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Key Points:
- A negative shortwave cloud feedback is observed in middle to high southern latitudes
- This negative feedback results from increasing cloud optical depth with temperature
- Models are in qualitative agreement with observations in middle to high latitudes

Supporting Information:
- Supporting Information S1

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Observational evidence for a negative shortwave cloud feedback in middle to high latitudes

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Abstract Exploiting the observed robust relationships between temperature and optical depth in extratropical clouds, we calculate the shortwave cloud feedback from historical data, by regressing observed and modeled cloud property histograms onto local temperature in middle to high southern latitudes. In this region, all CMIP5 models and observational data sets predict a negative cloud feedback, mainly driven by optical thickening. Between 45° and 60°S, the mean observed shortwave feedback (-0.91 ± 0.82 W m^{-2} K^{-1}, relative to local rather than global mean warming) is very close to the multimodel mean feedback in RCP8.5 (-0.98 W m^{-2} K^{-1}), despite differences in the meridional structure. In models, historical temperature-cloud property relationships reliably predict the forced RCP8.5 response. Because simple theory predicts this optical thickening with warming, and cloud amount changes are relatively small, we conclude that the shortwave cloud feedback is very likely negative in the real world at middle to high latitudes.

1. Introduction

The cloud feedback has been identified as the dominant source of uncertainty in model-based estimates of climate sensitivity, primarily because of the shortwave radiation response associated with tropical low clouds [*Boucher et al.*, 2013]. To a large extent, the uncertain cloud-radiative response reflects difficulties in representing the effects of small-scale processes on the cloud water budget in coarse climate model grids using parameterizations. Among the most uncertain parameterized processes are those related to convective mixing [*Zhao*, 2014; *Sherwood et al.*, 2014; *Webb et al.*, 2015] as well as ice-phase cloud microphysics [*Storelvmo et al.*, 2015, and references therein].

Despite these large uncertainties persisting across generations of climate models, some robust signals emerge. In terms of the shortwave (SW) cloud feedback, current models agree on a negative feedback in middle to high latitudes, mainly caused by an optical thickening and brightening of the clouds [*Zelinka et al.*, 2012a; *Gordon and Klein*, 2014; *Ceppi et al.*, 2016]. Warming-induced phase changes in mixed-phase clouds (dominant in middle to high latitudes) are believed to be an important driver of this optical thickening, at least in models [*Tsushima et al.*, 2006; *McCoy et al.*, 2014; *Ceppi et al.*, 2016], although increases in the "adiabatic" cloud water content could also contribute [*Somerville and Remer*, 1984; *Betts and Harshvardhan*, 1987; *Tselioudis et al.*, 1992]. In models, the relationship between optical depth and temperature remains similar across time scales, so that the forced optical depth response in global warming experiments is well predicted by unforced seasonal or interannual fluctuations [*Gordon and Klein*, 2014]. This supports the idea that the cloud optical depth increase in high latitudes is a direct response to warming and suggests that the associated negative SW feedback might be predictable from historical data. To our knowledge, however, the robust optical depth-temperature relationships have not been exploited thus far to predict the SW cloud feedback in models and observations.

The purpose of this paper is to demonstrate that the cloud water increase, and the associated optical thickening and negative SW feedback in middle to high latitudes, can all be detected from historical data in both models and observations in the Southern Hemisphere. Furthermore, the SW cloud feedback in the RCP8.5 experiment is well predicted from historical model simulations in mixed-phase regions, consistent with the time scale invariance of optical depth-temperature relationships found in previous studies. While observational uncertainties and disagreements between satellite products limit our ability to produce accurate quantitative estimates of the SW cloud feedback in the real world, we will show that models and observations are in qualitative agreement on this negative SW cloud feedback.

2. Data and Methods

This study combines observed and modeled cloud property data, all in monthly mean resolution. We first briefly describe the satellite observations. Liquid water path changes are assessed using 20 years of satellite microwave retrievals (UWisc data set) [*O'Dell et al.*, 2008], covering the period January 1989 to December 2008. Additionally, we use cloud amount retrievals, available from three satellite-based data sets: International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1999], Multiangle Imaging Spectroradiometer (MISR) [*Diner et al.*, 1998], and Moderate Resolution Imaging Spectroradiometer (MODIS) [*King et al.*, 2003; *Platnick et al.*, 2003], providing 25, 12, and 14 years of data, respectively. These cloud amount retrievals have been binned into cloud top pressure (or height) versus optical depth histograms. For details on the preparation of these simulator-oriented data sets, see *Marchand et al.* [2010], *Zhang et al.* [2012], *Pincus et al.* [2012], and *Marchand* [2013], as well as Text S1 in the supporting information.

The model data used here include output from the historical and RCP8.5 experiments, where the RCP8.5 response or feedback is based on differences between 1981–2000 and 2081–2100. The 30 models included in this study are listed in the supporting information, Table S1. Only a subset of these models provide cloud property histograms for comparison with observations, and due to limited availability of historical cloud histogram data, we also use Atmospheric Model Intercomparison Project (AMIP) output (see Table S1). These cloud histograms are produced using satellite simulators, which mimic the cloud properties that would be retrieved by a satellite if the modeled clouds existed in the real world (for details, see *Klein and Jakob* [1999], *Webb et al.* [2001], and *Klein et al.* [2013]). We have verified correct simulator implementation in these models as in *Zelinka et al.* [2012b] (see Text S1 for details).

As outlined in section 1, the main goal of this study is to demonstrate the existence of a negative cloud optical depth feedback in middle to high latitudes that is detectable in the context of unforced seasonal or interannual variability. Assuming this feedback is mainly driven by the direct effect of local warming, we estimate the SW cloud feedback in two steps. In the first step, we regress cloud property histograms onto local lower tropospheric temperature (defined as the 500–850 hPa layer mean) in models and observations. The choice of this pressure range is based on the fact that the bulk of cloud water is typically contained in this layer in models [see, e.g., *Komurcu et al.*, 2014; *Ceppi et al.*, 2016]. For models, we use 1981–2000 historical or AMIP data; for observations, the satellite data are regressed onto ERA-Interim reanalysis temperature using the full length of each of the satellite products. The regressions are calculated at each latitude, using data for all months and longitudes linearly interpolated onto the cloud histogram grid. Prior to the regression analysis, we remove the annual mean value at every grid point and average the data over nonoverlapping, 20° wide longitude boxes. This last step ensures that the cloud anomalies are nearly uncorrelated between adjacent longitude points and can be treated as independent realizations in both time and longitude space, which is necessary for an accurate estimation of confidence intervals for the regression slopes.

Note that since some of the satellite instruments do not report values over land or sea ice grid points, only ocean grid points are included in the regression analysis, and we restrict the analysis to the Southern Hemisphere where most midlatitude areas are ocean covered. Furthermore, because instruments measuring solar reflectance (such as ISCCP, MISR, and MODIS) are known to produce large positive biases in cloud optical depth at high solar zenith angles [*Loeb and Davies*, 1996], for MISR and MODIS we exclude points with solar zenith angle $> 60°$ at the time of satellite overpass. For ISCCP, the results exhibit very little sensitivity to the exclusion of high solar zenith angle retrievals (not shown), so such retrievals are included in the analysis. The sensitivity of the results to these choices is discussed in the supporting information.

In the second step, the cloud property histogram regressions are converted to anomalous top-of-atmosphere SW radiative fluxes by multiplying with SW cloud-radiative kernels (described in *Zelinka et al.* [2012b]) and integrating over all 49 (7×7) cloud top pressure-optical depth bins. This yields a cloud feedback in units of W m^{-2} K^{-1}, which we call the "predicted" cloud feedback, and we compare it with the "actual" feedback in RCP8.5 obtained by the approximate partial radiative perturbation method (APRP) [*Taylor et al.*, 2007]. Since the cloud-radiative kernels are functions of surface albedo, we use a 15 year climatology (March 2000 to February 2015) of Clouds and the Earth's Radiant Energy System Energy Balance and Filled clear-sky surface upward and downward SW fluxes [*Loeb et al.*, 2009] to calculate the observed surface albedo. Also, because we assume that the cloud property-temperature relationships are independent of the month of the year, the cloud-radiative kernels are averaged over all calendar months prior to multiplication with the cloud histogram regression matrices.

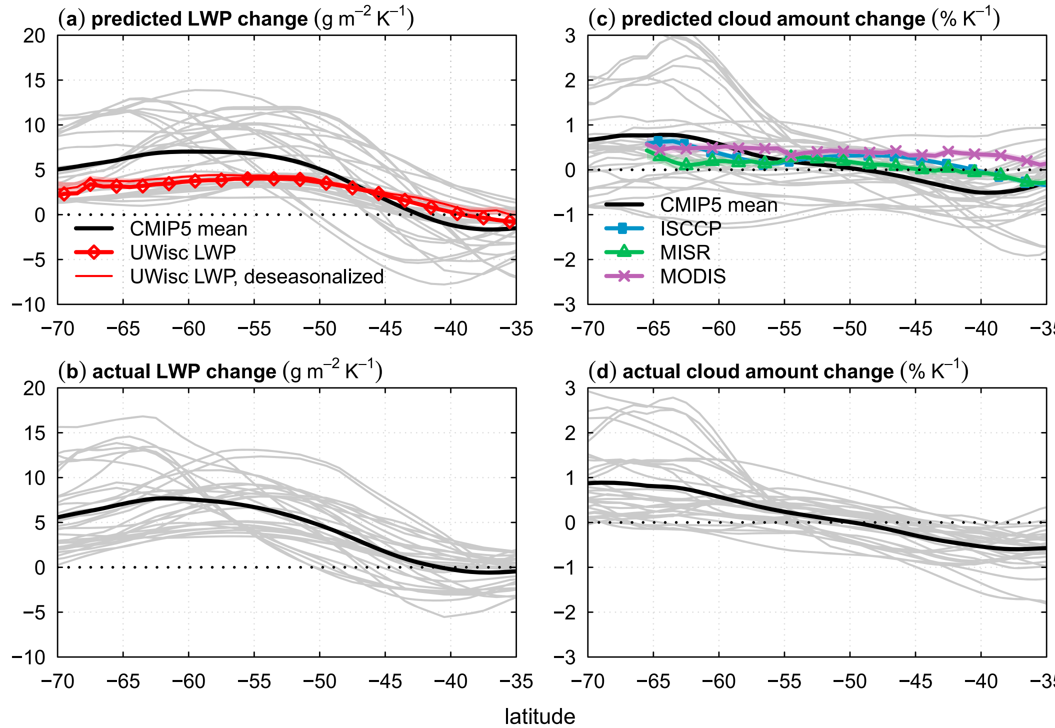

Figure 1. Predicted and actual change in liquid water path (LWP) and cloud amount in CMIP5 models and in observations. (a, c) The predicted changes are based on regressions onto low-level (500–850 hPa) temperature (see section 2); (b, d) the actual changes are calculated as 2081–2100 minus 1981–2000 in the RCP8.5 experiment, normalized by the low-level temperature change in each model. Observed cloud amount is obtained by integrating the cloud property histograms over all cloud top pressure and optical depth bins. Grey curves denote individual models, the thick black curve represents the multimodel mean, and colored curves correspond to observational data sets. For observations, pale color shading denotes the 95% confidence intervals based on a two-sided significance test for the regression slope; these confidence intervals are often not visible due to their narrowness.

3. Results

3.1. Observed and Modeled Changes in LWP and Cloud Amount

We begin by assessing how temperature affects two key cloud properties relevant to SW radiation, cloud liquid water path (LWP), and cloud amount (or fractional coverage), in the middle to high southern latitudes. Models and observations agree on a positive relationship between LWP and low-level temperature (Figure 1a), although the magnitude of the relationship varies considerably among models. Compared to most models, the observed LWP-temperature relationship is weaker in magnitude poleward of about 47°S and stronger equatorward thereof, but is very highly statistically significant, and remains the same whether the seasonal cycle is removed or not (thin and thick red curves in Figure 1a). Because cloud optical thickness is approximately linearly proportional to the LWP [*Stephens*, 1978], the positive LWP-temperature relationships imply optical thickening with warming. Assuming these relationships hold for the forced global warming case, and all other things remaining equal, one would thus expect brighter clouds and therefore a negative SW cloud feedback to occur in middle to high latitudes.

Note that although Figures 1a and 1b shows gridbox mean rather than in-cloud LWP values, the LWP increases are *not* due to cloud amount increases; the results remain qualitatively unchanged if the LWP values are normalized by cloud fraction before calculating the response (not shown). Furthermore, the cloud amount and LWP changes are essentially uncorrelated across models over the 45°–60°S region ($r = 0.06$). While cloud reflectivity is also affected by changes in ice water path (not shown here), the cloud ice response is substantially smaller than the LWP change in RCP8.5 [see *Ceppi et al.*, 2016, Figure 1], suggesting this is a second-order effect in models.

Another potential effect of clouds on SW radiation comes from cloud amount changes. While the cloud amount sensitivity to low-level temperature is very model dependent, the mean model behavior is to increase

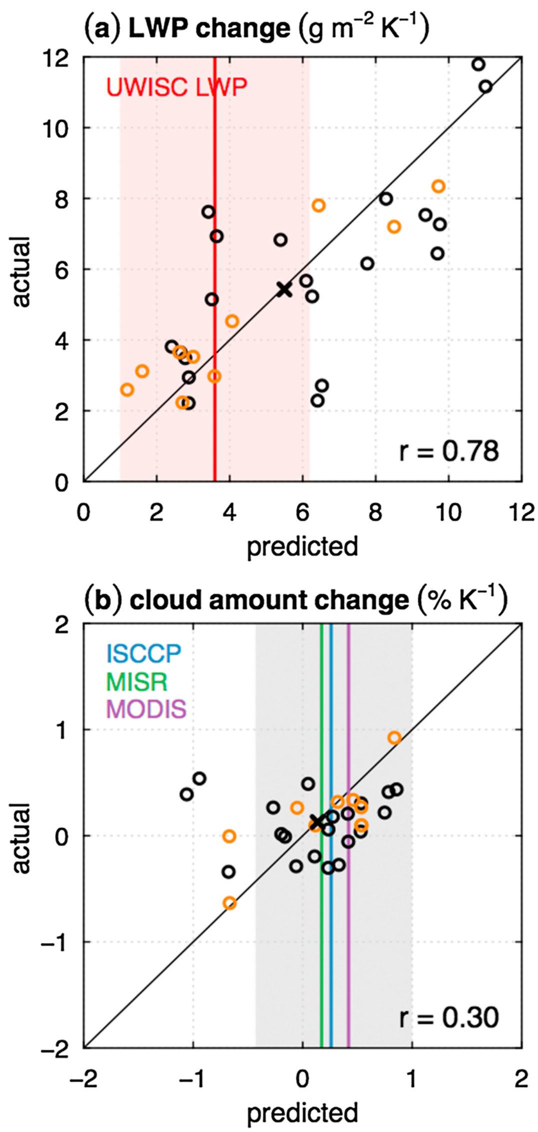

Figure 2. Scatterplots of actual versus predicted (a) LWP change and (b) cloud amount change, both averaged over 45°–60°S. The black crosses mark the multimodel mean. Vertical colored bars denote the predictions associated with observational data sets, and orange open circles indicate the models with cloud property histogram data that were used for the SW cloud feedback calculation in Figures 4 and 5. Shading represents the 95% uncertainty interval for the mean observational estimates, calculated as described in Text S3.

cloud cover poleward of about 50°S with warming, with a weak decrease equatorward thereof (Figure 1c). By contrast, all three satellite instruments show a weak but statistically significant cloud amount increase with warming at all latitudes poleward of about 40°S. Although they agree on the sign of the response, quantitative differences exist, with MODIS systematically indicating the largest cloud fraction increases. It should be noted that in observations, low-level temperature is highly correlated with lower tropospheric stability (as measured by the estimated inversion strength) [*Wood and Bretherton*, 2006] over the southern midlatitudes (not shown). Since low-level stability is an important control on low cloud amount [*Klein and Hartmann*, 1993; *Wood and Bretherton*, 2006], the observed positive cloud amount-temperature relationship may, in fact, reflect the effect of boundary layer stability on low cloud amount, rather than a direct effect of temperature. The influence of low-level stability on low cloud amount appears to be underestimated by models [*Qu et al.*, 2015].

The historical relationships between cloud properties and temperature are useful indicators of the cloud feedback only to the extent that they accurately predict future changes. So are the predicted and actual cloud responses similar? Figures 1b and 1d show the actual LWP and cloud amount response in the RCP8.5 experiment, for comparison with the predicted response. Note that although the RCP8.5 response is not purely temperature driven and also contains a direct CO_2 effect [*Sherwood et al.*, 2015], the cloud response in AMIP4K is very similar (not shown), suggesting that the response is mainly warming induced. Overall, the actual responses are remarkably similar to those predicted from historical model data in an ensemble mean sense. Comparing the responses across models, we find that the predicted and actual LWP changes are well correlated over the 45°–60°S latitude range and close to the one-to-one line (Figure 2a), suggesting that future LWP changes are reasonably well predicted by historical relationships. In this and following scatterplots, we use the uncertainty in the relationship between predicted and actual response in models to derive observational confidence intervals, such that the confidence interval width is proportional to the standard deviation of the residuals relative to the one-to-one line (Text S3).

The relationship between actual and predicted cloud amount change is also positive, but the agreement is weaker than for LWP (Figure 2b). However, we will show that increasing optical depth, rather than cloud amount, is the main driver of the negative SW cloud feedback simulated by models in middle to high latitudes. The scatterplots in Figure 2 demonstrate that historical, seasonal relationships between cloud properties and local temperature are representative of the forced, long-term cloud response to future warming. They also illustrate that in the 45°–60°S region, models generally overestimate the LWP increase compared to observations (vertical red bar in Figure 2a), in some cases by a considerable amount. By contrast, the predicted

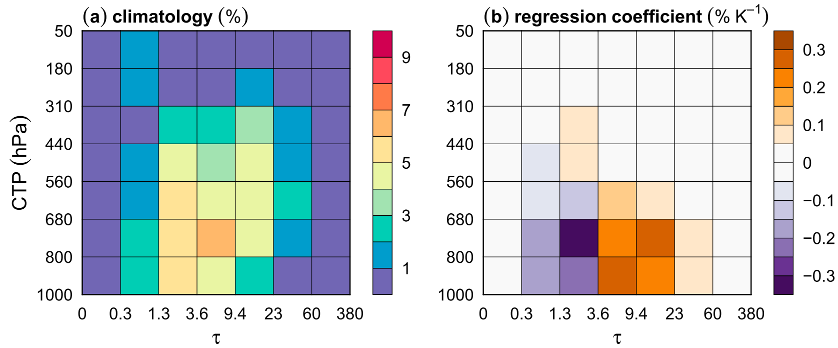

Figure 3. ISCCP cloud fraction histograms binned by cloud top pressure (CTP) and optical depth (τ). (a) Mean climatology and (b) regression coefficient on low-level temperature, both averaged over the 45°–60°S latitude range.

cloud amount change tends to be less positive than in observations, although the difference is small. The implications of these differences on the SW cloud feedback will be discussed in the next subsection.

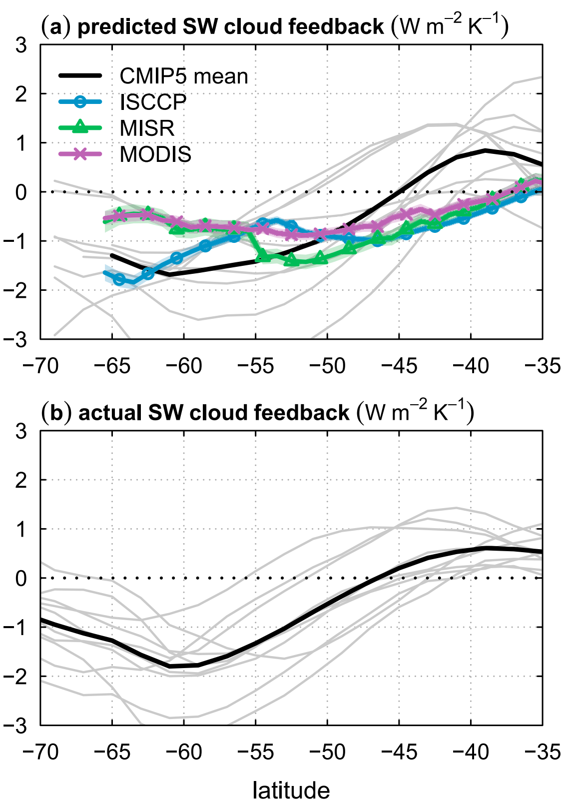

Figure 4. Predicted and actual SW cloud feedback in models and observations. Curves are defined as in Figure 1. The predicted cloud feedback is obtained by multiplying cloud-radiative kernels [*Zelinka et al.*, 2012b] with cloud fraction histograms regressed on temperature. The actual cloud feedback in (b) is calculated using APRP with RCP8.5 data (see text) and includes cloud adjustments to CO_2 forcing. The feedbacks are normalized by the local low-level temperature change rather than global mean surface temperature. For observations, pale color shading denotes the 95% confidence intervals based on a two-sided significance test for the regression slope. In (a), missing data at high latitudes result from the exclusion of ice- and land-covered grid points from the regression analysis.

3.2. Observed and Modeled SW Cloud Feedback

To estimate the SW cloud feedback in models and observations, under the assumption the feedback is mainly driven by local temperature changes, we proceed as in the previous section and regress the cloud amount histograms onto low-level temperature. Given the robust increases in LWP seen in the middle to high southern latitudes, we expect to find a shift in the cloud amount histogram toward higher optical depth as temperature increases. As illustrated in Figure 3, this is indeed the case: over the 45°–60°S region, the cloud amount response mainly consists of a dipole along the optical depth dimension, reflecting a shift of the climatological cloud distribution toward higher τ values. The cloud histogram responses in MISR (Figure S1), MODIS (Figure S2), and the model ISCCP simulators (not shown) are all qualitatively similar. The cloud histogram regression matrices (illustrated in Figure 3b) are multiplied with the SW cloud-radiative kernel at each latitude to yield a predicted SW cloud feedback (see section 2).

As expected from the results above, models and observations predict a negative SW cloud feedback poleward of about 45°S, coincident with the region of increasing LWP with temperature (Figure 4a). While different observational data sets disagree on the magnitude of the negative feedback, especially at the highest latitudes, they agree on the sign and overall latitudinal structure. They are also consistent with the bulk of the model distribution, although the observed negative feedback pattern appears to be shifted toward lower latitudes compared

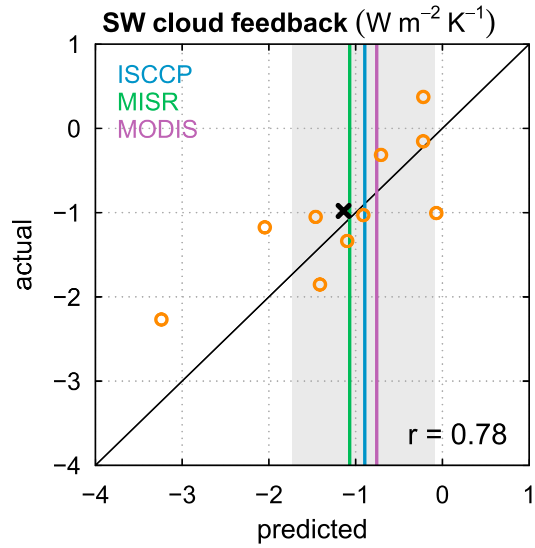

Figure 5. Scatterplot of actual versus predicted SW cloud feedback, averaged over 45°–60°S. Vertical colored bars denote the predictions associated with satellite observations. Grey shading represents the 95% uncertainty interval for the mean of the three observational estimates (Text S3). The black cross marks the multimodel mean. The orange open circles are as in Figure 2.

with most models. This shift agrees qualitatively with the differences in the LWP and cloud amount responses to warming (cf. Figures 1a and 1b). The predicted cloud feedback is remarkably similar to the actual RCP8.5 cloud feedback in this set of climate models both in terms of magnitude and meridional structure (Figure 4b), and the values are well correlated across models in the 45°–60°S latitude band (Figure 5), confirming the idea that historical temperature-cloud brightness relationships are representative of long-term changes [*Gordon and Klein*, 2014].

Averaging the three observational estimates together, we find a mean observed SW feedback of −0.91 ± 0.82 W m^{-2} K^{-1}, significantly negative, and close to the mean actual feedback in RCP8.5 (−0.98 W m^{-2} K^{-1}). It should be noted, however, that the close agreement between observations and models in Figure 5 masks disagreements in the meridional structure of the cloud feedback, as described in the previous paragraph. Such disagreements may have important implications for the models' ability to correctly simulate the spatial distribution of the temperature response.

Using the cloud property histograms allows us to decompose the cloud feedback into effects of cloud optical depth and cloud amount changes (Figure S3), following the method of *Zelinka et al.* [2013]. In general, the optical depth increase explains most of the negative SW cloud feedback in observations and for the multimodel mean, although cloud amount changes do contribute substantially to the intermodel spread in SW feedback. For MODIS, the optical depth and cloud amount effects appear to be of comparable magnitude poleward of 45°S, while the other two satellite data sets predict a larger (more negative) optical depth feedback. Hence, Figure S3 shows that the disagreement in the magnitude of the observed negative cloud feedback in southern midlatitudes between satellite products is mainly associated with the optical depth effect rather than with cloud amount changes. Note that there are two additional terms in this decomposition of the cloud histogram response, one reflecting the effect of cloud altitude changes and another representing a residual term [see *Zelinka et al.*, 2013]; both are very small (not shown).

4. Discussion

The results in the previous section have shown that in middle to high southern latitudes, (1) cloud optical depth increases with warming are detectable in observations and historical model simulations, (2) in models the historical seasonal optical depth-temperature relationships are good predictors of the future SW cloud feedback, and (3) the predicted negative SW cloud feedback is qualitatively similar in models and observations.

The ubiquity of this negative feedback across models and observations is likely at least in part a result of robust phase changes in mixed-phase cloud regions, which cause increases in LWP and optical depth with warming [*Tsushima et al.*, 2006; *McCoy et al.*, 2014; *Storelvmo et al.*, 2015; *Ceppi et al.*, 2016]. While the possible importance of the phase change effect in the real world is difficult to demonstrate due to limitations in the availability and quality of cloud phase observations, changes in microphysical phase conversion rates have been shown to be the main driver of the negative optical depth feedback in models [*Ceppi et al.*, 2016]. Differences in the parameterization of microphysical phase change processes also likely account for at least part of the large intermodel differences in LWP and cloud optical depth sensitivity to warming [*Komurcu et al.*, 2014; *McCoy et al.*, 2015; *Cesana et al.*, 2015].

Although the three satellite data sets are in qualitative agreement on an optical thickening (and associated negative SW cloud feedback) in high southern latitudes, and are in relatively close agreement in a regional mean sense (the 45°–60°S mean feedback ranging between -0.76 W m^{-2} K^{-1} for MODIS and -1.07 W m^{-2} K^{-1} for MISR), the differences between data sets are not negligible locally (cf. Figures 4 and S3), reflecting disagreements in the cloud optical depth response to warming (Figure S4). We believe the differences between observational data sets result from relatively large uncertainties in the satellite retrievals of cloud properties, with the uncertainty sources being specific to each data set. Some known error sources, and their possible impacts on our results, are discussed in the supporting information (Text S2). It should be kept in mind that measurement errors due to illumination and viewing angle, for example, are not included in the instrument simulators in climate models. For this reason, instrument simulators may better reflect the clouds in the models than real satellite observations characterize clouds in nature.

In addition to the uncertainty associated with errors in satellite retrievals, further uncertainty in the magnitude of the real SW cloud feedback results from the imperfect prediction of future responses from historical model data, as illustrated in the scatterplots in Figures 2 and 5; the calculation of the observational confidence intervals is derived from this uncertainty (Text S3). The differences between predicted and actual response result from effects not accounted for by the simple regression on local temperature; an obvious example would be the radiative effect of increasing CO_2 concentrations, but other factors such as atmospheric circulation, lower tropospheric stability, and vertical and horizontal moisture fluxes, to name a few, are likely also contributing to the forced cloud response.

Despite the current shortcomings of cloud property observations, we believe that the positive optical depth-temperature relationships are real and physical for the following two reasons: (1) four independent observational data sets and all CMIP5 models agree on mixed-phase clouds becoming optically thicker (or equivalently, their water content increasing) with warming and (2) in such cold clouds a positive optical depth-temperature relationship is *expected* from relatively basic physical temperature-related mechanisms (phase transitions and increasing adiabatic water content). (Note that while optical depth increases linearly with LWP only assuming constant droplet radius [*Stephens*, 1978], a more realistic assumption of constant particle number also leads to higher optical depth as LWP increases.) With no indication of compensating large cloud amount decreases with warming in the real world, and strong observational and modeling evidence for optical depth increases, we conclude that the shortwave cloud feedback in a future warmer climate will very likely be negative in middle to high southern latitudes.

5. Conclusions

Using historical CMIP5 model data and satellite retrievals of cloud properties, we have shown that as the atmosphere warms, cloud liquid water (and hence optical depth) consistently increase in middle to high latitudes (poleward of ∼45°) in the Southern Hemisphere, with an additional weak cloud amount response to warming. Although models disagree on the magnitude of the cloud liquid water increase, it is present in all models and in observations and is supported by robust temperature-dependent mechanisms (phase changes in mixed-phase clouds and adiabatic cloud water content increases). To estimate the SW radiation response associated with the optical thickening of the clouds, cloud property histograms binned by cloud top pressure and optical depth are regressed on lower tropospheric temperature and combined with cloud-radiative kernels [*Zelinka et al.*, 2012b]. Consistent with the cloud water response, all models and observational data sets predict a negative SW cloud feedback in middle to high southern latitudes, and observations lie well within the model distribution. In the 45°–60°S latitude band, the predicted feedback in observations ranges between -0.76 W m^{-2} K^{-1} (MODIS) and -1.07 W m^{-2} K^{-1} (MISR), with an estimated mean value of -0.91 ± 0.82 W m^{-2} K^{-1}, close to the actual feedback in RCP8.5 (-0.98 W m^{-2} K^{-1}). For models, the feedback predicted from historical seasonal temperature variations is a good predictor of the actual feedback in the RCP8.5 experiment ($r = 0.78$), supporting the idea that a warming-induced cloud optical depth increase is detectable in the historical record.

Observed cloud optical depth-temperature relationships in extratropical clouds have been proposed as a promising potential observational constraint on modeled cloud feedbacks by *Klein and Hall* [2015], who also note that such observational constraints must be supported by a robust, well-understood physical mechanism in order to be credible. In the context of the cloud optical depth feedback, an important question for future work is therefore to clarify the relative importance of phase change effects and adiabatic water content increases in observations and models. This highlights the need for reliable cloud property observations — particularly cloud phase — in sufficient spatial and temporal coverage.

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