

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.

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, 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, b), as well as in the remote sensing of aerosols (Sun et al., 2011b; Omar et al., 2013) and surface temperature (Sun et al., 2011a). 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

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

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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 Fig. 1 of Sun and Lukashin (2013), and it is $\sim 0^\circ/180^\circ$ in term 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 ms^{-1} , 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. 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. Therefore, using the near-backscatter p -polarization feature of the reflected light, we can detect any water clouds, including subvisible ones with OD < 0.03 , over oceans.

Figure 2 shows the modeled AOLP of reflected sunlight as a function of VZA and RAZ at a wavelength of 670 nm from cirrus clouds. 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 ms^{-1} , the SZA is 29.17° , and the AOD is 0.06. The cirrus cloud is within an altitude range of 7–8 km. 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). The calculation of the single-scattering properties of the ice crystals is described in Baum et al. (2000). We can see that similar to water clouds, cirrus clouds composed of hexagonal column ice crystals reflect sunlight with a significant near-backscatter p -polarization feature even when their OD is only ~ 0.01 . This means that

if ice cloud particle shapes are not complex, the clouds can be detected by the near-backscatter p -polarization feature even if it is invisible with respect to standard passive remote sensing techniques. It is known that super-thin cirrus clouds more often appear in the tropical tropopause layer from 14.5 to 18.5 km (Fu et al., 2007; Virts et al., 2010), where the shapes of ice particles are more regular hexagonal columns since they form in-situ due to the large-scale slow uplift. Our results in Fig. 2 shows that these clouds could be well detected by the near-backscatter p -polarization feature of the reflected light. However, when cloud particle shapes are complex, such as a mixture of irregular particle shapes for tropical cirrus clouds as described in Meyer et al. (2004), Fig. 3 demonstrates that the near-backscatter p -polarization feature can hardly be seen for cloud ODs $< \sim 0.02$. Despite this limitation, the approach should be able to reliably detect ice clouds with a mixture of complex particle shapes when their OD $> \sim 0.06$ (Sun et al., 2014).

We briefly explained the background physics of the near-backscatter p -polarization feature of reflected sunlight from clouds in Sun et al. (2014). To further explain the physics behind the optical phenomenon, we refer to well-known aspects of reflection theory in geometric optics as illustrated in Fig. 4. When natural light interacts with a water surface, the reflected field tends to be polarized parallel to the surface (s -polarized) and the transmitted field tends to be polarized within the plane of incidence (p -polarized). This occurs in ray-tracing from large water droplets also, where the internal fields have a tendency to favor the p -polarization state. 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. In addition, if the particle shape/surface is complex, like ice particle aggregates, the refracted light has weaker constructive interference, resulting in a weaker p -polarization feature. As the particle size becomes small, like stratospheric liquid sulfur aerosols, the little phase differences occur between paths within the particle, scattering features become broader, and the glory feature disappears. Furthermore, if the background sur-

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a wavelength of $\lambda = 670$ nm can be used to locate super-thin clouds. In this study, we further find that the optical depth of super-thin clouds can be retrieved at viewing angles in the neighborhood of the backscattering direction. Following the previous discussion (Sun et al., 2014), we refer to these regions as the “glory angles” that are within $\pm \sim 8^\circ$ around the backscattering direction and include the blue and yellow spots in Fig. 5b. 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. 5a), 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 E_p , we can express its p -polarized component as (see Fig. 1 in Sun and Lukashin, 2013),

$$E_p^\perp = E_p \cos(\text{AOLP}). \quad (1)$$

Therefore, the p -polarized reflectance is in the form

$$I_p^\perp = I_p \cos^2(\text{AOLP}), \quad (2)$$

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, $[I_p \cos^2(\text{AOLP})] \sim 0$. In a system containing super-thin clouds or heavy aerosols in which the AOLP $\sim 0^\circ/180^\circ$ in the observation direction, $[I_p \cos^2(\text{AOLP})] \sim I_p$. At this specific observation direction, the OD can be retrieved from the polarized reflectance and the AOLP as

$$\text{OD} = f^{-1} \left[I_p \cos^2(\text{AOLP}) \right], \quad (3)$$

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

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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 ms^{-1} (black), 7.5 ms^{-1} (red), and 12.5 ms^{-1} (blue). We can see that for clear-sky oceans, $[I_p \cos^2(\text{AOLP})]$ 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, $[I_p \cos^2(\text{AOLP})]$ 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 $[I_p \cos^2(\text{AOLP})]$ 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 ms^{-1} , 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, $[I_p \cos^2(\text{AOLP})]$ systematically increases at the glory angle region. When cloud OD approaches ~ 0.6 , $[I_p \cos^2(\text{AOLP})]$ 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 $\text{OD} < \sim 0.6$. From

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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 $[I_p \cos^2(\text{AOLP})]$ 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 $[I_p \cos^2(\text{AOLP})]$. The OD and $[I_p \cos^2(\text{AOLP})]$ correlation curve in Fig. 8 is just an example of the $f^{-1}[\]$ in Eq. (3).

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, $[I_p \cos^2(\text{AOLP})]$ 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) $[I_p \cos^2(\text{AOLP})]$ 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, Fig. 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 ms^{-1} , 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 $[I_p \cos^2(\text{AOLP})]$. 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 $[I_p \cos^2(\text{AOLP})]$

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 $I_p \cos^2(\text{AOLP})$ can be very small.

4 Conclusions

In summary, our previous studies with the PARASOL satellite data in Sun et al. (2014) 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 [$I_p \cos^2(\text{AOLP})$] 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. 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, obviously it 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 and produces 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; however, exploring innovative algorithms to make greater use of existing passive remote-sensing instruments and to complement

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active remote-sensing instruments is an obvious benefit. Moreover, 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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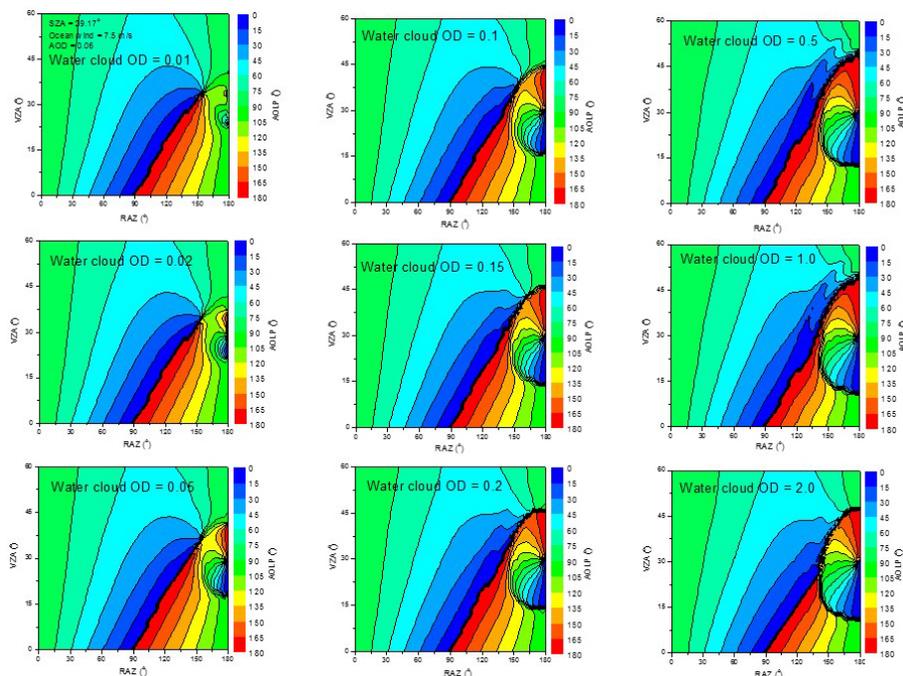


Figure 1. The angle of linear polarization (AOLP) of reflected sunlight at 670 nm from water clouds showing that even clouds with optical depths (OD) of 0.01 exhibit the near-backscatter p -polarization feature. In the ADRTM modeling, the clouds' ODs are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m s^{-1} , 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.

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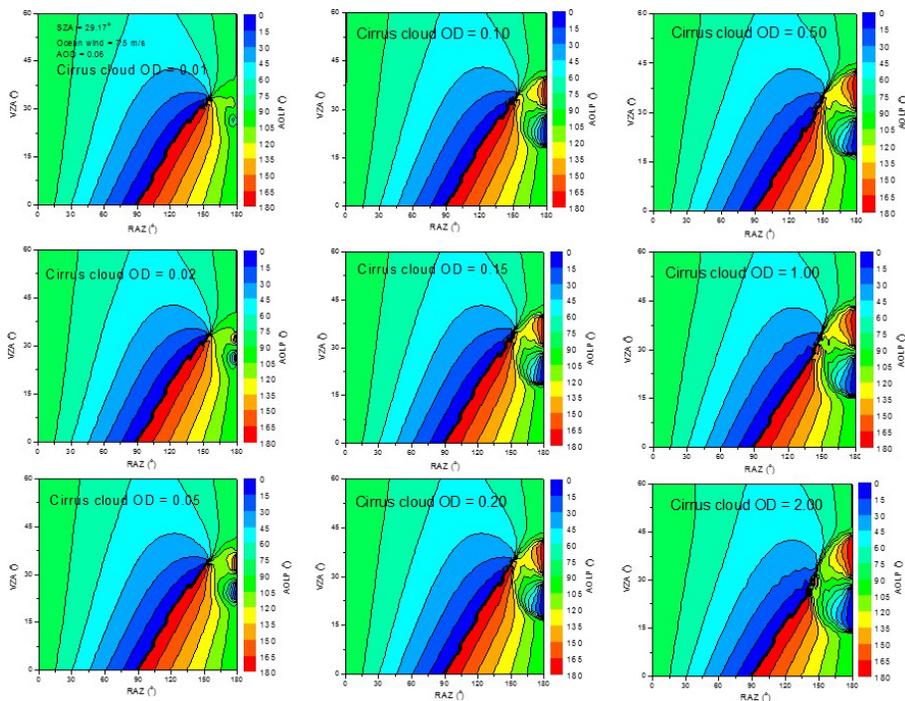


Figure 2. The modeled AOLP of reflected sunlight at a wavelength of 670 nm from cirrus clouds (hexagonal column particle shapes). In the ADRTM modeling, the clouds' optical depths (OD) are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 m s^{-1} , the solar zenith angle (SZA) is 29.17° , 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 .

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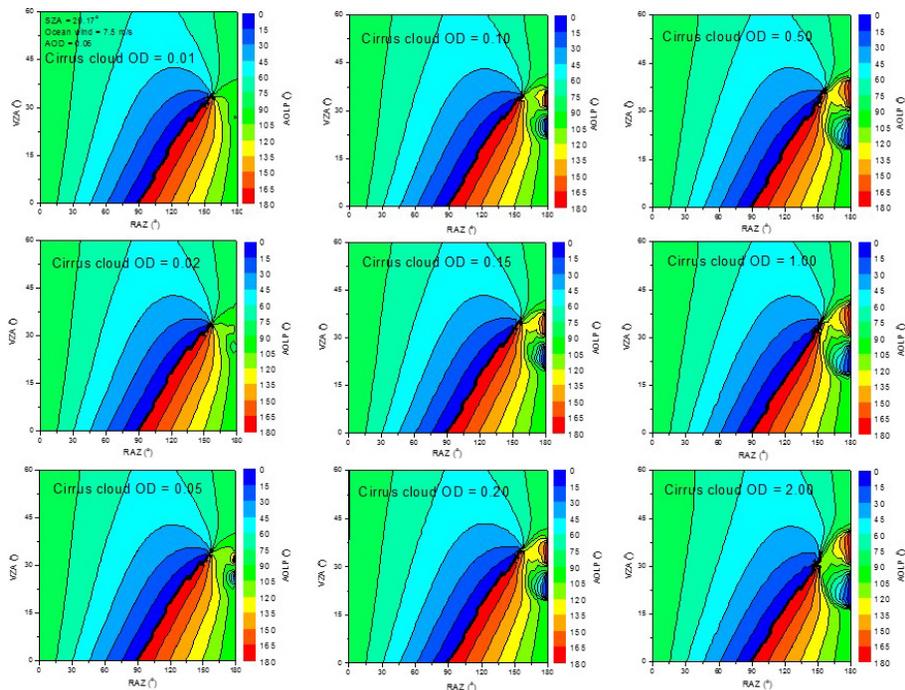


Figure 3. The modeled AOLP of reflected sunlight at a wavelength of 670 nm from cirrus clouds (complex particle shapes). In the ADRTM modeling, the clouds' optical depths (OD) are set from 0.01 to 2.0, the ocean wind speed is assumed to be 7.5 ms^{-1} , the solar zenith angle (SZA) is 29.17° , and the 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 .

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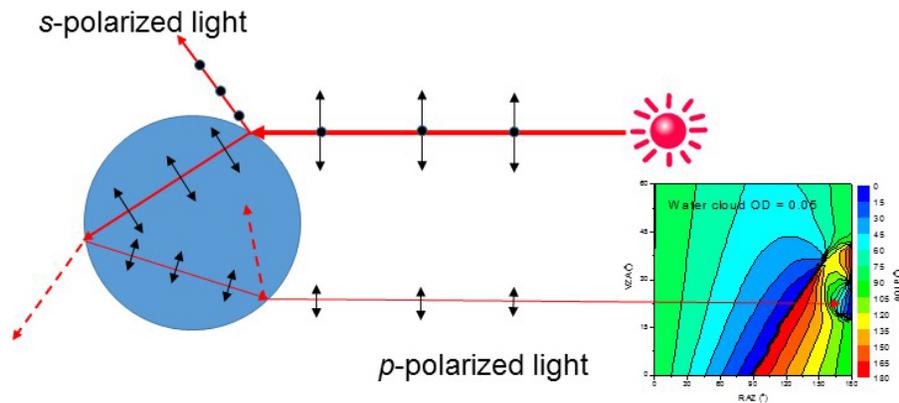


Figure 4. Illustration of the physics for the near-backscatter p -polarization feature of the reflected light from clouds.

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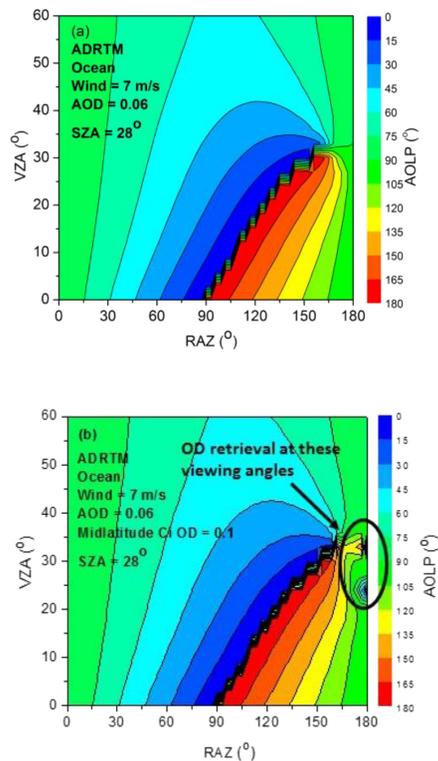


Figure 5. The modeled AOLP at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and relative azimuth angle (RAZ) from **(a)** the ADRTM for clear-sky oceans and **(b)** the ADRTM for oceans with a layer of super-thin clouds. In the modeling, the solar zenith angle (SZA) is 28°, ocean wind speed is 7 ms⁻¹, 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 **(a)** and **(b)** shows the effect of super-thin clouds on the reflected sunlight's AOLP. This figure is reproduced from Sun et al. (2014).

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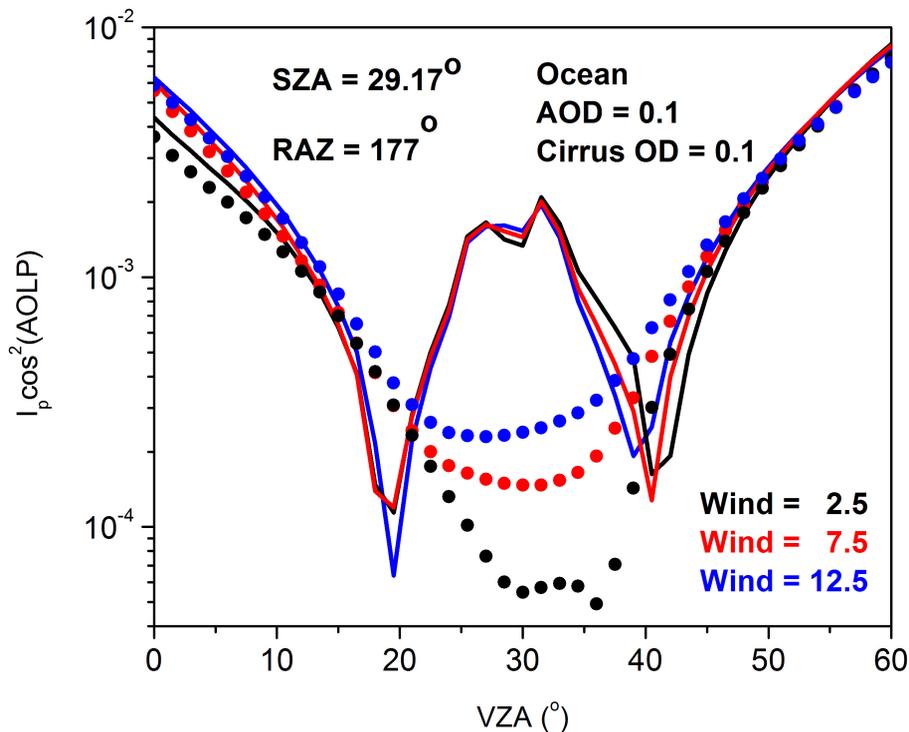


Figure 6. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for clear and super-thin clouds over oceans with different wind speeds. In the modeling, the solar zenith angle (SZA) is 29.17° , 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).

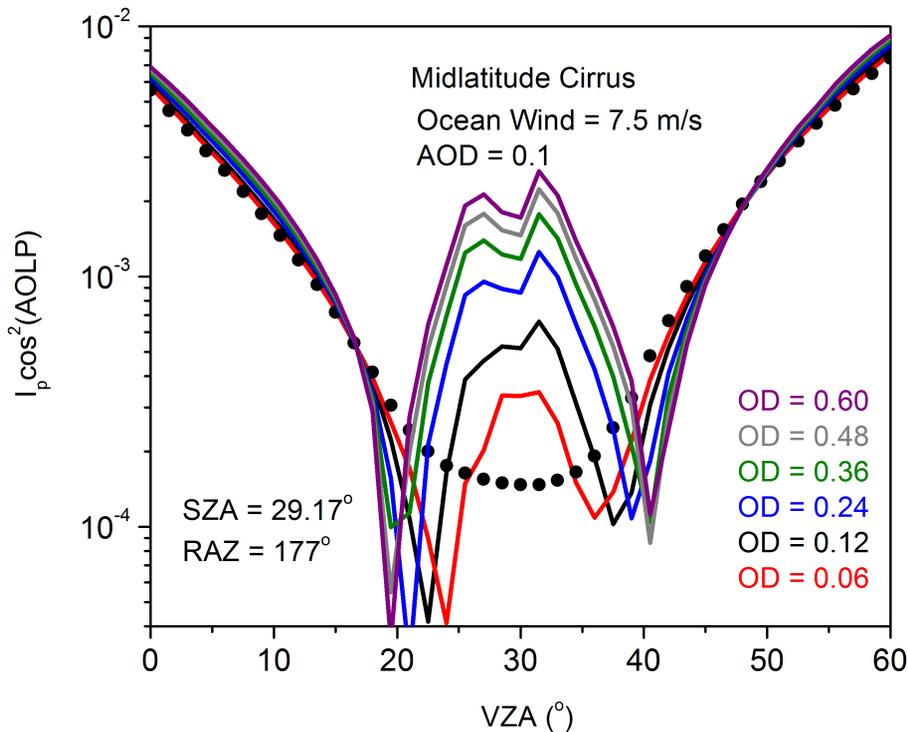


Figure 7. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans with different optical depth (OD) (solid curves). Also shown in the figure is the result for clear oceans (black dots). In the modeling, the solar zenith angle (SZA) is 29.17°, the wind speed is 7.5 m s⁻¹, 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 <~ 0.6.

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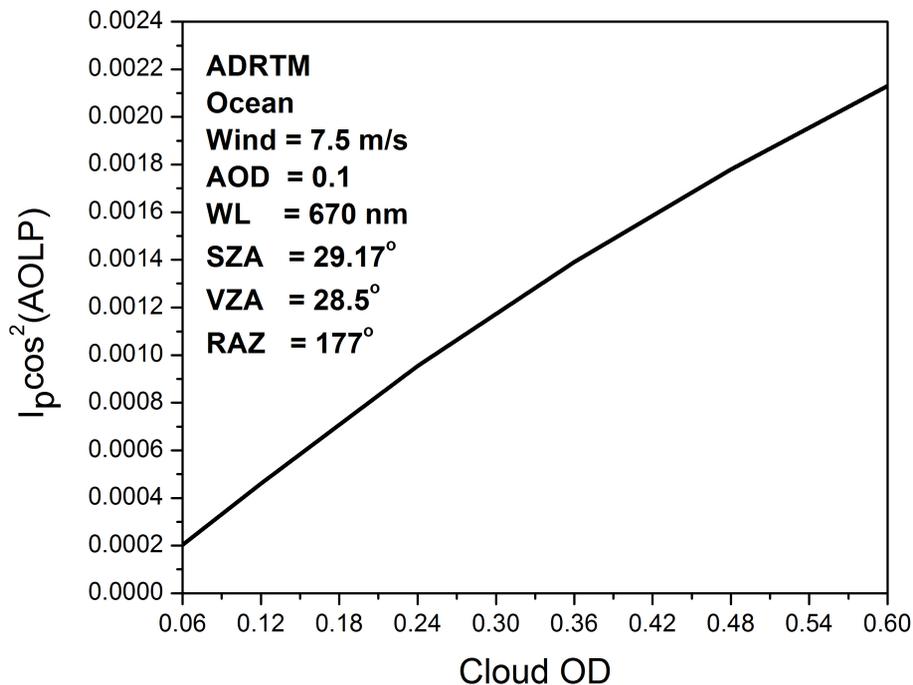


Figure 8. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of cloud optical depth (OD) at a viewing zenith angle (VZA) of 28.5° and a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans. The solar zenith angle (SZA) is 29.17° , the wind speed is 7.5 ms^{-1} , 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 $\text{OD} < 0.6$.

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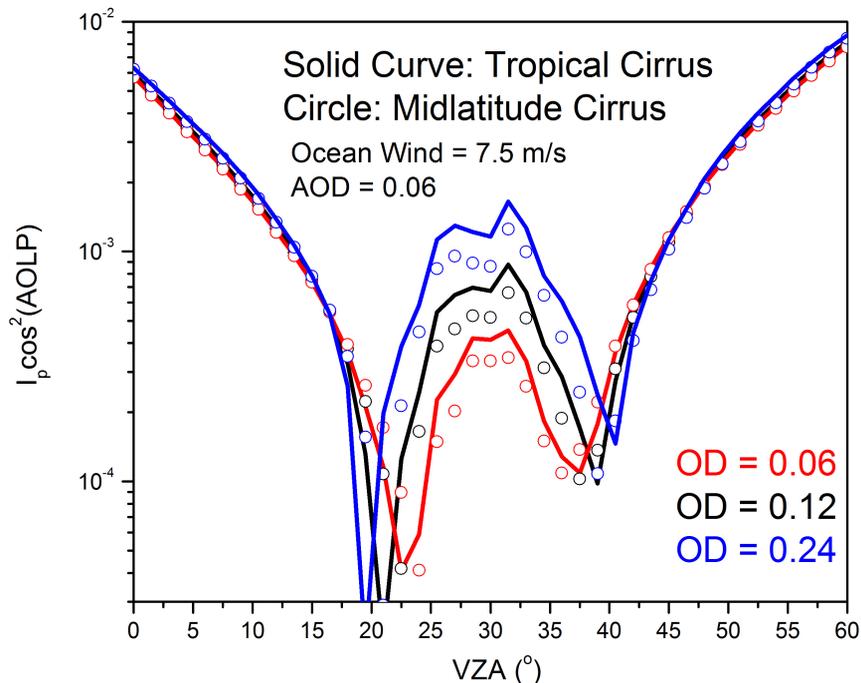


Figure 9. Modeled perpendicularly polarized reflectance at a wavelength of 670 nm as a function of viewing zenith angle (VZA) and at a relative azimuth angle (RAZ) of 177° for super-thin cirrus clouds over oceans with different optical depth (OD). In the modeling, the solar zenith angle (SZA) is 29.17° , the wind speed is 7.5 m s^{-1} , 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.