

Article

The Influence of Meltwater on Centennial Variability of Australian Summer Monsoon Precipitation and Its Relevance to Sustainable Water Resources and Climate Adaptation

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Abstract

Research on centennial-scale precipitation variability within the Australian summer monsoon (AUSM) remains limited, particularly regarding its driving mechanisms and the sustainability-relevant implications for long-term water security and climate adaptation. Here, we use the TraCE-21ka transient simulation, which credibly reproduces the centennial periodicities documented in Holocene proxy records, to attribute the physical drivers of AUSM centennial variability. Attribution is conducted by contrasting the all-forcing (AF) simulation with four single-forcing experiments that isolate the effects of orbital parameters, ice sheets, meltwater flux, and greenhouse gases. Among these experiments, the meltwater-forcing run best reproduces the centennial periodicities found in the AF simulation, indicating that meltwater input is the leading contributor to Holocene AUSM centennial variability. We further identify a dynamical pathway in which Atlantic Meridional Overturning Circulation (AMOC) variability acts as the key mediator linking meltwater perturbations to Australian hydroclimate. The enhanced AMOC amplitude during the meltwater interval (0.14 at 9–8 ka BP), compared with much weaker fluctuations during the non-meltwater interval (0.01 at 4–3 ka BP), is accompanied by a ~200-year periodicity in AUSM precipitation. This periodicity arises through an interhemispheric teleconnection: a strengthened AMOC cools Southern Hemisphere sea surface temperatures, reduces moisture availability for northern Australia, and promotes large-scale subsidence that suppresses monsoon rainfall. By contrast, during 4–3 ka BP, when meltwater forcing was negligible, weaker AMOC variability coincides with warmer Southern Hemisphere sea surface temperature (SST), favoring cyclonic circulation over northwestern Australia, enhanced moisture convergence, and stronger ascent, ultimately intensifying AUSM precipitation. Beyond advancing process understanding, these results provide a sustainability-oriented framework for interpreting low-frequency hydroclimate variability relevant to Australia's water resources and climate adaptation. Specifically, the identified meltwater–AMOC–SST–AUSM pathway offers a physical basis for developing and evaluating long-horizon indicators of monsoon-driven rainfall variability, informing monitoring strategies and scenario planning for drought–flood risk management, water allocation, and climate-resilient infrastructure. By linking centennial-scale monsoon variability to an identifiable remote driver, this study contributes to quantifying and contextualizing natural hydroclimate variability that can confound near-term trends, thereby supporting more robust sustainability assessments, adaptation policy design, and integrated water-resource management under ongoing climate change.



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1. Introduction

The Australian summer monsoon (AUSM) delivers substantial rainfall to inland regions, sustaining local livelihoods and supporting socio-economic development. This hydrological importance has motivated extensive research into the characteristics, drivers, and mechanisms of AUSM precipitation, as such knowledge informs efforts to mitigate climate-related risks. The scientific and societal relevance of understanding AUSM variability is further underscored by the system's role as a key component of the global monsoon. Its broader climatic significance therefore positions the AUSM as a critical entry point for examining large-scale monsoon responses to climate forcing.

Globally, paleoclimatic archives dating to approximately 550 ka BP—including lakes, fluvial deposits, marine sediments, speleothems, and vegetation records—provide essential constraints on past hydroclimatic change [1,2]. This diversity of archives is echoed in the Kimberley region of northwestern Australia, where peat deposits offer an additional means of reconstructing local environmental conditions. The region's climate is dominated by the AUSM [3,4], which delivers roughly 70% of its ~1000 mm annual rainfall during summer. This monsoon dependence, combined with high evapotranspiration (~1900 mm), contributes to persistent semi-arid conditions. Such hydrological sensitivity also exposes local sediments to drought, intense rainfall, and flooding, processes that frequently disrupt depositional continuity [5]. This instability limits the availability of high-resolution archives, leaving most detailed reconstructions reliant on speleothem records [6–8]. The ~15,000-year Black Springs record exemplifies the climatic insights these materials can yield [9,10], although their highly localized nature constrains broader regional inference. Pollen and sedimentary sequences from northwestern Kimberley provide additional evidence, yet their interpretation remains contested. These limitations collectively hinder the development of a comprehensive understanding of Holocene AUSM dynamics across the region.

On longer timescales, external forcing exerts a dominant influence on monsoon variability [11]. Orbital variations, particularly precession-driven insolation changes [12–14], govern hemispheric radiation balance and produce antiphased humidity patterns between the Northern and Southern Hemispheres. This orbital control has been widely demonstrated in both modeling studies and proxy analyses. Modeling results consistently show a strong AUSM sensitivity to precession and obliquity [15–17], with enhanced early-Holocene humidity commonly attributed to the precessional cycle. Proxy evidence from sediment carbon flux and pollen records further substantiates this influence, exhibiting spectral peaks at 19, 23, 41, and 100 ka that align with Milankovitch periodicities [18–20].

Despite these advances, most Holocene reconstructions of centennial-scale AUSM precipitation variability remain proxy-dependent, limiting understanding of the underlying drivers and mechanisms. This limitation highlights the value of numerical simulations in elucidating causal processes. To address this gap, we employed the TraCE-21ka transient simulation to investigate the characteristics and controls of centennial-scale AUSM variability. A bandpass filter was applied to isolate the centennial signal (approximately 100–1000 years), removing higher-frequency variability and lower-frequency trends. This framework enabled an assessment of the spatiotemporal structure of centennial precipitation variations, followed by an attribution analysis comparing the all-forcing (AF) experiment with four single-forcing experiments. These analyses culminated in an evaluation of

the physical pathways through which external forcings modulate AUSM precipitation on centennial timescales.

2. Data and Methods

The TraCE-21ka simulation incorporates boundary conditions that include Earth's orbital configuration, greenhouse gas concentrations, ice-sheet extent, and meltwater fluxes [21]. This experimental configuration is implemented using a model with a horizontal resolution of approximately $3.75^\circ \times 3.75^\circ$ (T31) and a dynamic vegetation module that represents 15 plant functional types. Building on this framework, the all-forcing experiment reproduces key features of deglacial climate evolution, including Southern Ocean and deep-ocean dynamics as well as warming trends over Greenland, Antarctica, and the tropical Pacific [21–23]. The capacity of the TraCE-21ka dataset to capture these large-scale climate responses has led to its widespread application in paleoclimate studies [24,25], reinforcing its suitability for investigating long-term variability. The external forcing histories applied in the simulation—orbital parameters [19], greenhouse gases [26], ice sheets [27], and meltwater fluxes [28] are shown in Figure 1.

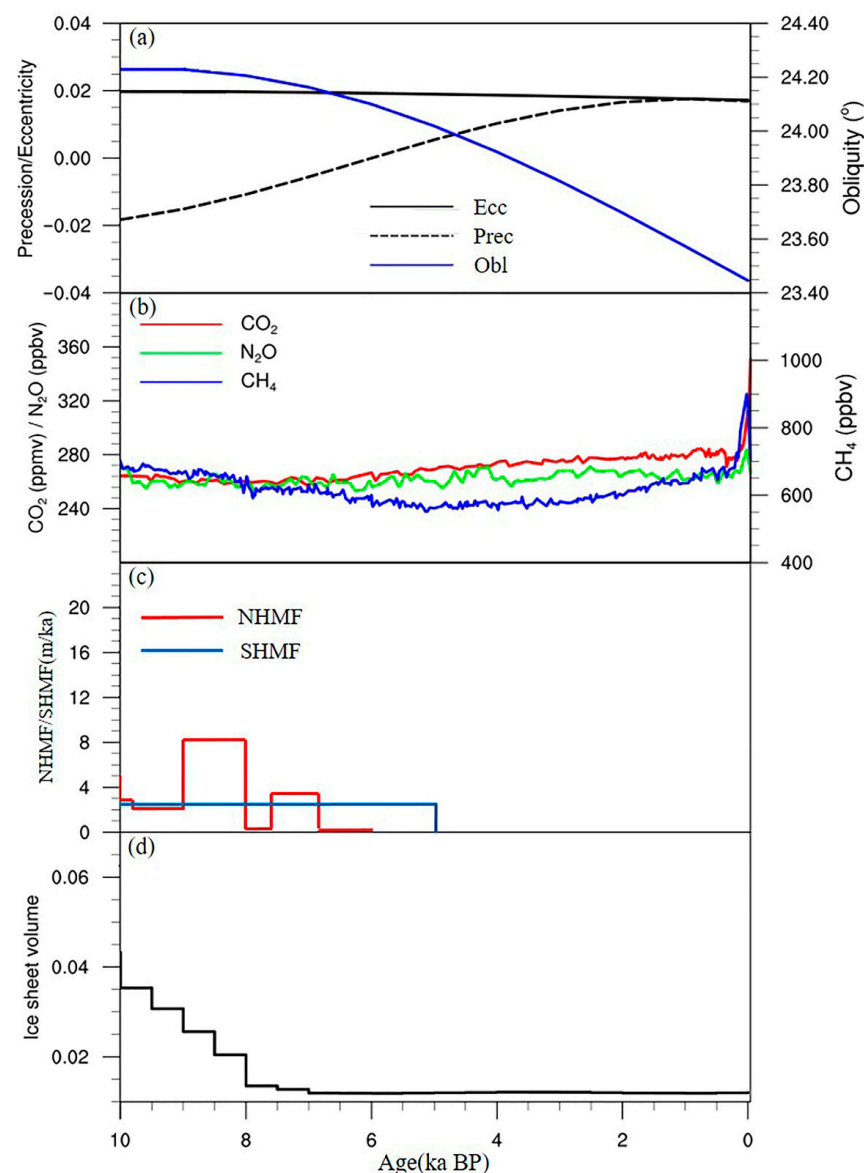


Figure 1. The time series of major individual forcings in the AF experiment and four single forcing experiments during the Holocene. (a) Earth's orbital parameters include the obliquity (blue), eccentricity

(black solid line), and precession (black dash line) [19]. (b) Greenhouse gases include CO₂ (red), N₂O (green), and CH₄ (blue) [26]. (c) Northern Hemisphere Meltwater Fluxes (NHMFs; red) and Southern Hemisphere Meltwater Fluxes (SHMFs; blue) [28]. (d) Ice-sheet volume (dimensionless) [27].

Meltwater forcing exerts a major influence on the Atlantic Meridional Overturning Circulation (AMOC), weakening northward heat transport and inducing Northern Hemisphere cooling. This cooling signal aligns with AMOC reconstructions and Greenland ice-core records, which both indicate that the last glacial termination occurred around 10 ka BP. To simulate the climatic effects of meltwater pulses, freshwater fluxes were prescribed in TraCE-21ka. A modest background flux of 2.5 m/ka (sea level rises by 2.5 m per thousand years) was applied to the Antarctic region from 11.7 to 5 ka BP to minimize its direct impact on the Northern Hemisphere. Stronger perturbations were introduced between 9 and 8 ka BP to represent the abrupt drainage of proglacial lakes, with fluxes reaching approximately 10 m/ka. Following the final major Northern Hemisphere meltwater events at 7.6 and 6.8 ka BP, the flux was reduced to about 5 m/ka. Through these prescribed anomalies, the simulation demonstrates credible sensitivity to freshwater perturbations and successfully captures extreme climatic events, supporting its use in paleoclimate applications. The Australian summer monsoon index (AUSMI), used to quantify monsoon strength, is defined here as the December–February mean precipitation averaged over 10–20° S and 115–150° E [29].

Reliable paleoclimate records reflecting AUSM variability are scarce in northern Australia. The present study employs two high-resolution speleothem records that preserve clear monsoon signals (Table 1). The first is a stalagmite $\delta^{18}\text{O}$ series from KNI-51 Cave in eastern Kimberley (Figure 2) [7], a region strongly influenced by the northwest monsoon. The second record, C126 from Cape Range Peninsula [30], likewise provides a continuous archive of hydroclimatic variability associated with monsoon activity. Together, these records offer robust constraints for evaluating past AUSM variability.

Table 1. The proxy data of the AUSM precipitation used in this study.

Site Name	Location	Time/Year BP	Resolution/Year
Cave KNI-51	15.18° S, 128.37° E	8806~4028	4~30
Cave C126	22.1° S, 113.9° E	10,000~5736	6~97

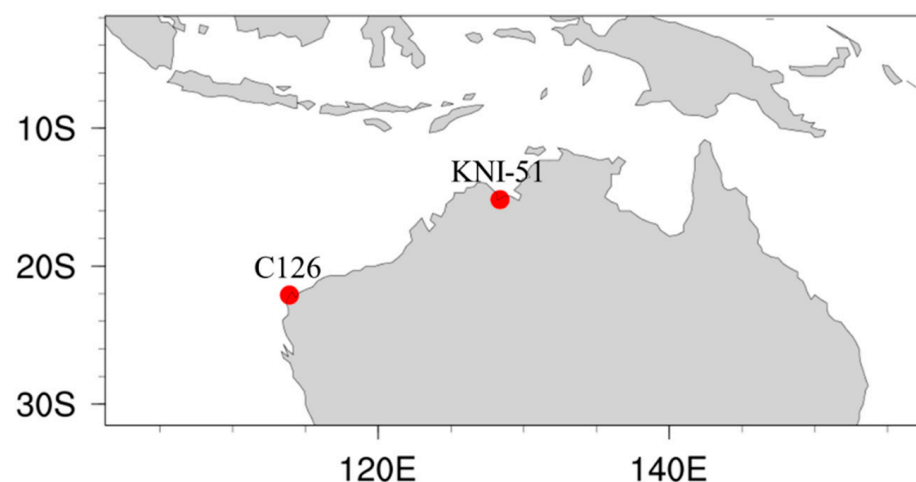


Figure 2. The location of KNI-51 and C126 [7,30].

3. Results and Discussion

3.1. Characteristics and Causes of Centennial Variations in AUSM Precipitation

To identify centennial-scale periodicities in Holocene AUSM precipitation, power spectral analyses were applied to both proxy-based reconstructions and model simulations. These spectra, shown in Figure 3, derive from AUSMI anomalies of the KNI-51 (a) and C126 (b) speleothem records, calculated relative to their respective Holocene means [7,30]. KNI-51 uses stalagmite $\delta^{18}\text{O}$ as the proxy. The KNI-51 cave extends to ~15 m below the surface at its deepest point and has an approximate length of ~600 m. The floor elevation of Cave C126 is ~54 m. The resulting spectra reveal pronounced peaks near 100, 150, and 200 years in the KNI-51 record, while C126 reveals significant 100 year, 150 year, 200 year, 250 year, 300 year, 450 year, and 600 year periodicities. This distribution of centennial peaks provides a benchmark for evaluating the model output. Figure 4 presents the AF experiment spectrum, which contains major peaks at 100, 150, 200, and 250 years—the same centennial scales detected in the proxy data. This alignment between proxy-derived and simulated periodicities, particularly around 100–250 years, indicates that the AF simulation captures the dominant centennial-scale structure of AUSM variability. Such agreement supports the credibility of the simulated monsoon response.

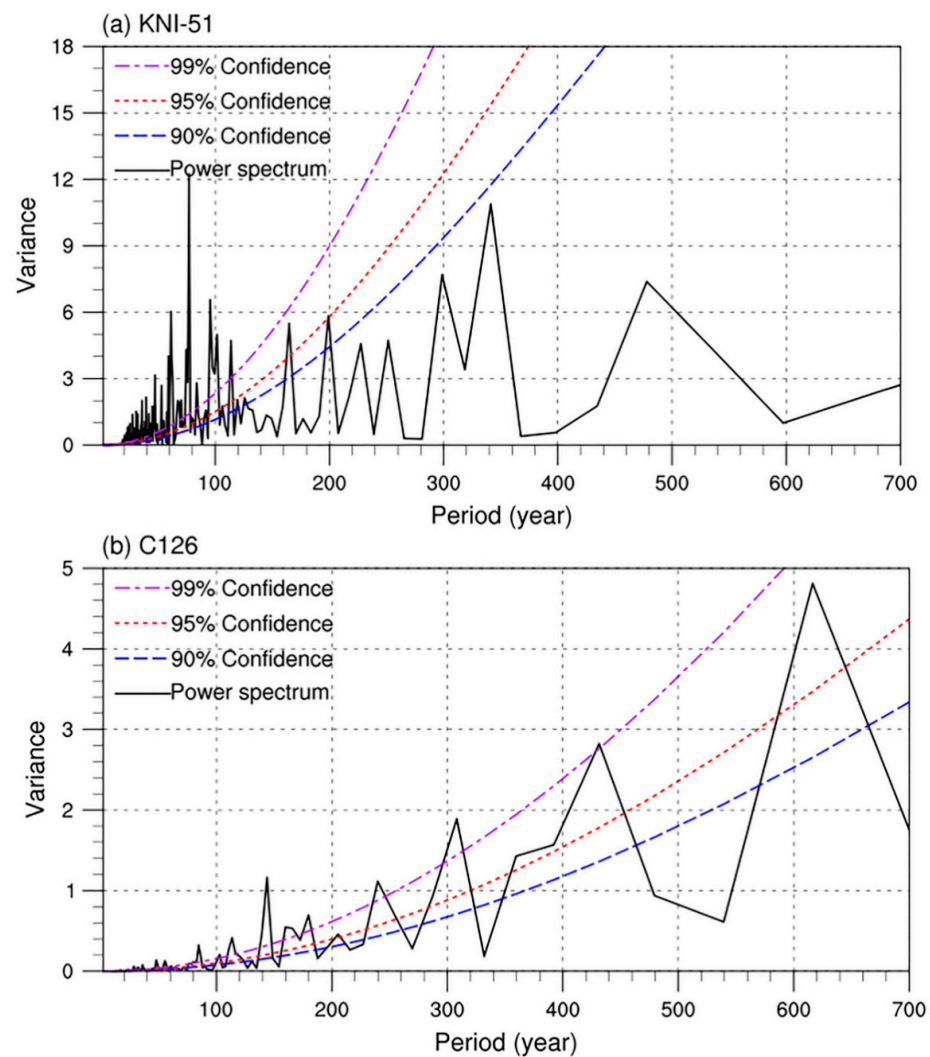


Figure 3. The power spectra of the AUSMI anomalies of KNI-51 (a) and C126 (b) [7,30]. The AUSMI anomalies of KNI-51 are with respect to AUSMI values from 8806 to 4028 year BP. The AUSMI anomalies of C126 are with respect to AUSMI values from 10,000 to 5736 year BP. The blue dash line, red dot line, and purple dot–dash line indicate confidence levels at 90%, 95%, and 99%, respectively.

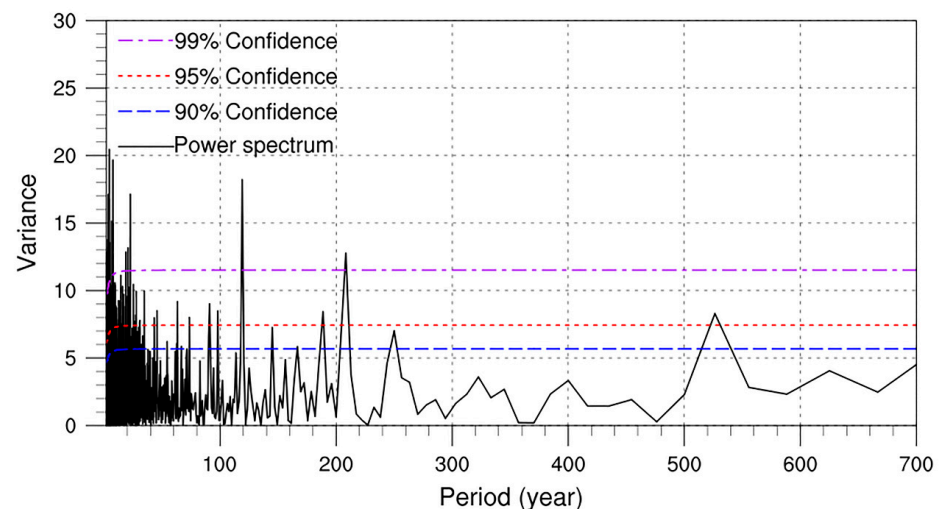


Figure 4. The power spectra of the AUSMI anomalies in AF experiment during the Holocene. The AUSMI anomalies are with respect to AUSMI values during the Holocene. The blue dash line, red dot line, and purple dot–dash line indicate confidence levels at 90%, 95%, and 99%, respectively.

Attribution of this modeled variability was pursued through a systematic comparison of the AF experiment with four single forcing experiments. Figure 5 presents the corresponding time series of AUSMI anomalies (relative to the Holocene mean) after applying a 91–950 year bandpass filter. The black, blue, red, green, and orange lines represent the AF, ORBIT, ICE, GHG, and MWF experiments [28], respectively. Distinct evolutions of centennial-scale amplitude are evident across the experiments. In the AF experiment, the amplitude of AUSM precipitation variability was strongest during the mid-Holocene, relative to the early and late Holocene. In contrast, the ORBIT experiment exhibited maximum amplitude in the early Holocene, with reduced variability thereafter. In the ICE, GHG, and MWF experiments, however, the amplitude remains relatively stable throughout the period, forming a contrast with the pronounced changes seen in AF and ORBIT.

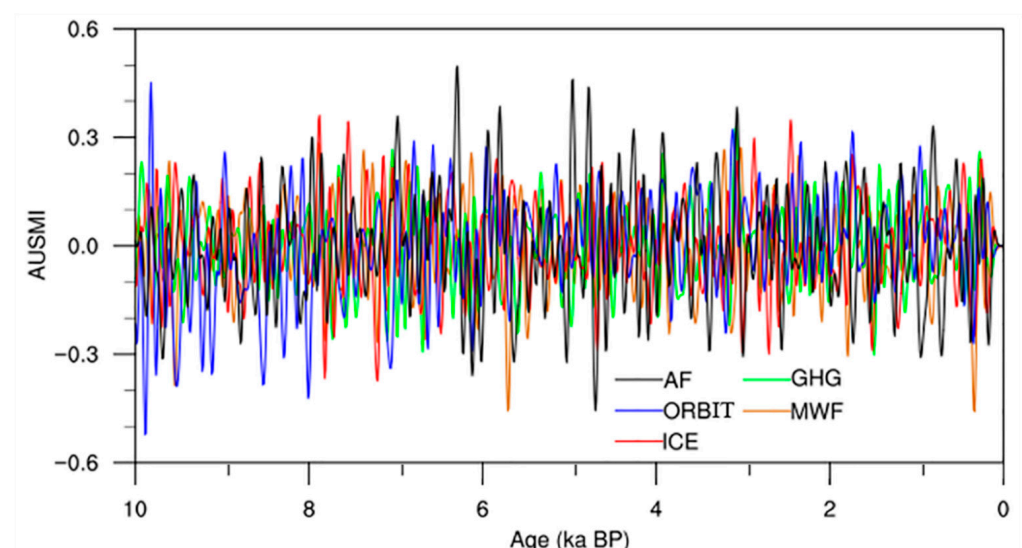


Figure 5. Time series of the AUSMI anomalies in the AF experiment and four single-forcing experiments during the Holocene. The AUSMI anomalies are with respect to AUSMI values during the Holocene. The 91–950 year bandpass filtering was applied to the data. The black, blue, red, green, and orange lines indicate the AF experiment, ORBIT experiment, ICE experiment, GHG experiment, and MWF experiment, respectively.

Figure 6 shows the power spectra of AUSMI anomalies (relative to the Holocene mean) from the MWF, GHG, ICE, and ORBIT experiments during the Holocene. Spectral peaks exceeding the 99% confidence level ($p < 0.01$) at approximately 100 year, 150 year, and 200 year periods are evident in the AF experiment. Correspondingly, the MWF experiment exhibits distinct periodicities around 100, 150, and 200 years, while the ICE experiment shows significant peaks at approximately 100, 150, and 250 years. In contrast, only the approximate 100 year periodicity is pronounced in the GHG experiment. This clustering of periodicities across experiments indicates that meltwater forcing played the leading role in generating centennial-scale AUSM variability during the Holocene, with additional contributions from ice-sheet and greenhouse-gas forcings, whereas orbital forcing exerted a comparatively minor influence.

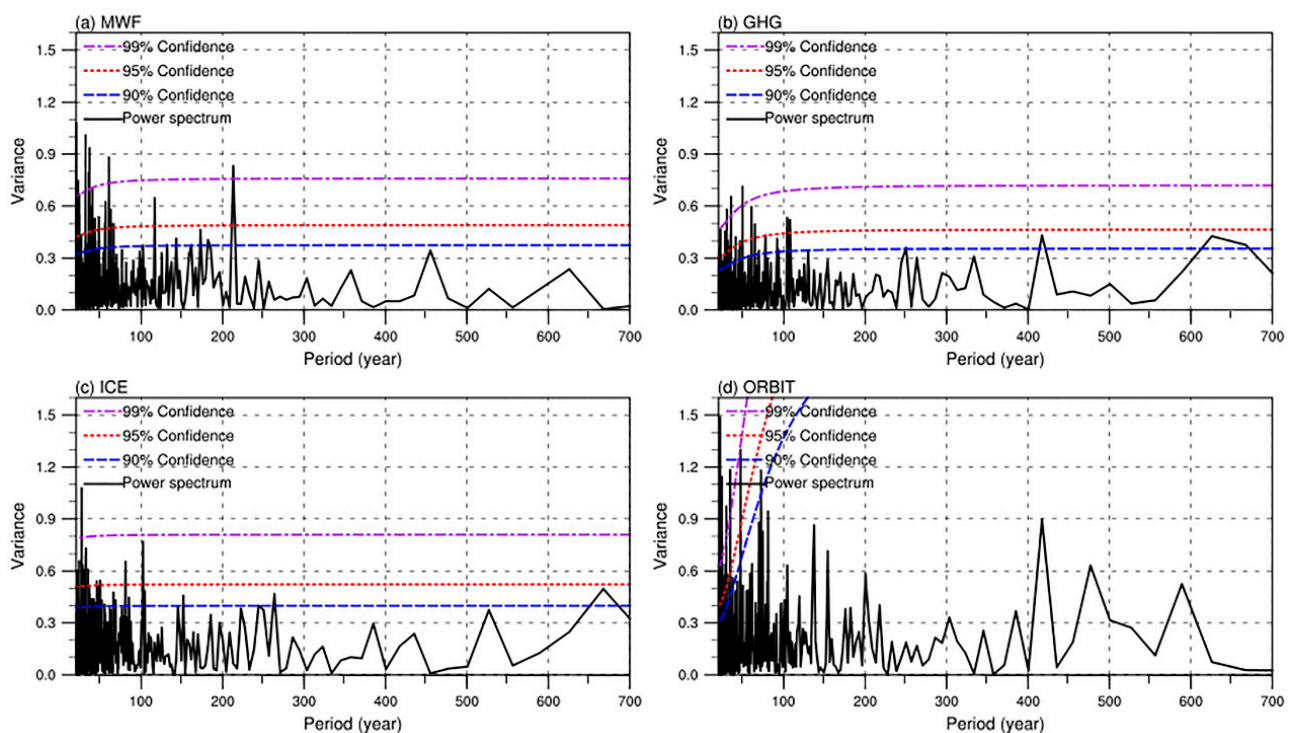


Figure 6. The power spectra of the AUSMI anomalies in MWF experiment (a), GHG experiment (b), ICE experiment (c), and ORBIT experiment (d) during the Holocene. The AUSMI anomalies are with respect to AUSMI values during the Holocene. The blue dash line, red dot line, and purple dot–dash line indicate confidence levels at 90%, 95%, and 99%, respectively.

3.2. Impact of Meltwater on Centennial Variations in AUSM Precipitation

3.2.1. Characteristics of Centennial Variations in AUSM Precipitation with Meltwater and Non-Meltwater

To investigate the influence of meltwater forcing on centennial-scale variability of AUSM precipitation, we compared two contrasting periods during the Holocene based on the meltwater flux evolution in the TraCE-21ka simulation: a meltwater-dominated period (9–8 ka BP) and a non-meltwater period (4–3 ka BP). During the meltwater-dominated period (9–8 ka BP), the bandpass-filtered AUSMI anomalies (Figure 7) display notably reduced fluctuations, yielding an amplitude of 0.009 relative to the Holocene mean. This subdued behavior contrasts with the non-meltwater interval (4–3 ka BP), whose corresponding series exhibits an amplitude of 0.018 (Figure 8). These results indicate that strong meltwater forcing during the early Holocene suppressed the centennial-scale amplitude of AUSM precipitation, whereas reduced meltwater input during the mid-to-late Holocene was associated with enhanced variability.

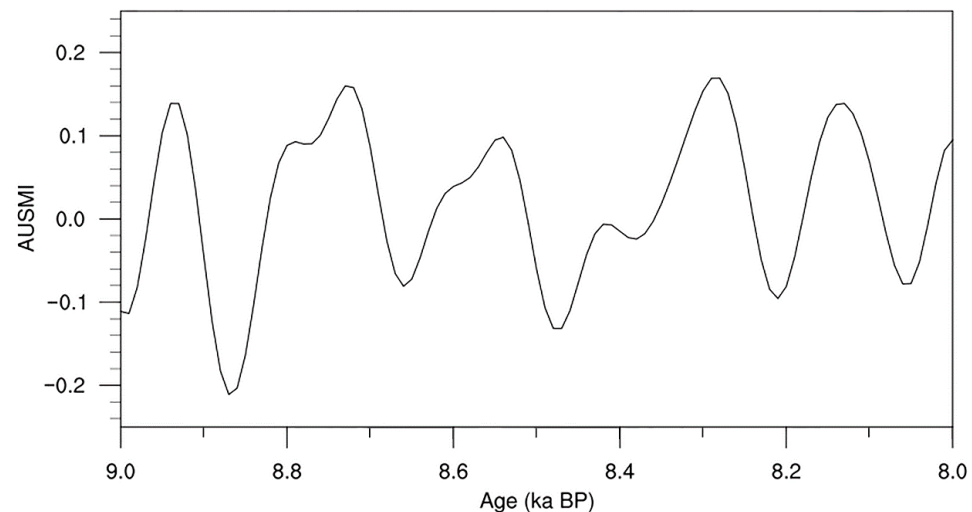


Figure 7. Time series of the AUSMI anomalies in the MWF experiment from 9 to 8 ka BP. The AUSMI anomalies are with respect to AUSMI mean values during the Holocene. The 91~950 year bandpass filtering was applied to the data.

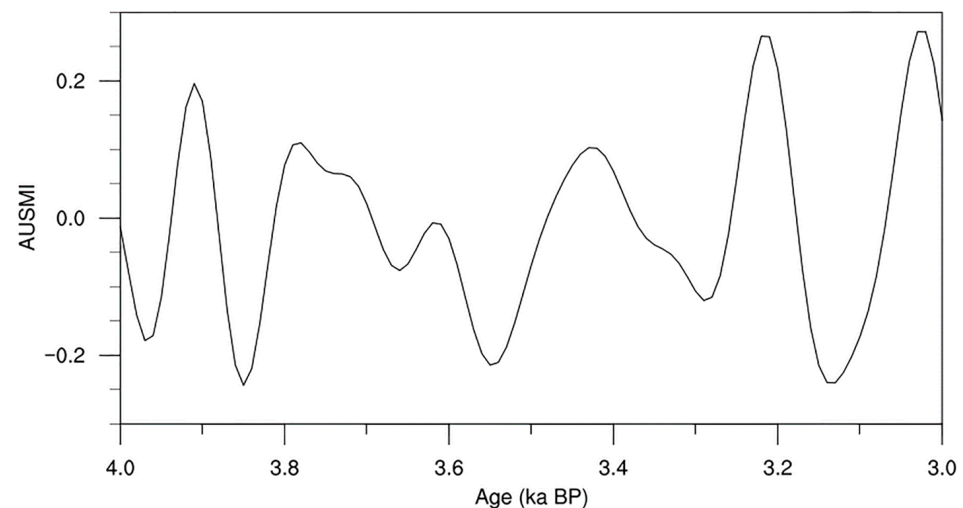


Figure 8. Time series of the AUSMI anomalies in the MWF experiment from 4 to 3 ka BP. The AUSMI anomalies are with respect to AUSMI mean values during the Holocene. The 91~950 year bandpass filtering was applied to the data.

To examine how meltwater forcing modulates the centennial-scale periodicities of AUSM precipitation, we compared the power spectra of the AUSMI between the meltwater (9–8 ka BP) and non-meltwater (4–3 ka BP) intervals within the MWF experiment (Figure 9). During the meltwater period, the power spectrum is dominated by a peak near 200 years (Figure 9), a pattern that shifts toward a shorter, ~150 year periodicity during the non-meltwater interval. This shift in primary periodicity suggests that meltwater forcing affects not only the amplitude of centennial variability but also its intrinsic timescale.

The influence of meltwater forcing further extends to the mean climate state. We compared the DJF mean precipitation and surface temperature between the meltwater period (9–8 ka BP) and the non-meltwater period (4–3 ka BP) in the MWF experiment. Differences in DJF precipitation and surface temperature between the two intervals (Figure 10) show that the meltwater period is marked by reduced rainfall over northwestern Australia along with a modest regional warming. This mean-state contrast provides additional evidence that strong meltwater fluxes acted to suppress both the magnitude and structure of AUSM-related hydroclimate variability. The DJF precipitation in eastern Australia also shows a

decreasing trend, but the decrease is not significant, indicating that eastern Australian DJF precipitation is not sensitive to AMOC signals.

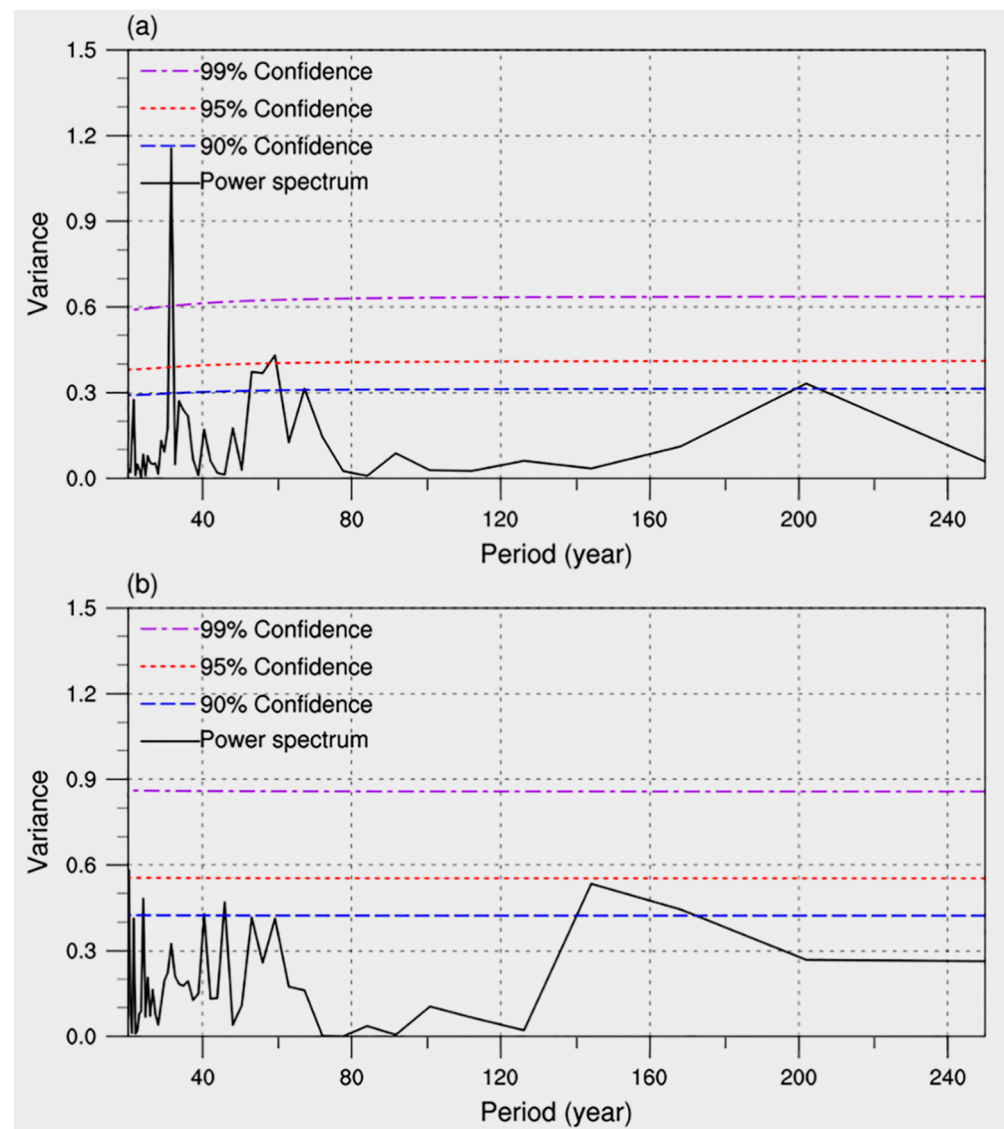


Figure 9. The power spectra of the AUSMI in the meltwater period (a) and non-meltwater period (b) in the MWF experiment. The blue dash line, red dot line, and purple dot–dash line indicate confidence levels at 90%, 95%, and 99%, respectively.

3.2.2. The Centennial Variability of AMOC in the Meltwater Period and Non-Meltwater Period

A collapse of the Atlantic Meridional Overturning Circulation (AMOC) would profoundly reorganize global precipitation, with particularly acute consequences for vulnerable tropical monsoon regions [31]. Late Pleistocene paleoclimate reconstructions further indicate a robust coupling between Indian Ocean circulation and AMOC strength, expressed across both millennial and orbital timescales [32]. Because meltwater forcing can weaken the AMOC and thereby induce large-scale climatic anomalies, it offers a physically grounded framework for evaluating how centennial-scale precipitation variability in the Australian summer monsoon (AUSM) is mediated through changes in the overturning circulation. To characterize this response, the AMOC index was defined following Ottera et al. [33] as the maximum Atlantic meridional stream function between 20° N and 50° N at depths of 500–5000 m in the MWF experiment. The time series of the annual mean

AMOC index throughout the Holocene is shown in Figure 11. Our analysis reveals a weakened AMOC during the meltwater period and a strengthened AMOC during the non-meltwater period.

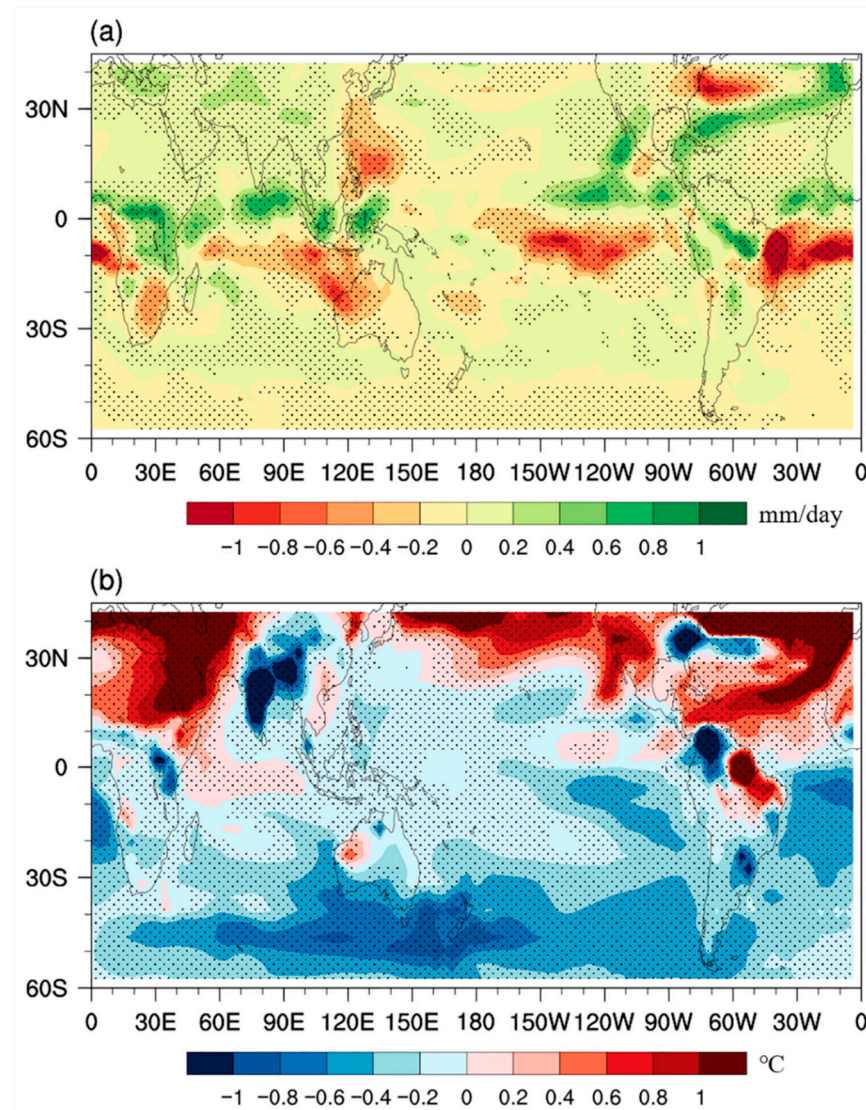


Figure 10. The changes in DJF mean precipitation ((a); mm/day) and surface temperature ((b); °C) in the meltwater period and non-meltwater period in the MWF experiment (the results in the meltwater period minus that in the non-meltwater period). The black dots denote the areas with significant differences at the 99% confidence level, based on Student's *t* test.

Figures 12 and 13 show the bandpass-filtered (91–950 year) time series of annual mean AMOC anomalies during the meltwater and non-meltwater periods, respectively, in the MWF experiment. The red dashed lines indicate ± 0.5 standard deviations, with red and blue shading highlighting intervals of high and low AMOC, respectively. The annual mean AMOC varied between 0.3 and -1.4 , with strong amplification (amplitude = 0.14). This meltwater-induced reduction in North Atlantic salinity likely suppressed deep-water formation and weakened the AMOC [34]. During the meltwater interval (Figure 12), the AMOC weakened after about 8.9 ka BP, remained relatively steady between 8.8 and 8.1 ka BP, briefly strengthened near 8.5 ka BP, and then declined again after 8.1 ka BP. By contrast, the non-meltwater interval exhibited a much narrower amplitude range (0.3 to -0.2) and markedly lower amplitude (0.01), and this contrast in amplitude is statistically significant ($p < 0.01$; Figure 13). In summary, the meltwater period was characterized by a

declining trend in the annual mean AMOC along with enhanced amplitude of its variability, which appears to have favored the emergence of a distinct ~200 year periodicity in AUSM precipitation. The influence of AMOC on centennial AUSM variability was further assessed by comparing phases in which the filtered AMOC index exceeded ± 0.5 standard deviations.

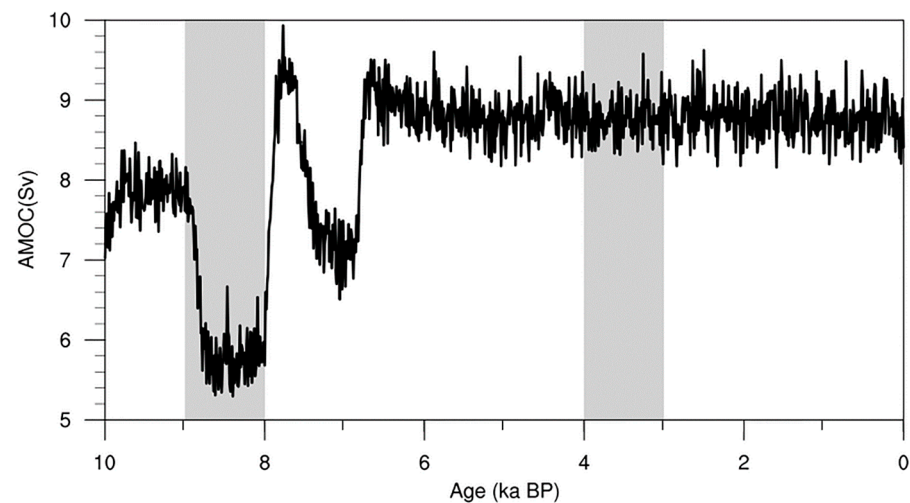


Figure 11. Time series of the annual mean AMOC (Sv) in the MWF experiment during the Holocene. The grey areas are from 9 to 8 ka BP (meltwater period) and from 4 to 3 ka BP (non-meltwater period).

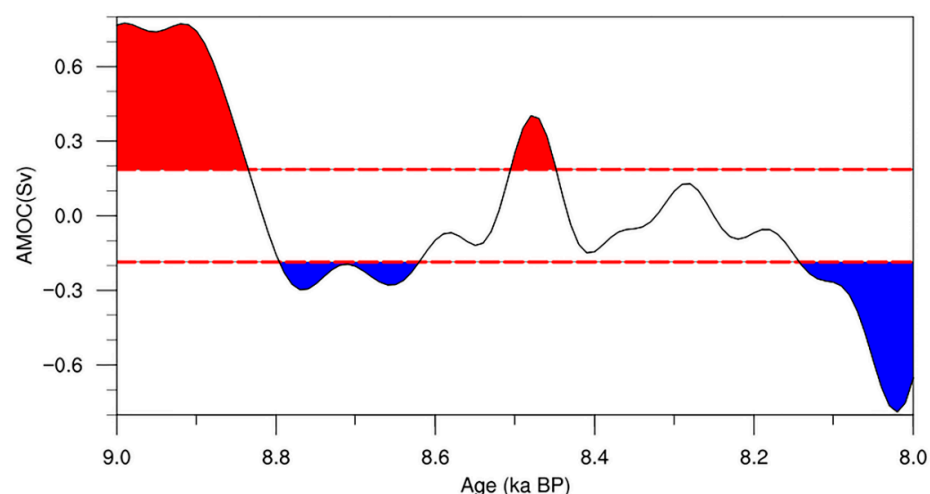


Figure 12. Time series of the annual mean AMOC (Sv) anomalies in the meltwater period of the MWF experiment. The AMOC anomalies are with respect to AMOC values from 9 to 8 ka BP. The 91–950 year bandpass filtering was applied to the data. The red dash line indicates 0.5 times the standard deviation. The red areas are periods of high AMOC. The blue areas are periods of low AMOC.

To investigate the influence of meltwater forcing on deep-ocean circulation, we compared the annual mean Meridional Overturning Circulation (MOC) at various depths between the meltwater and non-meltwater periods, based on phases of high and low AMOC index. The MOC index was defined as the maximum meridional stream function at depths of 500–5000 m. As shown in Figure 14, the difference between these phases highlights how the MOC structure changed under meltwater forcing. The panel shows the difference between the high and low AMOC phases (high minus low). During the meltwater interval, the MOC strengthened mainly between 20° N and 40° N at depths of roughly 500–2000 m, indicating a deep-intensified response. In the non-meltwater interval, however, the intensification was concentrated in the surface layer. These contrasting

structures suggest that meltwater forcing not only modulates the surface expression of the AMOC but also reshapes its vertical configuration, thereby altering patterns of heat and freshwater redistribution across the Atlantic basin.

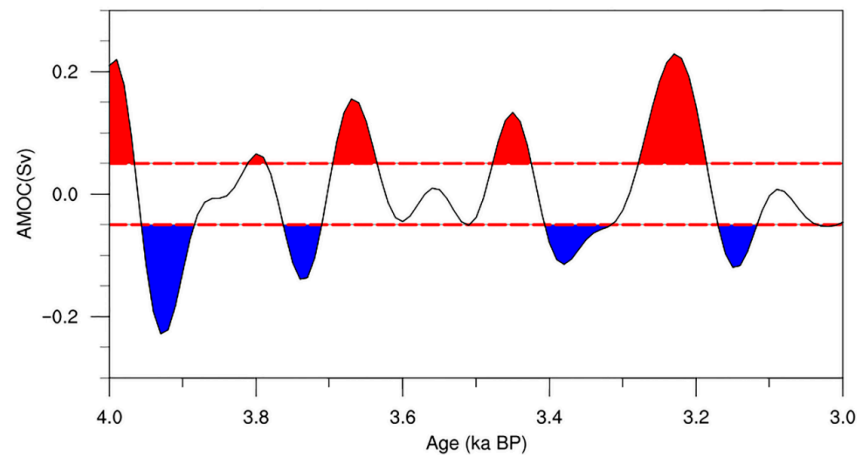


Figure 13. Time series of the annual mean AMOC (Sv) anomalies in the non-meltwater period of the MWF experiment. The AMOC anomalies are with respect to AMOC values from 4 to 3 ka BP. The 91–950 year bandpass filtering was applied to the data. The red dash line indicates 0.5 times the standard deviation. The red areas are periods of high AMOC. The blue areas are periods of low AMOC.

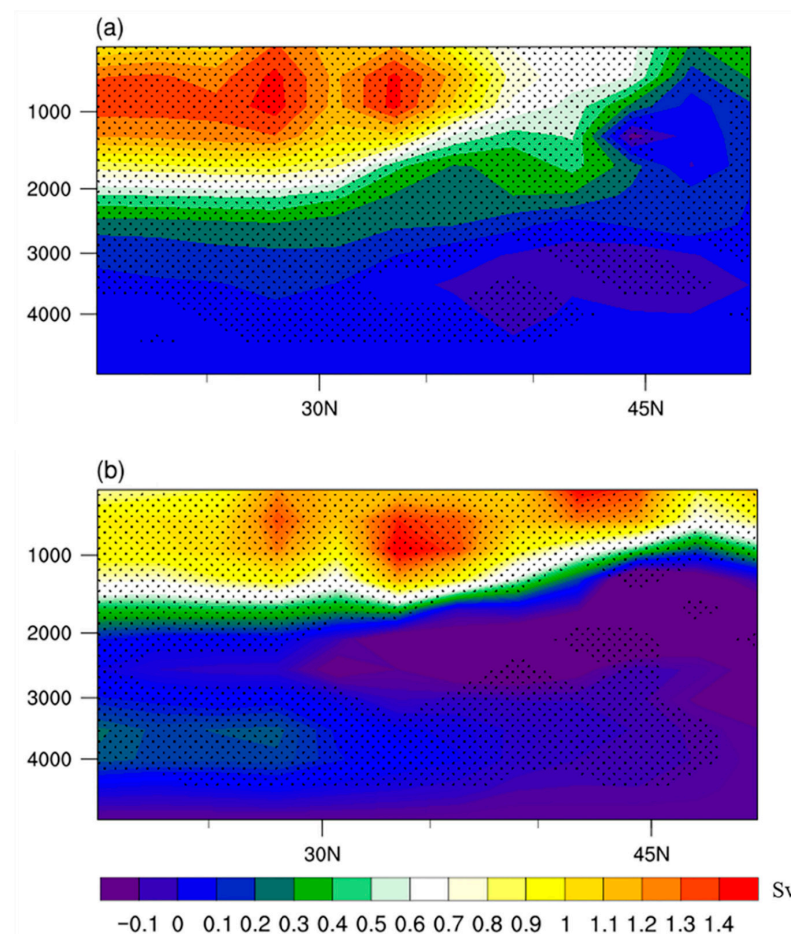


Figure 14. The annual mean MOC (Sv) at different depths (km) in the meltwater period (a) and non-meltwater period (b) of the MWF experiment (the results in yjr high AMOC period minus that in the low AMOC period). The 91–950 year bandpass filtering was applied to the data. The black dots denote the areas with significant differences at the 90% confidence level, based on Student's *t* test.

3.2.3. The Influence of AMOC on Centennial Variability of the AUSM Precipitation in the Meltwater Period and Non-Meltwater Period

To elucidate how AMOC variability modulates centennial-scale AUSM precipitation under different meltwater regimes, differences in DJF mean 850 hPa winds, sea surface temperature, precipitation, and sea level pressure were analyzed between high- and low- AMOC phases during both intervals (Figure 15). All fields were bandpass-filtered (91–950 year) prior to analysis. During the meltwater period, when the AMOC exhibited stronger centennial-scale amplitude, an enhanced AMOC generated a dipole sea surface temperature (SST) pattern—cooling in the Southern Hemisphere and warming in the Northern Hemisphere—which strengthened the interhemispheric temperature gradient. This SST configuration, together with higher SLP over northern Australia, promoted large-scale subsidence and ultimately suppressed AUSM precipitation. During the non-meltwater period, by contrast, the weaker AMOC amplitude produced a different response. In this reduced-amplitude regime, a stronger AMOC coincided with warmer Southern Hemisphere SSTs and the development of a cyclonic circulation over northwestern Australia, a circulation pattern that enhanced moisture convergence and ascent, thereby strengthening AUSM precipitation.

To elucidate the atmospheric processes through which meltwater forcing modulates centennial-scale AUSM precipitation variability, we examined differences in DJF mean specific humidity (1000–700 hPa; Figure 16) and vertical velocity (Figure 17) between high- and low-AMOC phases during the meltwater and non-meltwater periods. All fields were bandpass-filtered (91–950 year). During the meltwater period, the cooler Southern Hemisphere SSTs (Figure 15a) reduced moisture over northern Australia (Figure 16a) and promoted large-scale subsidence over the region (Figure 17a), which in turn ultimately suppressed AUSM precipitation (Figure 15b). In contrast, during the non-meltwater period, warmer Southern Hemisphere SSTs (Figure 15c) enhanced moisture availability over western Australia (Figure 16b) and fostered ascending motion (Figure 17b), thereby strengthening AUSM precipitation (Figure 15d).

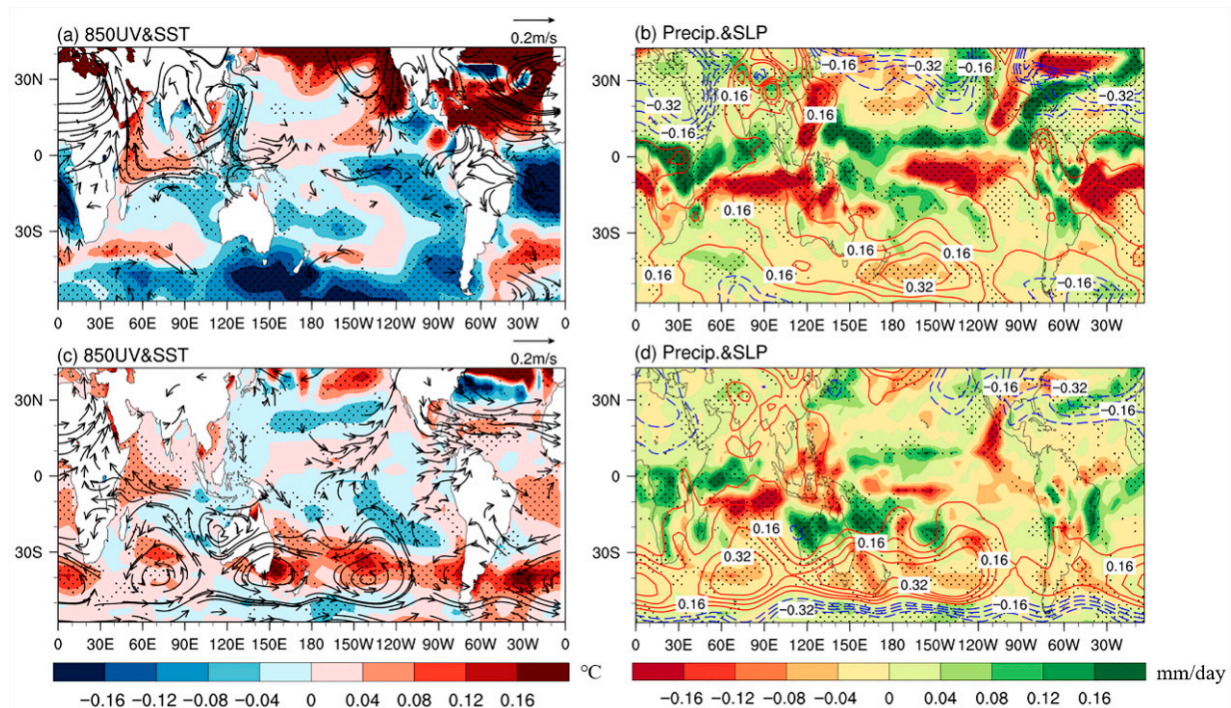


Figure 15. The change in DJF mean 850-hPa wind (vectors; m/s), sea surface temperature (shading; °C), precipitation (shading; mm/day), sea level pressure (contours; 0.08 hPa contour interval) in the

meltwater period (a,b) and non-meltwater period (c,d) of the MWF experiment (the results in the high AMOC period minus that in the low AMOC period). The 91~950 year bandpass filtering was applied to the data. The black dots denote the areas with significant differences at the 90% confidence level, based on Student's *t* test.

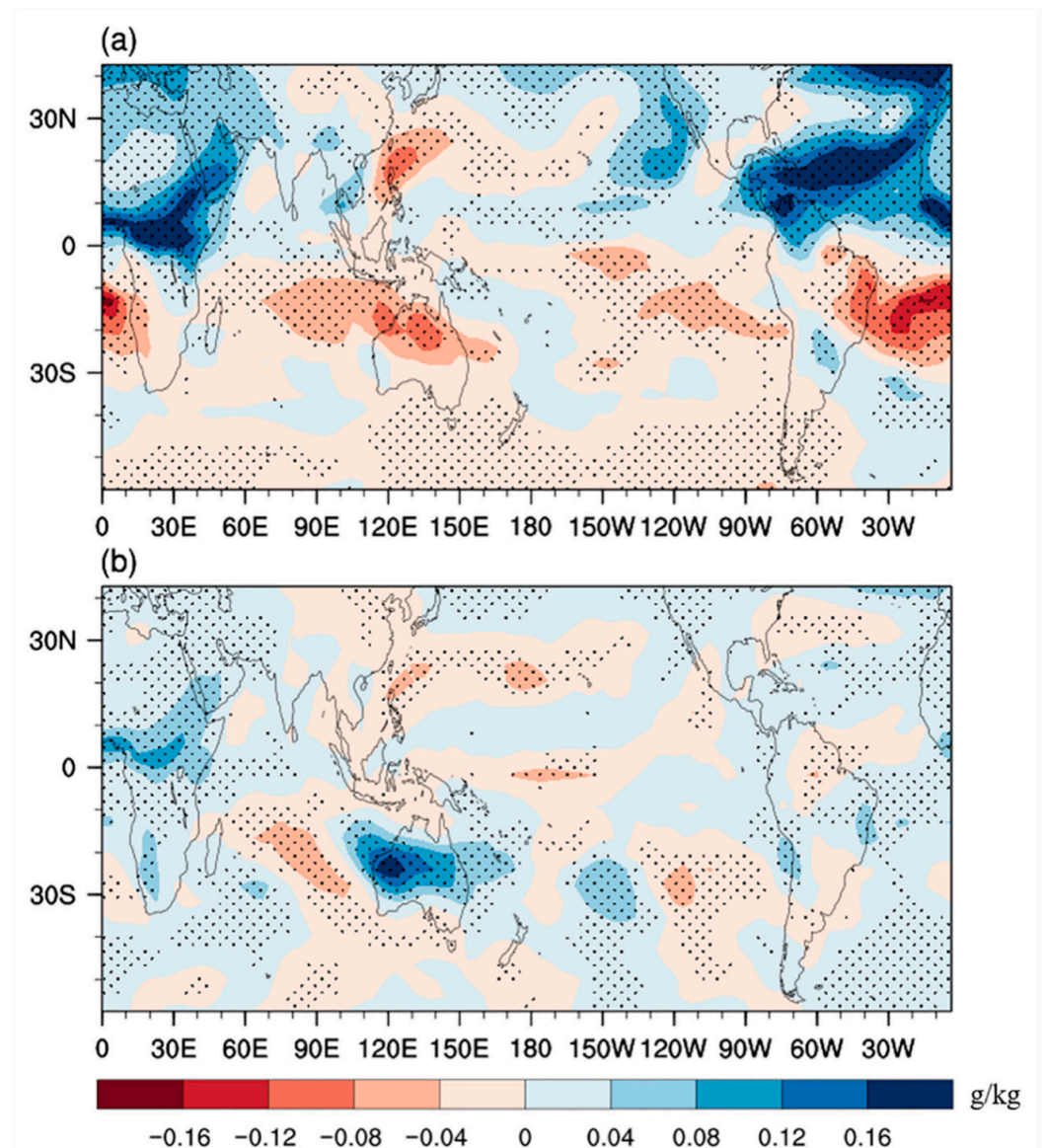


Figure 16. The change in DJF mean 1000~700-hPa specific humidity (g/kg) in the meltwater period (a) and non-meltwater period (b) of the MWF experiment (the results in the high AMOC period minus that in the low AMOC period). The 91~950 year bandpass filtering was applied to the data. The black dots denote the areas with significant differences at the 90% confidence level, based on Student's *t* test.

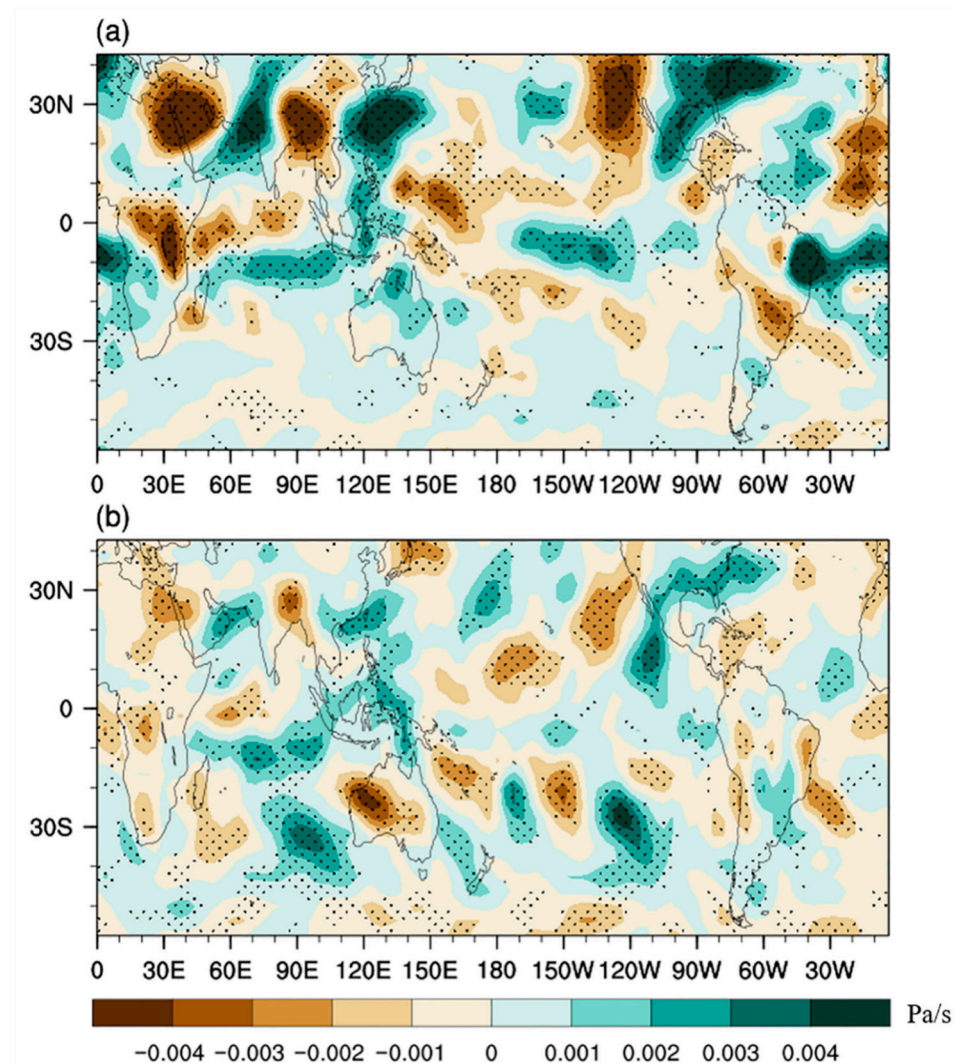


Figure 17. The change in DJF mean 500-hPa vertical velocity (Pa/s) in the meltwater period (a) and non-meltwater period (b) of the MWF experiment (the results in the high AMOC period minus that in the low AMOC period). The 91–950 year bandpass filtering was applied to the data. The black dots denote the areas with significant differences at the 90% confidence level, based on Student's *t* test.

4. Conclusions

This study investigated the characteristics and drivers of Holocene centennial-scale variability in Australian summer monsoon (AUSM) precipitation, with particular attention to the role of meltwater forcing, and clarified why understanding such low-frequency variability is relevant for sustainable water-resource management and climate adaptation in monsoon-influenced northern Australia. The all-forcing (AF) experiment reproduced the observed centennial periodicities (~100, 150, 200, 250 years), demonstrating that TraCE-21ka is suitable for diagnosing long-term monsoon variability beyond interannual-to-decadal scales. These periodicities also emerged in the meltwater-forcing (MWF) experiment, indicating that meltwater variability constitutes a principal source of the simulated centennial oscillations.

This correspondence motivated a direct comparison between intervals with contrasting meltwater input. During the strong meltwater period (9–8 ka BP), the AMOC exhibited a declining trend and markedly larger amplitude (0.14), reinforcing a ~200-year periodicity in AUSM precipitation. The amplified AMOC fluctuations were accompanied by cooler Southern Hemisphere conditions that reduced moisture availability and promoted sub-

sidence over northern Australia, thereby weakening monsoon rainfall. During the weak meltwater period (4–3 ka BP), reduced AMOC variability coincided with warmer Southern Hemisphere SSTs; these warmer conditions favored cyclonic circulation, enhanced moisture convergence and ascent over western/northern Australia, and produced stronger monsoon precipitation. Together, these responses indicate that meltwater forcing governed Holocene centennial-scale AUSM variability primarily through modulation of AMOC behavior and the associated interhemispheric thermal contrast. Together, these responses indicate that meltwater forcing governed Holocene centennial-scale AUSM variability primarily through modulation of AMOC behavior and the associated interhemispheric thermal contrast. Nevertheless, the relationship between AMOC and AUSM precipitation should be interpreted as a strong association rather than definitive causality, and other modes of internal variability may also contribute.

From a sustainability perspective, the main contribution of this work is to provide a physically grounded basis for quantifying the background envelope of natural, centennial-scale hydroclimate variability that underpins water-security planning, drought–flood risk management, and climate-resilient development. By identifying the meltwater–AMOC–Southern Hemisphere SST teleconnection as a key mechanism, our results help translate paleoclimate-scale variability into actionable knowledge for (i) defining long-horizon “baseline variability” metrics against which anthropogenic trends and extremes can be assessed; (ii) informing the design of monitoring and early-warning approaches that track relevant large-scale oceanic states as indicators of multi-decadal to centennial shifts in monsoon rainfall risk; and (iii) supporting integrated adaptation pathways and policy decisions (e.g., infrastructure sizing, water allocation, and ecosystem management) that must remain robust under non-stationary monsoon behavior. Overall, this study connects fundamental climate dynamics with sustainability-oriented assessment needs by linking process attribution to the development of interpretable indicators and decision-relevant context for long-term water resources and climate adaptation in Australia.

In addition to its Holocene relevance, the mechanism identified here has clear implications for future climate scenarios under ongoing polar ice-sheet mass loss. Contemporary observations and projections indicate increasing freshwater input to the North Atlantic from Greenland melt and enhanced high-latitude hydrological change, which could weaken and increase the variability of the AMOC. Our paleoclimate results suggest that such meltwater-driven AMOC changes are capable of reorganizing the interhemispheric thermal contrast and Southern Hemisphere SST patterns, with downstream effects on moisture availability, vertical motion, and circulation over monsoon-influenced northern Australia. Although the magnitude and boundary conditions of future forcing differ from those in the early–mid Holocene (e.g., greenhouse gas warming, aerosol forcing, and altered background stratification), the directionality of the process chain—freshwater forcing modulating AMOC behavior and propagating into Southern Hemisphere climate—highlights a potential pathway by which cryosphere change could amplify low-frequency variability and shift the baseline risk of prolonged wet or dry epochs in the AUSM region. This link between past meltwater episodes and monsoon hydroclimate variability therefore provides a process-based context for interpreting near-term AMOC indicators and for stress-testing adaptation strategies against plausible future states that include increased polar meltwater forcing.

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