

Observed Southern Ocean Cloud Properties and Shortwave Reflection. Part II: Phase Changes and Low Cloud Feedback*

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ABSTRACT

Climate models produce an increase in cloud optical depth in midlatitudes associated with climate warming, but the magnitude of this increase and its impact on reflected solar radiation vary from model to model. Transition from ice to liquid in midlatitude clouds is thought to be one mechanism for producing increased cloud optical depth. Here observations of cloud properties are used from a suite of remote sensing instruments to estimate the effect of conversion of ice to liquid associated with warming on reflected solar radiation in the latitude band from 40° to 60°S. The calculated increase in upwelling shortwave radiation ($SW^\uparrow$) is found to be important and of comparable magnitude to the increase in $SW^\uparrow$ associated with warming-induced increases of optical depth in climate models. The region where the authors' estimate increases $SW^\uparrow$ extends farther equatorward than the region where optical depth increases with warming in models. This difference is likely caused by other mechanisms at work in the models but is also sensitive to the amount of ice present in climate models and its susceptibility to warming.

1. Introduction

McCoy et al. (2014, hereinafter Part I) studied the effect on the reflected shortwave radiation ($SW^\uparrow$) of the observed seasonal cycles of cloud properties derived from an array of remote sensing platforms in the Southern Ocean region (40°–60°S). Calculations of $SW^\uparrow$ over the Southern Ocean were performed based on remotely sensed cloud properties. This was accomplished by synthesizing the observed cloud properties in the Southern Ocean into a data structure containing cloud properties consistent with observations. The method for this synthesis was to begin with the granular description of the distribution of clouds in height and optical depth contained in the MISR cloud-top height–optical depth (CTH–OD) histogram (Marchand et al. 2010) and then combine this with the area-averaged and observations of liquid and ice water paths vertically resolved into

pressure (P) regimes where $P > 680$ hPa, $680 \text{ hPa} > P > 440$ hPa, and $P < 440$ hPa and with the effective radii of liquid and ice. Using this technique a database of observed cloud properties was created covering the period 2007–08. The Rapid Radiative Transfer Model for GCMs (RRTMG) was used to calculate $SW^\uparrow$ from the cloud properties database, assuming plane-parallel radiative transfer. The ability of this database to reproduce the observed upwelling shortwave radiation was tested through comparisons to Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) 2.6r (Loeb et al. 2009). Agreements between observed and reconstructed $SW^\uparrow$ were found to have values of $R \geq 0.95$ and a mean bias of -1.37 W m^{-2} . Comparisons of observed and calculated reflectivity, which is more sensitive to small errors in wintertime shortwave flux, found values of $R \geq 0.67$ with a mean bias of -0.02 .

Low cloud fraction was found to peak in summer in sync with increased lower-tropospheric stability, which is consistent with previous work studying the behavior of low cloud (Klein and Hartmann 1993; Wood and Bretherton 2006) and studies of the Southern Ocean low cloud (Haynes et al. 2011; Bromwich et al. 2012). Upper-level cloud was found to peak in winter along with enhanced synoptic activity, which is consistent with

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previous studies of this region (Haynes et al. 2011; Bromwich et al. 2012; Verlinden et al. 2011). Effective radius r_e is smallest in summer, which is consistent with the notion of biogenic cloud condensation nuclei (CCN) production in summer driving increases in droplet number concentration (Korhonen et al. 2008; Vallina et al. 2006). Low-level in-cloud liquid water path was found to be maximum in fall and winter and low-level in-cloud ice water path was found to be maximum in winter, which is consistent with efficient longwave cooling at cloud top during the high-latitude winter darkness, leading to buoyant production of turbulence and an increase in liquid, where some of which transitions to ice (Curry 1986; H. Morrison et al. 2011; Solomon et al. 2011), as well as more active dynamics during the winter season (Simmonds et al. 2003; Verlinden et al. 2011).

The database described above was constructed such that individual cloud properties could be manipulated and the change in $SW^\uparrow$ due to these manipulations could be calculated. In Part I, this was used to test the importance of the seasonal cycle of cloud properties to the seasonal cycle of upwelling shortwave radiation. The transition between ice and liquid as the clouds warm was shown to have an impact of up to 5 W m^{-2} on $SW^\uparrow$. Given the potentially significant effect of temperature on the liquid to ice ratio and upwelling shortwave radiation, we investigate the projection of changes in the ice to liquid ratio in a warmed climate.

The effect of shifts in the partitioning of mixed-phase condensate may significantly affect regional climate feedbacks. One of the robust feedbacks that is emerging in GCMs is a negative cloud feedback owing to increases in optical depth in the midlatitudes (Zelinka et al. 2012, 2013). This increase in cloud optical depth is thought to derive in part from the transition from ice to liquid in clouds with warming (Tsushima et al. 2006; Zelinka et al. 2012). Increases in water path due to decreased precipitation efficiency and an overall increase in liquid water path with warming (Betts and Harshvardhan 1987) probably also contribute a negative cloud feedback. Here we focus on the increase in $SW^\uparrow$ due to ice transitioning to liquid. For constant concentrations of ice nuclei (IN), the partitioning between condensate phase should be primarily dependent on the atmospheric temperature (H. Morrison et al. 2011; Hu et al. 2010), offering the possibility of a simple calculation of the change in $SW^\uparrow$ due to an increase in atmospheric temperature. It should be noted that the change in ice to liquid ratio and the overall alterations in mixed-phase clouds in a warmed climate are not equivalent. In a warmed climate decreases in precipitation efficiency should increase the total water path in clouds (H. Morrison et al. 2011), while enhanced entrainment of dry air should thin cloud (Tsushima et al.

2006; Zelinka et al. 2012; Sherwood et al. 2014). These changes are poorly constrained even in highly idealized cases (Klein et al. 2009) and thus we do not attempt to project a behavior for total water path in this work. GCMs show that the changes in total water path (TWP) are dominated by changes in precipitation efficiency in mixed-phase regions (Zelinka et al. 2012; Tsushima et al. 2006); thus, the melt feedback is very likely to be an underestimate of the strength of the optical depth feedback.

In this study, we utilize the framework described in part one of this paper that allowed the calculation of the upwelling shortwave radiation based on the observed cloud properties to estimate the increase in $SW^\uparrow$ consistent with a warming of the Southern Ocean clouds. This framework is used in combination with the remotely sensed dependence of the partitioning of liquid and ice on temperature. The correlation between the ratio of liquid to ice and temperature is used to create a data structure of cloud properties consistent with a warmed climate in which a greater proportion of cloud condensate is liquid.

This is a simplified approach to understanding how clouds will respond to warming in the Southern Ocean. Mixed-phase clouds are dependent on a complicated interplay of mechanisms, but the variables that affect these mechanisms are extremely difficult to predict; thus, we make a simple calculation using the current observations of Southern Ocean clouds and the dependence of the partitioning of cloud condensate phase on temperature. These calculations allow us to estimate the likely strength of the Southern Ocean increase in $SW^\uparrow$ due to temperature to study the impact of uncertainties in microphysical quantities. Calculations using this framework shed light on sources of the uncertainty and indicate potential limitations in the predictability of cloud radiative effect in these regions. They also point toward elements of climate models that must be improved in order to offer a more accurate prediction of the Southern Ocean cloud response to warming.

2. Methodology

Using the database of cloud properties compiled in Part I, we now estimate the strength of the climate change cloud feedback due to only one aspect: changes in the ratio of cloud water to cloud ice as a function of temperature at fixed total water path. We will call this the “melt feedback” for convenience. The feedback due to the transition from mixed-phase to liquid clouds as the climate warms has been hypothesized to be a key contributor to the optical depth feedback observed in GCMs in the Southern Ocean (Zelinka et al. 2012, 2013). While the cloud optical depth feedback is related to the melt feedback, it should be noted that they are not equivalent

quantities. The GCM optical depth feedback should include additional mechanisms not considered in the melt feedback that we estimate, but examining the differences between the two may provide insight into the treatment of mixed-phase clouds in models.

Utilizing the observed ratio of ice to liquid mass in the low and middle clouds and the cycle of tropospheric temperature throughout the year, we create an approximate relationship between the two that we can use to simulate a change in upwelling shortwave radiation associated with 1 K of tropospheric warming. The fit between low cloud thermodynamic phase ratio and temperature is shown in Fig. 1a, and the fit between middle cloud thermodynamic phase ratio and temperature is shown in Fig. 1b. The change in ratio of ice to liquid in low [cloud-top pressure (CTP) > 680 hPa] and middle (680 hPa > CTP > 440 hPa) clouds for 1 K of warming is estimated to be -0.08 ± 0.01 and $-0.3 \pm 0.2 \text{ K}^{-1}$, respectively, as determined by a linear fit between zonal by 1° -latitude monthly daytime ice water path (IWP) to LWP ratio and 700-hPa temperature from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kistler et al. 2001) for the Southern Ocean region between 50° and 40°S . Liquid water content was derived from the combination of the University of Wisconsin (UWISC) climatology (O'Dell et al. 2008) with the *CloudSat* level 2B radar-only cloud water content product (2B-CWC-RO; Austin and Stephens 2001) and ice water content was retrieved from the level 2C ice cloud property retrieval product (2C-ICE; Mace and Deng 2011) dataset. The preparation of these datasets is consistent with the treatment discussed in Part I. All data are gridded over the Southern Ocean in $1.18^\circ \times 12^\circ$ (latitude $\times$ longitude) regions for the period 2007–08.

The change in upwelling shortwave radiation that results from altering the mixture of liquid and ice in the clouds consistent with 1 K of warming is shown in Fig. 2. For consistency with the optical depth feedback, which is defined to be negative with increasing reflectivity, the melt feedback is also shown as negative for increased reflectivity. In calculating the altered $\text{SW}^\uparrow$ from the database of cloud properties, all middle and low clouds are assumed to be warmed uniformly by 1 K and the ratio of liquid to ice is changed proportional to the slope of the curves shown in Fig. 1 while the total water path is held fixed. It should also be noted that this method assumes equivalency between a greenhouse gas-induced warming and the seasonal cycle. As the liquid amount increases with increasing temperature, some assumptions must be made as to how the microphysics of the clouds will behave.

Determining the future behavior of the cloud droplet number concentration N_d is difficult because it depends

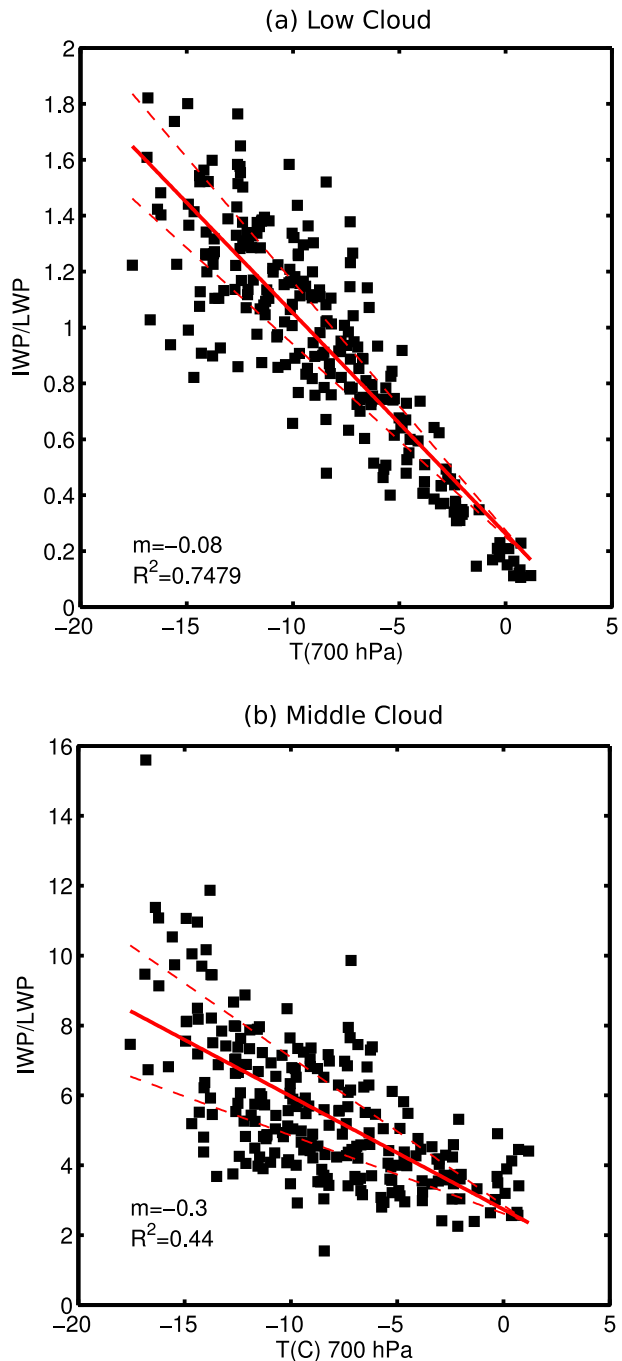


FIG. 1. The linear fit of relative proportions of cloud IWP retrieved from 2C-ICE to LWP derived from UWISC and 2B-CWC-RO over the period 2007–08 in the Southern Ocean region (40° – 50°S) against the temperature at 700 hPa for zonal by 1° -latitude monthly data for (a) low and (b) middle cloud. The least squares fit is given by the solid red line, and the dashed lines are the slopes used to test the sensitivity of the upwelling shortwave radiation to the liquid to ice ratio behavior.

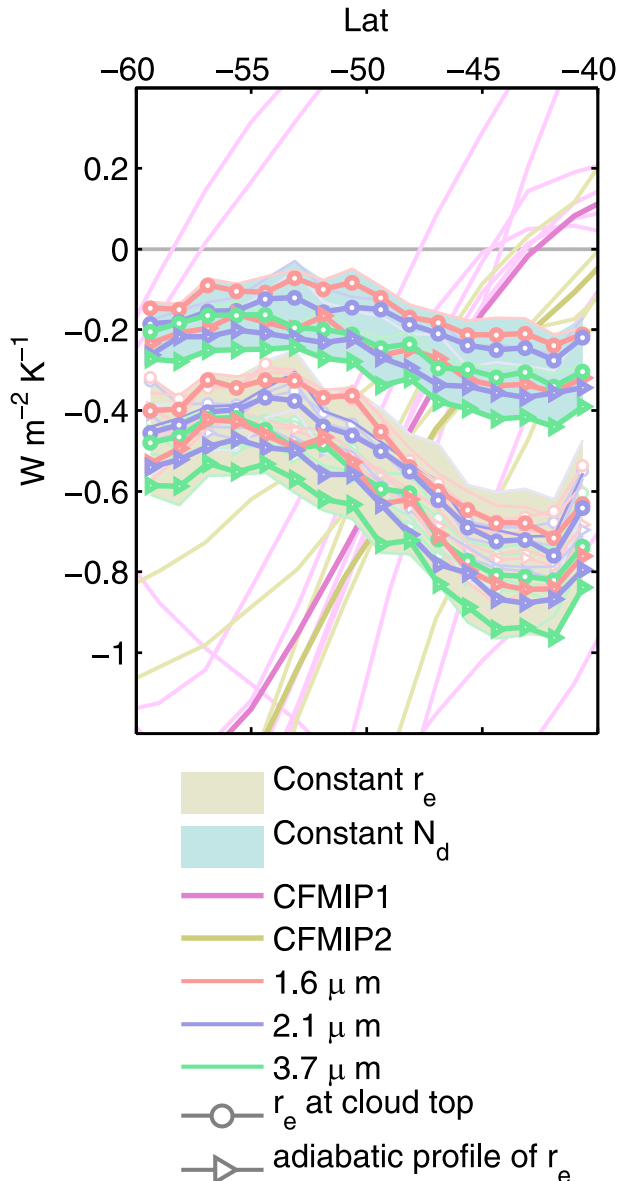


FIG. 2. Change in shortwave flux at the top of the atmosphere (TOA) from a melt proportional to the change in the ratio of liquid to ice water path due to a 1-K warming as predicted by the annual cycle. The analysis is performed individually using the 1.6-, 2.1-, and 3.7- μm retrieval bands of MODIS for r_e and assuming both uniform and adiabatic profiles within the clouds. The analysis is performed both when r_e is held fixed and when the total number of droplets is held constant. Thicker solid lines show change in $\text{SW}^\uparrow$ using the linear fit shown in Fig. 1. Lighter lines correspond to variation of the slope as shown in Fig. 1, and marked light lines assume no change in midlevel clouds. Results from Zelinka et al. (2012, 2013) for the optical depth feedback from CFMIP1 (CMIP3) and CFMIP2 (CMIP5) are shown in purple and yellow. Darker lines give the multimodel mean and lighter lines show individual model feedbacks, which vary widely. See text for further discussion.

on a variety of complicated natural and anthropogenic factors as well as microphysical mechanisms (Carslaw et al. 2013). To demonstrate the sensitivity of the melt feedback to assumptions about the microphysical behavior of the warmed clouds, we examine two simple cases. In the first case, the extra liquid mass resulting from decreases in ice mass is transferred to the existing number of droplets so that r_e increases. In the second case, r_e is held constant and increasing water mass increases the number of droplets. For each of these cases, the melt feedback has been calculated using several different measurements of the mean climate r_e from each retrieval band of Moderate Resolution Imaging Spectroradiometer (MODIS) for retrievals with a solar zenith angle (SZA) less than 65° . Solar zenith angle screening was done to filter for the high SZA bias described in Grosvenor and Wood (2014). A further restriction to scenes with $>80\%$ cloud fraction was also applied. The filtering of MODIS data is further described in Part I. It should be noted that the two cases we have selected to demonstrate the sensitivity to what microphysics occur in a future climate encompass a wide range of possible future states, but the future climate microphysics may still exist outside of these cases. The constant r_e case is in keeping with the notion that cloud droplet size is tolerant to alterations in condensate partitioning due to the complete evaporation of droplets through vapor deposition onto ice within pocket regions of ice formation and that the CCN in the Southern Ocean is unchanged. The constant N_d case is consistent with GCMs with simple cloud nucleation schemes where CCN is constant over oceans (Ekman 2014; Tsushima et al. 2006).

3. Results

Depending on the assumptions made regarding the effective radius of the altered clouds, the increase in $\text{SW}^\uparrow$ due to changes in liquid to ice ratio is between 0.1 and $1 \text{ W m}^{-2} \text{ K}^{-1}$ (Fig. 2). Assuming a constant number of droplets indicates a weaker melt feedback with an increase in $\text{SW}^\uparrow$ between 0.1 and $0.4 \text{ W m}^{-2} \text{ K}^{-1}$. If the effective radius of liquid droplets is held constant the melt feedback varies between an increase in $\text{SW}^\uparrow$ between 0.3 and $1 \text{ W m}^{-2} \text{ K}^{-1}$. The choice of r_e in the basic state climate also affects the melt feedback to a lesser extent, with the smaller base state r_e leading to a larger melt feedback. This significant modulation of the melt feedback estimate due to the variation in microphysical assumptions and mean effective radius highlights the importance of a better understanding of aerosol and cloud processes in the Southern Ocean region as well as the accurate measurement of r_e in the current climate.

The dependence of the melt feedback on microphysical changes is discussed in more detail later in this section.

The optical depth feedbacks from phase 3 of the Coupled Model Intercomparison Project [CMIP3; Cloud Feedback Model Intercomparison Project, phase 1 (CFMIP1)] and phase 5 of CMIP [CMIP5; CFMIP, phase 2 (CFMIP2)] GCM simulations are also presented in Fig. 2. They are calculated using the method of Zelinka et al. (2013), which accounts for rapid adjustments due to CO₂. For consistency, both the melt feedback and the cloud optical depth feedback are presented, with negative numbers indicating increased reflectivity with warming. A large range of cloud optical depth feedbacks is calculated from the CMIP3 and CMIP5 models, and these are shown in the background of Fig. 2. The multimodel-mean cloud optical depth feedback is shown for both CMIP3 and CMIP5. The multimodel-mean cloud feedbacks from Zelinka et al. (2013, 2012) ranges between -1 and $0.1 \text{ W m}^{-2} \text{ K}^{-1}$.

A strong, negative melt feedback appears near 50°S (Fig. 2), which is comparable to the multimodel-mean optical depth feedback predicted by CMIP3 and CMIP5 models. Instead of transitioning rapidly to a near-zero feedback equatorward of 50°S as the CMIP5 and CMIP3 multimodel-mean optical depth feedback does, however, our estimate maintains a strong negative feedback into lower latitudes. The continuation of the negative feedback into lower-latitude regions results from the combination of ice in the basic state climate that can transition to liquid and the stronger insolation. The feedback predicted by our analysis does not begin to disappear until close to 40°S, where the low cloud ice as diagnosed by *CloudSat* and *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIPSO) in the 2C-ICE product also disappears. This is in sharp contrast to the mean optical depth feedback predicted by CMIP3 and CMIP5 models, which is only consistently negative poleward of 50°S in the Southern Ocean and is stronger near 60°S.

These differences may be due in part to additional processes that are simulated in the GCMs but are not accounted for in our melt feedback estimate. These additional processes will be discussed shortly. The discrepancy in the feedback equatorward of 50°S is also consistent with a lack of cloud ice in the climate models. As can be seen in Fig. 3, in comparison several major CMIP5 (Taylor et al. 2012) models' condensed ice water paths are biased low compared to estimates from 2C-ICE. (A list of the CMIP5 models is included in Table S1 of the supplementary material) Other studies of CMIP5 and CMIP3 IWP and LWP found a similar underestimate of the ice water path, although this result is highly sensitive to whether columns flagged as containing precipitation are removed from the satellite estimates (Jiang et al. 2012;

Waliser et al. 2009). In contrast, the CMIP5 models' LWP agrees better with the observed microwave estimates. In the region equatorward of 50°S, many models have little or no low cloud ice. Climate models predict that liquid clouds decrease in water path in a warmed climate while mixed-phase clouds increase in water path (Tsushima et al. 2006; Senior and Mitchell 1993; Mitchell et al. 1989; Wetherald and Manabe 1988). Underrepresentation of cloud ice in climate models means an overrepresentation of liquid clouds that are likely to thin with warming and an underestimation of mixed-phase clouds that are likely to thicken. Thus, the amount of ice that model clouds contain has the potential to be critical for determining the sign of the optical depth feedback and may lead to the strong latitudinal gradient in this feedback diagnosed in CMIP3 and CMIP5 models by Zelinka et al. (2012, 2013). While the biases for the models shown here and for CMIP3 (Waliser et al. 2009) are quite large, it is important to keep in mind that the observed cloud ice water content may also contain large, systematic biases, as described by Chubb et al. (2013) and Jiang et al. (2012) and explored in Part I. It is therefore important to refine observations of tropospheric cloud ice in addition to the model estimates.

4. Discussion

We have estimated the increase in $\text{SW}^\dagger$ in the Southern Ocean due to a change in the partitioning in condensate phase assuming a constant total water path. This simple calculation has estimated the strength of this effect and demonstrated its sensitivity to microphysical quantities. In reality, the increase in water path for mixed-phase clouds under a warming scenario is likely related to the complex and nonlinear feedbacks that occur between cloud microphysics, dynamics, and radiative processes as described in H. Morrison et al. (2011). As mixed-phase clouds warm and begin to contain less ice and more liquid, they should increase in total water path because liquid bolsters several processes that increase the overall water path: liquid precipitates less efficiently than ice, thus removing less water; liquid increases cloud-top cooling, which increases buoyancy-driven turbulent updrafts and condensation; and increased liquid increases longwave warming of the surface and thus surface fluxes of moisture and energy. The exact effect of these processes on mixed-phase clouds in a warmed climate is difficult to predict but should increase water path and strengthen the melt feedback estimated here, causing cloud albedo to increase even more strongly with warming. The mechanism for the reduction in water path of liquid clouds as observed in GCMs by Tsushima et al. (2006) is hypothesized to occur via midlatitude tropospheric drying due to intensified

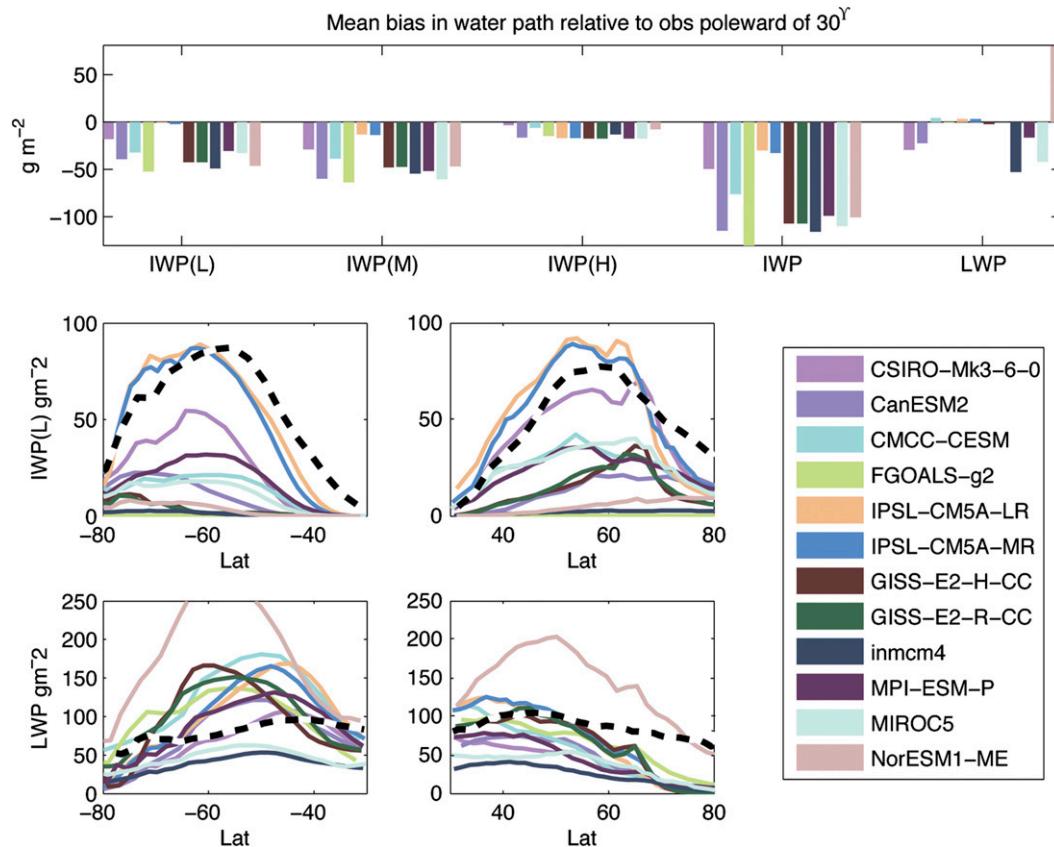


FIG. 3. Water paths for CMIP5 models compared to measurements from 2C-ICE and UWISC. Water paths are area averaged, rather than in cloud. All model data are calculated from the mass fractions of ice and liquid. Observations are from 2C-ICE and UWISC datasets are for the periods 2007–08 and 1998–2008, respectively. All data are over oceans. Dashed lines show the observations from (bottom) UWISC for the total LWP and (middle) 2C-ICE for low cloud IWP. (top) The bar chart shows the mean bias over the latitudes poleward of 30° in both hemispheres for low cloud IWP, middle cloud IWP, high cloud IWP, total IWP, and total LWP.

vertical motions (Mitchell et al. 1989; Wetherald and Manabe 1988). However, it is unlikely that GCMs correctly capture the full complexity of these mechanisms, and thus the magnitude of the GCM negative feedback is likely to be uncertain. There are also several other sources of uncertainty relating to the representation of this feedback in GCMs, which we discuss below.

As shown earlier, our estimated melt feedback is dependent upon the value of the droplet effective radius. At low r_e , optical depth changes more rapidly for a given increase in LWP. This means that predicting the correct r_e in GCMs is likely to be critical to estimating accurate feedbacks because of this effect. This requires the accurate simulation of LWP and N_d for the present day, as well as during climate change. At least broadly, r_e should be more sensitive to variations in the latter quantity. Following the equations presented in Bennartz (2007), if one assumes a liquid cloud in which N_d is vertically uniform and LWC varies adiabatically, r_e should be

proportional to $N_d^{-1/3}$ and to $LWP^{1/6}$, which indicates a higher sensitivity to variations in N_d .

At cloud base, the droplet number concentration is affected by both CCN abundance and cloud updraft speed, although within a system of cloud cells a number of feedbacks can take place between droplet concentration and other cloud properties via microphysical and dynamical pathways. The prediction of future CCN abundance is an extremely difficult problem because it is dependent on a variety of geophysical parameters. For example, global aerosol microphysics models show dimethyl sulfide (DMS) contributing positively to CCN amount over the Southern Ocean in a warmed climate, although the sensitivity of CCN loading to changes in DMS was found to be low by Woodhouse et al. (2010). Scavenging by precipitation was shown by Wood et al. (2012) to be the major sink of CCN below subsidence-driven low cloud, and the bulk of climate models indicate an increase in precipitation in the Southern

Ocean, consistent with a general intensification of the hydrological cycle (Held and Soden 2006). It is difficult to offer predictions of precipitation or biogenic aerosol emissions in an altered climate, and it is unclear to what extent the competing effects of CCN increases and precipitation scavenging might alter the CCN abundance in the Southern Ocean. Similarly, the updraft and LWP response of clouds during climate change are complicated and difficult to simulate.

The glaciation of supercooled liquid by IN is also subject to large uncertainties (Murray et al. 2012). We do not treat these uncertainties in our calculation of the melt feedback, but they bear consideration given their implications for the predictability of the Southern Ocean cloud feedbacks and are briefly outlined here. Southern Ocean concentrations of dust IN are low compared to the concentrations in the Northern Hemisphere, which are nearer to large sources of dust (Atkinson et al. 2013). This is consistent with the lower temperature at which midlatitude Southern Ocean clouds glaciate as compared to midlatitude Northern Hemisphere clouds (Kanitz et al. 2011; Choi et al. 2010) and with the very low concentrations of ice observed from aircraft in clouds in the Antarctic Peninsula region close to 67.6°S (Grosvenor et al. 2012) and in the High-Performance Instrumented Airborne Platform for Environmental Research transects performed south of New Zealand (Chubb et al. 2013), as well as the frequent occurrence of supercooled cloud tops in the Southern Ocean region (A. E. Morrison et al. 2011). Simulated biogenic and dust IN concentrations by Burrows et al. (2013) indicated significant biogenic contributions to IN in the Southern Ocean. Southern continental biomass burning and desertification may also increase IN and glaciate Southern Ocean clouds (Tan et al. 2014; McConnell et al. 2007). Increases in IN might act particularly strongly to increase glaciation in the Southern Ocean due to the relatively IN-poor environment that seems to exist there. While its prediction is uncertain, IN surely play a role in determining the glaciation of mixed-phase clouds in the Southern Ocean and its treatment in GCMs will be of importance in correctly treating the cloud feedback in this region. The glaciation mechanisms of this region may be further complicated by secondary ice multiplication processes such as the Hallett–Mossop process (Hallett and Mossop 1974). The number concentrations of ice produced by this process can be orders of magnitude larger than those produced by heterogeneous IN (Crawford et al. 2012; Crosier et al. 2011; Grosvenor et al. 2012). The representation of this process in climate models is also highly uncertain and likely to also be linked to IN availability.

In the comparison of the melt feedback and the modeled cloud optical depth feedback, it is possible that

the position and intensity of the Southern midlatitude jet may also influence the cloud optical depth feedback. Analysis of observations by Hartmann and Ceppi (2013) found that the increase in zonal wind speed during the period 2000–13 correlated with increased reflected shortwave radiation as detected by CERES; however, this effect is likely linked to interannual variability rather than a long-term shift in jet position. Analysis of GCM shortwave feedbacks does not seem to find much evidence of changes in $SW^{\uparrow}$ being driven by changes in the midlatitude jet. In-depth studies of the Community Earth System Model (CESM) by Kay et al. (2014) have found little impact from jet shifts on the Southern Ocean shortwave climate feedback and find most of the shortwave feedback is explainable by changes in stability, the low-level liquid cloud, and sea ice. Similarly, a survey of CMIP5 models conducted by Ceppi et al. (2014) showed little to no correspondence between shifting jet position and changes in cloud radiative effect further indicating that the changes in the Southern Ocean albedo are governed by low-level cloud.

We have mentioned that our calculation of the melt feedback is simplified relative to the mechanisms that govern mixed-phase cloud. Now that we have discussed the results of our calculation and compared them to GCM estimates of the cloud optical depth feedback, we will outline several important provisos to our methodology. First, the feedbacks between mixed-phase cloud processes are neglected. We consider only the sink of supercooled liquid due to freezing and potential variations in r_e . As noted above the actual cloud climate feedback due to cloud phase changes is likely larger than we present here because of positive cloud-scale feedbacks onto the total water path and cloud fraction as the clouds warm in the absence of changes in IN and CCN. Second, we assume homogeneously distributed liquid and ice within clouds in our calculation of the melt feedback. The effect of changes in condensate phase on $SW^{\uparrow}$ may be altered by the heterogeneity of mixed-phase and liquid clouds. That is to say, the effect of altering the partitioning of cloud condensate phase in favor of liquid will only increase the albedo of mixed-phase clouds. Although we do not consider changes in total water path with warming, the heterogeneity of mixed-phase clouds may also have a significant impact on the change in $SW^{\uparrow}$ due to changes in total water path. Unfortunately determination of the distribution of cloud phase is problematic. Passive sensors frequently have difficulty retrieving the cloud-top phase and cannot determine what phase exists below cloud top (A. E. Morrison et al. 2011). Active sensors must make assumptions as to the assignment of thermodynamic phase within the cloud for water within the mixed-phase

temperature range (Huang et al. 2012). Finally, the relationship between ice to liquid ratio and temperature that we have used to calculate $SW^{\uparrow}$ consistent with warming is derived from observations and is subject to measurement error. As pointed out in Part I, systematic errors are likely to exist in the remote sensing of tropospheric ice in the Southern Ocean (Chubb et al. 2013; Huang et al. 2012; Jiang et al. 2012). Biases may also exist in the microwave liquid water path retrieval (O'Dell et al. 2008) and the vertical profile of liquid water content (Austin and Stephens 2001). Biases in these quantities will lead to an incorrect portrayal of the relationship between ice to liquid ratio and temperature. These last points indicate the importance of improved measurements of the temperature dependence of thermodynamic phase within clouds as well as the prevalence of mixed-phase clouds in the Southern Ocean. An improved understanding of these factors would allow better constraint of the cloud feedback due to transition from ice to liquid cloud condensate in this region.

5. Summary

We have presented calculations of the strength of the change in $SW^{\uparrow}$ owing to ice transitioning to liquid, based upon extrapolations from the observed seasonal cycles of liquid and ice. In addition, the impact of differing microphysical assumptions during such transitions has been examined. The strength of the melting feedback is dependent on the mean r_e in the low cloud, with a noticeably stronger feedback produced by assuming an adiabatic profile within the clouds from which r_e was retrieved and by using the effective radius retrieved by MODIS using the 3.7- μm channel (which produces the smallest retrieved r_e). The dependence of the estimated feedback upon r_e indicates that the correct simulation of r_e in GCMs for both the present and future climate will be important for an accurate phase transition feedback. The sensitivity to r_e also means that the availability of CCN will likely play an important role in governing the strength of the melting feedback. In addition, r_e is also affected by cloud liquid water content and thus the accurate simulation of LWP is also likely to be important.

Although the estimated melt feedback and the GCM cloud optical depth feedbacks are similar in strength, they differ in structure. An important difference between the structures of the GCM cloud optical depth feedback and the melt feedback is the existence of a dipole in the former. In poleward regions, both the GCM multimodel-mean cloud optical depth feedback and the estimated melt feedback were found to be strongly negative. In more equatorward regions, the cloud optical depth calculated from GCMs was found to be weak

to positive while the melt feedback maintained a significant increase in $SW^{\uparrow}$ with warming. Other mechanisms than the ice to liquid transition may explain the difference in structure between the GCM cloud optical depth feedback and the melt feedback computed here; however, the differences between them are also consistent with mechanisms not considered in our estimation of the melt feedback but related to the ice to liquid transition, which we will now discuss.

In GCMs liquid clouds tend to thin as the climate warms, while clouds that initially contain ice increase in total water path as ice transitions to less easily precipitable liquid (Tsushima et al. 2006; Senior and Mitchell 1993). Thus, a given model's optical depth feedback could be sensitive to the treatment of ice in boundary layer clouds as the optical depth feedback would tend to change sign depending on whether the clouds have been diagnosed as liquid or mixed phase. The small/positive optical depth feedback equatorward of 45°S in the multimodel mean of CMIP5/CMIP3 may be due to a combination of the sensitivity of optical depth feedback to cloud phase and too little low cloud ice in climate models. Underrepresentation of mixed-phase clouds, which should become brighter with warming, may lead model optical depth feedbacks to have a positive bias in a given region. If models are underpredicting mixed-phase clouds as indicated by comparison to remote sensing estimates, then the region of climate change-induced optical thickening due to melting may extend farther equatorward than predicted by GCMs. Because of the reliance of remote sensing estimates of boundary layer ice on an assumed partitioning of condensate as a function of temperature (Huang et al. 2012), it is possible that the actual amount of Southern Ocean low cloud ice may be much less than detected by active remote sensing. If this is the case, the optical depth feedback in the Southern Ocean may only be negative at higher latitudes and be relatively weak. The possible dependence of the negative optical depth feedback on the amount of boundary layer cloud ice in the Southern Ocean reinforces the importance of accurate measurement of this quantity. Overall, it is difficult to disentangle the source of differences between the cloud optical depth feedback in GCMs and the melt feedback; however, the estimated strength of the melt feedback and the potential linkage between cloud phase and the sign of the optical depth feedback indicate that the melt feedback should be carefully evaluated as a potentially significant component of the midlatitude optical depth feedback.

The interplay between boundary layer ice cloud amount and the optical depth feedback described above ignores alterations in the regional microphysics. It is found that the melt feedback is likely to be sensitive to

CCN concentrations and it is hypothesized to be sensitive to IN concentrations. The concentrations of CCN and IN in a warmed climate are highly uncertain and may cause the GCM optical depth feedback to be biased in either direction, providing that it is significantly influenced by the melt feedback.

As evinced by the spread in climate model optical depth feedbacks in the Southern Ocean, the prediction of changes in cloud optical depth with warming is a difficult problem. A variety of cloud-scale feedbacks complicate the exact prediction of the future total cloud water path in the Southern Ocean. Microphysical changes to the Southern Ocean region are likely to play an important role, but the nature of these changes is subject to a great deal of uncertainty. We have offered an estimate of the effect of changes in condensate partitioning on the Southern Ocean cloud in the absence of changes in total water path and have shown its sensitivity to both the uncertainty in observations of Southern Ocean microphysics and how the microphysical state of this region will change in a warmed climate. The estimated magnitude of the melt feedback is similar to the magnitude of the cloud optical depth feedback that it is hypothesized to augment, and thus it should be carefully evaluated as it potentially contributes significantly to the cloud optical depth feedback. Overall, our results underline the importance of not only a better understanding of cloud and aerosol interaction processes but also the partitioning of mixed-phase cloud condensate in the Southern Ocean region in order to reasonably constrain the melt feedback contribution to the cloud optical depth feedback.

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