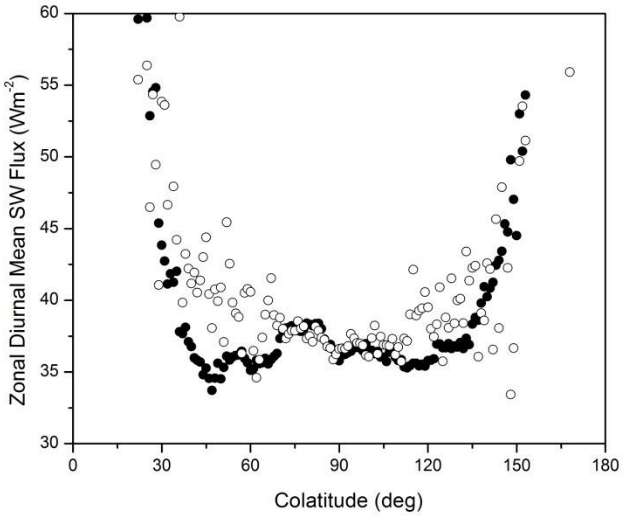
Nighttime

Zonal and altitude distribution of super-thin cloud occurrence frequency over oceans (in the unit of CERES FOV number)

Daytime Super-thin Clouds' Radiation Effect



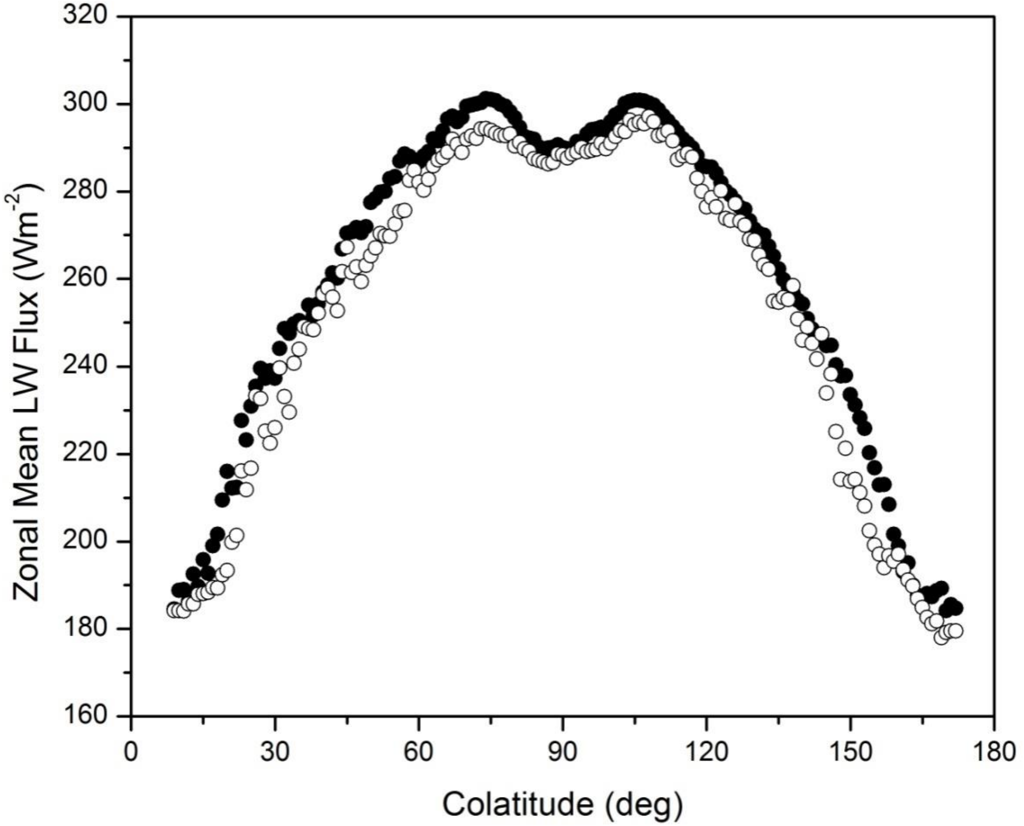




Instantaneous CERES SW flux is converted to diurnal 24-hour mean value by using previously made lookup tables from CERES TRMM processing-orbit data (Loeb & Manalo-Smith 2005).

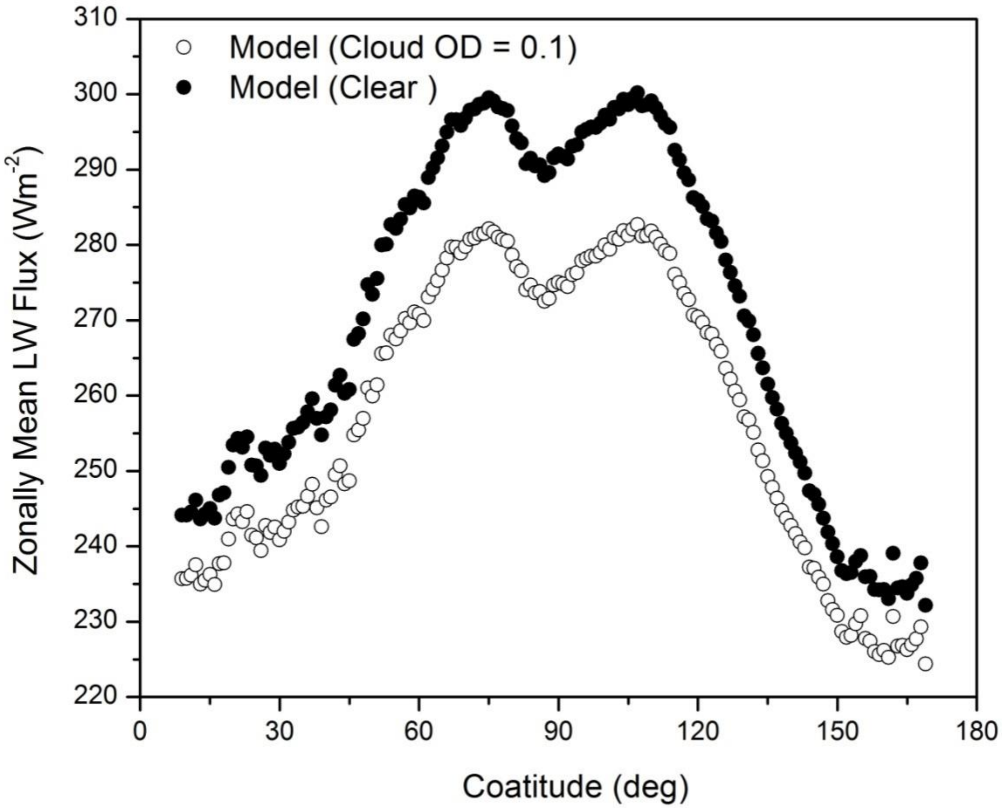
Super-thin clouds have ~2.5 Wm^{-2} diurnal mean SW cooling effect.

Nighttime Clear-Sky and Super-thin Clouds' Radiation



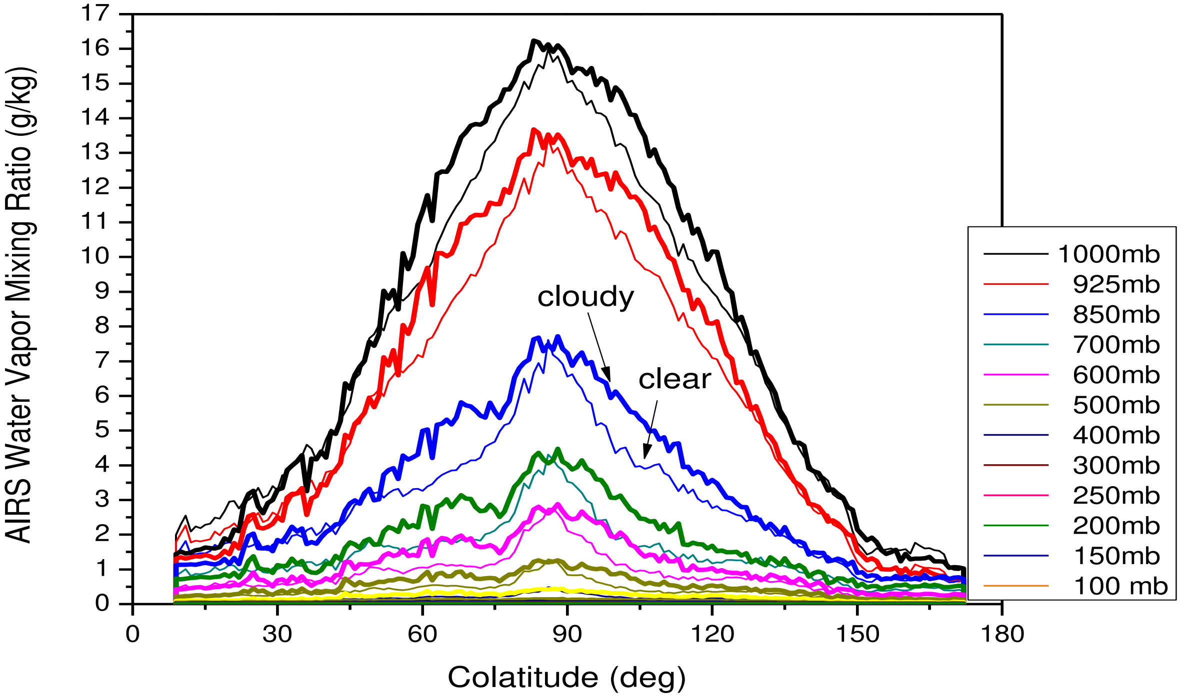
Comparison of CERES outgoing LW flux for clear (filled circle) and super-thin clouds (open circle) cases

Modeled Super-thin Clouds' Radiation Effect

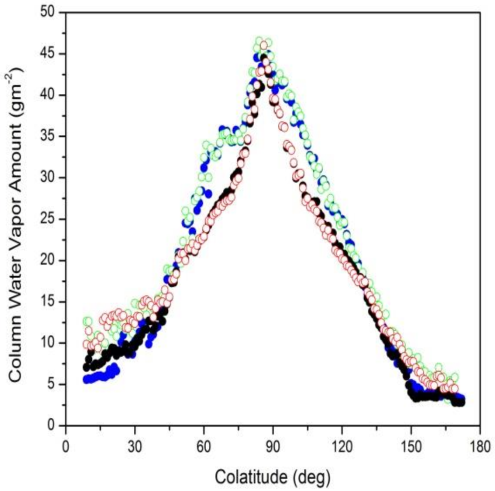


Comparison of modeled outgoing LW flux for clear (filled circle) and super-thin clouds (open circle) cases using atmospheric profiles of clear CERES FOVs.

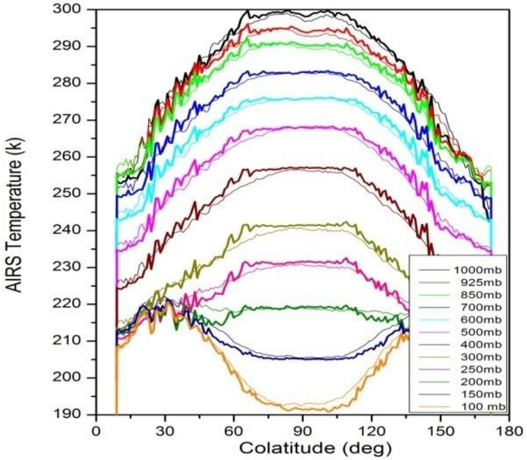
Humidity and Temperature Difference between Clear and Super-thin Clouds Environment



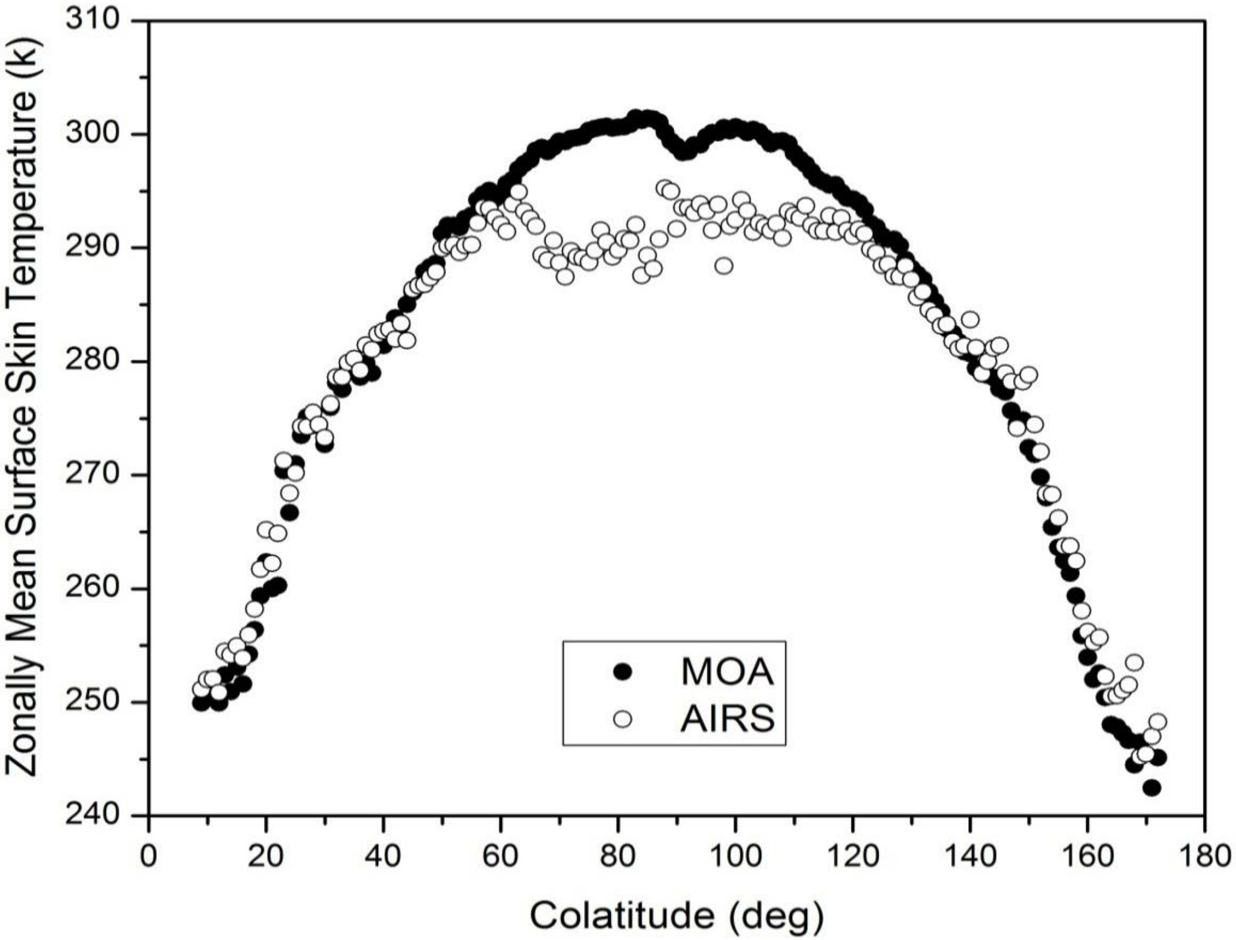
The CERES LW flux difference between clear and super-thin clouds FOVs could be a result of water vapor absorption. This makes the quantification of the super-thin clouds' effect on LW radiation difficult.



Daytime zonal mean instantaneous column water vapor amount from AMSR-E (filled circle) and AIRS (open circle) for clear (black and red) and super-thin clouds (blue and green) ocean

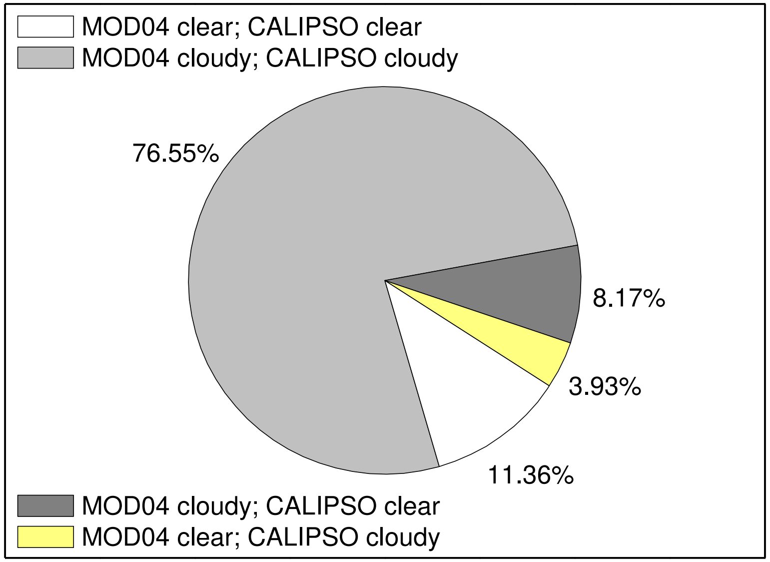


Daytime zonal mean instantaneous temperature profiles from AIRS for clear (thin curve) and super-thin clouds (thick curve) ocean

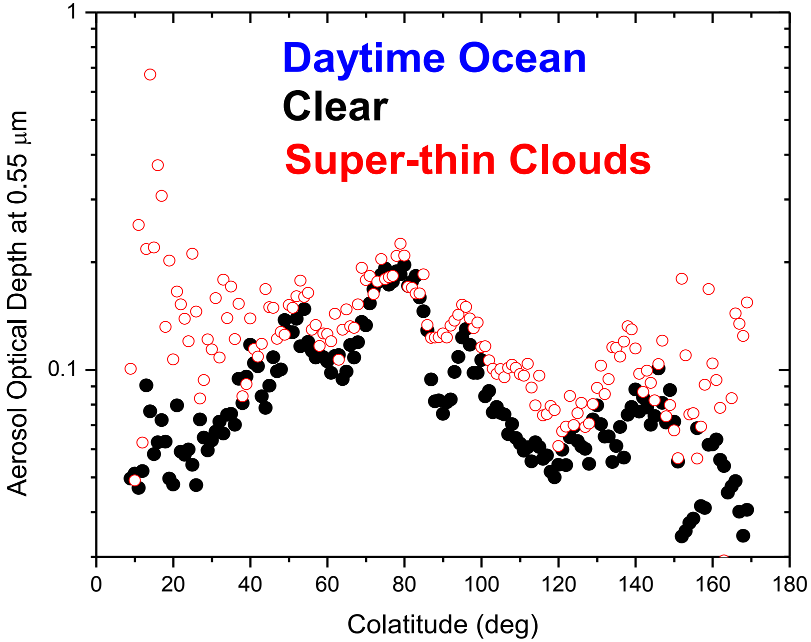


Failed to detect super-thin clouds, NASA AIRS satellite measured SST is ~10K lower than actual values.

Effect of Super-thin Clouds on MODIS Aerosol Product

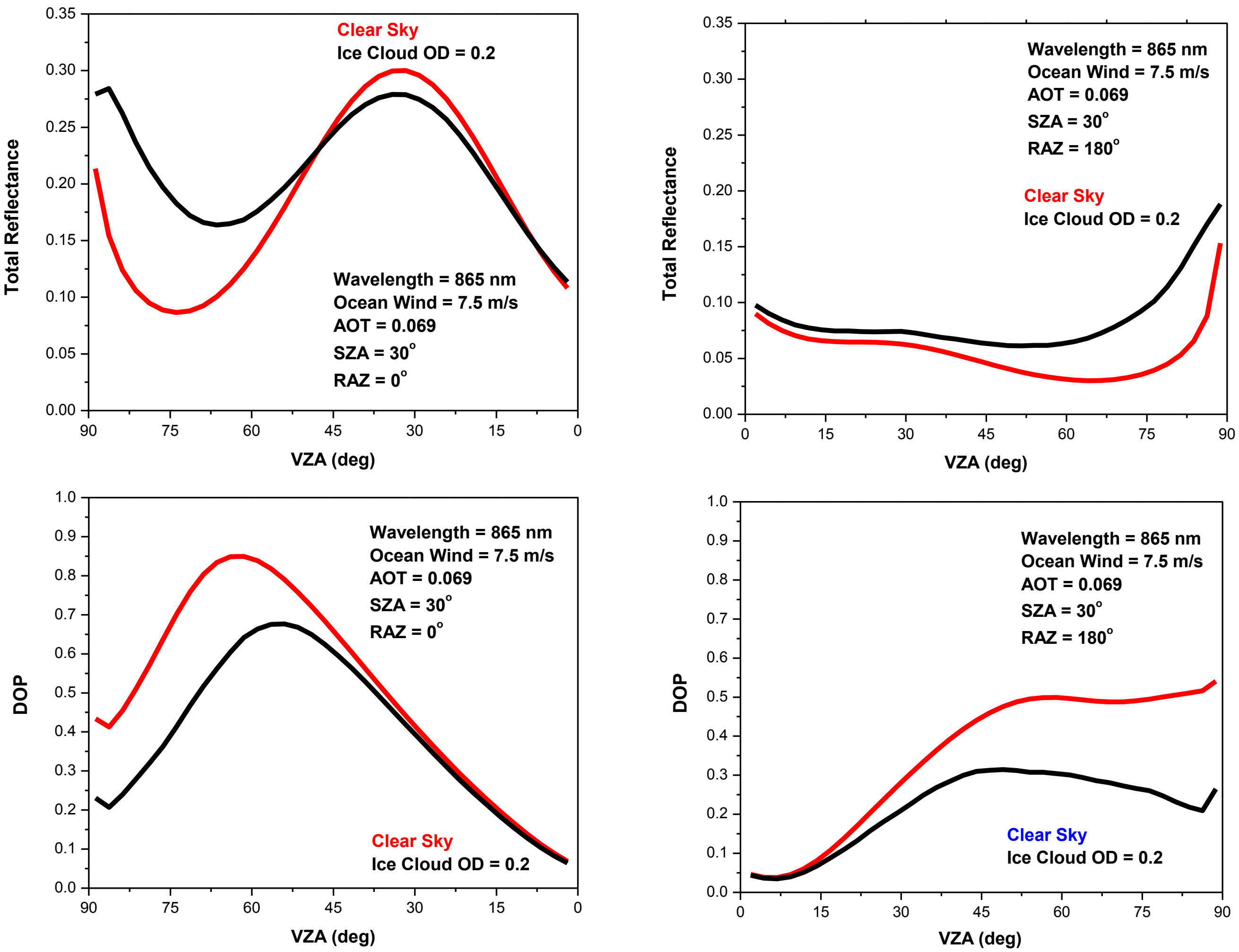


Statistics of 1km x 1km areas with matched and unmatched cloud masks from CALIPSO and MOD04



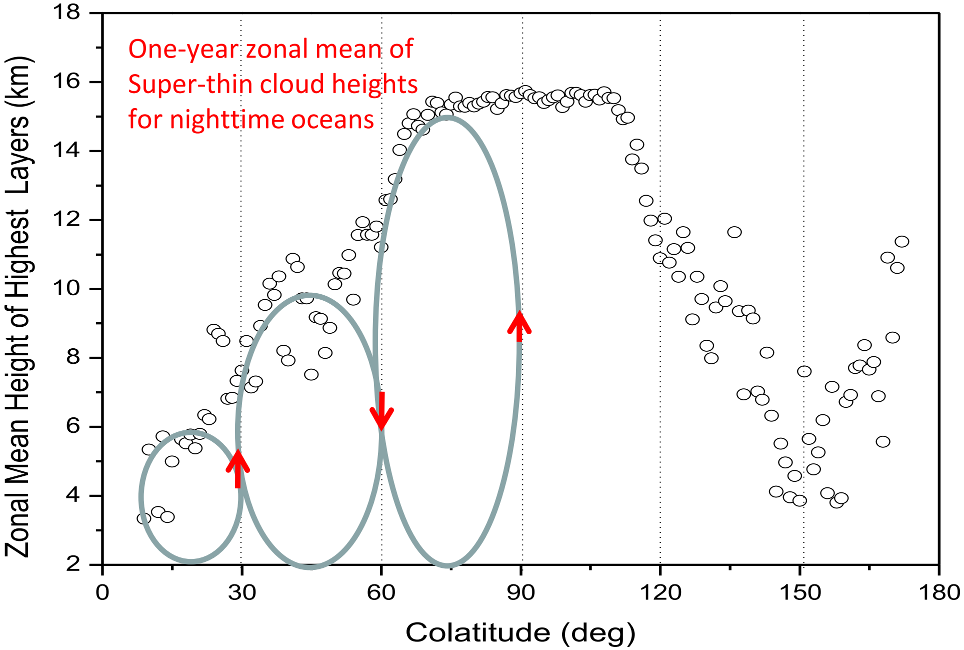
Zonal mean MOD04 aerosol optical depth at 0.55 µm for daytime ocean

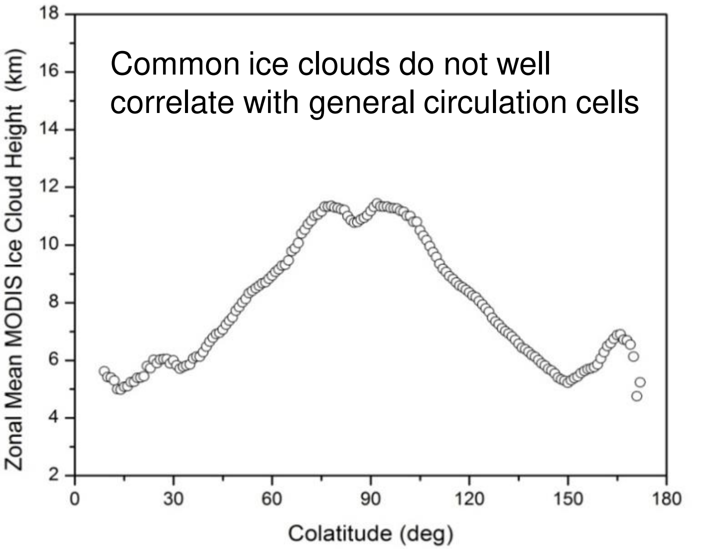
Effect of Super-thin Clouds on Polarized Radiance

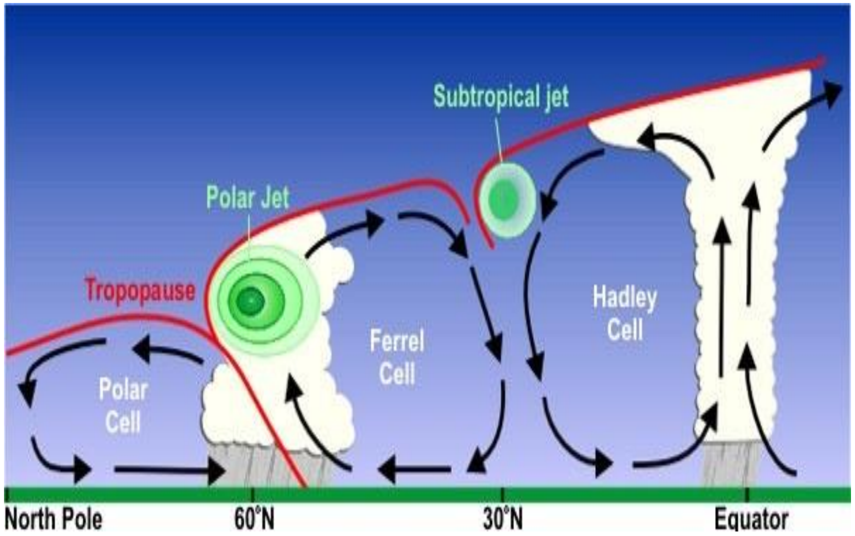


Total reflectance and degree of polarization (DOP) at 865 nm for clear ocean and for ocean with super-thin ice cloud of optical depth (OD) = 0.2 from the ADRTM (Sun and Lukashin 2013; Sun et al. 2015).

Super-thin Clouds Correlate with General Circulations



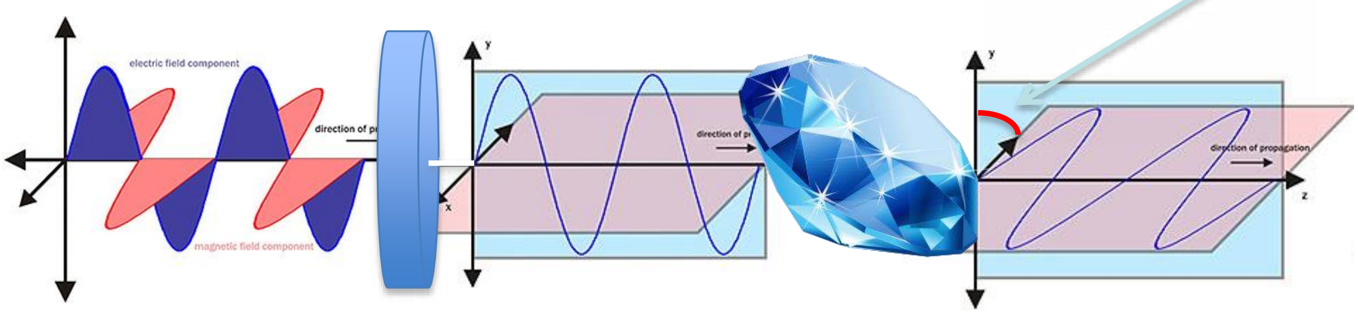




The extent of Hadley cell is a critical metric of climate change.

Super-thin clouds provide a novel way for satellite remote sensing of Hadley cell.

A new concept to detect super-thin clouds

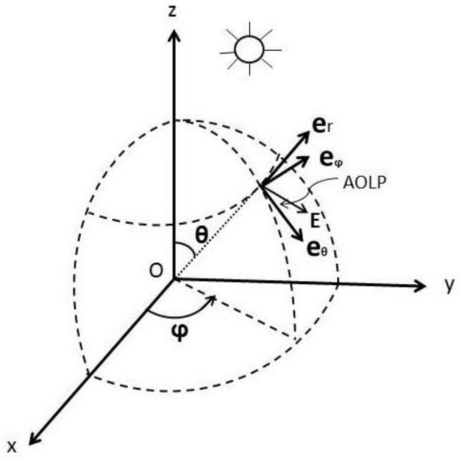


Transmitted light’s angle of linear polarization (AOLP) tells the target is quartz or diamond

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

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

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

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

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

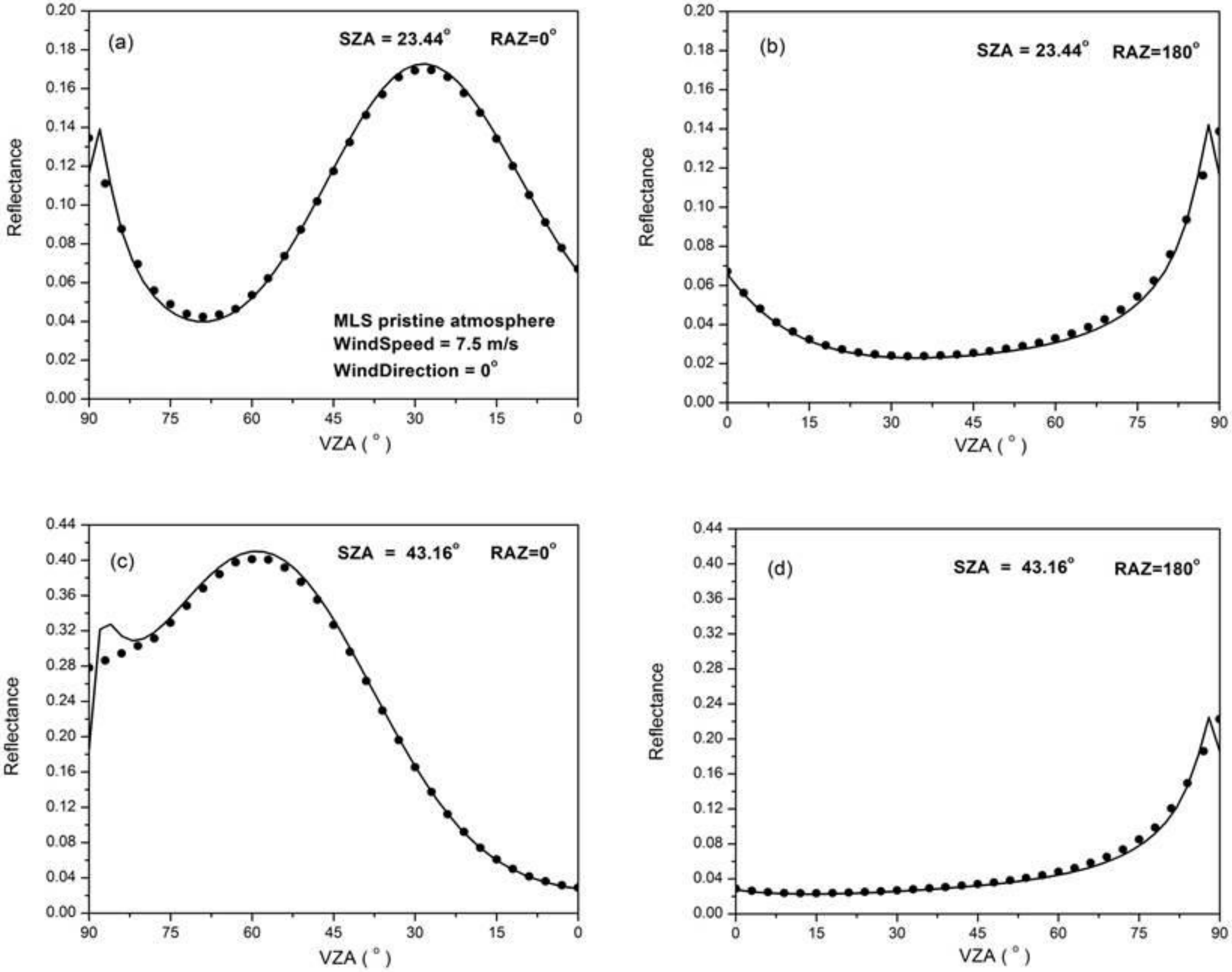
An airborne or space-borne polarimeter can measure Stokes parameters I, Q, U, and V.

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

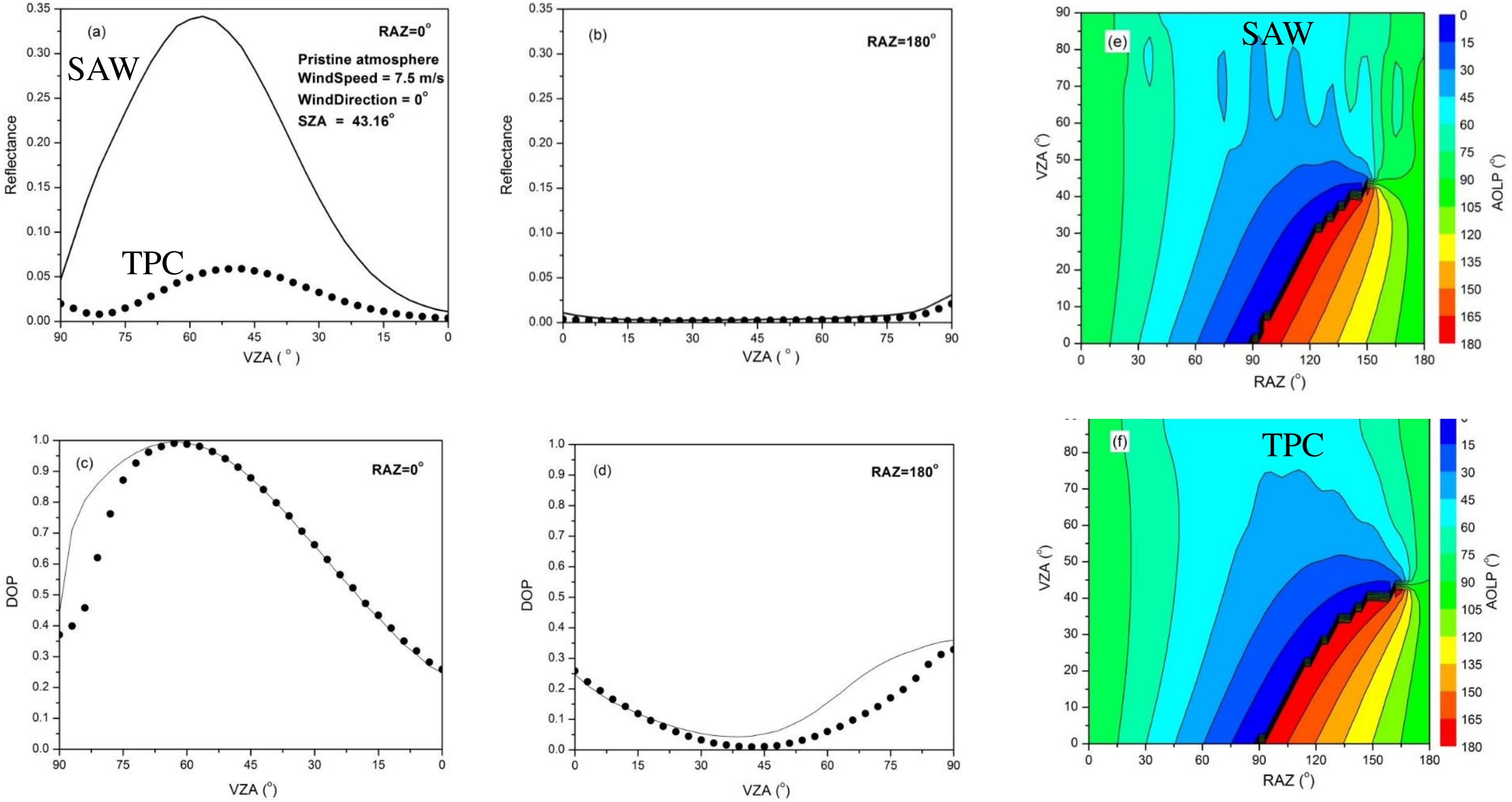
The adding-doubling radiative transfer model (ADRTM)

1. **ADRTM:**
   This can calculate full Stokes parameters (I, Q, U, V).
2. **Atmospheric profiles:**
   Any atmosphere profile.
3. **Spectral gas absorption:**
   Line-by-Line and *k*-distribution plus ozone cross-section table.
4. **Molecular scattering:**
   Rayleigh with depolarization factor.
5. **Particulate absorption and scattering:**
   Mie for water clouds (Gamma size distribution);
   DDA, PML/UPML FDTD for fine-mode aerosols;
   CPML PSTD code is developed for coarse-mode aerosols;
   FDTD, PSTD, and GOM for ice clouds are being considered...
6. **Surface reflection model:**
   Empirical model for desert/bare land surface.
   Lambert surface for other land scene type now.
   More practical model for land is being considered with PARASOL data…
   Cox & Munk with/without Gram-Charlier expansion plus foam for ocean;
   Wave shadowing effect is integrated in the ocean surface model;
   Lambert model for water-leaving radiance from ocean water volume.
   More practical model for water-leaving radiance is being considered…
7. **Output:**
   polarization parameters are mapped to uniform angular grids.
8. **Goal:**
   PDMs of whole CLARREO solar spectra for all major scene types …

Comparison of reflectance at 670 nm from DISORT (solid curves) and ADRTM (black dots)

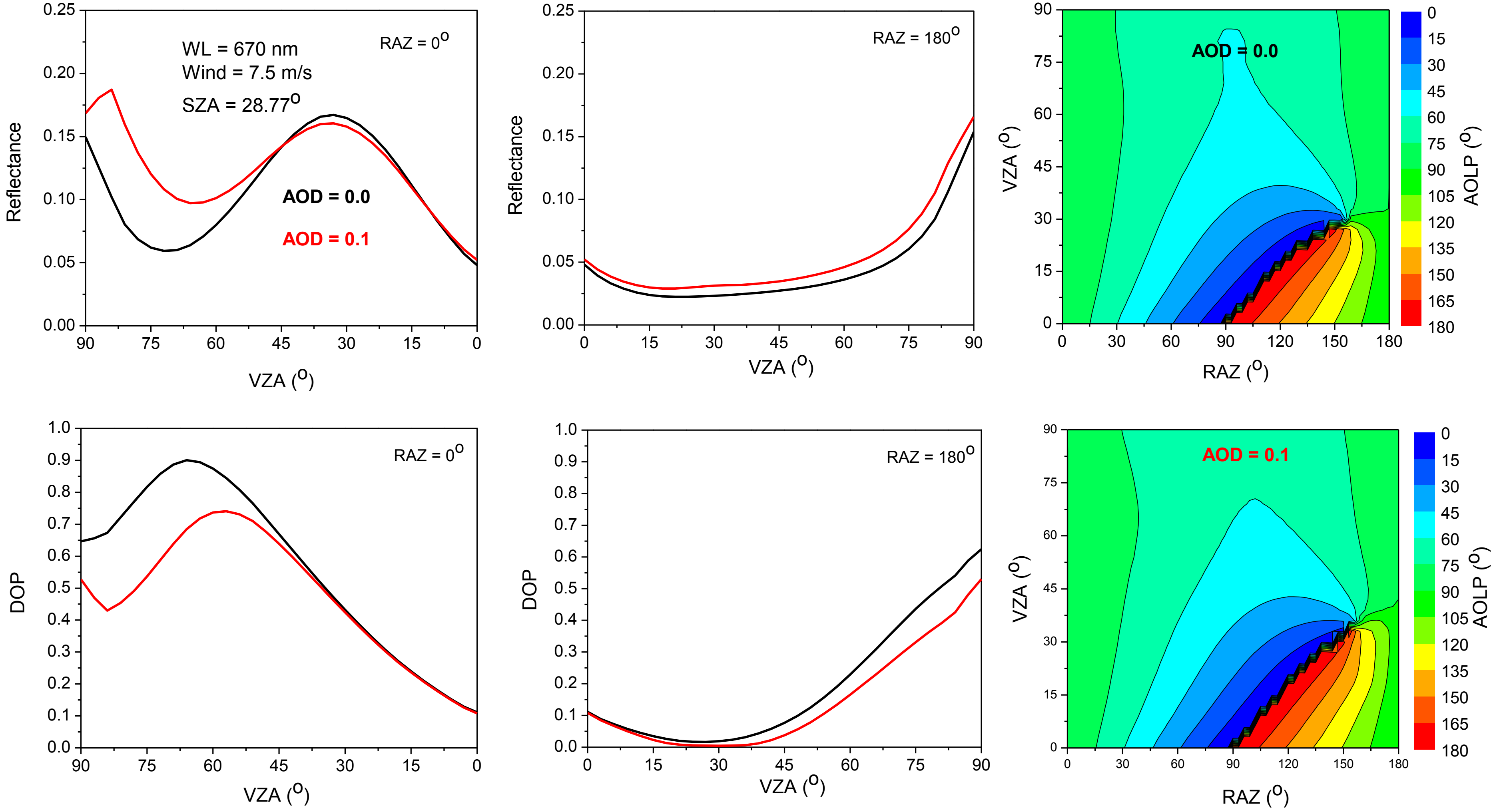


Atmospheric absorption has little effect on reflected solar light's polarization direction

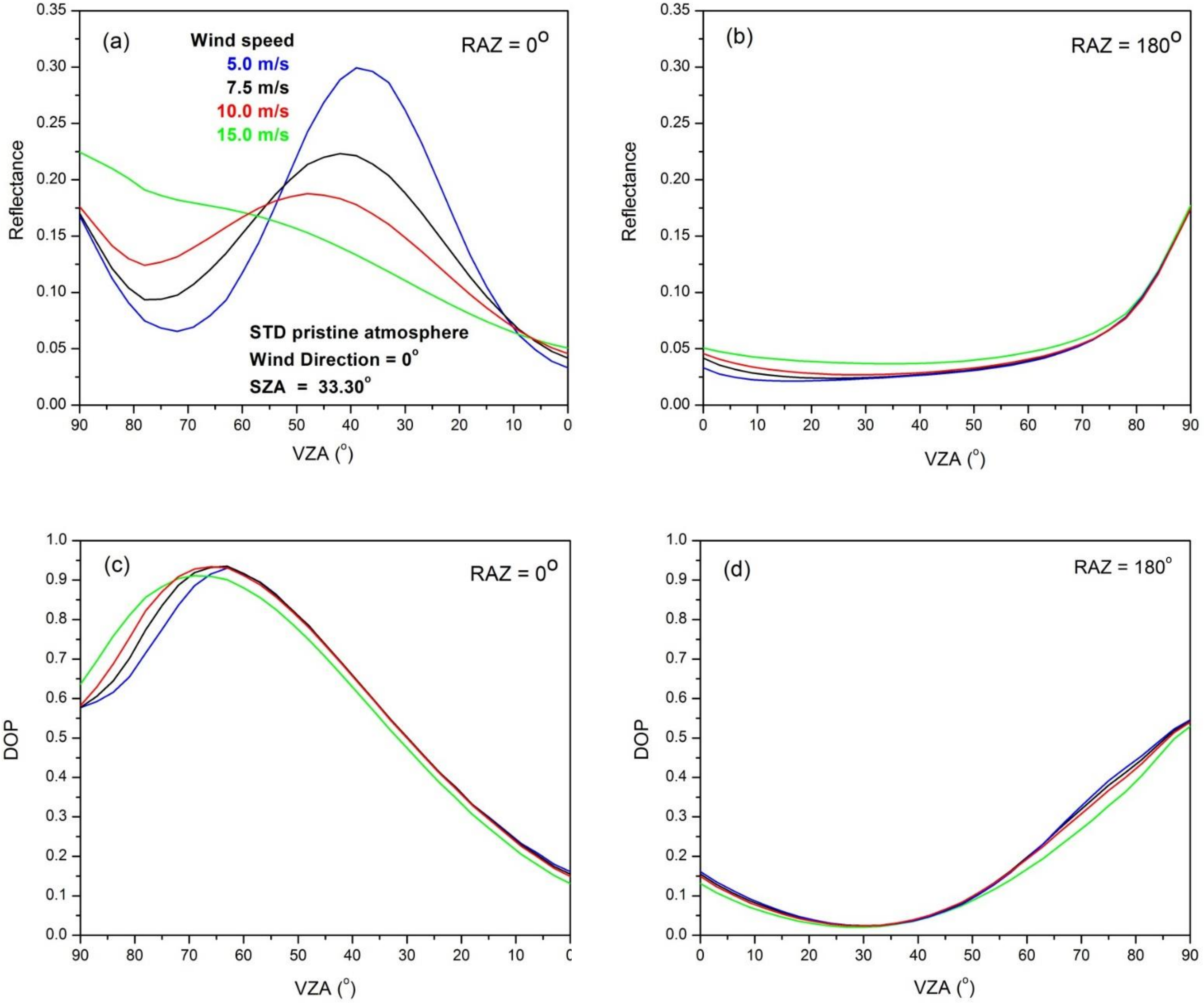


At wavelength = 1200 *nm*. Subarctic winter (SAW) and Tropical (TPC) atmosphere.

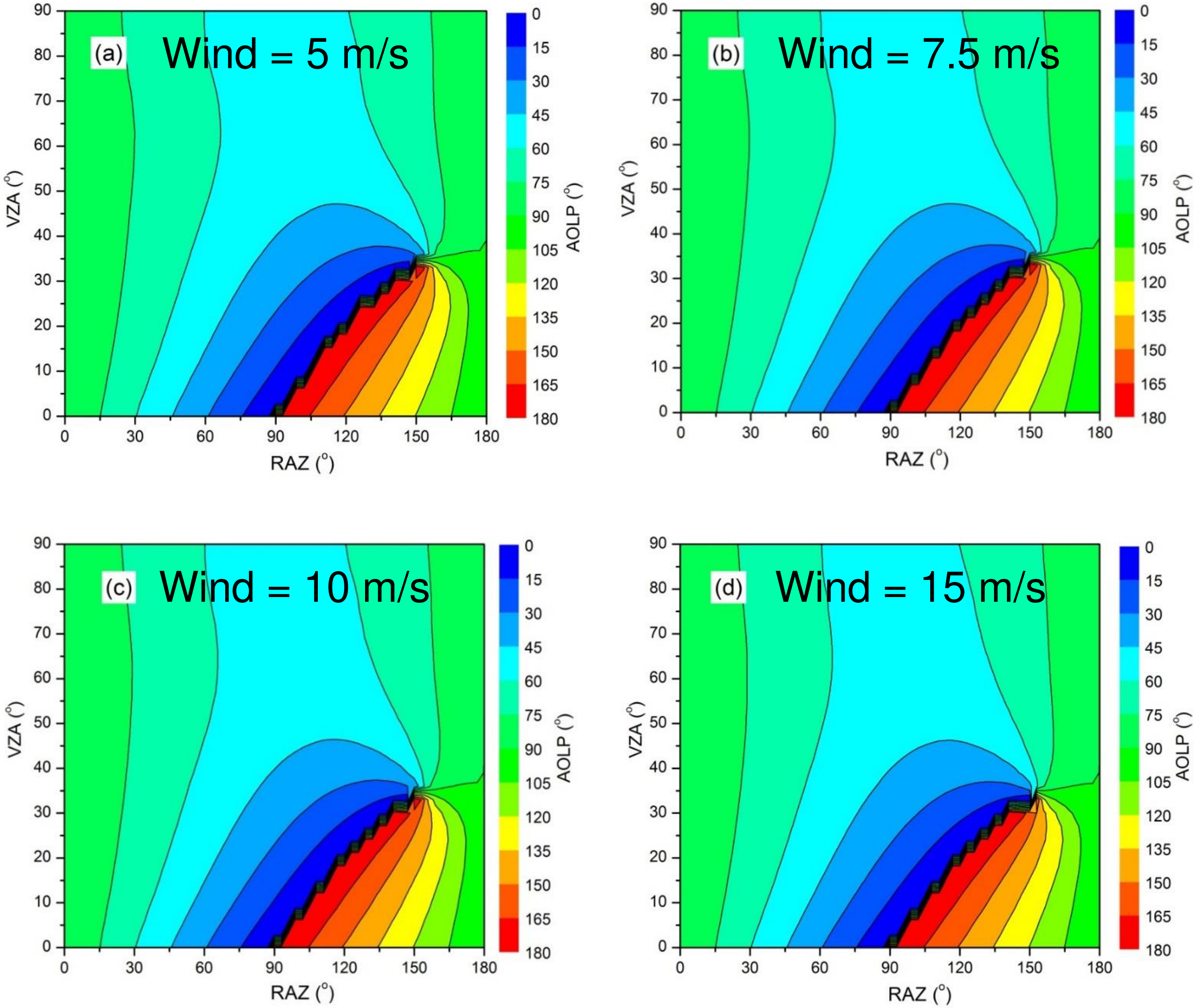
Aerosol effect on reflected solar light



Modeled clear ocean reflectance and degree of polarization (DOP) at 670 nm

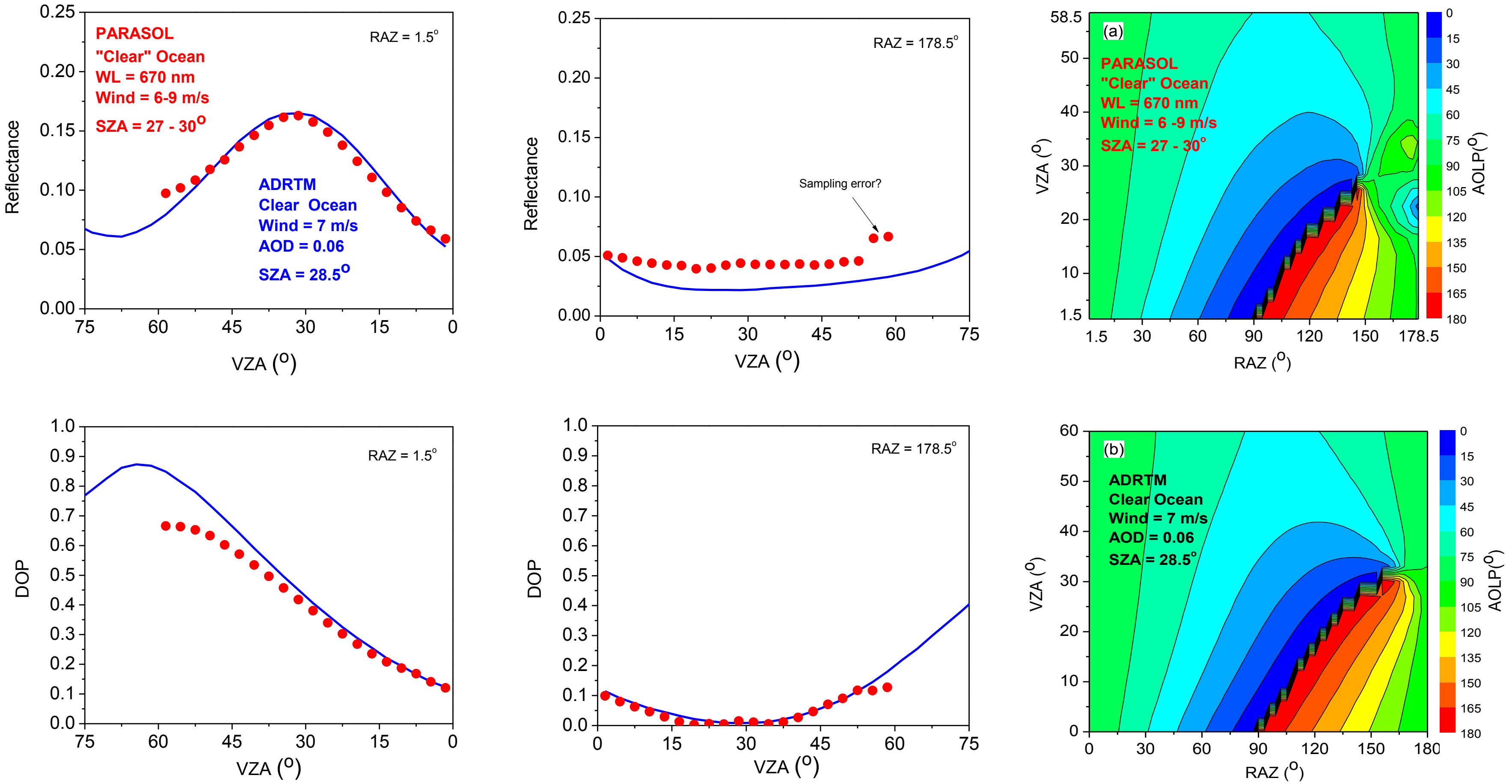


Ocean surface roughness has little effect on reflected solar light's polarization direction

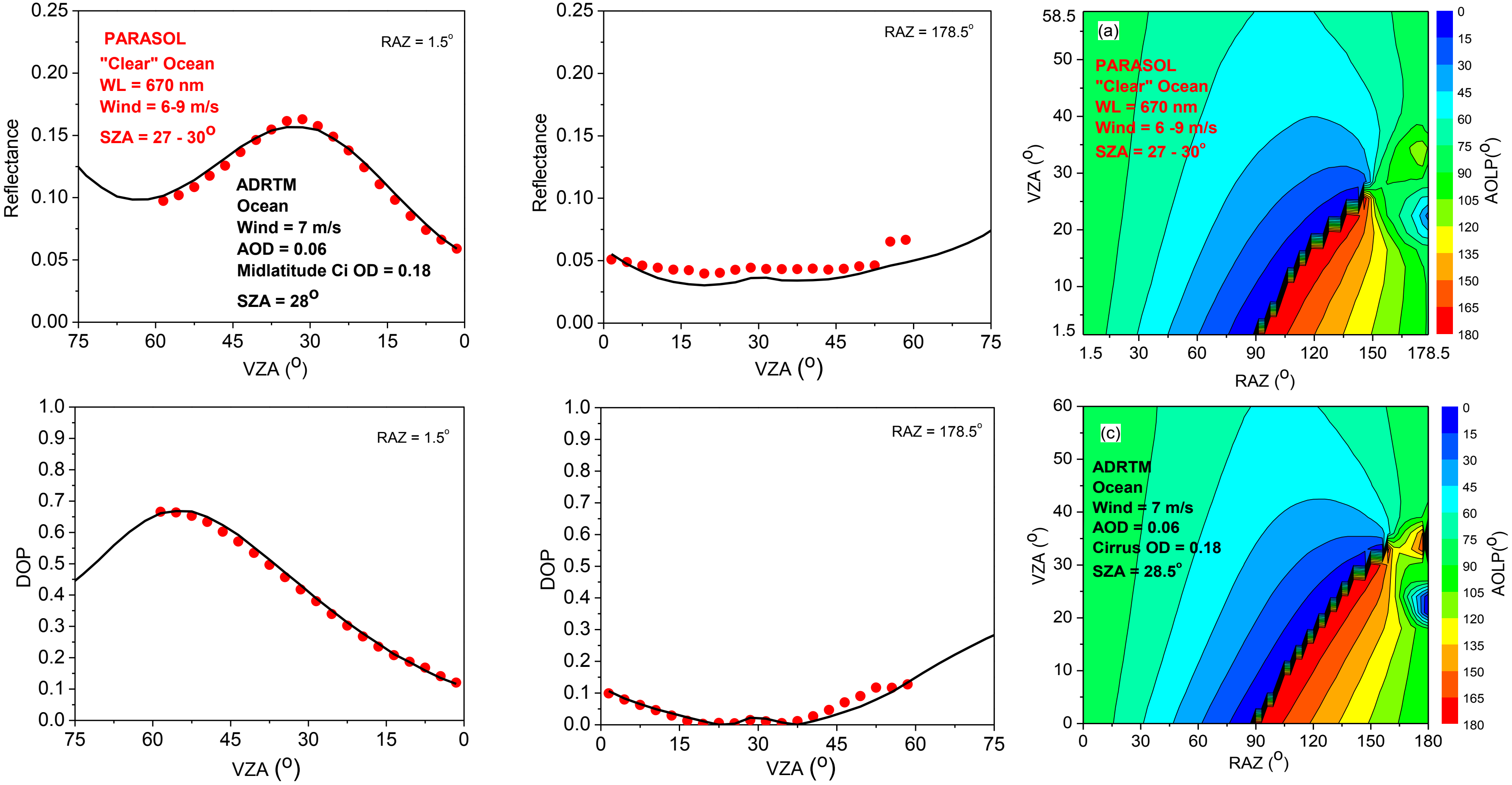


Comparison of ADRTM results with PARASOL data

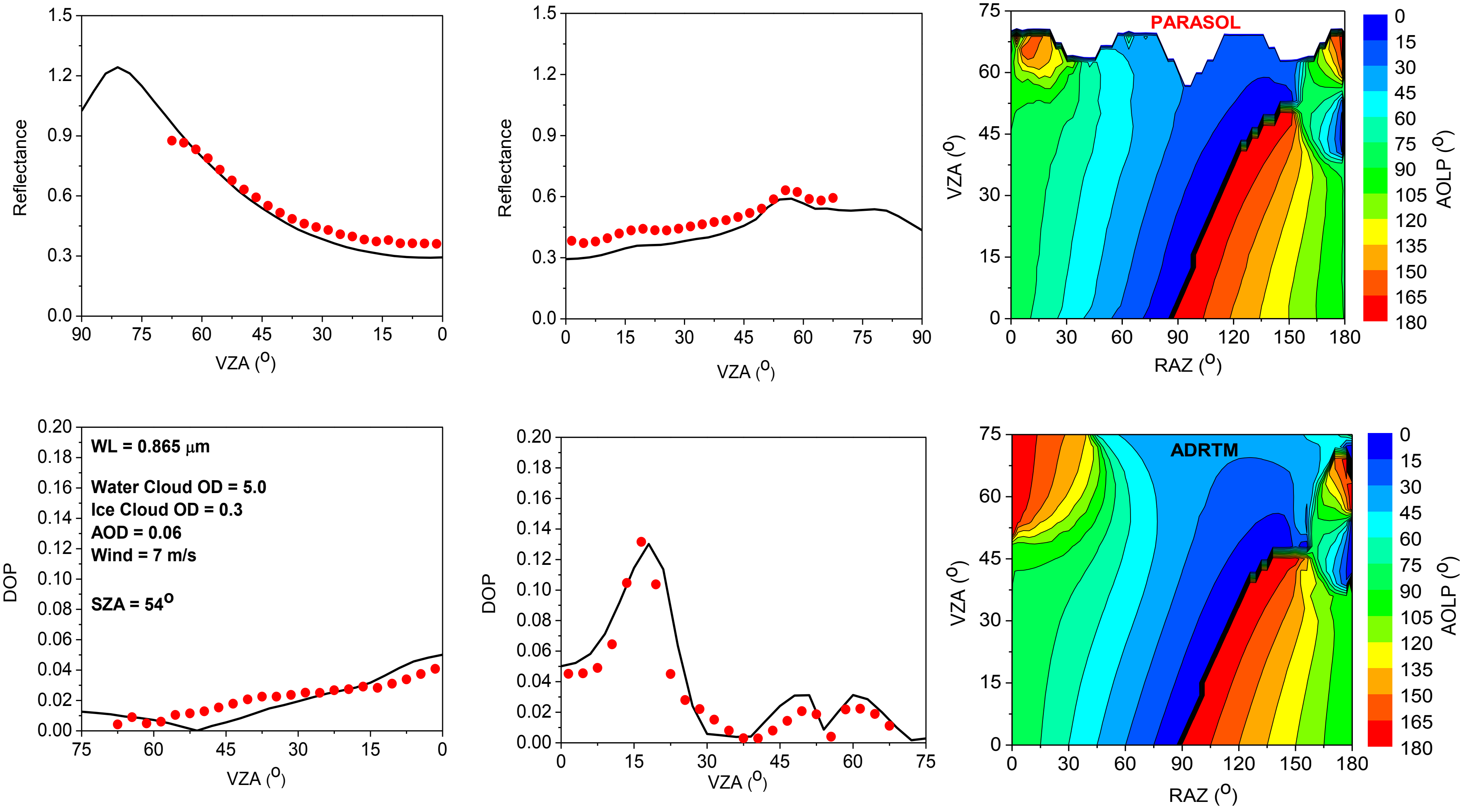
No cloud in the ADRTM



A layer of super-thin cirrus added in the ADRTM



Comparison of ADRTM results with PARASOL data for water clouds



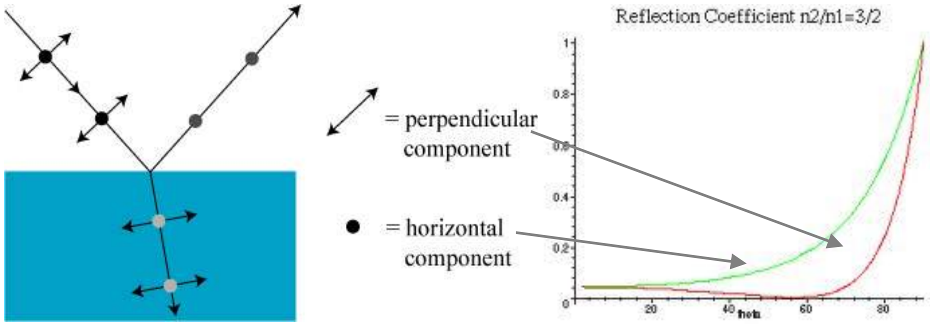
WL = 0.865 µm

Water Cloud OD = 5.0
Ice Cloud OD = 0.3
AOD = 0.06
Wind = 7 m/s

SZA = 54^{o}

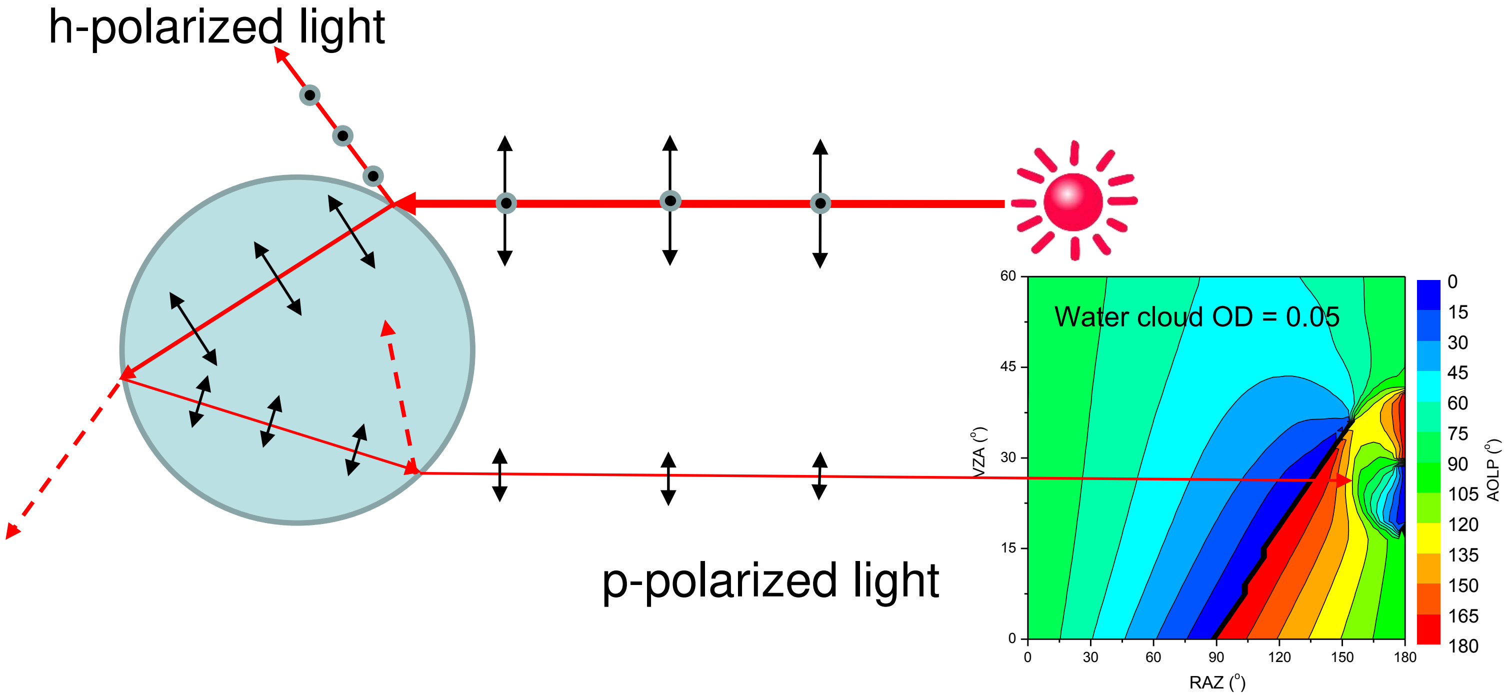
A plausible explanation of clouds’ special AOLP pattern

How is light reflected by a dielectric surface?



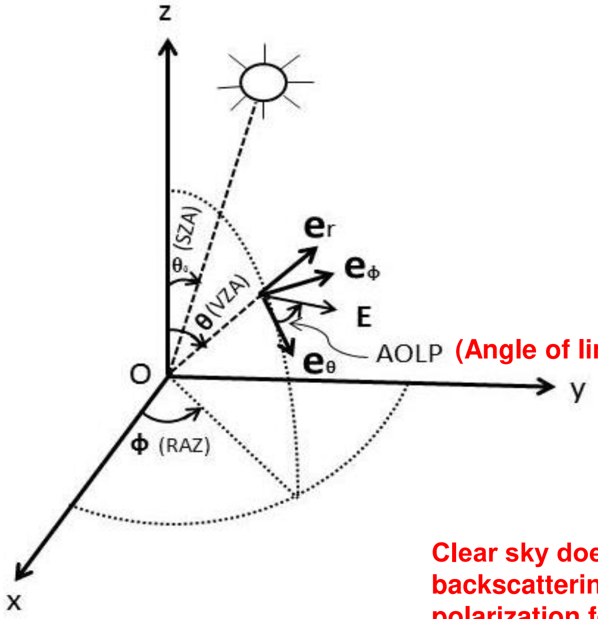
= perpendicular component

● = horizontal component

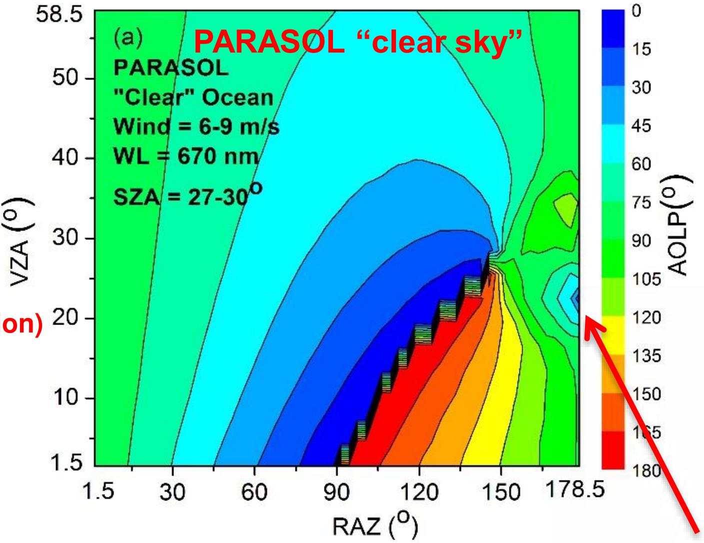

h-polarized light
p-polarized light
Water cloud OD = 0.05
VZA (°)
60
45
30
15
0
RAZ (°)
0
30
60
90
120
150
180
AOLP (°)
0
15
30
45
60
75
90
105
120
135
150
165
180

A novel technique for detecting super-thin clouds

P-polarization feature of clouds (ice)

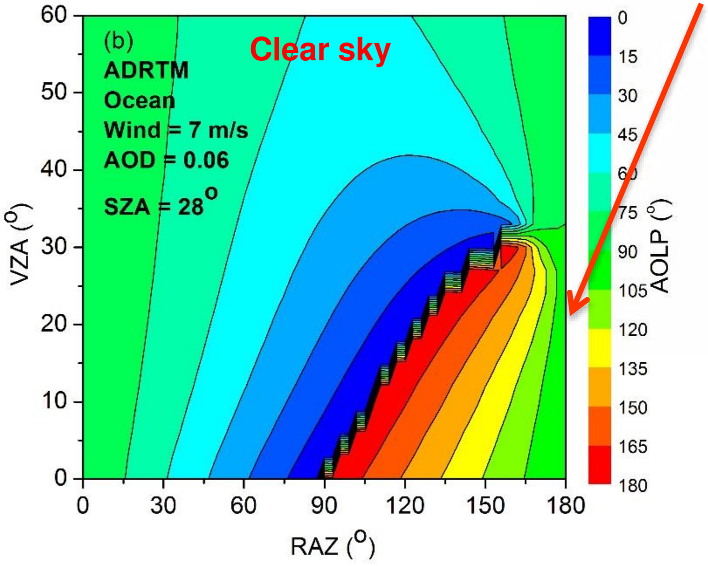


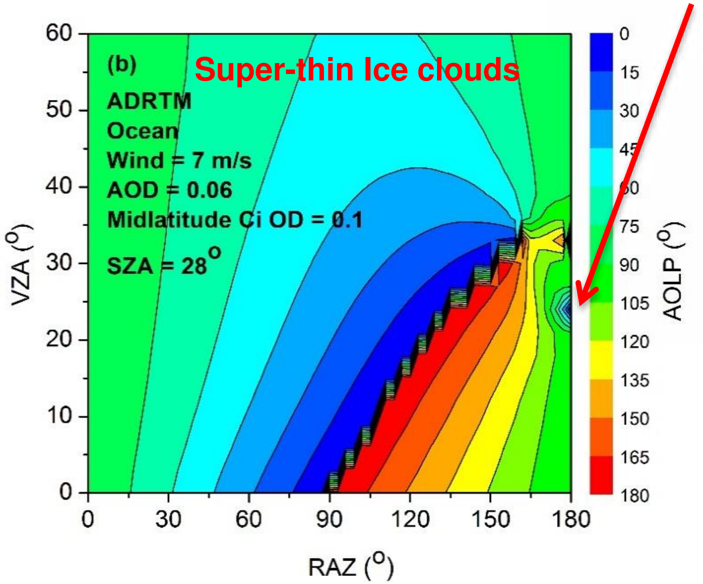
(Angle of linear polarization)



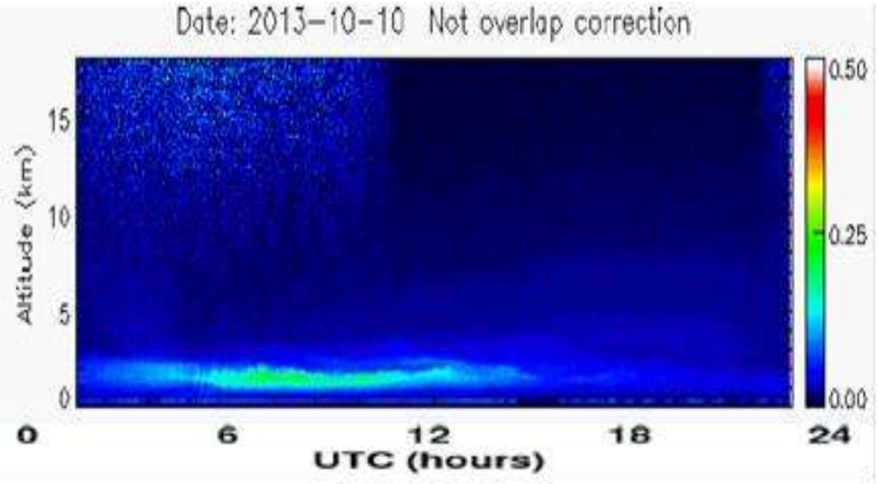
Clear sky doesn't have backscattering *p*-polarization feature

Backscattering *p*-polarization feature

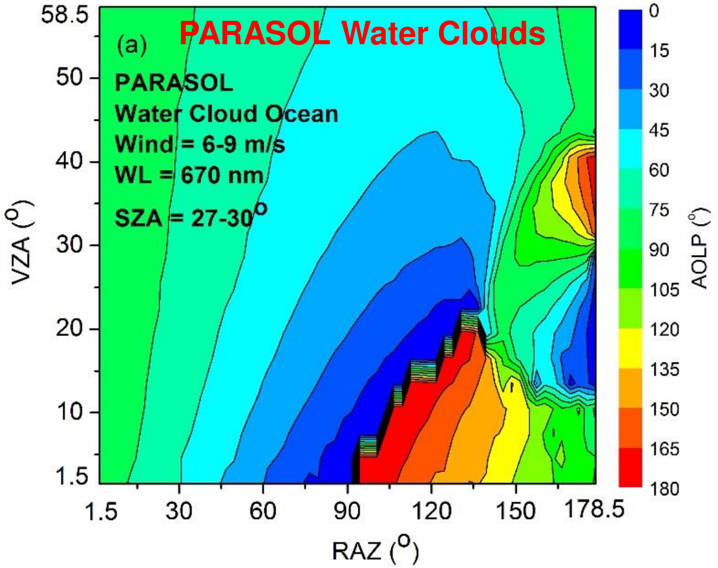


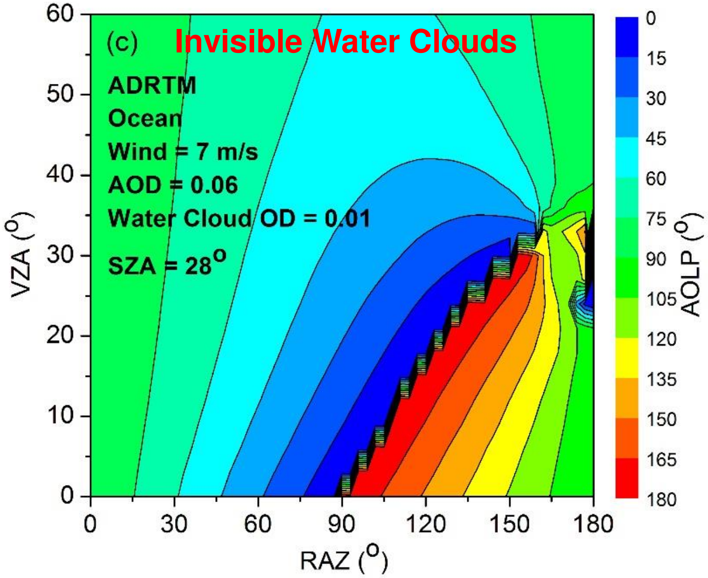


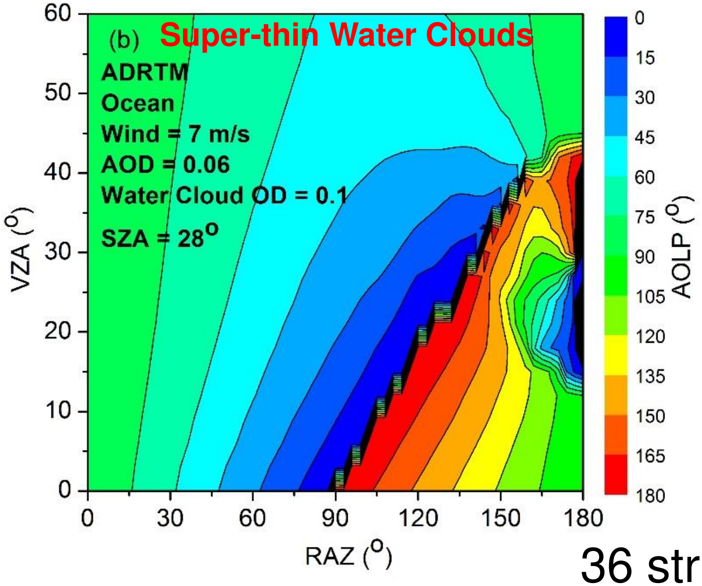
P-polarization feature of clouds (liquid water)



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.

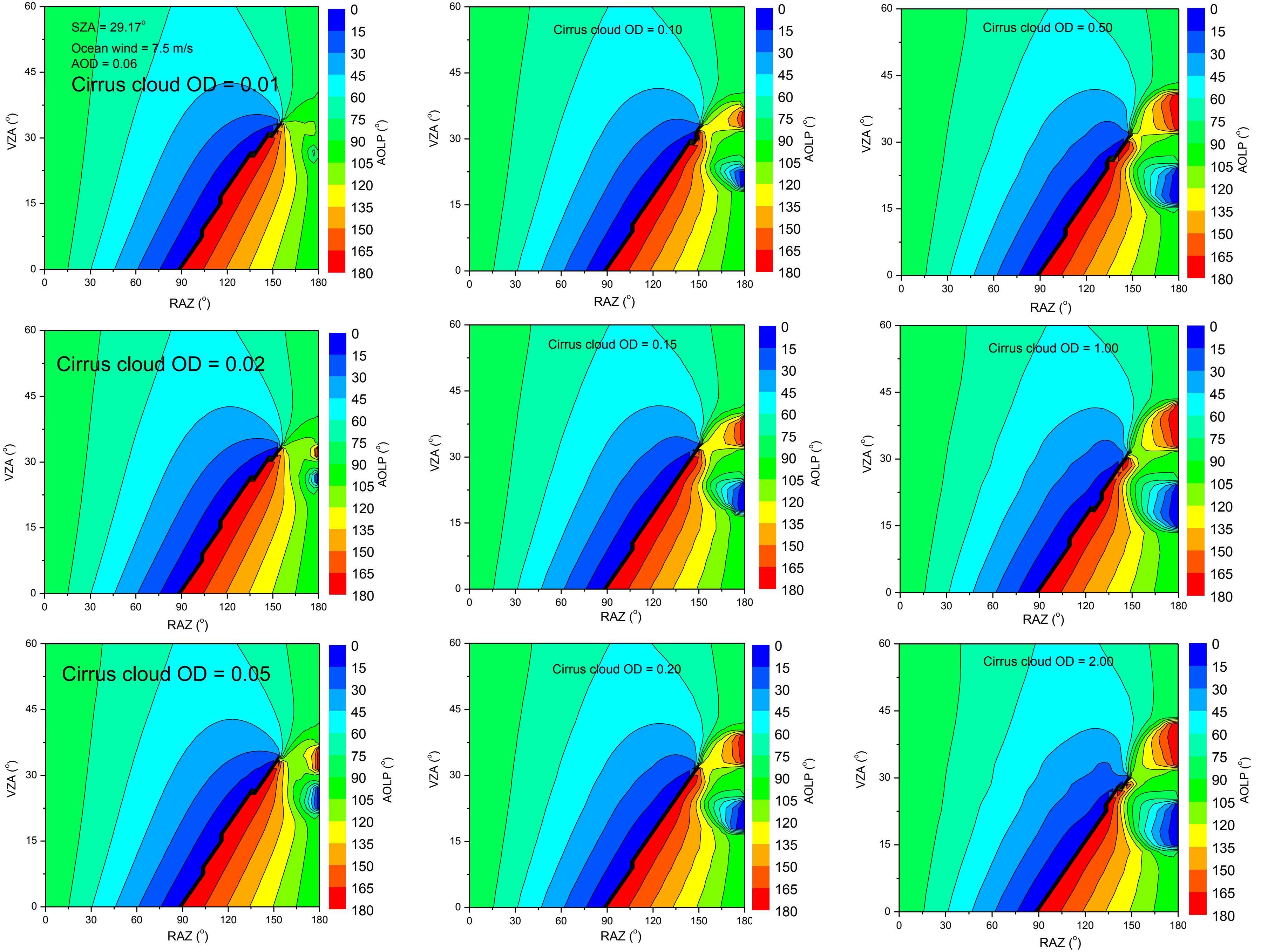




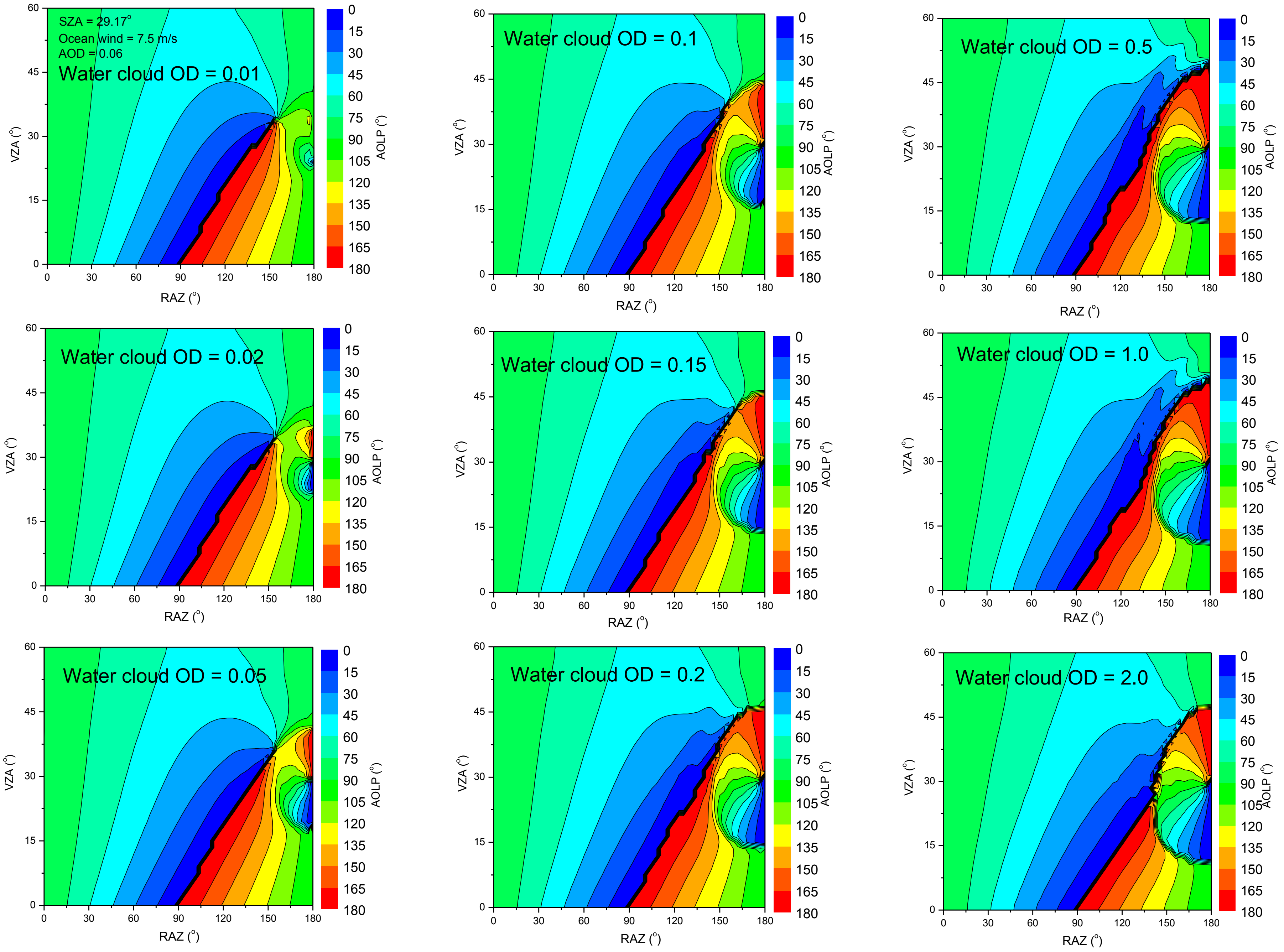


36 streams

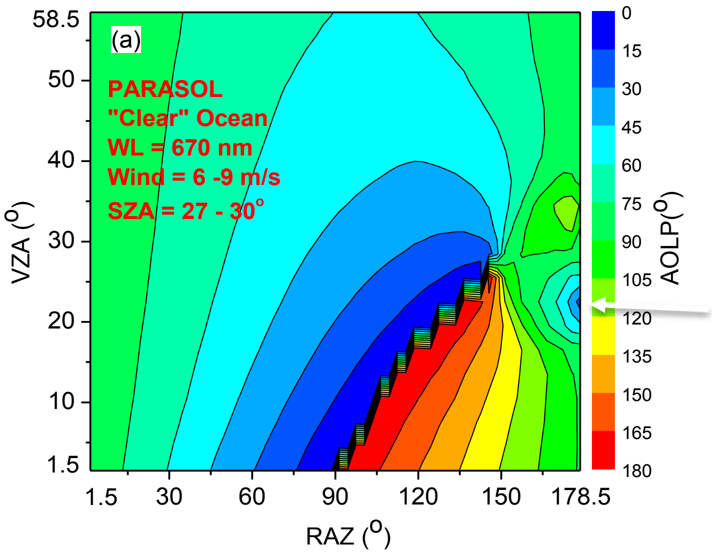
P-polarization feature of ice clouds as a function of optical depth



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



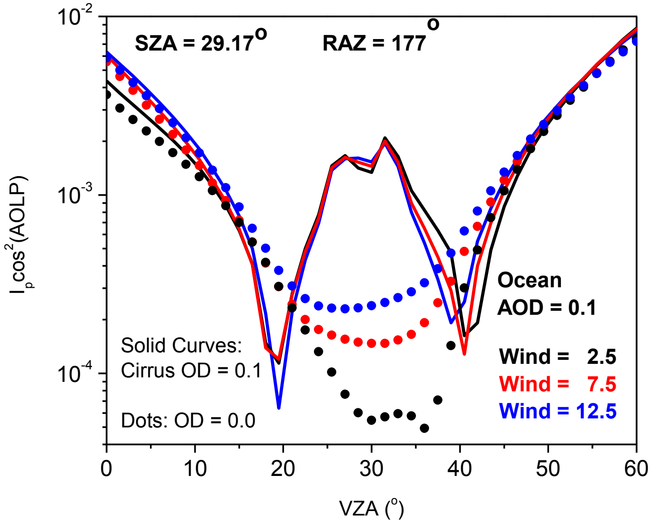
How to retrieve the optical depth of the super-thin clouds?



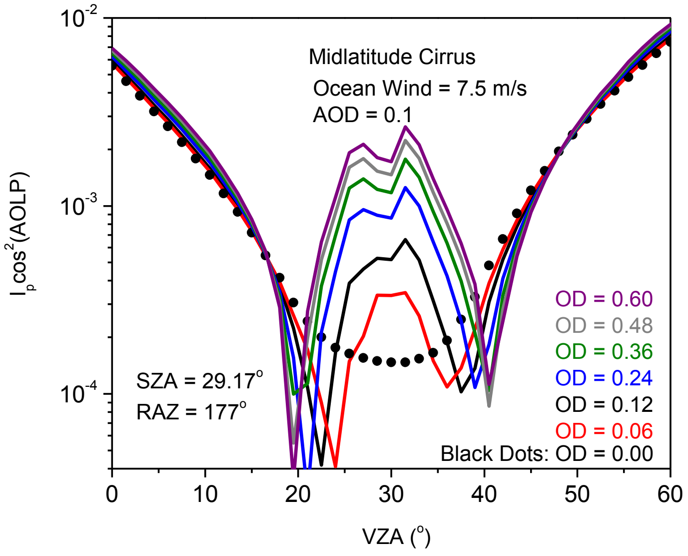
$$OD = f^{-1}[I_p \cos^2(AOLP)]$$

I_p is polarized reflectance

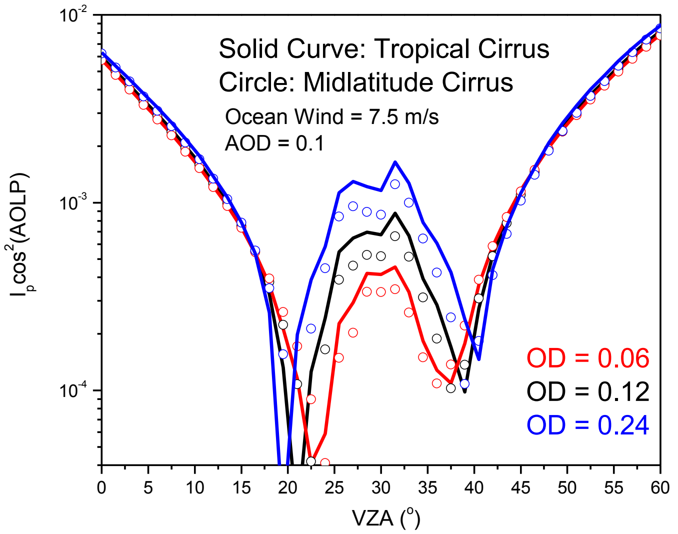
The retrieval is done at “blue spot”



At the “blue spot” $I_p \cos^2(AOLP)$ has little dependence on ocean surface when clouds’ OD > ~0.1.



At the “blue spot” $I_p \cos^2(AOLP)$ is nearly linearly correlated with OD, but it saturates when OD approaches to ~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).

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A Small Satellite with a Polarimeter to Detect Super-Thin Clouds Missed by Imagers

- Up to 50% of MODIS-derived clear-sky scenes are actually covered by super-thin clouds.
- By measuring the angle of linear polarization (AOLP) of reflected sunlight, clouds can be reliably detected, even if they are super-thin and at low altitude.
- This mission can have tremendous impacts on remote sensing of clouds, aerosols, surface temperatures, and data for modeling of climate change.

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Thank you for your attention!