A Three-Year Climatology of Cloud-Top Phase over the Southern Ocean and North Pacific

ANTHONY E. MORRISON, STEVEN T. SIEMS, AND MICHAEL J. MANTON

Monash University, Melbourne, Victoria, Australia

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ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) Level 2 observations from the Terra satellite are used to create a 3-yr climatology of cloud-top phase over a section of the Southern Ocean (south of Australia) and the North Pacific Ocean. The intent is to highlight the extensive presence of supercooled liquid water over the Southern Ocean region, particularly during summer. The phase of such clouds directly affects the absorbed shortwave radiation, which has recently been found to be “poorly simulated in both state-of-the-art reanalysis and coupled global climate models” (Trenberth and Fasullo).

The climatology finds that supercooled liquid water is present year-round in the low-altitude clouds across this section of the Southern Ocean. Further, the MODIS cloud phase algorithm identifies very few glaciated cloud tops at temperatures above \( -20^\circ \text{C} \), rather inferring a large portion of “uncertain” cloud tops. Between \( 50^\circ \) and \( 60^\circ \)S during the summer, the albedo effect is compounded by a seasonal reduction in high-level cirrus. This is in direct contrast to the Bering Sea and Gulf of Alaska. Here MODIS finds a higher likelihood of observing warm liquid water clouds during summer and a reduction in the relative frequency of cloud tops within the \( 0^\circ \) to \( -20^\circ \text{C} \) temperature range.

As the MODIS cloud phase product has limited ability to confidently identify cloud-top phase between \( -25^\circ \) and \( -25^\circ \text{C} \), future research should include observations from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and other space-based sensors to help with the classification within this temperature range. Further, multiregion in situ verification of any remotely sensed observations is vital to further understanding the cloud phase processes.

1. Introduction

The Southern Ocean region, together with the southern reaches of the Atlantic, Indian, and Pacific Oceans, represent approximately 15% of the earth’s surface. Home to the Antarctic Circumpolar Current, the largest movement of mass on the earth’s surface, the latitudinal band between \( 50^\circ \) and \( 70^\circ \text{S} \) contains a large amount of thermal inertia (Barker and Thomas 2004). The poor representation of energy fluxes over this region has the potential to drastically affect the simulated global energy balance within climate models.

Most immediately, the Southern Ocean and its accompanying atmosphere affect the climate through thermal emission together with the absorption and reflection of solar radiation. Recently, Trenberth and Fasullo (2010) found the energy budget over this region to be “poorly simulated in both state-of-the-art reanalysis and coupled global climate models.” In particular, “disproportionately large biases” were noted in the absorbed shortwave radiation, indicating an inability to accurately simulate the role of cloud over the Southern Ocean.

Satellite-derived climatologies of cloud cover reveal (Mace et al. 2007; Bennartz 2007) that many parts of the Southern Ocean experience cloud cover \( >80\% \) of the time with little seasonality. There is relatively little variation latitudinally or longitudinally, with the one notable exception being the Patagonian region of South America. Low-altitude clouds (cloud top \( \approx 3 \text{ km} \)), in particular, have been shown to have a fractional cloud cover of \( 70\%–90\% \) (Mace et al. 2007). Direct knowledge of these clouds is relatively limited as routine in situ observations are unavailable. High wind speeds and a lack of inhabited land have conspired to deter such observations. Indeed, the last major field experiments that undertook in situ observations of the Southern Ocean boundary layer and the ubiquitous low-level clouds were
the first Aerosol Characterization Experiment (ACE-1) in 1995 (Bates et al. 1998) and the Southern Ocean Cloud Experiments I and II in 1993 and 1995, respectively (Boers et al. 1998; Jensen et al. 2000).

More recently Morrison et al. (2010) examined the nature of these frequent low-level clouds through two case studies over Tasmania. Combining limited satellite, radar, and in situ observations with numerical simulations, Morrison et al. (2010) suggested that these low-level clouds may commonly exist in a supercooled state, rather than being glaciated or mixed phase. Furthermore, the numerical simulations suggested that such clouds should readily exist widely across the Southern Ocean (particularly to the west of Tasmania).

As a point of comparison, the Southern Ocean region is compared with an equivalent region of the North Pacific. During winter, the clouds of the North Pacific free troposphere are largely defined by the midlatitude cyclones that create the storm track, much as they are year-round in the Southern Ocean. Naud et al. (2006) employed Moderate Resolution Imaging Spectroradiometer (MODIS) observations to look at the cloud phase of these midlatitude storms in both the North Pacific and North Atlantic, finding a dependence of the cloud phase on the underlying SST. This study focused primarily on the structure of midlatitude cyclones, not the high fraction of low-altitude clouds that are present between fronts.

The phase of water exposed at cloud top has long been known to affect the local energy budget (Gregory and Morris 1996), especially regarding the absorption of shortwave radiation. Therefore, a better understanding of the phase of these very common low-altitude Southern Ocean clouds may be imperative to properly constrain the global energy budget. The primary objective of this paper is then, to present a climatology of cloud-top phase (CTP) over this section of the Southern Ocean as observed by MODIS (Platnick et al. 2003). The climatology is specifically employed to explore the extent to which low-altitude clouds are found to have supercooled cloud tops, rather than being mixed phase, glaciated, or unclassified. A comparable portion of the North Pacific is analyzed as a point of reference.

2. Data preparation and discussion of known issues

For this climatology approximately 30 000 MODIS images from the Terra satellite were processed. The climatology covers the 3 yr from 2006 to 2008 with the austral summer (winter) being defined as December, January, and February (June, July, and August). Note that climatological differences due to changes in the southern annual mode, El Niño, or the Indian Ocean dipole are not considered because of the limited number of years processed. For each image, each individual level 2 pixel was assigned to a $1^\circ \times 1^\circ$ bin and counted. If cloud was detected, then both the cloud-top temperature (CTT) and CTP were stored. The final dataset is simply the frequency with which a given CTP occurs for each individual $1^\circ \times 1^\circ$ bin.

Working with $5 \times 5$ blocks of pixels, the native MODIS level 2 data for CTP and CTT range in size from $5 \times 5$ to greater than $5 \times 20$ km, depending on the viewing angle. To produce an estimate of CTT or CTP, it is necessary to first identify cloudy- or clear-sky conditions. Holz et al. (2008) investigated cloud detection and height evaluation using both MODIS and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), finding generally good agreement. Regarding the classification of cloudy pixels, excluding the polar regions, MODIS and CALIOP agree $\sim$75% of the time. The biggest difference in cloudy scene classification occurs over deserts and polar regions and is due to incorrect classification in both instruments. Regarding the present study, incorrect classification is therefore most likely to occur within regions closest to the poles, due to the variability of surface properties and insufficient thermal differences between cloud and surface.

Cloud-top phase is inferred as a function of the brightness temperature difference between the 8.5- and 11-μm channels and the cloud-top temperature (Platnick et al. 2003). In particular, MODIS defines the CTP as either ice (I), mixed phase (MP), liquid, or uncertain (U) for blocks containing cloud. When coupled with cloud-top temperature, it is possible to further refine the liquid CTP into being either warm water (WW), CTT above freezing or supercooled liquid water (SLW) when CTT is below freezing.

An example, CTP retrieval is shown in Fig. 1. An uncertain phase may arise when the entire $5 \times 5$ block of pixels has mixed readings for either CTT or CTP. It may also occur as the default when the bispectral CTP algorithm fails to clearly define ice, liquid, or mixed phase. This commonly occurs when viewing multilayer clouds, such as optically thin cirrus over lower-level water/mixed-phase clouds or single-layer clouds, within the $0^\circ$ to $-40^\circ$C range (Platnick et al. 2003). It is noted that the $0^\circ$ to $-40^\circ$C range is particularly problematic for the passive MODIS sensor. Nasiri and Kahn (2008) highlights that >75% of cloudy retrievals between $-8^\circ$ and $-23^\circ$C are classified as either mixed phase or uncertain and that even though mixed-phase clouds are not uncommon, especially within this temperature range, multilayer clouds can have spectral signatures that imitate midlevel or mixed-phase clouds.

As a primary focus of the present research is to investigate the prevalence of supercooled clouds, an
estimate regarding any potential bias MODIS has with regard to this specific phase is desirable. Cho et al. (2009) compares MODIS-derived CTP with CALIOP (version 2 cloud phase product) and notes that there is a tendency to classify opaque midtemperature clouds as unknown or mixed phase, as such MODIS estimates of supercooled clouds are deemed conservative.

3. Southern Ocean climatology

For each $1^\circ \times 1^\circ$ bin in the domain (30$^\circ$–60$^\circ$S, 100$^\circ$–160$^\circ$E), Fig. 2a shows the frequency with which MODIS detects clouds during the austral winter. The frequency of clear-sky blocks (not shown) is simply the complement to this image. Further, Figs. 2b–f break down the cloudy blocks into the CTP classes of WW, SLW, I, MP, and U, respectively. As the radiometers within MODIS are passive, it is best to examine these images from the top down. MODIS views high-altitude clouds, presumably glaciated cirrus, first. If present, such ice clouds mask any underlying clouds and the frequency of observing any underlying CTP is accordingly underestimated. The frequency of occurrence of WW blocks will be the most underestimated, as the blocks containing overlying I, MP, and SLW clouds will all have been detected first and counted accordingly. Moreover, any pattern or bias in the spatial distribution of overlying clouds will be reflected in the distribution of the underlying classes.

The probability of observing glaciated clouds during winter (Fig. 2d) is greater over the higher latitudes. Near 60$^\circ$S ice is observed roughly 50% of the time; along the northern border at 30$^\circ$S, the frequency is commonly below 5%. This is not particularly surprising, as the midlatitude cyclones, which can produce high-altitude cirrus, are commonly centered around 50$^\circ$–60$^\circ$S (Simmonds and Keay 2000). The north–south gradient is relatively smooth, with no immediate impact when moving from maritime to continental pixels at the lower latitudes. Perhaps the one surprising feature is the east–west gradient observed in the distribution of glaciated cloud tops at the higher latitudes. Bins to the west of the domain are 10% more likely to contain ice relative to comparable bins in the eastern part of the domain. One may speculate that this, too, is a reflection of the common poleward deflection of the midlatitude storm track south of Tasmania (Simmonds and Keay 2000).

In comparison to ice, relatively few mixed-phase clouds are observed during winter (Fig. 2e), representing approximately 10% of all observations. There is a slight north–south gradient in MP clouds and an even weaker east–west gradient. Again, no difference is evident when crossing between the maritime Southern Ocean and the Australian continent at the lower latitudes. The spatial distribution of the uncertain CTP is similar to mixed phase, although more frequent.

The frequency of cloud tops composed of supercooled liquid water (Fig. 2c) ranges from roughly 10% at 30$^\circ$S to in excess of 30% near 50$^\circ$S. These frequencies are likely to be an underestimate of the total number of supercooled cloud tops, as 1) higher-level ice pixels will have been counted first and 2) MODIS has a tendency to categorize midtemperature clouds (those at temperatures greater than $-40^\circ$ and less than $0^\circ$C) as either MP or U (Nasiri and Kahn 2008; Cho et al. 2009). Overall the frequent observation of SLW by MODIS lends support to the claim by Morrison et al. (2010) that low-altitude clouds with supercooled tops should be widespread over the Southern Ocean to the west of Tasmania. Further, the finding is consistent with in situ observations indicating large concentrations of SLW (Ryan and King 1997).

Focusing on the warm water clouds (Fig. 2b), the image is somewhat complementary to the ice and SLW frequencies. The WW frequency decreases strongly when moving toward the pole, which is not surprising, considering that these clouds are at very low altitudes and strongly reflect the underlying SST. Perhaps the most striking feature of this image is the contrast between observations within the maritime and continental air masses; this difference is not seen in the other CTPs. A further analysis (not presented) finds that this difference actually arises at temperatures just below SST; that is, MODIS is consistently identifying a surface-level fog over the Southern Ocean.
The overall cloudiness (Fig. 2a) is simply the composite of the five cloud classes identified. The bias between continental and maritime pixels follows directly from the bias highlighted in the low-level clouds. Over the ocean, the fractional cloud cover is in excess of 80% and increases steadily when moving toward the pole. This is consistent with the earlier climatologies of Mace et al. (2007) and Bennartz (2007). Note that the Bennartz (2007) climatology, which also employed MODIS observations, similarly produced a strong maritime–terrestrial
contrast in clouds over the Southern Ocean, including along the coasts of South Africa and South America.

The same exercise may be undertaken for the austral summer and is presented in Fig. 3. Again, focusing on higher elevation clouds first, ice is found to be dramatically reduced at the higher latitudes when moving from winter to summer (Fig. 3d). During winter the frequency of ice between 50° and 60°S was commonly in excess of 35% with a peak near 50%. During the summer, the frequency drops to below 25% on average. Two possible contributing processes that could explain the observed reduction in ice are the 1) poleward shift in storm tracks and 2) increased evaporation of ice (because of increased solar radiation). It is also noted that the east–west
gradient in the distribution of ice observed during winter is considerably weaker over summer.

The images for the mixed-phase and uncertain cloud-top phases increase only modestly over the summer. This is perhaps surprising, given that a reduction in ice should directly increase the observation of any lower-altitude CTP classes. When focusing on SLW (Fig. 3c), however, a large increase in frequency is observed over the summer at the high latitudes when compared against winter. Between 50° and 60°S, SLW is often observed in excess of 35% of the time, whereas during winter it rarely exceeds 25%. Again, MODIS finds that low-altitude clouds over the Southern Ocean commonly exist with clouds tops of supercooled liquid water. Looking at WW (Fig. 3b), a poleward shift in the pattern is evident. Further, this pattern is highly correlated with the underlying SST. As with the winter image, a sharp gradient in the frequency is observed when moving from maritime to terrestrial bins.

The accurate subdivision of liquid water into warm and supercooled temperatures depends on the accuracy of the cloud-top temperature retrieval about the freezing level. Hanna et al. (2008) assessed the differences between sounding-derived, cloud-top temperatures and IR brightness temperatures from the Geostationary Operational Environmental Satellite (GOES) over North America. The uncertainty when brightness temperatures were between −25°C and 10°C was found to be “small” relative to cooler temperatures where differences of ±60°C were possible. In part to address these concerns, histograms showing the relative frequency of CTP decomposed into 5°C temperature bins are shown for the austral summer and winter over the full domain in Fig. 4. The relative frequencies of clear-sky (13% for winter and 14% for summer) blocks of pixels are not shown on these histograms.

At first glance, when moving from winter to summer, the histograms suggest a relatively uniform shift toward lower temperatures in cloud cover over the Southern Ocean. There is a reduction in the relative frequency (RF) for total cloud cover at temperatures colder than −40°C, while an increase in the RF of WW clouds at temperatures warmer than 5°C. This reduction in cirrus clouds during the summer should allow for more underlying SLW and WW clouds to be visible to MODIS. The bimodal structure is roughly consistent with Mace et al. (2007), who found that the Southern Ocean was predominantly covered in clouds with tops below 3 km in altitude. The minimum in this distribution occurs between −20° and −25°C. SLW cloud tops are observed at temperatures down to about −35°C. Further, this supercooled phase represents approximately 17% of all retrievals (both summer and winter), with 7% of all observations occurring at temperatures colder than −5°C. Mixed-phase tops occur mainly between −5°C and −45°C, with a peak between −15°C and −30°C. Uncertain retrievals occur mainly between freezing and −35°C, peaking at slightly warmer temperatures than MP. Interestingly, clouds with temperatures warmer than freezing may also be classified as uncertain, almost certainly because of multilayer clouds confusing either the CTT or CTP algorithm.

Focusing on the temperature range of 0°C to −20°C, SLW and U are the most commonly observed cloud-top phases. Overall, roughly 27% (31%) of the cloud tops reside in this band during summer (winter). Again, this is likely to be an underestimate because of any overlying cirrus. Between 0°C and −10°C, SLW is more commonly observed than uncertain; this is reversed between −10°C and −20°C. Within this range of temperatures, MODIS detects more U CTP during the winter than during the summer. Perhaps surprisingly, MODIS observes I less...
than 1% of the time in this range. MODIS detects virtually no I at temperatures greater than \(-15^\circ\)C. Only at temperatures colder than \(-20^\circ\)C does MODIS detect glaciated cloud tops more frequently than SLW.

To investigate further how the relative occurrences of the different CTPs stratify within latitude bands, Fig. 5 splits the observations into three latitude bands—30^\circ–40^\circ, 40^\circ–50^\circ, and 50^\circ–60^\circ—for the austral summer and winter seasons. The bimodal distribution is evident within all three bands during summer and winter. The RF of high-altitude I at colder temperatures increases markedly at the higher latitudes. Again, the decrease in the RF of the low-altitude WW clouds at higher latitudes mirrors the decrease in the SST when moving from low to high latitudes. Between 40^\circ and 50^\circ S, slightly more WW clouds are observed during summer than winter. Conversely, more glaciated clouds are observed during the winter months in this latitude band. Within the highest-latitude band, notably more glaciated clouds occur at temperatures below \(-50^\circ\)C. At all latitudes, it is evident that more U clouds are observed during winter than summer.

4. North Pacific climatology

As a point of comparison, a CTP climatology for the North Pacific Ocean between 30^\circ and 60^\circ N and 160^\circ E is also considered. While the domains are of the same size, the meteorology differs, as reflected in the CTP climatology. Perhaps the most immediate difference between the domains is the surface forcing arising from ocean dynamics. The currents of the Southern Ocean are strongly zonal, whereas the North Pacific is land locked. In the North Pacific, the Kuroshio along the western boundary provides an east–west gradient in the SST that is absent in the Southern Ocean. In addition to differences in the SST, the Northern Hemisphere has much higher aerosol concentrations than the pristine Southern Ocean, especially during winter (Yum and Hudson 2005). Note that the climate in this part of the world may be highly sensitive to ENSO; here, it is simply noted that 2006 had an extreme Southern Oscillation index (SOI) of \(-10\), 2007 +15, and 2008 +15 (Bureau of Meteorology 2009). Interannual differences do exist in the data; however, it is not possible to analyze these differences with much confidence, given that there are only 3 yr of data.

The images of the CTP climatology for both the boreal winter and summer are presented in Figs. 6 and 7, respectively. The relative frequencies of total cloud cover are comparable between hemispheres, with the North Pacific containing more clouds than the Southern Ocean in both winter (0.93 versus 0.87) and summer (0.90 versus 0.86). For both hemispheres, the cloud fraction minimum occurs at low latitudes.

Looking again at the ice CTP first, a strong seasonal cycle is evident in the North Pacific. During the winter, the RF approaches 50% along the storm track of the North Pacific, where the frequent midlatitude cyclones commonly produce convection through the troposphere. Outside of the storm track, however, the RF of I decreases to values less than 25%, even over the high latitudes of the Bering Sea. This is in direct contrast to the Southern Ocean, where the RF of I is greatest at the high latitudes. In the summer, the RF of I drops off to 10%–15% in the high latitudes, much lower than at these latitudes over the Southern Ocean.

The RF of mixed-phase clouds is small and comparable to that over the Southern Ocean. The one point of note is the peak in excess of 20% along the northern boundary of the Bering Sea during the winter. The
presence of mixed-phase clouds over the Arctic has been a topic of active research (Jiang et al. 2000; Morrison and Pinto 2005; Verlinde et al. 2007). The RF of uncertain pixels displays a similar pattern to that of MP clouds, only at a larger magnitude. This is particularly noteworthy over the Bering Sea in winter, when MODIS observes the U CTP >30% of the time in some locations. Within the low- and midlatitude bands, the RF of U clouds is comparable between the North Pacific and Southern Oceans. The overall magnitude of the RF of cloud-top SLW over the North Pacific is comparable to that over the Southern Ocean. Within the low- and midlatitude bands, a north–south gradient is present, which is negatively correlated with the underlying SST. In the higher-latitude bands,
however, the North Pacific and Southern Oceans differ notably. Little change is observed in the spatial pattern of SLW over the North Pacific throughout the seasons, whereas the high-latitude areas of the Southern Ocean show a strong seasonal cycle. Over the North Pacific, cloud-top SLW shows a slight minimum during the summer months; this trend is reversed over the Southern Ocean.

The CTP of low-altitude clouds is likely to have some relationship with the underlying SST (as well as the frequency and type of overlying clouds). Over the relatively shallow Bering Sea, the SST undergoes a fairly large seasonal cycle relative to that of the deep Southern Ocean (Stabeno et al. 2001). This strong seasonal change is reflected in the RF of WW clouds. During the

Fig. 7. As in Figs. 2 and 3, but for the boreal summer months.
winter, there are virtually no WW clouds over the Bering Sea; however, during the summer, the RF can be in excess of 40%. At high latitudes over the Southern Ocean, the RF is closer to 10% on average during summer. It is interesting to note that during summer, there is little land-maritime discontinuity in the RF of WW clouds, as is seen along the southern part of Australia.

As with the Southern Ocean, the RF of the various cloud-top phases over the North Pacific may be broken up into 5°C bins (Fig. 8) and further split into 10° latitude bands (Fig. 9). Focusing on the full domain, these histograms reveal that the North Pacific displays a larger seasonal cycle than the Southern Ocean. The RF of ice drops dramatically from approximately 32% to 18% when moving from winter to summer compared to 24% and 16% over the Southern Ocean. The RF of WW clouds also undergoes a strong seasonal cycle over the North Pacific, from 42% in summer to 18% in winter. Over the Southern Ocean, the RF of WW clouds had a range from 31% in summer to 25% winter.

In the range between 0° and −20°C, MODIS detects virtually no glaciation, as was the case for the Southern Ocean. Over the North Pacific, the RF of clouds within this temperature range undergoes a strong annual cycle, from 32% in winter to 21% in summer; over the Southern Ocean, the variability is slightly smaller, from 31% in winter to 26% in summer.

Breaking the histograms into latitude bands (Fig. 9) reveals that the increase in both ice during winter and WW during summer is widespread across the North Pacific, not just confined to regions of high latitude. Even in the 30°−40°N latitude band, ice cloud tops roughly double during winter. This seasonal change was negligible over low latitudes of the Southern Ocean. The histograms follow a bimodal distribution in the low- and midlatitude bands in the North Pacific. The high-latitude band, however, displays the greatest seasonal change, and a trimodal distribution is more applicable for this region during winter. MODIS observes a high RF of clouds between −10° and −30°C with a CTP of uncertain and mixed phase. These were found over the Bering Sea and Gulf of Alaska in Fig. 6. Overall, the North Pacific is found to display a much stronger seasonal signal for all CTP classes relative to the Southern Ocean.

A direct comparison of the CTP histograms for the Southern Ocean and North Pacific is found in Fig. 10. The results suggest that the two regions are most similar during their respective summer months, but their characteristics become quite different during winter. During winter, a greater fraction of I and MP cloud tops occurs over the North Pacific, over all temperature bins. At temperatures <−15°C, U retrievals are more likely over the North Pacific; however, at temperatures >−10°C, the Southern Ocean experiences more uncertain retrievals.

Finally, these histograms can be broken into latitude bands (Fig. 11). The most striking differences arise for the ice and MP CTPs within the low-latitude band during winter. Here, the North Pacific is roughly 2.5 times more likely to contain ice and mixed-phase clouds. Undoubtedly, some of this difference can be attributed to the large continental landmass of Australia affecting the storm track and wider meteorology of the Southern Ocean. Still, this same feature in the abundance of ice and mixed-phase clouds is also evident—to a lesser degree—in the midlatitude band. During summer the greatest differences are apparent at the high-latitude band. Here, the Southern Ocean can still support the convection of midlatitude cyclones, and more I, MP, and U clouds are observed relative to counts over the North Pacific; note that this also coincides with relatively fewer WW clouds.

It is perhaps most insightful to focus exclusively on the band between 40° and 50°S–N, as the Southern Ocean domain has land across much of the low latitudes and the North Pacific domain has land across the high latitudes.
In this midlatitude band and during the summer months, the similarity of the relative contributions for each CTP is most apparent. There are some differences in the low-altitude liquid CTPs, which most likely reflects differences in the SST. During the winter months, however, greater amounts of ice and mixed-phase clouds are readily apparent over the North Pacific. Correspondingly, substantially less WW clouds are observable by MODIS.

5. Concluding remarks

The primary aim of this article is to highlight the prevalence of supercooled liquid water in low-altitude cloud tops located within the higher latitudes over the Southern Ocean. In retrospect, this is not surprising, considering that CloudSat has identified the relative frequency of low-altitude clouds (cloud tops below 3-km altitude) to be between 70% and 90% of the time over the Southern Ocean (Mace et al. 2007). Over the higher latitudes (50°–60°S), most of these clouds have cloud-top temperatures between 0° and −20°C. The MODIS observations lend further support to results presented by Ryan and King (1997) and Morrison et al. (2010), indicating large quantities of supercooled liquid water within clouds in the vicinity of Tasmania.

Various in situ field observations have revealed many unique features of the ubiquitous low-altitude Southern Ocean clouds. In particular, they have been observed to

![Fig. 9. As in Fig. 8, but for (top) 30°–40°, (middle) 40°–50°, and (bottom) 50°–60°N. Gray shades are as described in Fig. 4.](image)

![Fig. 10. Histograms comparing the summer and winter distributions of CTT and the relative contributions of the various CTPs for the Southern Ocean (30°–60°S, solid line) and North Pacific (30°–60°N, dashed) during (left) summer and (right) winter.](image)
be highly pristine (Yum and Hudson 2005), especially during the winter, driven strongly by wind shear (Russell et al. 1998; Wang et al. 1999; Jensen et al. 2000) and a complex boundary layer structure. Further, the Hallett–Mossop process for ice multiplication was formulated upon observations of Southern Ocean clouds (Mossop et al. 1970). The unique nature of these clouds may in part help to explain the “disproportionately large biases” found in the present-day analysis and simulation of the energy budget over the Southern Ocean (Trenberth and Fasullo 2010). As highlighted by Naud et al. (2006), cloud ice process parameterizations should not be based on or validated against data from a single region.

Fig. 11. As in Fig. 8, but split into latitude bands.
The unique nature of these low-altitude Southern Ocean clouds adds an extra element of uncertainty to the MODIS observations. It has been noted by many authors that MODIS has particular trouble identifying clouds within the −5° to −25°C range as anything other than uncertain (Platnick et al. 2003; Nasiri and Kahn 2008; Cho et al. 2009). Results presented herein further highlight this problem. The MODIS instrument, like other new satellite-based instruments, has not been directly evaluated against in situ observations of pristine Southern Ocean clouds. This may in part help to further explain the failure of the MODIS cloud-top phase algorithm to clearly identify the phase of these mid-temperature range clouds. However, in the authors’ opinion, future research should include phase estimations of these clouds using other space-based sensors, such as CALIOP.

Further potential for error arises when the 5 × 5 block of ~1-km pixels does not provide a single confident measurement at the 8.5- and 11-μm channels. This happens when cloud fields are not uniform at scales <5 km, or equally when multiple cloud levels are observed simultaneously. Indeed, these are precisely the conditions described by Mossop et al. (1970) when observing ice in the “upper regions of small supercooled cumulus clouds.” Cloud tops were commonly observed to be at a width of 2–10 km. Finally, the presence of thin overlying cirrus has the potential to distort MODIS-derived observations in a similar manner to that possible for International Satellite Cloud Climatology Project (ISCCP) readings (Jin and Rossow 1997).

The full climatology of this region offers a number of insights. In addition to the relatively frequent occurrence of low-altitude supercooled liquid water clouds, it was noted that the amount of high-level cirrus/ice decreases substantially during the summer. The reduction in the ice CTP over the summer allows for more SLW and U clouds to be observed by MODIS and underscores the potential sensitivity of the albedo to these low-altitude clouds. At these high latitudes, individual 1° × 1° bins have relative frequencies of up to 50% for supercooled liquid water over the Southern Ocean.

When comparing the Southern Ocean against the North Pacific, notable differences arise. First and foremost, the CTP climatology of the North Pacific undergoes a much stronger seasonal cycle than the Southern Ocean, just as the SST over the North Pacific has a greater seasonal cycle. This is especially true in the high latitudes of the relatively shallow Bering Sea. The North Pacific experiences more warm water clouds during the summer and far less during the winter, relative to the Southern Ocean. Regarding the ice CTP, it was far more common for MODIS to observe glaciation in the North Pacific during the winter than over the Southern Ocean, especially in the latitude bands 30°–40° and 40°–50°N–S. The most immediate explanation for the enhanced observation of ice in the North Pacific during winter might simply be that winter storms are of greater intensity. A different explanation, however, could potentially be based on the difference in the aerosol loading between hemispheres. Across the 50°–60°N–S latitude band, the differences between hemispheres are evident in both winter and summer. During the summer, the North Pacific is strongly dominated by liquid-phase clouds between 10° and −10°C, whereas the Southern Ocean has far more clouds at colder cloud-top temperatures. Even in the North Pacific, MODIS does not observe significant glaciation at temperatures warmer than −20°C.

To correctly identify the energy budget of the Southern Ocean, a more comprehensive understanding of the ubiquitous low-altitude clouds present in this region is essential. The MODIS observations presented here suggest that during summer, the high latitudes of the Southern Ocean are dominated by low-altitude clouds with cloud-top temperatures between freezing and −20°C. These clouds are rarely glaciated. The current generation of satellites offers unprecedented insight into the structure of such clouds; the uncertainty in these observations, however, will remain high until they have been directly evaluated against in situ observations.

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