

Response to the comments of Reviewer 1

General comments: Super-thin clouds are very difficult to be detected by passive sensors, thus can complicate the retrieval of atmospheric constituents and sea surface temperature that require clear-sky conditions. The authors did lots of nice works about this topic by using observations and models. Based on their previous results and polarized sunlight, this paper presented a novel method to retrieve super-thin cloud optical depth over ocean. Overall, the method is innovative and the results also are reasonable. These results can be used to develop the new sensors and algorithm. I think that the paper can be published by ACP. Thus, I just have a little bit suggestions.

Answer: The authors of this manuscript greatly thank this reviewer for the helpful and insightful comments.

Specific Comments:

1. In the modeling, only single-layer cloud or aerosol is included in the atmosphere. The question is: The multilayered clouds are very frequent. When a cloud overlap system is present (such as, thin cloud over water cloud), is there any impact of underlying water cloud on your results?

Answer: Following this comment, we add in the text of Conclusion: “However, as an algorithm based on a low-cost passive instrument measuring reflected solar light, it has difficulties in detecting super-thin clouds over thick clouds, since the thick clouds’ glory pattern is much stronger than that of super-thin clouds. For those multilayer cases, this method can only tell there are thick clouds in the scene.”

2. The optical depth of aerosol also is constant values (0.06) in all simulations. What’s the uncertainty of fixed AOD? In addition, in the paper(page 6, Line 21): “ One manifestation of this can be seen in the glory, which occurs at near backscattered angles and is p-polarized. If the particle strongly absorbs light, like some aerosols, the refracted light cannot emerge from the particle, and the p-polarization feature is not observed”. Thus, my question is: the properties of aerosol (absorbing or shapes, et al.) whether can affect the cloud retrieval by using p-polarized sunlight when they co-exist? The method whether possible misclassifies some aerosols as clouds?

Answer: Following this comment, we add in the text of Conclusion: “Moreover, since glory pattern is a special optical phenomenon of transparent cloud droplets or ice crystals, this algorithm is not sensitive to background aerosols that coexist with super-thin clouds. However, heavy aerosols ($OD > 0.2$) can cause electric field on the principal plane not parallel to the ocean surface at viewing zenith angles smaller than the backscattering angle, which will result in some ambiguities for retrieval, but they cannot produce the full glory pattern as shown in Figs. 1-3, i.e. electric fields in all radial directions around the backscattering direction.”

3. Page 5, Line 12: What’s the C1 size distribution of water cloud droplets? Detailed parameter information (such as, distribution function, modal radius, shape of the distribution) are needed to be added in the paper.

Answer: Following this comment, we add in the text “The modified gamma (MG) particle size distribution (PSD) is assumed for water cloud droplets

$$dN/dR = N_0 R^\nu \exp(-\nu \frac{R}{R_0}), \quad (1)$$

where R denotes the droplet radius, R_0 is the modal radius, ν defines the shape of the distribution, and

$$N_0 = \frac{\nu^{\nu+1}}{\Gamma(\nu+1)R_0^{\nu+1}} N_{tot} \quad (2)$$

is a constant with $\Gamma(\nu+1)$ as the gamma function and N_{tot} as the total number of particles per unit volume (Petty and Huang, 2011). The commonly used C1 size distribution (Deirmendjian, 1969), which is defined by Eq. (1) with $R_0=4 \mu\text{m}$ and $\nu=6$, is applied in this study.”

Response to the comments of Reviewer 2

This work addresses a retrieval method of the optical depth of super-thin oceanic clouds using polarization as a theoretical study. This sort of cloud is quite difficult for detection with conventional passive sensors, but the authors had developed a detection method for the clouds using polarization in the previous study, and further proposed a retrieval method. Overall, this paper is well-written and the reviewer recommends the publication after solving the following points.

Answer: The authors of this manuscript greatly thank this reviewer for the helpful and insightful comments.

Specific points: The reviewer wonders how large the retrieval error would be. Could the authors give any sensitivity study within realistic ranges of calibration for PARASOL data?

Answer: Following this comment, we add in the text of Conclusion: “Our sensitivity study shows that for a polarization intensity measurements with ~10% calibration error such as those from the PARASOL 670 nm channel (Fougnie et al., 2007), this algorithm can have ~0.006 uncertainty in the retrieved super-thin cloud OD.”

Could the authors give any validation results using, for example, CALIOP and so on? Is it out of the scope?

Answer: Because “clear sky” between thick clouds over ocean generally are not in very big range in midlatitude and tropical areas, PARASOL’s resolution and acquiring rate have problem to obtain clear-sky data without thick clouds contamination and with densely multi-angle

1 measurements for glory patterns. On the other hand, the CALIOP has serious sunlight
2 contamination during daytime, super-thin cloud measurements from daytime CALIOP have very
3 large errors. It is not reliable to use the current data for validation of this method now.
4 We are proposing a new generation of fast and high-resolution polarimeter and improved lidar
5 technique for solution of this problem.
6

7 **Typographical points: Line 7, Page 21963: ‘term’ should be ‘terms’? Lines 8 and 9, Page**
8 **21969: If two descriptions of Sun et al. (2014) are the same, how about combining them into**
9 **one ‘Sun et al. (2014)’?**

10
11 Answer: These are corrected following this helpful comment.
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14 **Dear Editors: Since the track-change function in my Word**
15 **has some problem, I didn’t use this function but marked the**
16 **changes due to the review comments in green (for reviewer 1**
17 **questions), and red (for reviewer 2 questions). The change**
18 **not required by reviewers is in blue. Thanks for your**
19 **understanding**
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2 **A method to retrieve super-thin cloud optical depth over**
3 **ocean background with polarized sunlight**

4

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Highlights

1. A method for retrieving super-thin-cloud optical depth with polarized light is reported.
2. Near-backscatter p -polarized light is sensitive to clouds, but not to ocean conditions.
3. Near-backscatter p -polarized intensity linearly relates to super-thin cloud optical depth.
4. Super-thin cloud optical depth can be retrieved with little affect from surface reflection.

Abstract

In this work, an algorithm that uses the polarization angle of the backscattered solar radiation to detect clouds with optical depth (OD) $< \sim 0.3$ is further developed. We find that at viewing angles within $\pm \sim 8^\circ$ around the backscattering direction, the p -polarized intensity that is parallel to the meridian plane of reflected light from surface is sensitive to and nearly linearly related to the optical depth of super-thin clouds. Moreover, our sensitivity study suggests that the p -polarized intensity at these viewing angles is not sensitive to the ocean surface conditions. Using this property of p -polarized intensity, super-thin clouds' optical depth can be retrieved.

Key words: Super-thin clouds, detection, polarized sunlight, retrieval of optical depth.

1 Introduction

Super-thin clouds of optical depths smaller than ~ 0.3 cover $\sim 50\%$ of the globe (McFarquhar et al., 2000; Sun et al., 2011b; Sun et al., 2014) and play an important role in the radiation energy balance of the Earth (Dessler and Yang, 2003; Lee et al., 2009; Sun et al., 2011a; Sun et al., 2011b), as well as in the remote sensing of aerosols (Sun et al., 2011b; Omar et al., 2013) and surface temperature (Sun et al., 2011a). [Even a sky overhead that looks very clear and blue can still have “blue” clouds at over 34000 feet altitude \(Packer and Lock, 1951\).](#) These clouds are hard to be detected by space-borne instruments, thus complicate the retrieval of atmospheric constituents (Christi and Stephens, 2004). For example, the NASA Atmospheric CO₂ Observations from Space (ACOS) XCO₂ retrieval algorithm (O’Dell et al., 2012) defines clear-sky scenes for CO₂ retrieval as cases with atmospheric optical depth ≤ 0.3 , which may still have super-thin cloud contamination. When undetected, super-thin clouds can introduce significant bias errors in the atmospheric carbon data measured by the ACOS and by the Orbiting Carbon Observatory 2 (OCO-2) mission (Crisp et al., 2004) due to the scattering of incident light by these clouds. This scattering introduces uncertainties in the optical path length and thus the light absorption by CO₂, from which the CO₂ amount is retrieved. Unfortunately, the variation in surface background reflection means super-thin clouds generally cannot be detected by passive satellite instruments, like the OCO-2 (Crisp et al., 2004), the Moderate Resolution Imaging Spectroradiometer (MODIS) (King et al., 1992), and the Advanced Very High Resolution Radiometer (AVHRR) (Brest and Rossow, 1992), that only measure the total radiance of the reflected solar light (Minnis et al., 2002; Mace et al., 2005; Ackerman et al., 2008). Although many methods have been developed for detecting clouds (Gao and Kaufman, 1995; Wylie et al., 1995; Ackerman et al., 1998; Wylie and Menzel, 1999; Roskovensky and Liou, 2003), most of

1 super-thin clouds are still missing constituents of the atmosphere in satellite data. Lidars on
2 NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Winker
3 et al., 2007) and Cloud-Aerosol Transport System (CATS) missions are the only instruments in
4 orbit that can detect super-thin clouds; however, these only can cover small portions of the
5 atmosphere. Long-term global surveys of super-thin clouds using space-borne lidars are limited
6 by their large operational cost and narrow field of view. Also, noise in the lidar instantaneous
7 measurements can be significant, due to its relatively low transmitted power, range length,
8 narrow field of view, and contamination by sunlight. Although sunlight contamination is not an
9 issue for lidar in nighttime, limited photons from narrow field of view received by lidar sensors
10 still constitute errors for detection of super-thin atmospheric constituents. To identify optically
11 thin atmospheric components such as super-thin clouds, lidar data have to be averaged over a
12 large spatial area to increase the number of photons measured and reduce the overall noise level.
13 This spatial averaging could result in difficulties in using lidar data to study aerosol-cloud
14 interactions in the neighborhood of clouds. The High Spectral Resolution Lidar (HSRL)
15 technique (e.g. Rogers et al., 2011), which takes advantage of the spectral distribution of the lidar
16 return to discriminate aerosol and molecular signals and thereby measure aerosol extinction and
17 backscatter independently, would represent an advancement over the CALIPSO and the CATS
18 measurements, but will also be limited in spatial coverage. Also, the signal-to-noise levels
19 associated with lidar measurements can limit the frequency with which super-thin clouds can be
20 detected. Therefore, improving the space lidar systems and developing an inexpensive passive-
21 remote-sensing method with greater spatial coverage for reliable detection of super-thin clouds
22 have become critical issues for atmospheric remote-sensing practice.

1 In our previous work (Sun et al., 2014), we studied solar radiation backscattered from clouds
2 with both the Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with
3 Observations from a Lidar (PARASOL) (Deschamps et al., 1994) data and an adding-doubling
4 radiative-transfer model (ADRTM) (Sun and Lukashin, 2013). We found that the dominant
5 backscattered electric field from the clear-sky Earth-atmosphere system is nearly parallel to the
6 ocean surface. However, when clouds are present, this electric field can rotate significantly away
7 from the parallel direction. We further discovered that this polarization feature can be used to
8 detect super-thin cirrus clouds having an optical depth of only ~ 0.06 and super-thin liquid water
9 clouds having an optical depth of only ~ 0.01 . Such clouds are too thin to be sensed using any
10 current passive satellite instruments.

11 In this study, we further develop this algorithm not only to find super-thin clouds, but also to
12 retrieve quantitatively their optical depth (OD). Note that this algorithm is developed as a means
13 to remotely sense clouds that cannot be detected by other passive remote-sensing techniques, to
14 help the remote sensing of optically thin atmospheric constituents and sea surface temperature
15 that require clear-sky conditions. Any cases that include thick clouds which can be observed by
16 conventional ways are out of the scope of this study. In Section 2, modeling results
17 supplementary to the work in *Sun et al.* (2014) for the polarization feature of reflected sunlight
18 from clouds are reported. The algorithm for retrieving OD of super-thin clouds with polarized
19 sunlight is introduced in Section 3. We make concluding remarks in Section 4.

20 **2 *P*-polarization Feature of Reflected Sunlight from Clouds**

21 As a complement to the work in *Sun et al.* (2014), we further modeled the angle of linear
22 polarization (AOLP) of reflected sunlight from clouds of different thermodynamic phases,
23 particle shapes, and optical depth, over oceans. In the modeling, the atmosphere including the

cloud and aerosol layers is assumed to be plane-parallel. The cloud is assumed to be a homogeneous single layer over ocean surface. The atmospheric profiles are from the US Standard Atmosphere (1976). The p -polarization feature of the reflected sunlight from clouds is our focus in this study. Note that “ p -polarization” here means that the polarized electric field is parallel to the meridian plane of the reflected light as shown in Figure1 of *Sun and Lukashin* (2013), and it is $\sim 0^\circ/180^\circ$ in terms of the AOLP in this work.

Figure 1 shows the modeled AOLP of reflected sunlight as a function of viewing zenith angle (VZA) and relative azimuth angle (RAZ) at a wavelength of 670 nm from water clouds with different optical depth (OD) over ocean. In the ADRTM modeling, the ocean wind speed is assumed to be 7.5 m/s, the solar zenith angle (SZA) is 29.17° , and the aerosol optical depth (AOD) is 0.06. The modified gamma (MG) particle size distribution (PSD) is assumed for water cloud droplets

$$dN/dR = N_0 R^\nu \exp(-\nu \frac{R}{R_0}), \quad (1)$$

where R denotes the droplet radius, R_0 is the modal radius, ν defines the shape of the distribution, and

$$N_0 = \frac{\nu^{\nu+1}}{\Gamma(\nu+1)R_0^{\nu+1}} N_{tot} \quad (2)$$

is a constant with $\Gamma(\nu+1)$ as the gamma function and N_{tot} as the total number of particles per unit volume (Petty and Huang, 2011). The commonly used C1 size distribution (Deirmendjian, 1969), which is defined by Eq. (1) with $R_0=4 \mu\text{m}$ and $\nu=6$, is applied in this study. The water cloud is within an altitude range of 2-3 km. We can see that the near-backscatter p -polarization feature of the reflected light is evident even when the cloud OD is as small as 0.01. With the increase of the cloud OD, this pattern becomes stronger, and when cloud OD $> \sim 0.5$, it becomes saturated.

1 Therefore, using the near-backscatter p -polarization feature of the reflected light, we can detect
2 any water clouds, including subvisible ones with $OD < 0.03$, over oceans.

3 Figure 2 shows the modeled AOLP of reflected sunlight as a function of VZA and RAZ at a
4 wavelength of 670 nm from cirrus clouds. In the ADRTM modeling, the clouds' ODs are set
5 from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m/s, the SZA is 29.17° , and the
6 AOD is 0.06. The cirrus cloud is within an altitude range of 7-8 km. The size distribution of the
7 ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of
8 -20 to -25°C . The cirrus clouds are assumed to be composed of solid hexagonal column ice
9 crystals with aspect ratios as given in *Fu et al.* (1998). The calculation of the single-scattering
10 properties of the ice crystals is described in *Baum et al.* (2000). We can see that similar to water
11 clouds, cirrus clouds composed of hexagonal column ice crystals reflect sunlight with a
12 significant near-backscatter p -polarization feature even when their OD is only ~ 0.01 . This means
13 that if ice cloud particle shapes are not complex, the clouds can be detected by the near-
14 backscatter p -polarization feature even if it is invisible with respect to standard passive remote
15 sensing techniques. It is known that super-thin cirrus clouds more often appear in the tropical
16 tropopause layer from 14.5 to 18.5 km (Fu et al., 2007; Virts et al., 2010), where the shapes of
17 ice particles are more regular hexagonal columns since they form in-situ due to the large-scale
18 slow uplift. Our results in Fig. 2 shows that these clouds could be well detected by the near-
19 backscatter p -polarization feature of the reflected light. However, when cloud particle shapes are
20 complex, such as a mixture of irregular particle shapes for tropical cirrus clouds as described in
21 *Meyer et al.* (2004), Figure 3 demonstrates that the near-backscatter p -polarization feature can
22 hardly be seen for cloud ODs $< \sim 0.02$. Despite this limitation, the approach should be able to

1 reliably detect ice clouds with a mixture of complex particle shapes when their OD > ~0.06 (Sun
2 et al., 2014).

3 We briefly explained the background physics of the near-backscatter p -polarization feature of
4 reflected sunlight from clouds in *Sun et al.* (2014). To further explain the physics behind the
5 optical phenomenon, we refer to well-known aspects of reflection theory in geometric optics as
6 illustrated in Figure 4. When natural light interacts with a water surface, the reflected field tends
7 to be polarized parallel to the surface (s -polarized) and the transmitted field tends to be polarized
8 within the plane of incidence (p -polarized). This occurs in ray-tracing from large water droplets
9 also, where the internal fields have a tendency to favor the p -polarization state. One
10 manifestation of this can be seen in the glory, which occurs at near-backscattered angles and is p -
11 polarized. If the particle strongly absorbs light, like some aerosols, the refracted light cannot
12 emerge from the particle, and the p -polarization feature is not observed. In addition, if the
13 particle shape/surface is complex, like ice particle aggregates, the refracted light has weaker
14 constructive interference, resulting in a weaker p -polarization feature. As the particle size
15 becomes small, like stratospheric liquid sulfur aerosols, the little phase differences occur
16 between paths within the particle, scattering features become broader, and the glory feature
17 disappears. Furthermore, if the background surface can be characterized by single-scattering
18 facets, like a water surface, the dominant reflected electric field from the surface at the near-
19 backscatter direction is parallel to the surface (i.e., s -polarized to the meridian plane of reflected
20 light) (Sun et al., 2014), thus the p -polarization feature of the reflected light unambiguously
21 indicates the presence of clouds. However, if the ground surface is not single-scattering-
22 dominated, such as needle-leaf trees and grass lands, the electric field of reflected sunlight
23 directly from the surface may not always be parallel to the surface, where the p -polarized light

1 from the multiple-scattering surface introduces uncertainties in the method. Under this condition,
2 the OD must be large for the cloud to be identified unambiguously. For example, our modeling
3 shows that over the desert the OD should be larger than ~ 0.1 for a cloud to be detected by this
4 method. This highlights some limitations of using reflected light's p -polarization feature to
5 detect particulates in the atmosphere.

6 The results reported in *Sun et al.* (2014) and in this section clearly demonstrate that super-thin
7 clouds can be reliably detected by the p -polarization feature of reflected sunlight from them.
8 However, because the AOLP of reflected light (which can be derived from the ratio of polarized
9 intensities Q and U) is not very sensitive to cloud optical depth, we must develop new algorithm
10 for super-thin cloud optical depth's quantitative retrieval.

12 **3 Method for Retrieving Super-thin Cloud Optical Depth**

13 Because of variations in surface reflections and atmospheric profiles, using total reflected
14 intensity to detect super-thin clouds is generally difficult. Remote sensing atmospheric
15 particulates using polarization measurements in the backscattering region can minimize surface,
16 molecule, and absorbing gas interferences, thus increasing the sensitivity to atmospheric
17 particulates, like super-thin clouds (Sun et al., 2014). With super-thin cirrus clouds as an
18 example, the difference between Figs. 5 (a) and (b) from our previous work (Sun et al., 2014)
19 demonstrates that at viewing angles in the neighborhood of the backscattering direction, the
20 clear-sky AOLP of reflected sunlight at a wavelength of $\lambda = 670$ nm can be used to locate super-
21 thin clouds. In this study, we further find that the optical depth of super-thin clouds can be
22 retrieved at viewing angles in the neighborhood of the backscattering direction. Following the
23 previous discussion (Sun et al., 2014), we refer to these regions as the “glory angles” that are

within $\pm 8^\circ$ around the backscattering direction and include the blue and yellow spots in Fig. 5(b). To exclude the effect of background reflection, we will use only the polarized component of the backscattered light parallel to the meridian plane of the reflected light (p -polarized light) for the OD retrieval. Since the clear-sky surface background reflection is only perpendicular to the meridian plane of the reflected light (s -polarized) in the neighborhood of the backscattering direction (Fig. 5(a)), the p -polarized component of the backscattered light is caused by super-thin clouds (Sun et al., 2014). Assuming that the linearly polarized electric field of the reflected light from the Earth-atmosphere system is \mathbf{E}_p , we can express its p -polarized component as (See Fig. 1 in *Sun and Lukashin (2013)*),

$$E_p^\perp = E_p \cos(AOLP). \quad (3)$$

Therefore, the p -polarized reflectance is in the form

$$I_p^\perp = I_p \cos^2(AOLP), \quad (4)$$

where $I_p = \sqrt{Q^2 + U^2}$ denotes the polarized reflectance. For a clear-sky system in which the $AOLP \sim 90^\circ$ at our specific observation direction, $[I_p \cos^2(AOLP)] \sim 0$. In a system containing super-thin clouds or heavy aerosols in which the $AOLP \sim 0^\circ / 180^\circ$ in the observation direction, $[I_p \cos^2(AOLP)] \sim I_p$. At this specific observation direction, the OD can be retrieved from the polarized reflectance and the AOLP as

$$OD = f^{-1}[I_p \cos^2(AOLP)], \quad (5)$$

where $f^{-1}[\]$ denotes an function that will be determined by the OD and $[I_p \cos^2(AOLP)]$ correlation curve from modeling results for various super-thin clouds.

Figure 6 shows the modeled p -polarized reflectance at a wavelength of 670 nm as a function of VZA and at a RAZ of 177° for a clear and super-thin cloud scene over oceans with different wind speeds. In the modeling, the SZA is 29.17° and the AOD is 0.1. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C . The cirrus cloud is assumed to be composed of hexagonal ice columns and is contained within an altitude range of 7-8 km. Results for clear oceans (dotted curves) and oceans with a cirrus layer with an OD of 0.1 (solid curves) are shown. Different colors represent different wind speeds: 2.5 m/s (black), 7.5 m/s (red), and 12.5 m/s (blue). We can see that for clear-sky oceans, $[I_p \cos^2(AOLP)]$ varies with the ocean surface roughness (wind speed) and its magnitude is low. However, when there is a layer of thin cloud over the oceans, at the glory angles, $[I_p \cos^2(AOLP)]$ is about one order of magnitude larger than the clear-sky values and has a very small dependence on the ocean surface conditions. This is very important, since surface conditions can vary widely, and a significant dependence would complicate the OD retrievals. Figure 6 demonstrates that $[I_p \cos^2(AOLP)]$ is a robust quantity to use to retrieve the OD of optically thin clouds regardless of ocean surface conditions.

Figure 7 shows the modeled p -polarized reflectance at a wavelength of 670 nm as a function of VZA and at a RAZ of 177° for super-thin cirrus clouds over oceans with different ODs (solid curves). Also shown in the figure is the result for clear oceans (black dots). In the modeling, the SZA is 29.17° , the wind speed is 7.5 m/s, and the aerosol optical depth (AOD) is 0.1. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C . The midlatitude cirrus cloud is assumed to be composed of a mixture of complex particle shapes as described in *Baum et al.* (2000) and to be within an altitude range of 7-8 km. We can see that with the increase of cloud OD, $[I_p \cos^2(AOLP)]$

systematically increases at the glory angle region. When cloud OD approaches ~ 0.6 , $[I_p \cos^2(AOLP)]$ becomes saturated and it is difficult to differentiate the OD of the respective clouds. Therefore, this OD retrieval method may only work well for thin clouds that have OD $< \sim 0.6$. From the same calculations of Fig. 7, the modeled p -polarized reflectance at 670 nm as a function of cloud optical depth (OD) at a VZA of 28.5° and a RAZ of 177° for super-thin cirrus clouds over oceans is displayed in Fig. 8. We can see that $[I_p \cos^2(AOLP)]$ is nearly linearly related to cloud OD when the cloud OD $< \sim 0.6$. Therefore, based on this type of relationship, super-thin cloud OD can be retrieved from the $[I_p \cos^2(AOLP)]$. The OD and $[I_p \cos^2(AOLP)]$ correlation curve in Fig. 8 is just an example of the $f^{-1}[]$ in Eq. (5).

Since this algorithm uses near-backscatter polarized reflectance for retrieval of cloud optical depth, obviously it is sensitive to cloud thermodynamic phase or particle size and shape if the cloud is cirrus or mixed-phase cloud. Thus, $[I_p \cos^2(AOLP)]$ must be some function of ice-cloud particle size and shape, or liquid water cloud size distribution. Reliably detecting the thermodynamic phase of the clouds is a prerequisite for a good retrieval using this method. Using the oxygen A-band (759–770 nm) (Min et al., 2014) $[I_p \cos^2(AOLP)]$ to estimate the altitude of the clouds could help to determine the cloud thermodynamic phase. On the other hand, a detailed study of the effects of particle size and shape of the clouds on the polarized reflectance from them is also necessary in the application of this method. As an example, Figure 9 shows the modeled p -polarized reflectance at a wavelength of 670 nm as a function of VZA and at a RAZ of 177° for super-thin cirrus clouds over oceans with different ODs. In the modeling, the SZA is 29.17° , the wind speed is 7.5 m/s, and the AOD is 0.06. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -

25°C. The cirrus clouds are assumed to be within an altitude range of 7-8 km and composed of mixtures of complex particle shapes for typical midlatitude cirrus clouds as described in *Baum et al.* (2000) (open circles) and tropical cirrus clouds as described in *Meyer et al.* (2004) (solid curves), respectively. It can be seen that different mixtures of ice cloud particle shapes can result in different $[I_p \cos^2(AOLP)]$. This can cause an uncertainty of ~ 0.05 in the retrieved cloud OD.

It is worth noting here that in Figs. 6, 7, and 9, for each case of the p -polarized reflectance curves of clouds, at the boundary of the glory angle region $[I_p \cos^2(AOLP)]$ drastically dips to very small value and our angular discretization in the modeling sometimes misses capturing the lowest point. A plausible explanation for this phenomenon is that it is the transitional region between backscattered p -polarized rays from the particles and the s -polarized rays from the surface, where surface background s -polarized reflectance cancels p -polarized reflectance from clouds, thus p -polarized light is nearly zero and AOLP is close to 90° , so $I_p \cos^2(AOLP)$ can be very small.

4 Conclusion

In summary, our previous studies with the PARASOL satellite data and the ADRTM results in *Sun et al.* (2014) and in this work show that the AOLP of scattered sunlight observed in two distinct angular glory regions near the exact-backscatter direction can be used to detect water clouds having an OD of only ~ 0.01 and ice clouds having an OD of only ~ 0.06 . In this paper, we show that the p -polarized reflectance $[I_p \cos^2(AOLP)]$ at near-backscatter viewing angles can be used for the retrieval of the optical depth of super-thin clouds, with little affect from ocean surface conditions. Our sensitivity study shows that for a polarization intensity measurements with $\sim 10\%$ calibration error such as those from the PARASOL 670 nm channel (Fougnie et al.,

2007), this algorithm can have ~ 0.006 uncertainty in the retrieved super-thin cloud OD. This is a robust algorithm, which could be used to conduct inexpensive surveys for super-thin clouds over mid-latitude and tropical areas, where most super-thin clouds exist (Sun et al., 2011b). However, as an algorithm based on a low-cost passive instrument measuring reflected solar light, it has difficulties in detecting super-thin clouds over thick clouds, since the thick clouds' glory pattern is much stronger than that of super-thin clouds. For those multilayer cases, this method can only tell there are thick clouds in the scene. Moreover, since glory pattern is a special optical phenomenon of transparent cloud droplets or ice crystals, this algorithm is not sensitive to background aerosols that coexist with super-thin clouds. However, heavy aerosols ($OD > 0.2$) can cause electric field on the principal plane not parallel to the ocean surface at viewing zenith angles smaller than the backscattering angle, which will result in some ambiguities for retrieval, but they cannot produce the full glory pattern as shown in Figs. 1-3, i.e. electric fields in all radial directions around the backscattering direction. Also, as a method based on measurements of reflected sunlight, this algorithm obviously cannot work at night. However, it is important to note that our studies suggest, based on Raman lidar data, that super-thin clouds differ little between day and night, because of their insignificant absorption to solar radiation. Active instruments such as space-borne lidars can work during both day and night and can measure cloud/aerosol altitude, but their swath width is narrow though they produce profiles along the satellite track. In addition, the limited number of photons acquired from space-borne lidars, reduces signal-to-noise level and can introduce errors in their measured data. Thus, both passive and active instrument techniques have their advantages and disadvantages; exploring innovative algorithms to make greater use of existing passive remote-sensing instruments and to complement active remote-sensing instruments is an obvious benefit. The insights gained from

identifying super-thin clouds can have significant impact on surface and atmospheric constituents remote sensing and shed greater light on the role clouds play in the larger Earth-atmosphere system.

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References

1. Ackerman, S.A., Strabala, K.I., Menzel, W.P., Frey, R.A., Moeller, C.C., and Gumley, L.E.: Discriminating clear sky from clouds with MODIS, *J. Geophys. Res.*, 103, 32141-32157, doi: 10.1029/1998JD200032, 1998.
2. Ackerman, S.A., Holz, R.E., Frey, R., Eloranta, E.W., Maddux, B.C., and McGill, M.: Cloud detection with MODIS. Part II: Validation, *J. Atmos. Oceanic Technol.*, 25, 1073-1086, doi:10.1175/2007JTECHA1053.1, 2008.
3. Baum, B.A., Kratz, D.P., Yang, P., Ou, S.C., Hu, Y., Soulen, P.F., and Tsay, S.C.: Remote sensing of cloud properties using MODIS airborne simulator imagery during SUCCESS. I. Data and models, *J. Geophys. Res.*, 105, 11,767-11,780, 2000.
4. Brest, C.L. and Rossow, W.B.: Radiometric calibration and monitoring of NOAA AVHRR data for ISCCP, *International J. Remote Sens.*, 13, 235-273, 1992.
5. Christi, M.J. and Stephens, G.L.: Retrieving profiles of atmospheric CO₂ in clear sky and in the presence of thin cloud using spectroscopy from the near and thermal infrared: A

- preliminary case study, J. Geophys. Res., 109, D04316, doi: 10.1029/2003JD004058, 2004.
6. Crisp, D., Atlas, R.M., Breon, F.-M., Brown, L.R., Burrows, J.P., Ciais, P., Connor, B.J., Doney, S.C., Fung, I.Y., Jacob, D.J., Miller, C.E., O'Brien, D., Pawson, S., Randerson, J.T., Rayner, P., Salawitch, R.J., Sander, S.P., Sen, B., Stephens, G.L., Tans, P.P., Toon, G.C., Wennberg, P.O., Wofsy, S.C., Yung, Y.L., Kuang, Z., Chudasama, B., Sprague, G., Weiss, B., Pollock, R., Kenyon, D., and Schroll, S.: The orbiting carbon observatory (OCO) mission, Adv. Space Res., 34, 700-709, 2004.
7. Deirmendjian, D.: *Electromagnetic scattering on spherical polydispersions*, American Elsevier Publishing Company, Inc., New York, 1969.
8. Deschamps, P.Y., Breon, F.-M., Leroy, M., Podaire, A., Bricaud, A., Buriez, J.-C., and Seze, G.: The POLDER mission: Instrument characteristics and scientific objectives, IEEE Trans. Geosc. Rem. Sens., 32, 598-615, 1994.
9. Dessler, A.E. and Yang, P.: The distribution of tropical thin cirrus clouds inferred from Terra MODIS data, J. Climate, 16, 1241-1247, 2003.
10. Fougnie, B., Bracco, G., Lafrance, B., Ruffel, C., Hagolle, O., and Tinel C. : PARASOL in-flight calibration and performance, Appl. Opt., 46, 5435-5451, 2007.
11. Fu, Q., Yang, P., and Sun, W.: An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models, J. Climate, 11, 2223-2237, 1998
12. Fu, Q., Hu, Y.X., and Yang, Q.: Identifying the top of the tropical tropopause layer from vertical mass flux analysis and CALIPSO lidar cloud observations, Geophys. Res. Lett., 34, L14813, doi: 10.1029/2007GL030099, 2007.

- 1 13. Gao, B.C. and Kaufman, Y.J.: Selection of 1.375- μm MODIS channel for remote sensing
2 of cirrus clouds and stratospheric aerosols from space, *J. Atmos. Sci.*, 52, 4231-4237,
3 1995.
- 4 14. Heymsfield, A.J. and Platt, C.M.R.: A parameterization of the particle size spectrum of
5 ice clouds in terms of the ambient temperature and the ice water content, *J. Atmos. Sci.*,
6 41, 846-855, 1984.
- 7 15. King, M.D., Kaufman, Y.J., Menzel, W.P., and Tanre, D.: Remote-sensing of cloud,
8 aerosol, and water-vapor properties from the moderate resolution imaging spectrometer
9 (MODIS), *IEEE Transact. Geosci. Remote Sens.*, 30, 2-27, 1992.
- 10 16. Lee, J., Yang, P., Dessler, A.E., Gao, B.C., and Platnick, S.: Distribution and radiative
11 forcing of tropical thin cirrus clouds, *J. Atmos. Sci.*, 66, 3721-3731, 2009.
- 12 17. Mace, G.G., Zhang, Y., Platnick, S., King, M.D., Minnis, P., and Yang, P.: Evaluation of
13 cirrus cloud properties from MODIS radiances using cloud properties derived from
14 ground-based data collected at the ARM SGP site, *J. Appl. Meteorol.*, 44, 221-240, 2005.
- 15 18. McFarquhar, G.M., Heymsfield, A.J., Spinhirne, J., and Hart, B.: Thin and subvisual
16 tropopause tropical cirrus: Observations and radiative impacts, *J. Atmos. Sci.*, 57, 1841-
17 1853, 2000.
- 18 19. Meyer, K., Yang, P., and Gao, B.C.: Optical thickness of tropical cirrus clouds derived
19 from the MODIS 0.66- and 1.375- μm channels, *IEEE Transact. Geosci. Remote Sens.*,
20 42, 833-841, 2004.
- 21 20. Min, Q., Yin, B., Li, S., Berndt, J., Harrison, L., Joseph, E., Duan, M., and Kiedron, P.: A
22 high-resolution oxygen A-band spectrometer (HABS) and its radiation closure, *Atmos.*
23 *Meas. Tech.*, 7, 1711–1722, doi: 10.5194/amt-7-1711-2014, 2014.

- 1 21. Minnis, P., Young, D.F., Weilicki, B.A., Sun-Mack, S., Trepte, Q.Z., Chen, Y., Heck,
2 P.W., and Dong, X.: A global cloud database from VIRS and MODIS for CERES, Proc.
3 SPIE 3rd Intl. Asia-Pacific Environ. Remote Sensing Symp. 2002: Remote Sens. of
4 Atmosphere, Ocean, Environment, and Space, Hangzhou, China, October 23-27, 4891,
5 115-126 (2002).
- 6 22. National Oceanic and Atmospheric Administration, National Aeronautics and Space
7 Administration, and United States Air Force: *U.S. Standard Atmosphere*, NOAA-S/T 76-
8 1562, 1976.
- 9 23. Omar, A.H., Winker, D.M., Tackett, J.L., Giles, D.M., Kar, J., Liu, Z., Vaughan, M.A.,
10 Powell, K.A., and Trepte, C.R.: CALIOP and AERONET aerosol optical depth
11 comparisons: One size fits none, *J. Geophys. Res.*, 118: 4748-66,
12 doi: 10.1002/jgrd.50330, 2013.
- 13 24. O'Dell, C.W., Connor, B., Bosch, H., O'Brien, D., Frankenberg, C., Castano, R.,
14 Christi, M., Eldering, D., Fisher, B., Gunson, M. McDuffie, J., Miller, C.E., Natraj, V.,
15 Oyafuso, F., Polonsky, I., Smyth, M., Taylor, T., Toon, G.C., Wennberg, P.O., and
16 Wunch, D.: The ACOS CO₂ retrieval algorithm – Part 1: Description and validation
17 against synthetic observations, *Atmos. Meas. Tech.*, 5, 99–121, [www.atmos-meas-](http://www.atmos-meas-tech.net/5/99/2012/)
18 [tech.net/5/99/2012/](http://www.atmos-meas-tech.net/5/99/2012/) doi:10.5194/amt-5-99-2012, 2012.
- 19 25. Packer, D. M., and Lock, C. : The brightness and polarization of the daylight sky at
20 altitudes of 18,000 to 38,000 feet above sea level, *J. Opt. Soc. Amer.*, 41, 473-478, 1951.
- 21 26. Petty, G.W., and Huang, W.: The modified gamma size distribution applied to
22 inhomogeneous and nonspherical particles: Key relationships and conversions, *J. Atmos.*
23 *Sci.*, 68, 1460-1473, 2011.

27. Rogers, R.R., Hostetler, C.A., Hair, J.W., Ferrare, R.A., Liu, Z., Obland, M.D., Harper, D.B., Cook, A. L., Powell, K.A., Vaughan, M.A., and Winker, D. M.: Assessment of the CALIPSO lidar 532 nm attenuated backscatter calibration using the NASA LaRC airborne High Spectral Resolution Lidar, *Atmos. Chem. Phys.*, 11, 1295-1311, doi:10.5194/acp-11-1295-2011, 2011.
28. Roskovensky, J.K. and Liou, K.N.: Detection of thin cirrus from 1.38 μm /0.65 μm reflectance ratio combined with 8.6–11 μm brightness temperature difference, *Geophys. Res. Lett.*, 30, 1985, doi: 10.1029/2003GL018135, 2003.
29. Sun, W., Lin, B., Hu, Y., Lukashin, C., Kato, S., and Liu, Z.: On the consistency of CERES longwave flux and AIRS temperature and humidity profiles, *J. Geophys. Res.*, 116, D17101, doi: 10.1029/2011JD016153, 2011a.
30. Sun, W., Videen, G., Kato, S., Lin, B., Lukashin, C., and Hu, Y.: A study of subvisual clouds and their radiation effect with a synergy of CERES, MODIS, CALIPSO, and AIRS data, *J. Geophys. Res.*, 116, D22207, doi: 10.1029/2011JD016422, 2011b
31. Sun, W. and Lukashin, C.: Modeling polarized solar radiation from ocean-atmosphere system for CLARREO inter-calibration applications, *Atmos. Chem. Phys.*, 13, 10303-10324, doi: 10.5194/acp-13-10303-2103, 2013.
32. Sun, W., Videen, G., and Mishchenko, M.I.: Detecting super-thin clouds with polarized sunlight, *Geophys. Res. Lett.*, 41, 688-693, doi: 10.1002/2013GL058840, 2014.
33. Virts, K.S., Wallace, J.M., Fu, Q., and Ackerman, T.P.: Tropical tropopause transition layer cirrus as represented by CALIPSO lidar observations, *J. Atmos. Sci.*, 67, 3113-3129, 2010.

- 1 34. Winker, D.M., Hunt, W.H., and McGill, M.J.: Initial performance assessment of
2 CALIOP, *Geophys. Res. Lett.*, 34, L19803, doi: 10.1029/2007GL030135, 2007.
- 3 35. Wylie, D.P., Piironen, P., Wolf, W., and Eloranta, E.: Understanding satellite cirrus cloud
4 climatologies with calibrated lidar optical depths, *J. Atmos. Sci.*, 52, 4327-4343, 1995.
- 5 36. Wylie, D.P. and Menzel, W.P.: Eight years of high cloud statistics using HIRS, *J.*
6 *Climate*, 12, 170–184, 1999.

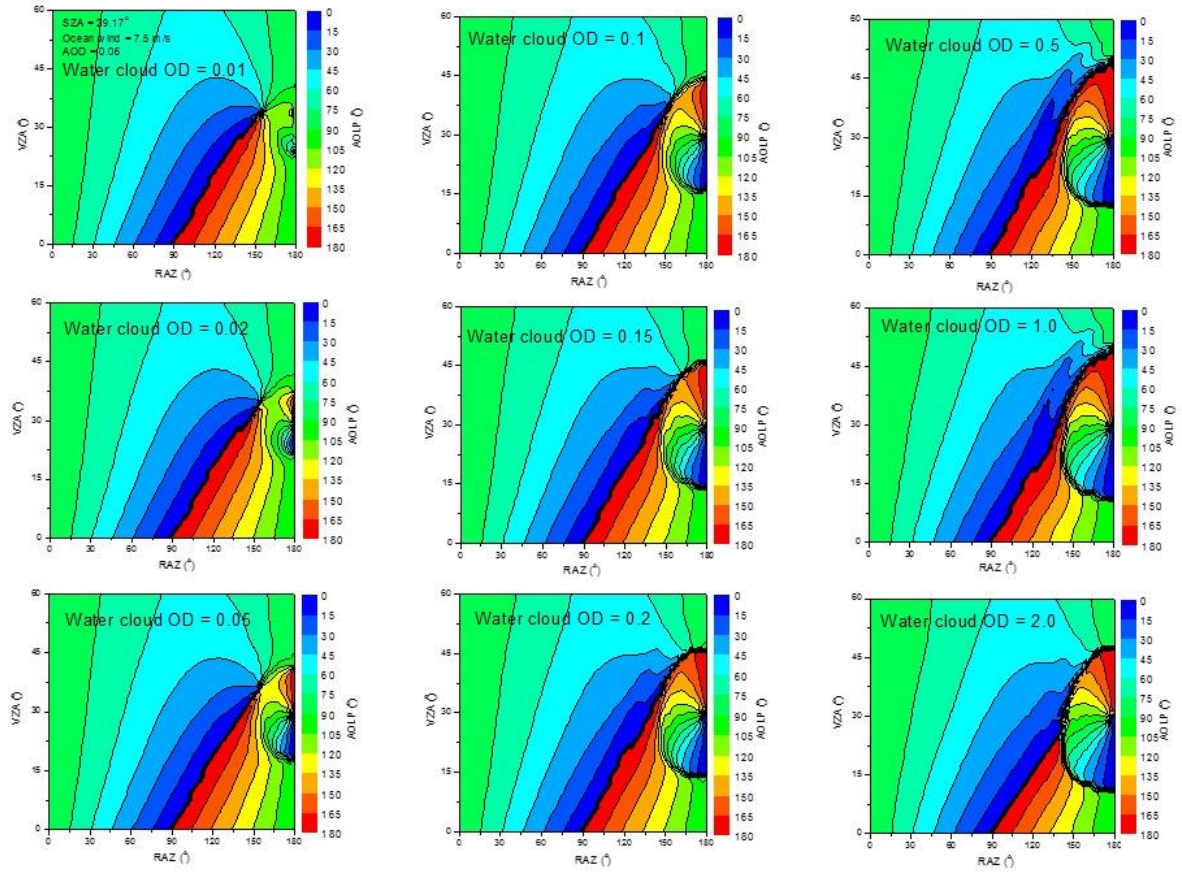


Figure 1. The angle of linear polarization (AOLP) of reflected sunlight at 670 nm from water clouds showing that even clouds with optical depths (OD) of 0.01 exhibit the near-backscatter *p*-polarization feature. In the ADRTM modeling, the clouds' ODs are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m/s, the solar zenith angle (SZA) is 29.17°, and the aerosol optical depth (AOD) is 0.06. The C1 size distribution (Deirmendjian, 1969) is used for water cloud droplets.

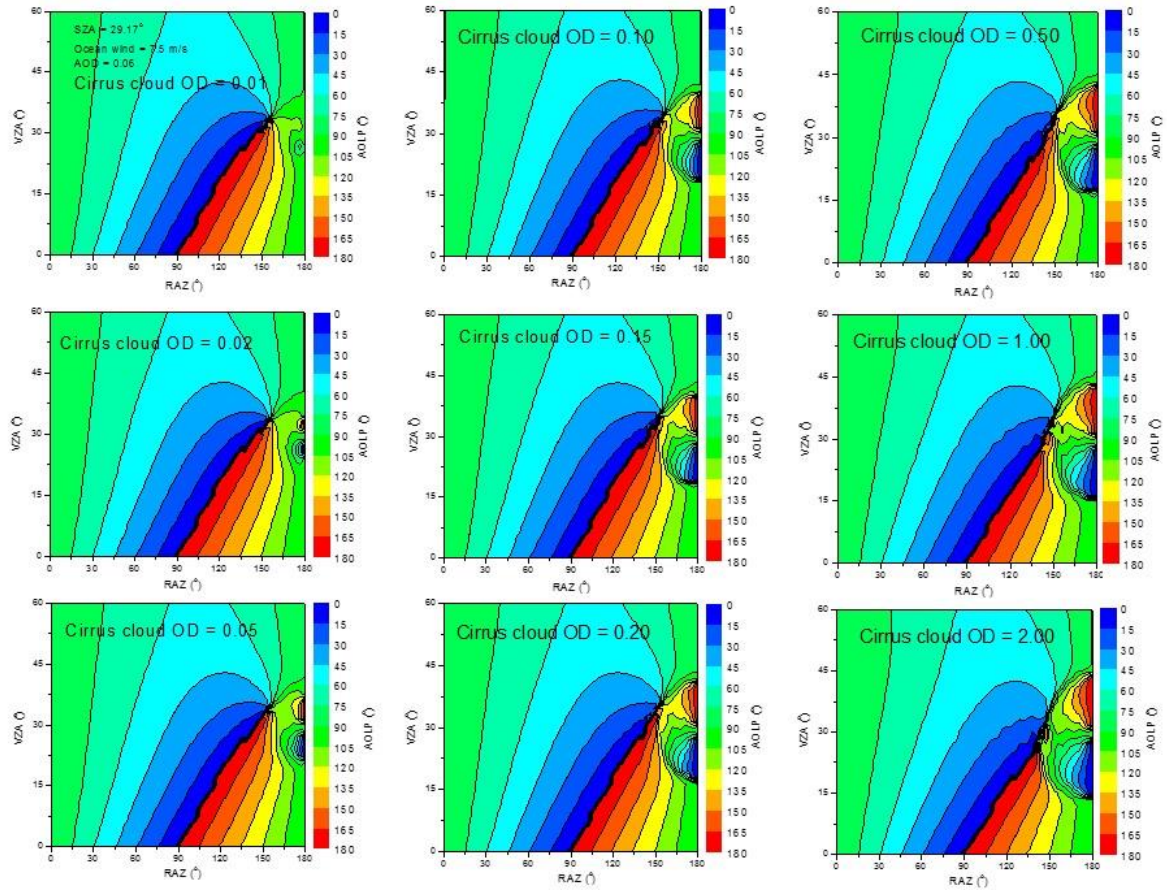


Figure 2. The modeled AOLP of reflected sunlight at a wavelength of 670 nm from cirrus clouds (hexagonal column particle shapes). In the ADRTM modeling, the clouds' optical depths (OD) are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m/s, the solar zenith angle (SZA) is 29.17°, and the aerosol optical depth (AOD) is 0.06. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C. The cirrus clouds are assumed to be composed of solid hexagonal column ice crystals with aspect ratios as given in *Fu et al.* (1998). Similar to water clouds, cirrus clouds composed of hexagonal column ice crystals exhibit the *p*-polarization feature even when their OD is ~0.01

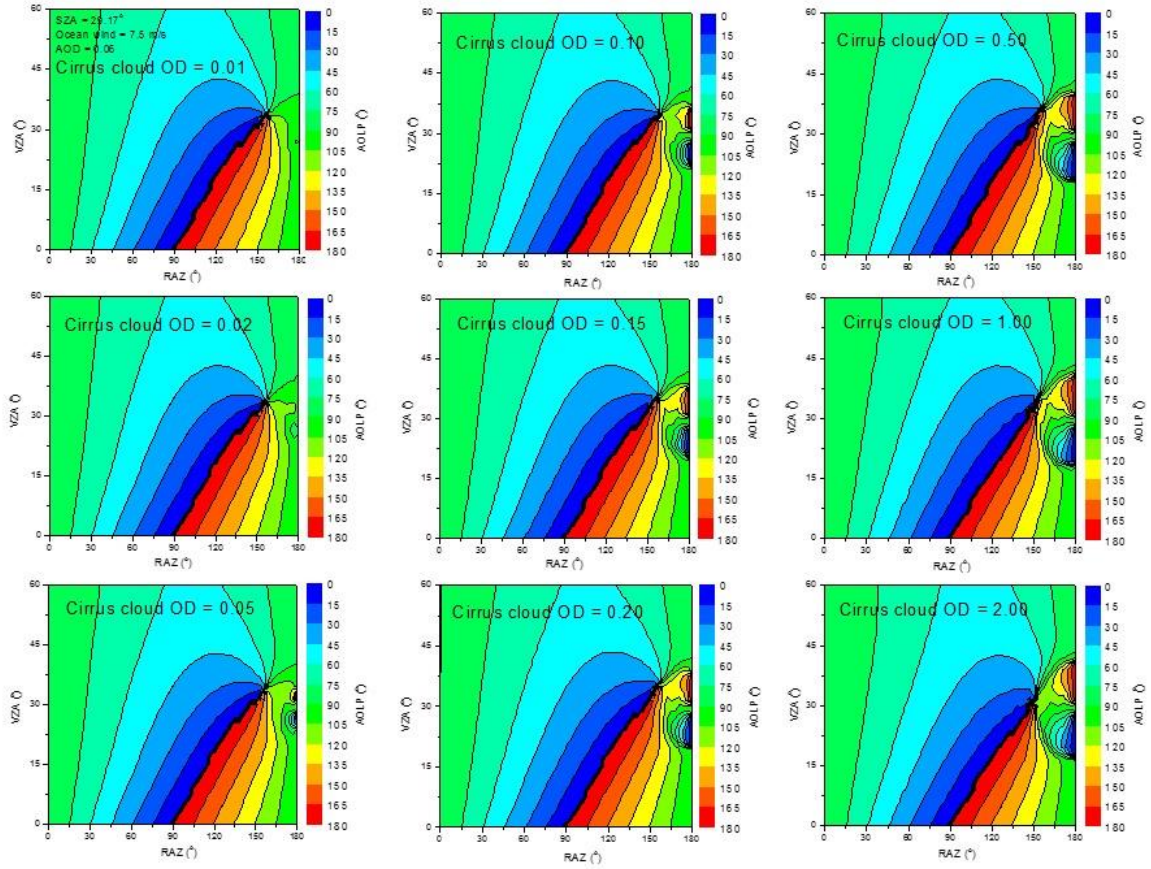


Figure 3. The modeled AOLP of reflected sunlight at a wavelength of 670 nm from cirrus clouds (complex particle shapes). In the ADRTM modeling, the clouds' optical depths (OD) are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m/s, the solar zenith angle (SZA) is 29.17°, and the aerosol optical depth (AOD) is 0.06. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C. The cirrus clouds are assumed to be composed of a mixture of complex particle shapes for tropical cirrus clouds as described in *Meyer et al.* (2004). Cirrus clouds composed of complex particle shapes crystals exhibit the *p*-polarization feature when their OD is >0.06.

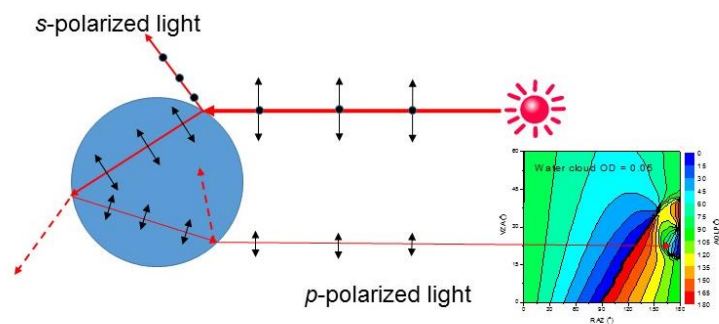


Figure 4. Illustration of the physics for the near-backscatter p -polarization feature of the reflected light from clouds.

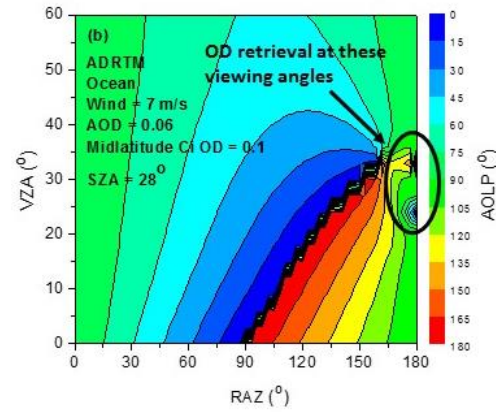
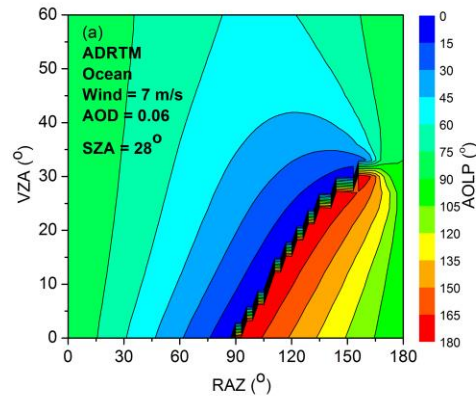


Figure 5. The modeled AOLP at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and relative azimuth angle (RAZ) from (a) the ADRTM for clear-sky oceans and (b) the ADRTM for oceans with a layer of super-thin clouds. In the modeling, the solar zenith angle (SZA) is 28° , ocean wind speed is 7 m/s, the sea-salt aerosol optical depth (AOD) is 0.06, and a layer of midlatitude cirrus cloud with an optical depth of 0.1 is assumed with an altitude range of 7-8 km. The difference of Fig. 5(a) and 5(b) shows the effect of super-thin clouds on the reflected sunlight's AOLP. This figure is reproduced from *Sun et al. (2014)*.

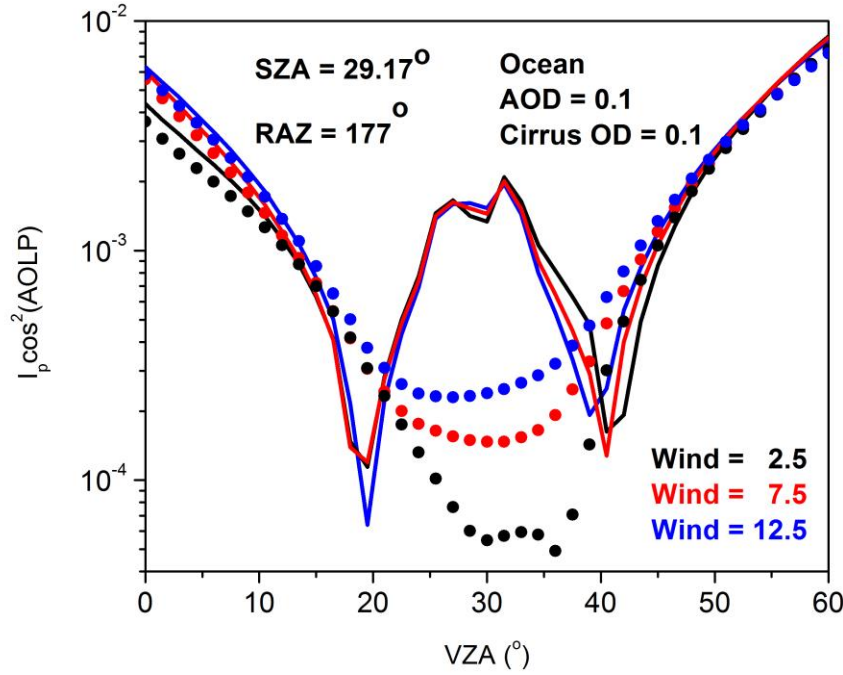


Figure 6. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for clear and super-thin clouds over oceans with different wind speeds. In the modeling, the solar zenith angle (SZA) is 29.17° , and the aerosol optical depth (AOD) is 0.1. Results for clear oceans (dots) and oceans with a cirrus layer with an optical depth (OD) of 0.1 (solid curves) are shown. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C . The cirrus clouds are assumed to be composed of hexagonal ice columns with aspect ratios as given in *Fu et al.* (1998).

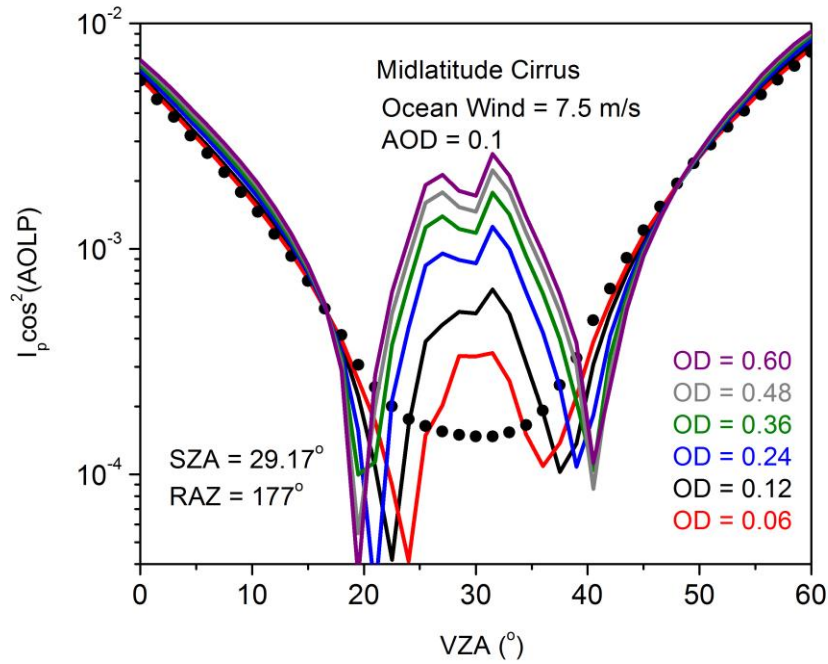


Figure 7. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans with different optical depth (OD) (solid curves). Also shown in the figure is the result for clear oceans (black dots). In the modeling, the solar zenith angle (SZA) is 29.17°, the wind speed is 7.5 m/s, and the aerosol optical depth (AOD) is 0.1. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C. The midlatitude cirrus clouds are composed of a mixture of complex particle shapes as described in *Baum et al.* (2000). These results suggest that the OD retrieval method may only work well for thin clouds which have $OD < \sim 0.6$.

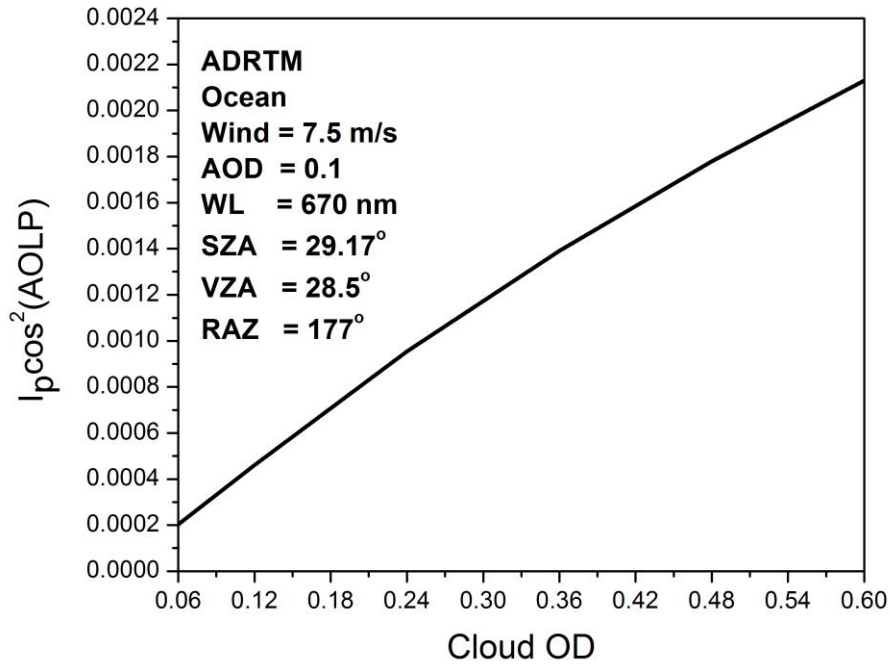


Figure 8. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of cloud optical depth (OD) at a viewing zenith angle (VZA) of 28.5° and a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans. The solar zenith angle (SZA) is 29.17°, the wind speed is 7.5 m/s, and the aerosol optical depth (AOD) is 0.1. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C. The midlatitude cirrus clouds are composed of a mixture of complex particle shapes as described in *Baum et al.* (2000). This figure shows the nearly linearly relationship between cloud OD and AOLP for OD < 0.6.

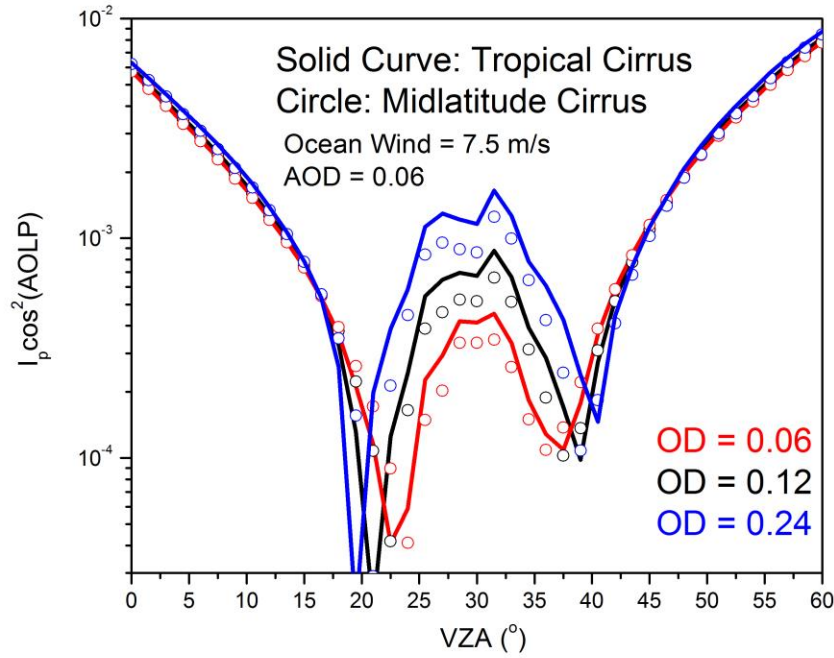


Figure 9. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans with different optical depth (OD). In the modeling, the solar zenith angle (SZA) is 29.17° , the wind speed is 7.5 m/s, and the aerosol optical depth (AOD) is 0.06. The size distribution of the ice particles in the cirrus clouds is from *Heymsfield and Platt* (1984) for the cloud temperature of -20 to -25°C . The clouds are composed of mixtures of complex particle shapes for typical midlatitude cirrus clouds as described in *Baum et al.* (2000) (open circles) and tropical cirrus clouds as described in *Meyer et al.* (2004) (solid curves), respectively. This illustrates that with inadequate knowledge of cloud particle shapes uncertainties of up to ~ 0.05 in the retrieved cloud OD can be obtained.