

We thank Reviewer 2 for their detailed and helpful comments. The comments provided thoughtful guidance for revising the paper, and we gratefully acknowledge the reviewers' time and feedback. The following response to review addresses each of the reviewers' comments and/or questions.

Our responses are given below with reviewer comments in italics; author response in regular font, and revised text from the paper is provided in blue.

Major Comments:

I think the fact that CPP rises because the fine fraction drops faster than the coarse fraction is an important result. This could easily be shown in an additional figure, or even within Figure 1 using a stacked plot instead of the current good looking but not so informative shaded areas. Within that context, I don't think the authors have made a strong case for a strengthening of the SHWW. If that were the case, one would expect increasing coarse particle concentrations. But this is not the case, CPP increases only because the coarse fraction decreases less than the fine fraction. Basing the conclusions on the CPP alone may therefore be deceptive. Similarly, a southward shift of the SHWW should increase the local (Antarctic) contribution. In line 180, the authors write "A southward shift in the core of the SHWW can simultaneously explain the opposing trends in CPP and total particle concentration ...", but do not proceed to explain this in actual words. I think the authors should take a good look at Lamy et al., 2010 Nature Geoscience, and rethink their interpretation of the data, looking more at the absolute concentration trends and less at the relative CPP. This paper potentially offers a framework that may better explain the trends apparent in the absolute data, and which is still consistent with the studies cited in lines 183-196.

We refocus our argument on the total particle concentration and less so on coarse particle percentage. To do so, we add a new Supplementary Figure (Figure S2) to show the changes between Holocene temperature gradients in the Pacific based on the Osman et al. (2021) dataset. We add the following sentences to Section 4.2 to support our argument.

"Furthermore, we also compare our dust number concentration results using Osman et al. (2021) surface air temperature record throughout the Holocene (11300 – 100 years ago) from the Western and Eastern Pacific Ocean 30 – 55°S similarly to Lamy et al. (2010) to assess temperature (wind) gradients (Figure S2). We find that average temperature gradients steepen, which we interpret to reflect a strengthening of the winds throughout the Holocene. Statistically, the dust concentration record has a significant anticorrelating relationship to both temperature gradients (p-value < 0.01) for both the western and eastern mid-latitudinal Pacific Ocean. However, the South Pole dust concentration has a stronger anticorrelating relationship to the western Pacific Ocean compared to the eastern Pacific Ocean ($r = -0.76$ and -0.65 , respectively). We interpret this relationship to reflect changes in the Westerly Winds shifts and warm water circulation into the south Pacific gyre described in Denton et al. (2021). The small variations between the Western and Eastern Pacific further suggest asymmetrical wind changes, which support the conclusions of Lamy et al. (2010), Kaplan et al. (2016) with a cooling of coastal

South American temperatures throughout the Holocene, and support increased upwelling in Pine Island Bay during the early Holocene Hillenbrand et al. (2017).”

We also add a new Figure S2 shown below with the following caption to support our interpretations

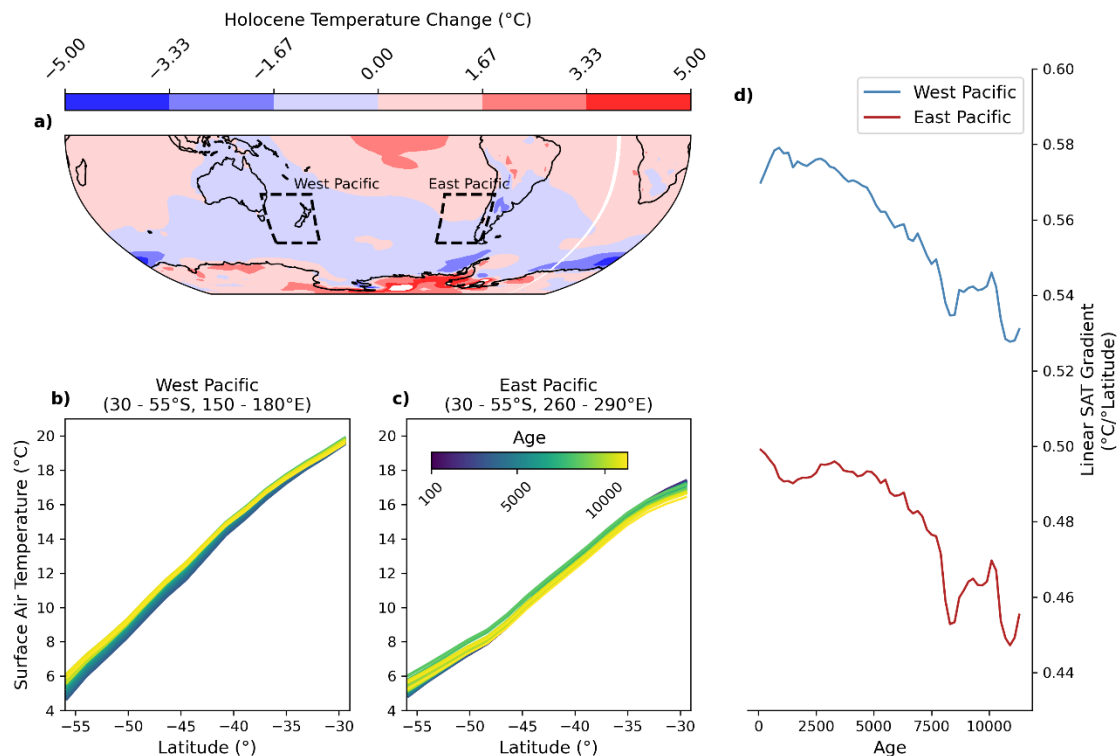


Figure S2 a – d: Surface air temperature data (11300 – 100 years ago) from Osman et al. (2021). S2a) highlights Southern Hemisphere average temperature change from the early Holocene (11300 – 7000 years ago) to pre-Industrial (300 – 100 years ago). S2b and c) are temperature gradients, colored by model age, from the eastern and western Pacific basin (highlighted in S2a). Slope values of linear regressions for each age (°C/°Latitude) are plotted in S2d.

The authors attribute the 3-5 μm coarse fraction of their measured dust particles to local, and the 1-3 μm fine fraction to remote sources. However, recent research has shown that coarser particles can travel a very long way and should not be excluded from remote sources (see recent papers by (Jasper Kok and Yemi Adebisi). That interpretation should therefore be revisited taking into account the recent development in coarse particle transport research.

We reframe the argument by including coarse particle concentration in our results (Section 3.2 and now Figure 1 and in our discussion section (Section 4.4). The coarse particle concentration is similar to the total particle concentration at a different order of magnitude with the small variations between the two trends creating an increase in CPP throughout the Holocene. We now

place the coarse particle concentration within the context of interpretations from Adebiyi and Kok (2020) and Albani et al. (2012). We still interpret the CPP increase as an increase in the SHWW strength given the evidence of the CMIP6 - PMIP4 model agreement results, mid-latitude proxy evidence, and additional data from surface air temperature change from Osman et al. (2021). We now suggest that the coarse dust concentration change was driven by a combination of decreased mid-latitude sources and deflation of exposed Antarctic dust source regions.

Below we include the updated text from Section 3.2 and the new Figure 2 (originally Figure 1).

Section 3.2 Holocene trends in dust deposited at the South Pole

“Coarse particle concentrations have a similar decrease compared to the fine particles, however, at an order of magnitude smaller (total dust concentration slope = ~ -20 # particles mL⁻¹ kyr⁻¹ compared to coarse particle decrease ~ -2 # particles mL⁻¹ kyr⁻¹. The total and coarse particle fractions have similar, albeit slightly different changes throughout the Holocene, whereas there is a $\sim -40\%$ difference between the Early Holocene and Late Holocene for total dust concentration and a $\sim -35\%$ difference between the Early Holocene and Late Holocene for coarse dust concentration. This 5% difference results in an increase in the CPP starting at ~ 7000 years BP.”

Section 4.4 Antarctic ice sheet thinning and CPP increase

We rephrase Section 4.4 to say, “Previous studies have linked CPP variability with changes in air mass advection and/or activation of local dust sources (Delmonte et al., 2020; Koffman et al., 2014; Albani et al., 2012; Wegner et al., 2012; Aarons et al., 2017; Gabrielli et al., 2010). We explore the changes in the SPC14 CPP within the context of the coarse particle concentration. The coarse particle concentration has a similar trend throughout the Holocene as the total particle concentration, suggesting predominantly similar dynamics between coarse and total particle concentration change. However, because the CPP increases throughout the Holocene there must be an additional forcing mechanism(s) acting upon the coarse particles.

The increase in SPC14 CPP begins $\sim 8000 - 6000$ yr B.P. (Figure 1 and 4a) coinciding with the timing of glacial retreat and dust source exposure in lower-elevation regions of Antarctica between $\sim 7500 - 6000$ y B.P. (Figure 4h; Jones et al., 2020; Jones et al., 2015; Stutz et al., 2021; Stone et al., 2003; Hein et al., 2016; Kawamata et al., 2020). For consistency, we recalibrate ¹⁰Be surface exposure ages using production rates from Putnam et al. (2010) and (Kaplan et al., 2011; Supplementary S1). Newly exposed source areas in the Weddell Sea sector are plausible origins of dust in SPC14 given prevailing low-level wind patterns (Lazzara et al., 2012; Winski et al., 2021; Clem et al., 2020). However, because the South Pole has multiple air sources, either moving into the East Antarctic plateau via in the Weddell Sea (Winski et al., 2021; Clem et al., 2020; Lazzara et al., 2012) or across West Antarctica (Nicolas and Bromwich, 2011), we interpret the changes in coarse particles to reflect broader scale Antarctic changes rather than to indicate activation of a specific local source (Figure 2).

Holocene icesheet thinning, leading to exposure of Antarctic dust sources, is primarily related to 1) ocean warming (Jones et al., 2020; Stutz et al., 2021), 2) change in glacial flow patterns (Hein et al., 2016), and/or 3) reduced buttressing (Stutz et al., 2021). Strengthening

and/or southward latitudinal shifts in the SHWW have been shown to increase surface upwelling of relatively warmer circumpolar deep water (CDW) and increase air mass incursions driven by cyclogenesis into the Antarctic plateau (Hillenbrand et al., 2017; Carrasco et al., 2003). It seems likely that contracting, southward shifting, and accelerating SHWW, leading to warming ocean and atmosphere, is linked to the mid-Holocene glacial retreat (i.e., Albani et al., 2012; Koffman et al., 2014) and would increase Antarctic dust sources and the increase in CPP observed in SPC14, however, the coarse dust concentration has a slight decrease and a strong running correlation until ~4000 years BP, suggesting a similar dust source and/or dynamics, which could indicate either 1) deflation of local Antarctic dust sources, similar to Holocene dynamics at Talos Dome (i.e., Albani et al., 2012) or 2) transport from mid-latitudinal sources (Adebiyi and Kok, 2020). As further evidence, the timing of decreasing surface elevation around Antarctica corresponds to increases in SPC14 CPP as a southward shift in the Atlantic ITCZ, representing warming of the Southern Hemisphere relative to the Northern Hemisphere and the Lago Guanaco which was interpreted to reflect latitudinal migrations in the SHWW (Figure 4a, c, and e; Haug et al., 2001; Moreno et al., 2010; respectively). We suggest the CPP increase is primarily related to changes in remote dust contributions in the mid-latitudinal regions and also secondarily related to Antarctic dust source deflation.”

Minor Comments:

Abstract: Not sure if the guidelines for CP abstracts have changed recently, but if allowed, it would be good to add 1-2 sentences after the first sentence about the state-of-the-art of SHWW changes through the Holocene. Also, I recommend against elevating the 20 particles /mL /kyr average number to the abstract. This will be picked up by many people and used as is. The real behavior shown in Figure 1 and discussed by the authors is significantly different than this average value.

We remove the average linear regression values in the abstract and add the following sentence, so the abstract now reads, “The Southern Hemisphere Westerly Winds (SHWW) play an important role in global climate and Antarctic ice sheet dynamics; however, high-resolution proxy reconstructions are sparse. Conflicting evidence suggests SHWW latitudinal change weakening and/or strengthening throughout the Holocene. Dust microparticles preserved in Antarctic ice cores provide valuable paleo-perspectives on SHWW behavior. We present South Pole Ice Core (SPC14) dust records spanning the Holocene. Dust concentrations (1.1 – 5.1 μm) decrease through the Holocene, while the coarse particle percentage (CPP) increase due a relatively larger decrease in finer (1.1 – 3.2 μm) dust. Dust trends, CMIP6-PMIP4 model results, and SH proxy records are consistent with an increase in wind speed south of the SHWW core ($>\sim 51^\circ\text{S}$) across the mid-Holocene. The decrease in dust concentration may reflect weakening winds coupled with precipitation and/or vegetation changes over mid-latitude dust source regions, while the CPP increase may indicate strengthening of the SHWW south of the core. Our findings suggest that following a stable early Holocene, the SHWW began contracting towards Antarctica ~7 – 6 ka.”

Lines 68-70: Please indicate the time resolution of the resulting dataset.

We add the following statement to the following sentence, “Uncertainty during the Holocene is ± 18 years while between 1800 – 3100 years BP the uncertainty increases to ± 25 years (Winski et al., 2019). There while the CFA can produce sub-annual resolution, we resample the data using the median value to 50-year intervals.”

Lines 72-76: This first sentence doesn't make much sense (particle shape does not cover the Holocene?). And the second sentence doesn't follow from the first one (therefore,...). Please clarify these two sentences. Also, the choice of 2-3 μm for the FPP or CPP cutoff in the Delmonte papers is based on the size-distributions shown in Fig. 3 of Delmonte et al., 2002 (Climate Dynamics). To justify the same cutoff (and generally, for good measure), it would be good to show the size distribution from this core as well.

We add, “We use a spherical particle shape assumption to facilitate comparison to other Antarctica ice core particle records that include a volume assumption (i.e., flux) using particles that range between 1.1 – 5.1 μm due to the particle number concentration distribution (Figure 1e). We use particle number concentration measured between 1.1 – 5.1 μm and CPP (defined as number of particles mL^{-1} $[3.2 - 5.1] / [1.1-5.1] \mu\text{m diameter} \times 100$) following other East Antarctic studies due to the similarity of the South Pole particle flux to other East Antarctic core records (Figure 1e; i.e., Delmonte et al., 2020).”

Line 83: 1850 – 2014 AD is the historical simulation, not PI. Did you compare to PI or to historical?

As we have received a similar comment from Reviewer 1, we reran the models with the piControl to more accurately represent change from the mid-Holocene to the pre-Industrial period. All text has been appropriately corrected to reflect the change in model runs. The updated runs have been included in the new Figure 4 (originally Figure 3).

Line 84-85: That method is very confusing and badly described. What were the positive values replaced with? Positive differences mean that pi values are higher than MH, not a change in time. If all negative values are replaced by zero then how can you assess if there is an increase/decrease in a variable? Please clarify.

We clarify by changing the sentence to, “We replace all positive values with a value of 1, which signifies an increase with time, and replace all negative values with a 0 and sum all model runs. Our method allows us to assess if the models agree to an increase/decrease in each climate variable rather than assessing the magnitude of change between each model.

Table 1: Add length of simulation used for pi and mh.

Length of simulation has been added to Table 1 along with experimental IDs (Reviewer 1). We include the updated version of the table below.

Model	Institute	Time Resolution	Grid Size		Model Run Time		Variables
			Latitude (°)	Longitude (°)	mid-Holocene	piControl	
ACCESS-ESM 1-5 or CM2	Commonwealth Scientific and Industrial Research Organization, Australia	Amon	1.25	1.88	501 - 800	101 - 0600	pr, sfcWind, tas
AWI-ESM-1-1-LR	Alfred Wegner Institute, Germany	Amon	1.85	1.88	3106 - 3205	1850 - 1954	pr, sfcWind, tas
FGOALS-f3-L	Chinese Academy of Sciences, China	Amon	1	1.25	720 - 1219	600 - 1160	pr, sfcWind, tas
GISS-E2-1-G	Goddard Institute for Space Studies, USA	Amon	2	2.5	2900 - 3199	4150 - 5000	pr, sfcWind, tas
INM-CM4-8	Institute for Numerical Mathematics, Russian Academy of Science, Russia	Amon	1.5	2	1880 - 2079	1850 - 2380	pr, sfcWind, tas
IPSL-CM6A-LR	L'Institut Pierre-Simon Laplace, France	Amon	1.27	2.5	1850 - 2399	1850 - 2349	pr, sfcWind, tas
MPI-ESM1-2-LR	Max Planck Institute for Meteorology, Germany	Amon	1.85	1.88	1001 - 1500	1850 - 2849	sfcWind
MRI-ESM2-0	Meteorological Research Institute, Japan	Amon	1.11	1.13	1951 -2150	1850-2550	pr, sfcWind, tas
NCAR - CESM2	National Center for Atmospheric Research, USA	Amon	0.94	1.25	0 - 700	1 - 1200	pr, sfcWind, tas
NUIST - NESM3	Nanjing University of Information Science and Technology, China	Amon	1.875	1.875	1798 - 1897	500 - 0999	pr, tas
NorESM2-LM	Norwegian Climate Centre	Amon	1.875	2.5	2101 - 2200	1600 - 2100	pr, tas

Line 95: Here would be a good place for a size-distribution graph. In particular to indicate how much of the dust is finer than 1.1 μm (even if it's not actively measured in the Klotz device) and how much is coarser than 5.1 μm . Incidentally, naming the 1-5 μm fraction “fine” dust is a bit confusing when the authors name the 3-5 μm fraction “coarse”. Below, the authors use mostly the word “dust” (like dust flux), so it would probably be best to just define here that dust means the 1.1-5.1 fraction for the rest of the document.

We have added a new Figure 1e that displays particle size distributions. For clarity we remove the use of “fine” to describe dust concentration and replace any instance of fine particle number concentration to **total** particle number concentration. The new figure can be seen below.

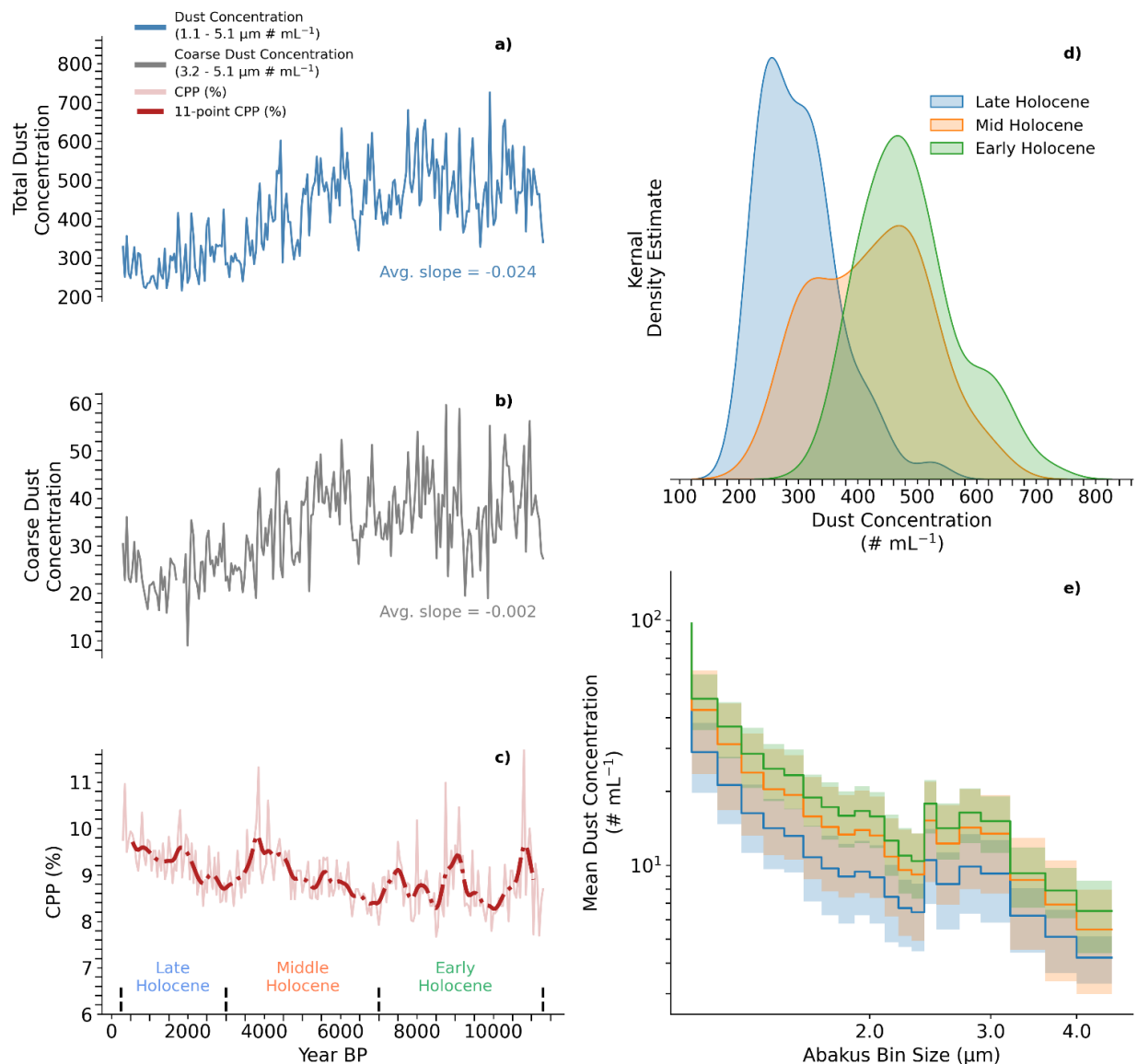


Figure 2a – e: 2a) 50-year median resampled SPC14 dust concentration (1.1 – 5.1 μm # particles mL^{-1} ; blue line), 2b) coarse particles (3.2 - 5.1 μm # particles mL^{-1} ; grey line), 2c) 50-year median resampled CPP (light red) and CPP 11-point rolling Gaussian mean (2 σ ; red dashed line), 2d) total dust # particles mL^{-1} concentration distributions, and 2e) total dust # particles mL^{-1} size distributions by time period. The figure is limited to 11,300 – 250 years BP to highlight Holocene variability recorded in the South Pole annually resolved record. Inset shows histograms of dust concentration from each of the three time periods highlighted in the record. Note the bimodal distribution during the mid-Holocene highlighting the transition from early to late Holocene. Average median absolute deviation (MAD) for the particle concentration is ~ 84 (Figure S1).

Lines 153-154: I don't understand these grids very well. Could you show them in Figure 2?

We use the term “grid” as a term to describe the sector of Antarctica since all directions could be described as “north” or “south”. We replace the use of “grid” with the respective ocean sector (i.e., Atlantic, Pacific, or Indian) for clarity.

Line 159: Fluctuations are not advected. Please rephrase

Per comments from Reviewer 1, we replaced these sentence (158 – 160) with the following statement, “While we recognize that some air masses and dust particles can be sourced from the East Antarctic Plateau, this area would not be the primary source of reduced dust emission during the mid-Holocene since southern South America and Australia are the primary sources of dust during the Holocene and modern period (Wegner et al., 2012; Vecchio et al., 2024; Delmonte et al., 2020). Rather we suggest that the decrease in dust concentration was driven by reduced SHWW activity in the wind in the mid-latitudinal regions (Figure 4).”

Figure 3: An aesthetic suggestion: If you copy-paste your data from 0 deg longitude to an additional column at 360 deg longitude, you avoid the white slice between 358 and 0 deg in the figure.

We have removed the white slice in Figure 4 (originally Figure 3).

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