Supporting Information for "Observational Constraints on Southern Ocean Cloud-phase Feedback"

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11 **Contents of this file**

14

15 **Introduction**

16   This file includes an example of the procedure for estimating the scattering

17 component of cloud-phase feedback (Text S1). It also contains tables that list the

18 MODIS histogram bin boundaries (Table S1), the names of CMIP6 models

19 analyzed in this study (Table S2), and the cloud-feedback estimates (Table S3).

20

21 **Text S1**

22   Here we show an example to illustrate the method for estimating the

23 scattering component of cloud-phase feedback. The calculations are performed

24 separately for each latitude, calendar month, and cloud-top pressure (CTP) bin,

25 so we consider a single latitude-month-CTP combination from a hypothetical

26 MODIS-like histogram. In this example the histogram has four optical depth (τ)

27 bins for both liquid and ice clouds. Suppose that the climatological cloud fraction

28 for the CTP-latitude-month combination is

29 $$\overline{c_{liq}} = \begin{bmatrix} 2 & 2 & 4 & 1 \end{bmatrix}$$

30 $$\overline{c_{ice}} = \begin{bmatrix} 1 & 2 & 1 & 1 \end{bmatrix}$$

31 in units of %. The climatological total liquid- and ice-cloud fractions are

32 $$\overline{C_{liq}} = \sum_{k=1}^{4} \overline{c_{liq,k}} = 9\%;$$

33 $$\overline{C_{ice}} = \sum_{l=1}^{4} \overline{c_{ice,l}} = 5\%.$$

34 The proportion of liquid cloud in the CTP bin, P_{liq}, is then regressed on the

35 meteorological predictors. Suppose that the regression analysis finds that

36 $\partial P_{liq}/\partial T = 0.04 \,°\text{C}^{-1}$, where T is temperature in the CTP interval. The total liquid-

37 and ice-cloud fraction changes arising from the cloud-phase scattering feedback

38 are

39
$$\frac{\partial C_{liq}}{\partial T} = \frac{\partial P_{liq}}{\partial T}\left(\overline{C_{liq}} + \overline{C_{ice}}\right) = (0.04\,°\mathrm{C}^{-1})(9\% + 5\%) = 0.56\%\,°\mathrm{C}^{-1}$$

40
$$\frac{\partial C_{ice}}{\partial T} = -\frac{\partial P_{liq}}{\partial T}\left(\overline{C_{liq}} + \overline{C_{ice}}\right) = -(0.04\,°\mathrm{C}^{-1})(9\% + 5\%) = -0.56\%\,°\mathrm{C}^{-1}$$

41 The values of $\partial C_{liq}/\partial T$ and $\partial C_{ice}/\partial T$ are then partitioned among the τ bins in

42 proportion to the climatological τ distributions:

43
$$\frac{\partial c_{liq}}{\partial T} = \frac{\partial C_{liq}}{\partial T}\frac{\overline{c_{liq}}}{\overline{C_{liq}}} = 0.56 \times \begin{bmatrix} \frac{2}{9} & \frac{2}{9} & \frac{4}{9} & \frac{1}{9} \end{bmatrix} = \begin{bmatrix} 0.12 & 0.12 & 0.25 & 0.06 \end{bmatrix}$$

44
$$\frac{\partial c_{ice}}{\partial T} = \frac{\partial C_{ice}}{\partial T}\frac{\overline{c_{ice}}}{\overline{C_{ice}}} = -0.56 \times \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} \end{bmatrix} = \begin{bmatrix} -0.11 & -0.22 & -0.11 & -0.11 \end{bmatrix}$$

45 where the units are % °C⁻¹. This procedure is repeated for every latitude-month-

46 CTP combination, and the results are multiplied by the radiative kernels and ratio

47 of local warming to global-mean surface warming (dT/dT_{2m}) to infer the cloud-

48 phase scattering feedback.

Histogram	CTP Bin Boundaries (hPa)	τ Bin Boundaries
Liquid Clouds - Original	50*, 250*, 300, 350, 400, 450, 500, 550, 600, 700, 800, 900, 1000**, 1100**	0, 2, 4, 6, 8, 10, 15, 20, 30, 40, 50, 100, 150
Liquid Clouds - Merged	50*, 150*, 250*, 350, 450, 600, 800**, 1000**	0, 2, 4, 6, 10, 15, 20, 30, 50, 150
Ice Clouds - Original	50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 700, 800, 900, 1000**, 1100**	0, 0.5, 1, 2.5, 5, 7.5, 10, 15, 20, 30, 50, 100, 150
Ice Clouds - Merged	50, 150, 250, 350, 450, 600, 800**, 1000**	0, 1, 2.5, 5, 10, 15, 20, 30, 50, 150

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50 **Table S1.** MODIS histogram bin boundaries. "Original" values are the standard
51 bin boundaries, and "Merged" values are the bin boundaries used in the analysis.
52 *It is assumed that no liquid clouds exist in the 50-150 hPa CTP interval, so the
53 50-250 hPa bin in the Original liquid-cloud histogram is assigned to the 150-250
54 hPa bin in the Merged histogram. **Clouds in the 1000-1100 hPa CTP bin of the
55 Original histogram are assigned to the 800-1000 hPa bin in the Merged
56 histogram.

ACCESS-CM2	CESM2-WACCM-FV2	GISS-E2-2-G	MRI-ESM2-0
ACCESS-ESM1-5	CIESM	IITM-ESM	NESM3
AWI-CM-1-1-MR	CMCC-CM2-SR5	INM-CM4-8	NorCPM1
CAMS-CSM1-0	EC-Earth3-AerChem	INM-CM5-0	NorESM2-LM
CanESM5	FGOALS-f3-L	IPSL-CM6A-LR	NorESM2-MM
CAS-ESM2-0	FGOALS-g3	MCM-UA-1-0	TaiESM1
CESM2	FIO-ESM-2-0	MIROC6	
CESM2-FV2	GISS-E2-1-G	MPI-ESM1-2-HR	
CESM2-WACCM	GISS-E2-1-H	MPI-ESM-1-2-HAM	

57

58 **Table S2.** CMIP6 models used in the analysis. Models are listed by their source

59 ID on the World Climate Research Programme CMIP6 archive (https://esgf-

60 node.llnl.gov/projects/cmip6/).

Feedback	Ice-cloud Component (Wm^{-2}K^{-1})	Liquid-cloud Component (Wm^{-2}K^{-1})	Both (Wm^{-2}K^{-1})	Figure
Temp.-mediated Feedback - Low Clouds	0.12 ± 0.02	0.38 ± 0.33	0.50 ± 0.30	Fig. 3c
Temp.-mediated Feedback - Non-low Clouds	0.39 ± 0.17	-0.23 ± 0.14	0.16 ± 0.22	Fig. 3c
Temp.-mediated Feedback - Total	0.51 ± 0.19	0.14 ± 0.36	0.65 ± 0.32	Fig. 4a
Cloud-phase Scattering Feedback - Low Clouds	0.01 ± 0.01	-0.02 ± 0.02	-0.007 ± 0.004	Fig. 3f
Cloud-phase Scattering Feedback - Non-low Clouds	0.77 ± 0.13	-0.78 ± 0.13	-0.01 ± 0.05	Fig. 3f
Cloud-phase Scattering Feedback - Total	0.78 ± 0.13	-0.80 ± 0.14	-0.02 ± 0.05	Fig. 4a
Feedback	$g + \widetilde{\omega}$ Component (Wm^{-2}K^{-1})	τ Component (Wm^{-2}K^{-1})	Both (Wm^{-2}K^{-1})	Figure
Cloud-phase Scattering Feedback - Total	0.14 ± 0.05	-0.16 ± 0.03	-0.02 ± 0.05	Fig. 4b

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62 **Table S3.** Components of Southern Ocean SW cloud feedback. Feedbacks are

63 spatially and temporally averaged over ice-free ocean between 40°-60°S. "Total"

64 indicates the sum of the low and non-low cloud components. The stated

65 uncertainty is the 95% confidence interval.