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The Holocene hypsithermal in the Australian region

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A R T I C L E I N F O

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A B S T R A C T

Close examination of key and well-dated Holocene sites, both on land and at sea in the Australian region indicates that at the very beginning of the Holocene, as a result of strong westerlies, there must have been a continuous positive Southern Annular Mode (SAM). Following from that, the entire region switched to a negative SAM scenario and, during that time, the westerlies must have retreated further south. Afterwards, a period of time spaning ~8200 to ~5500 years ago temperatures were higher than today. We refer to it as the *Holocene Hyspithermal*. Coincident to this period, lake levels and postulated rainfall were extraordinarily high and vegetation spectra in places very different compared to today. The extent of this period varies by a few centuries between sites, but this may result from the level of resolution and also appears to be controlled by latitude. There is also clear indication that the influence of the westerlies was reduced over Australia during those two and a half millennia.

Nevertheless, air temperatures recognised in Antarctic ice cores are at the opposite to those recognised in Australia. In addition, during the Australian Holocene Hypsithermal, CO_2 levels were at their lowest in Antarctic ice cores.

Climatic conditions then progressively deteriorated everywhere a bit after ~6000 years BP until recent times as ENSO signals with alternating El Niño and La Niña conditions across the entire Pacific region as already described by Perner et al. (2018) based on the same cores studied here.

Brief mention is also made to the presence of humans in SE Australia during the Holocene. It seems that human activities changed well after the period of high temperatures and rainfall, with more sedentary activities along the major rivers, with an enhancement of food production in organized settings suggestive of villages.

1. Introduction

The Holocene is an important part of the geological record, especially for us humans as this is the period of time when human societies developed. It covers the last 11,700 years (Walker et al., 2009) and ends with the Anthropocene, the period that is characterized by significant and irreversible changes in climate caused by human activity (Steffen, 2016). Many people consider the Holocene to have been rather stable climatically compared to the previous period of geological history that saw the Last Glacial Maximum (LGM) and the ensuing deglaciation. However, sea level commenced rising from the time after the world experienced extremely cold conditions- and in Australia very dry ones – during the LGM some 20,000 years ago (Barrows et al., 2001; Lambeck et al., 2014; De Deckker et al., 2020). At that time, there was only a small glacier in the Snowy Mountains of southeastern Australia. Sea level rapidly rose up to 8200 years ago, then rose at a slower rate for 1500 years before progressively declining to 150 years ago (Lambeck et al., 2014). Nevertheless, during the Holocene the impact of humans is clearly noticeable already outside Australia, as a result of human population growth, the switch to agriculture and sedentary activities, the clearance of land and the domestication of animals as well as plant and animal extinctions, many of which were caused by humans, and importantly fire activities. Emiliani et al. (1991) briefly argued that point by saying that soot and graphitic carbon particles within the 0.01–1 μm size range generated by intensive fires by 'early agriculturalists' could scatter solar radiation and affect global climate.

In this paper, I aim at characterising significant periods of change during the Holocene in the Australian region, and in particular detailing what has already been coined the Holocene Optimum, or more appropriately the Holocene Hypsithermal Interval, a term coined by Deevey and Flint (1957) following the first recognition by Chiarugi in 1936 for a warmer period defined by pollen changes in lake and bog sediments. Deevey and Flint (1957) had indicated that the term Holocene Optimum was subjective so the word *Hypsithermal* is also preferred here as it

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relates to a period of higher temperatures than the end of the Holocene, before anthropogenic effects on climate that commenced at the start of the Anthropocene. I will document the timing and temperature hike during the hypsithermal and also examine all the other changes that coincided with this period in Australia and its surrounding waters.

2. Methodology

There are ample Holocene records for the Australian region, but unfortunately many of those early records relied on scant chronologies, simply because radiocarbon dates at the time were very expensive. The best example is with the seminal paper by Macphail (1979) that described seven pollen sequences from Tasmania, but his chronologies for three sequences relied on three dates (n = 3), one with two, and the other three with one date only. Hence, it was decided not to ignore these records, but to discuss here those records with ample dates knowing also that the new records would assimilate the findings of previous ones in their discussion. Many of the records used here, especially the marine ones, contain ample radiocarbon dates, complemented at times by Optically Stimulated Luminescence (OSL) dates (see Olley et al. 2004; De Deckker et al., 2014; Lopes Dos Santos et al., 2012, 2013). The same approach using a combination of OSL and radiocarbon dates was also applied to lacustrine sequences (Kemp et al., 2011; Wilkins et al., 2012a, b) and are preferred here. However, other records that have a moderate number of radiocarbon dates (~10) are also used here for the nature of the information they hold (e.g land temperatures by Woltering et al., 2014) and which so far have not been duplicated. They are considered to be of relevance to the reconstruction of the hypsithermal.

Equally there have already been important examinations of the Holocene such as the OZ-INTIMATE review by Reeves (2013) which examined the last 35 ka of the Australian record in time slices which, concerning the Holocene looked at the 12–8 ka early Holocene, followed by the 8–5 ka mid-Holocene, and then the 5–0 ka late-Holocene. Unfortunately no detailed chronology was provided in this review. For example, it stated: "The mid-Holocene period represents maximum temperature in terrestrial records throughout the Australasian region, although it was expressed in different places at different times. By 8 ka both sea level and SST had reached essentially modern conditions (Lewis et al., 2013)". I will re-examine this statement in the paper herein. In addition, the important and highly cited review by Pickett et al. (2004) that documents reconstructions of the vegetation patterns in Australia, Southeast Asia and the Pacific in the mid-Holocene and at the last glacial maximum, only covers the 6 ka period and cannot be used for the current paper.

3. Brief outline of meteorological conditions in the Australian region of importance to palaeoclimatic records, both on land and at sea

Today, the belt of Southern Hemisphere Westerly Winds (SHWW, also referred to as the westerlies), that broadly encompasses the 30 to 60°S latitudes, strongly affects weather of southern and even at times central Australia, including also other parts of the Southern Hemisphere. Changes and the position of the core of the SHWW will strongly affect precipitation on land or the lack of it.

In addition, southern Australia is also strongly affected by atmospheric conditions that are linked to the Southern Ocean such that a belt of high surface air pressure (associated with descending air), called the Subtropical Ridge (SR), that sits south of Australia in summer (Suppl. Fig. 1 A, D) and moves north over the southern part of mainland Australia in winter (Suppl. Fig. 1B and C). Thus, in winter, this northward shift allows westerly winds to move over southern Australia, with ensuing wetter and stormier conditions. In summer, on the other hand, an anticyclonic gyre will generally develop over southeastern Australia (Suppl. Fig. 1 E, H) as the westerlies occur further south in the Southeastern Indian Ocean.

During a positive Southern Annular Mode (SAM) in summer, the winds move in an anticlockwise gyre over Tasmania and Victoria and the westbound Flinders Current (FC) (Fig. 1) will be strengthened, such that ephemeral upwelling may occur along the Bonney Coast of South Australia (Fig. 1, Suppl. Fig. 2 A,C,D,F) and may even appear offshore Kangaroo Island (Suppl. Fig. 2F) (for more details, refer to Richardson et al., 2020). In winter during a positive SAM, the southern part of the continent will be dry and eastern Queensland wet. In contrast, during a negative SAM, southern Australia will see wet conditions (for further details, refer to Hendon et al. (2007) and also http://www.bom.gov.au/climate/sam/). In other words, when the Subtropical Ridge is close to the Australian continent, the westerlies will permit the Leeuwin Current (LC) to flow as far as Tasmania (Suppl. Fig. 2 B,E). This current, that originates in the tropics of the Southeast Indian Ocean, then circumnavigates Western Australia, and it is particularly strong in winter during La Niña years. If, on the other hand, the westerlies belt is weak or located further south in the Southeastern Indian Ocean, the FC will be weaker while flowing towards the Great Australian Bight (Fig. 1), and will be over-ridden by the LC that will continue as far as Tasmania (Fig. 1, Suppl. Fig. 2B) and is thus seen as a transfer of tropical heat down to the southern margin of Australia. For more information on the FC, refer to Middleton and Cirano (2002); Middleton and Bye (2007). The intensity of the upwellings offshore South Australia is caused by southeasterly winds along the South Australian coast and in particular during El Niño events (Middleton and Bye, 2007). As a result, westward-driven shelf currents will force the thermocline to be raised (Middleton and Bye, 2007) and this is reflected by the composition of the planktonic foraminiferal fauna (see Perner et al., 2018, Fig 6 A, B).

Upwelling intensity is dependent on both the strength of favourable winds and the presence of El Niño events in the eastern Pacific Ocean. The southeasterly winds will engender favourable upwellings to occur during summer, as they drive a westward shelf current, thus inducing transport of water offshore that eventually promote upwelling (Suppl. Fig. 2 A, C, D, F).

La Niña conditions, on the other hand, see the thermocline to be significantly deeper and, at the same time, the shallow water (<200 m) Leeuwin Current is much more prevalent. It also overrides the Flinders Current (Fig. 1) and can even reach the western coast of Tasmania (see Wijffels et al., 2018, Fig. 26).

3.1. Marine cores

The multidisciplinary records of deep-sea cores obtained offshore southern Australia are particularly relevant to the present study because a number of proxies were obtained from them, and in particular sea-surface temperature (SST) obtained by alkenometry, and foraminiferal faunal analyses that help determine conditions at sea above the cores, plus there is an ample array for radiocarbon dates done on planktic foraminifera. All these analyses have shown no hiatus in both cores nor evidence of reworking/downslope contamination.

. **Core MD03–2611** (36°43.8′S, 136°32.9′E) (called here 2611) was obtained in 2003 at a water depth of 2420 m in the Murray Canyons Group (Hill and De Deckker, 2004) and is located not far from Kangaroo Island (Fig. 1) where ephemeral upwelling can be witnessed at times under specific winds (see Richardson et al., 2020). Numerous studies were already carried out on that core such as by Calvo et al. (2007), Moros et al. (2009), De Deckker et al. (2012), Perner et al. (2018), De Deckker et al. (2020), and Moros et al. (2021). Little emphasis on the Holocene record had been paid on this core, except for the last 7 ka by Perner et al. (2018) and since then additional radiocarbon dates were obtained from that core. Already, Calvo et al.(2007) had reconstructed SST based on alkenones, but at lower resolution than conducted later by De Deckker et al. (2020). For the Holocene, Calvo et al. (2007) had 33 SST analyses and the chronology relied on 14 radiocarbon dates.

Proxies of relevance to the study here are SST, change of the thermocline distinguished by the abundance of the foraminifer *Globorotalia*

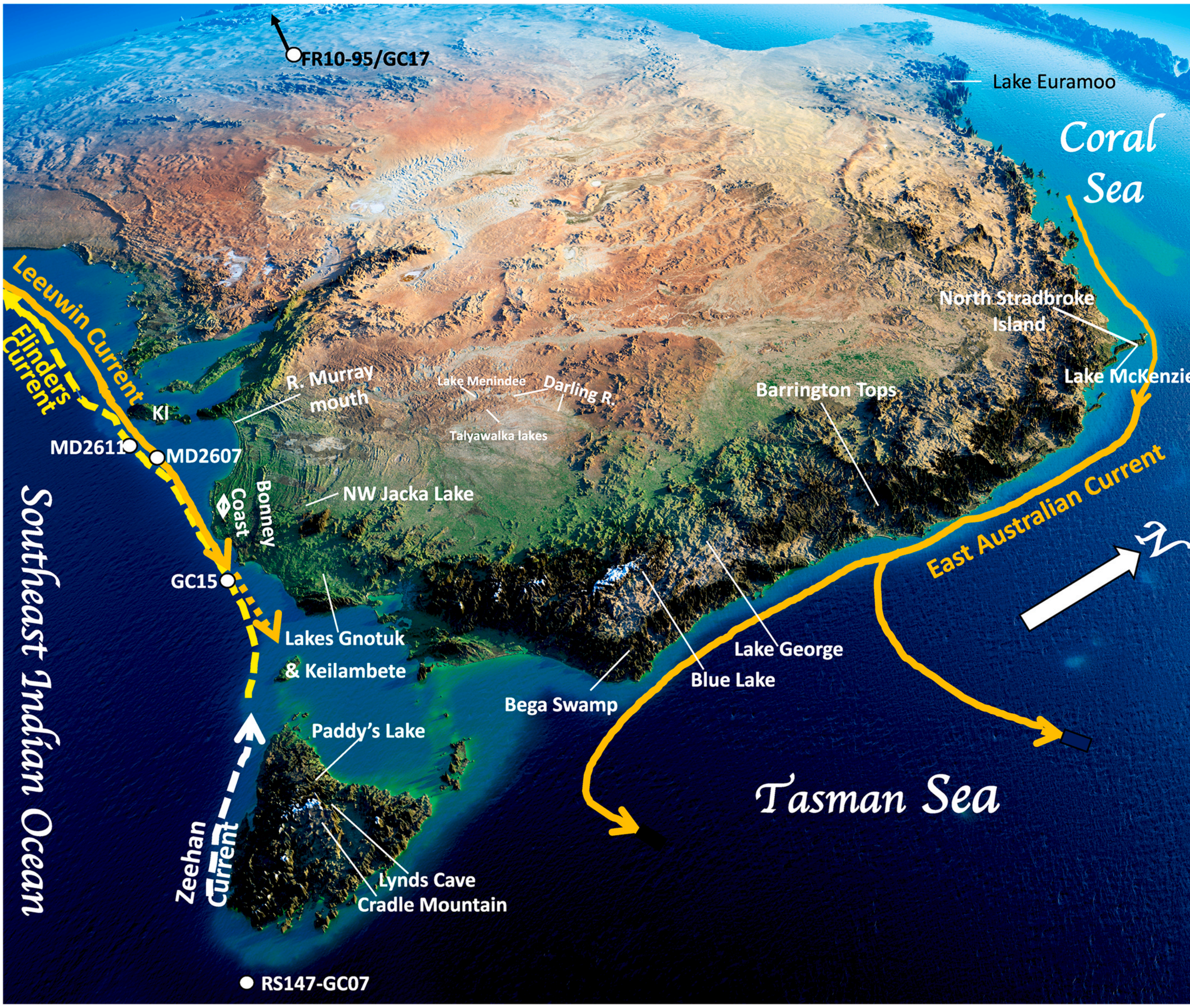

Fig. 1. Tilted satellite originally from NASA and processed by Anton Balazh from 'Shutterstock images' showing the major oceanic currents and localities and marine core sites discussed in this paper.

truncatulinoides and the influence of the Leeuwin Current recognised by the foraminifer *Globigerinoides ruber* (for more information consult Perner et al., 2018). 37 AMS radiocarbon dates were obtained from that core spanning the Holocene (Table 1, De Deckker et al., 2020).

. **Core SS0206-GC15** (38°11.26′S, 142°24.62′E) (called here GC15) was obtained in 2006 at a water depth of 907 m. It is located some 600 km to the southeast of core 2611 (Fig. 1) and was taken offshore the coast of western Victoria where ephemeral upwelling has also been recorded in an area referred to as the 'Bonney Upwelling' (Schahinger, 1987). Like for core 2611, it is located below the path of the LC when in force. Numerous studies were already carried out on that core; these were by Perner et al. (2018); De Deckker et al. (2020); and Moros et al. (2021). Little emphasis on the Holocene record had been paid on this core, except for the last 7 ka by Perner et al. (2018). The same proxies obtained for core 2611 were used for this core. Some 27 radiocarbon dates were obtained for the Holocene part of this core (Table 1). There are 27 AMS radiocarbon dates for the Holocene part of this core.

. **Core MD03–2607** (36°57.64′S, 137°24.39′E) (called here 2607) was obtained in 2003 at a water depth of 865 m in the Murray Canyons Group, east of Sprigg Canyon and is located some 90 km to the SE of core 2611 (see Hill and De Deckker, 2004). There are only 9 AMS radiocarbon dates and 7 OSL for the Holocene part of this core and alkenone analyses to reconstruct SST and foraminifer analyses to reconstruct the stratification of the water column (see information later in the paper) are at lower resolution than for core 2611.

SST obtained from alkenones shows broad trends that are clearly visible. The highest SSTs are recorded between 8.4 and 4.2 ka in core 2611 and 8.3 and 4.3 ka in core GC15 (Fig. 2). These represent summer temperatures as argued by De Deckker et al. (2020) as confirmed by the Modern Analogue Technique for temperature reconstructions using planktonic foraminiferal analysis (calculated by T.T. Barrows in De Deckker et al., 2020; suppl. Fig. 7). On either sides of this warm phase, SST progressively increased up to this phase and decreased after it. In core 2611, SSTs decreased by approximately 1.6 °C but slightly less in GC15, although the last 600 years off the record is missing due to the gravity coring technique that usually misses the upper (soupy) surface sediments. Nevertheless, during the warm phase, the highest SSTs were recorded ~6.3 ka in core 2611 and at 6.4 ka in core GC15, but

Table 1
Relevant data for the important sites discussesd in the text.

Site	Proxi (es)	Number of dates for interval of interest	Author(s)	Comments
Lake McKenzie, Fraser Island, Queensland	GDGT temperatures	5 radiocarbon dates, 5 ^{210}Pb dates	Woltering et al. (2014)	
Blue Lake, Snowy Mountains, NSW, core BL 4	Selected pollen *	13 radiocarbon (3 reversals)	Raine IR PhD thesis, 1974	The ages were recalibrated and dated intervals were ~20 cm thick
Blue Lake, Snowy Mountains, NSW, core NC	Maximum grain size of textured grains	6 radiocarbon	Stanley & De Deckker (2002)	
Lakes Gnotuk and Keilambete, Victoria	>63 μm grain size used for lake level reconstruction; lake depth related to modern for the 2 lakes combined	29 OSL, 30 radiocarbon	Wilkins et al. (2012), 2013	Ostracod chemistry was used to confirm lake level and salinity
Fluvial system, Victoria and NSW	Valley fills	33 radiocarbon	Cohen & Nanson (2007)	Relies on a selection of radiocarbon dates from numerous publications
Jakka Lake, Victoria	Ostracod salinities	5 OSL, 2 radiocarbon	Kemp et al., 2011	
MD03-2611 core offshore South Australia	Foraminifera species, alkenone SST	37 radiocarbon	Moros et al. (2021); De Deckker et al. (2020); Perner et al. (2018)	
SS0206-GC15 core offshore Victoria	Foraminifera species, alkenone SST	27 radiocarbon	Moros et al. (2021); De Deckker et al. (2020); Perner et al. (2018)	
Paddy's Lake, Tasmania	Selected pollen combining rainforest taxa	15 radiocarbon	Beck et al. (2017, 2019)	

* *Pomaderris aspera* is found today at 860 m Leaterh Band Creek, Geehi Crossing on Alpine Way west of Mt. Kosciuszko, 16 km from Khancoban toward Geehi, beyond Murray 1 Power Station, alpine way, Geehi wall area. Information from Keith McDonald, Greg Baines, Neville Walshe, Dave Albrecht.

considering the error bars of this proxy, not much ought to be made of this result.

Coinciding with the interval of high STTs, the percentages of *G. truncatulinoides* are in general the lowest for both core records (Suppl. Fig 3). Following Perner et al. (2018) assessment, this foraminifera species is an indicator of the level of stratification of the water column above the core sites with high percentages of *G. truncatulinoides* indicating a shallow thermocline. We now interpret this phenomenon as resulting from the absence of strong winds above the two core sites as a result of the westerlies being located further south of Australia as already discussed in the section above on meteorological conditions. Consequently, a scenario similar to what was observed in Supplementary Fig. S2 B,D is envisaged for a warmer sea offshore southern Australia with no evidence of upwelling, and this lasted about two millennia.

. **Core Fr10/95-GC17** (22° 07.74′S, 113°30.11′E) was obtained in 1995 offshore Northwest Cape on the Exmouth Plateau in Western Australia at a water depth of 1093 m. It is located under the pathway of the LC and numerous proxies were applied to the 34 ka record of this core. The age model for the Holocene part of this the core is based on 9 radiocarbon dates complemented by 3 luminescence ages and an oxygen isotope record (see Olley et al., 2004). One of the important proxies of relevance to this present study is the reconstruction of SST calculated this time using the MAT in conjunction with the AUSMAT-F4 core top database (Barrows and Juggins, 2005).

3.2. . Other marine core records

Core RS147-GC7 located south of Tasmania (45°09S, 146°1E) has a record of SST based on alkenones and also from foraminifera assemblages but is not discussed here as the Holocene alkenone temperature record is based on only 9 samples (Sikes et al., 2009) and the foraminifera SST based on the Modern Analogue Technique relies on 12 samples only. In addition, this chronology for this record is only based on 4 radiocarbon dates. Despite the poor dating, the alkenone-reconstructed SST indicates a drop in temperatures around 6 ka that is also matched by the MAT-reconstructed SST.

4. Selected terrestrial archives/cores

The records discussed here are presented from the lowest to the highest latitude across eastern Australia.

. **Lake Euramoo,** northern Queensland **(**17° 9′ S, 145° 37′ E; 718 m asl was studied in great detail by Haberle (2005). It is a crater lake surrounded by warm temperate rainforest today. The record relies on 12 radiocarbon dates. Between 7.3 and 6.3 ka, the rainforest achieved its maximum extent with 'higher than present season temperatures and dry season precipitation' (Haberle, 2005). Prior to this work, Kershaw and Nix (1988) attempted to use both range distributions and abundance from a relatively large number of floral taxa to derive palaeoclimatic estimates for a core from Lake Euramoo, but this record only extended back to 7.5 ka. Nevertheless, they estimated that, for the period of 7.5 to 6 ka, the range of mean annual temperature was much lower than today, but the range of mean annual rainfall well above today. There are other lacustrine records form the Atherton Tableland such as from Quincan Crater (Kershaw, 1971), Bromfield Swamp (Kershaw, 1975) but the chronologies for these only rely on too few dates (Quincan: n = 4, Bromfield: n = 5). Nevertheless, Haberle (2005) in his synthesis refers to these records.

. **Lake McKenzie** (25°26′51″S, 153°03′12″E) is found on the large Fraser Island (K'gari) off the Queensland coast. Although the core chronology relies on 5 radiocarbon dates and 5 ^{210}Pb dates, it is an important record as it details mean annual air temperature (MAAT) based on branched glycerol dialkyl glycerol tetraether (GDGT) as calculated by Woltering et al. (2014) for the last 37 ka, with a gap between 18.3 and 14 ka. The warmest Holocene temperature (21.4 °C) was recorded at 5.7 ka with other slightly lower temperatures at 6.4, 7.1, 8.1 and 9.4 ka (Fig. 3A). Note that the pollen investigations by Atahan et al. (2015) from this site are too few (6 samples for the entire Holocene) to warrant any interpretation on vegetation changes during that period.

Barr et al. (2019) provided a quantitative precipitation record using carbon isotope ratios from leaves of the evergreen tree *Melaleuca quinquenervia* preserved in lake sediments from **Swallow Lagoon** (27°29′S, 153°27′E; 18 radiocarbon dates) from nearby Minjerribah (=North Stradbroke Island), which unfortunately does not extent before 7.7 ka, but which nevertheless shows that the highest precipitation (>2 m yr^{-1}) occurred around 7.7–7.2 ka, and that was matched only once more at ~3.2–3.0 ka.

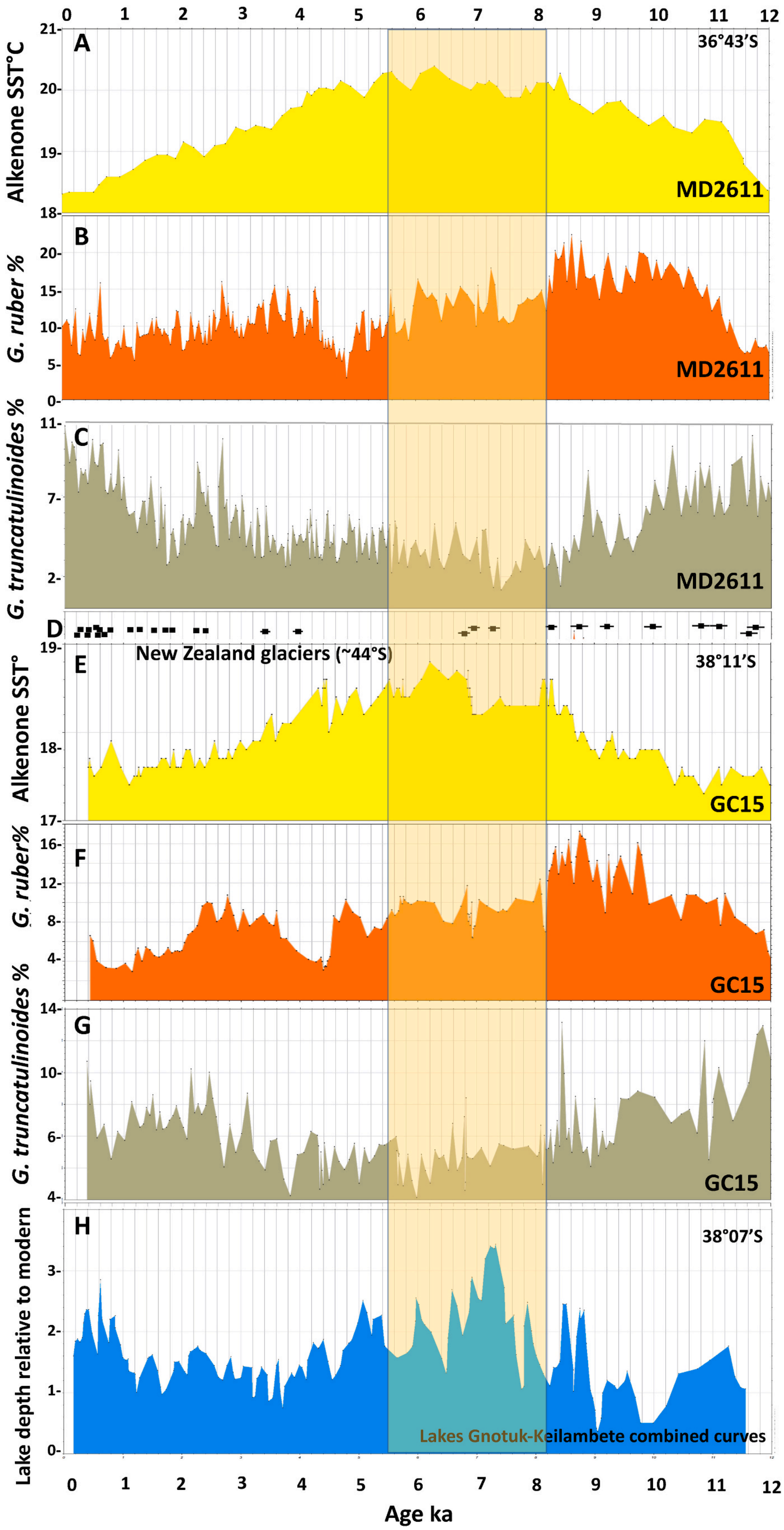

Fig. 2. Composite of selected marine core records spaning the Holocene, in addition to the occurrence of glacial advances on the South Island of New Zealand, as well as lake level changes recorded from a combination of records from the crater Lakes Gnotuk and Keilambete in western Victoria. **A, E:** Sea-surface temperatures obtained from alkenometry for core MD03-2611 **(A)** and core SS0206-GC15 **(E)** taken from De Deckker et al., 2020) and Moros et al. (2021); **B, F:** percentages of the foraminifera *Globigerina ruber* indicative of the presence of the Leeuwin Current (LC) above the core sites (note that GC 15 is some 600 km further downstream the flow of the LC); **C, G:** percentages of *Globorotalia truncatulinoides* indicative a the status of the thermocline above the core site for core MD03-2611 **(C)** and core SS0206-GC15 **(F)**; **(D)** timing of glacial advances recorded in New Zealand taken from Denton et al. (2021) (note error bars are minuscule on this figure; **F:** Lake depth relative to the present for a combination of the two crater lakes taken from Wilkins et al. (2012a,b). This record only commenced when Lake Keilambete started to fill at 11.7 ka (Note the latitude of the two lakes is almost identical to core GC15). The pale apricot coloured rectangle defines the hypsithermal that spans between 8.2 and 5.5 ka.

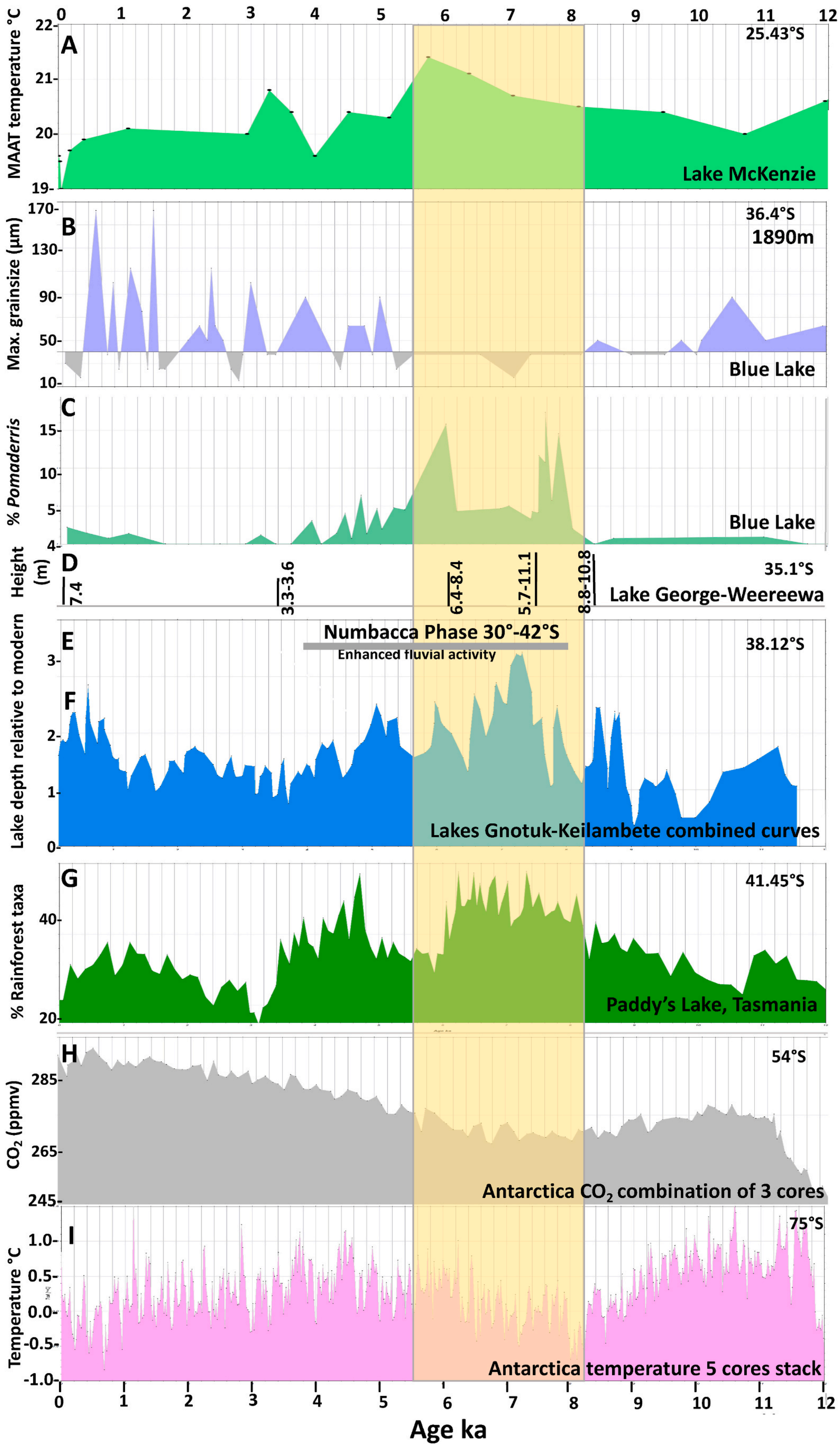

Fig. 3. Composite of selected continental records from Australia, Macquarie Island and Antarctic ice cores. **A:** Mean annual atmospheric temperatures above Lake McKenzie on Fraser Island (K'gari) reconstructed from branched glycerol dialkyl glycerol tetraether (GDGT) by Woltering et al. (2014); **B:** Maximum aeolian quartz grain sizes in µmm recorded in a core at Blue Lake in the Snowy Mountains by Stanley and De Deckker (2002) that are indicative of wind intensity; **C:** percentages of the pollen of *Pomaderris aspera* recorded from another core from Blue Lake by Raine (1974). This taxon does not exist today in the catchment of this alpine lake; **D:** Lake level heights summarized in Janconski et al. (2021) for Lake George-Weereewa near Canberra; **E:** Period of enhanced fluvial activity in eastern Australia (grey horizontal bar) called 'Numbacca Phase' by Cohen and Nanson (2007); **F:** Lake depth relative to the present for a combination of the two crater lakes in western Victoria taken from Wilkins et al. (2012a,b).; **G:** Percentages of rainforest tress recorded in a core from Paddy's Lake in Tasmania taken from Beck et al. (2017, 2018); **H:** CO_2 levels in ice bubbles extracted from a combination of three ice cores in Antarctica (EDC TALDICE) by Monnin et al. (2004); **I:** Synchronised atmospheric temperatures in Antarctica using a stack of 5 core records (EDC, TALDICE, EDML and Dome Fuji) reported by Parrenin et al. (2013). Note that additional records are also discussed in the text. The pale apricot coloured rectangle defines the hypsithermal that spans between 8.2 and 5.5 ka. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

On North Stradbroke Island (Minjerribah), three sites were examined by Moss et al. (2013); these are Native Companion Lagoon with only 17 Holocene pollen samples being analysed and 7 radiocarbon dates, Welsby Lagoon 31 pollen samples and 6 radiocarbon dates; and Tortoise Lagoon 16 pollen samples and 5 radiocarbon dates. Moss et al. (2013) stated that ‘in terms of broader climate change during the Holocene, all three sites experience wetter conditions through the early to mid- Holocene period (10–5 ka BP), and in the late Holocene climates of the region became drier’.

. Mires on Barrington Tops, on the Northern Tablelands of New South Wales (~32°S; 524 m asl) is characterized by subalpine vegetation on several of the peaks reaching 1500 m asl. Dodson (1987) found that sediments began accumulating in nine mires on Barrington Tops, before 11 ka, but that peat became common in the region by 8.6 ka. He suggested that conditions in the early Holocene were warmer and moister than at present.

. Blue Lake in the Snowy Mountains in NSW (36°24′39″S, 148°19′ 07″E, 1890 m asl) sits in an excavated cirque by the Twynam Glacier and was the subject of two separated studies. In 1974, Raine completed the examination of the palynoflora of a combination of cores which were dated using 13 radiocarbon dates, 3 of which had reversed ages. The record covered the last 13.5 ka. However, his PhD thesis remains unpublished. The original pollen data counts formatted by the late Geoff Hope were obtained from Drs Janelle Stevenson and Felicitas Hopft from the ANU. Stanley and De Deckker (2002) examined the nature, morphology and size of allochtonous grains found in another core spaning the last 12 ka, with a gap caused by a slump between 9.4 ka and 10.3 ka. A total of 6 radiocarbon dates were obtained for that core. (Table 1).

Raine (1974) identified the presence *Pomaderris* pollen between 7.8 and 5.2 ka (which does not grow in the catchment today), with peaks at 7.8, 7.6, 7.5 and 6 ka (Fig. 3B).

Stanley and De Deckker (2002), based on the low diameters of the quartz grains, postulated a low level of wind activity over the lake between 8.2 and 5.3 ka (Fig. 3C), implying perhaps that the westerlies were located further south of Australia.

. Lake George-Weereewa, NSW (centered on 35° 06′ E, 149° 25’ E, 672 m asl was extensively studied but the chronology of the core records is in need of revision (see Singh et al., 1981; De Deckker, 2020). Janconski et al. (2021) reassessed and dated ancient shorelines of the lake, and summarized their data in conjunction with the findings of Fitzsimmons and Barrows (2010). All those dates were based on the Optically Stimulated Luminescence technique. They identified several phases during the Holocene with substantially high lake levels. These are: at 8.3 ±0.40.4 00.4 0.4 ka (8.8–10.8 m high), 7.4±0.60 to 6.5 ± 0.4 ka (5.7–11.1 m high), 6 ka (6.4–8.4 ±0.4 m high), and 3.4 ± 0.3 ka (3.3–3.6 m high) (Fig. 3D).

. Bega Swamp, coastal New South Wales (~36°S), although being a high-resolution record, it remains unpublished. Nevertheless, Hope et al. (2004) claim that, between 8.5 and 6.6 ka, a lengthy mid-Holocene development of wet forest elements occurred (based on Fig. 7 in Hope et al. (2004) and G. Hope, unpublished).

.The crater (maar) Lakes Keilambete and Gnotuk in western Victoria. Keilambete (38°13′15″S, 142°52′46″E, ~120 m asl) is located near the township of Terang and has extensively been studied (Bowler, 1981; De Deckker, 1982; Chivas et al. 1985, 1986, 1993; Wilkins et al., 2012a,b, 2013; Gouramanis et al., 2013). These two crater lakes are located at almost the same latitude as marine core SS02-GC15. Lake Gnotuk is near the township of Camperdown at a slightly higher altitude. Both lakes are hypersaline today and did not dry during the Holocene. A total of 29 OSL, 30 radiocarbon dates were obtained for the combination of the two cores (Wilkins et al., 2012a,b). Here, we rely on the reconstruction of lake levels based on grain size analysis of core sediments from both lakes (Wilkins et al., 2012) which is also supported by ostracod faunal analysis (De Deckker, 1982) and the geochemistry of ostracod shells (see references above).

The combined lake level curve documents that for the period of two centuries the highest levels were around 7.2 ka with high levels between 8.9 and 5.1 ka, with some significant fluctuations, and even a short dry phase at 7.8 ka (Fig. 3F). Note that because of the conical shape of both lakes, levels take a while to adjust to precipitation/evaporation changes (Jones et al., 1998, 2001).

. NW Jakka Lake, western Victoria (36°48′18″ S, 141°48′ 36″E, 132 m asl) is located to the southwest of Mount Arapiles in northwestern Victoria. The chronology relies on 5 OSL, 2 radiocarbon dates. Kemp et al. (2011) reconstructed water salinity using ostracod species assemblages covering the last 10 ka. These authors concluded that there were relatively wet conditions (marked by lower water salinities) between 9.6 ka and 5.7 ka, with also high salinities recorded around 8.2 to 8 ka.

. Paddy's Lake, Tasmania is a cirque lake located on the Black Bluff Massif in northwestern Tasmania (41°27′04″ S, 145°57′41″E, 1065 m asl). The chronology of the 13.4 ka core relies on 15 radiocarbon palynoflora (Beck et al. 2017, 2018) as well as on other proxies. These authors stated that the “dominance of rainforest pollen types (>50% of the pollen sum) between ca. 7.5–6.5 ka indicates peak Holocene positive moisture balance at Paddy's Lake” (Fig. 3G). The trends identified in the above mentioned publications confirm the region trends recognised in Tasmania in the significant investigations by Macphail (1979) which unfortunately relied on too few radiocarbon dates (see comment in the methodology section).

. Small Lake in Cradle Mountain National Park, Tasmania (41° 39′ S, 145° 57′ E, 999 m a.s.l.) is adjacent to Lake Tilla. Stahle et al. (2016) studied a core to obtain information on the vegetation and fire history as well as human activities in the area. Their chronology relied on 14 radiocarbon dates for the Holocene. Importantly, it was found that montane rainforest in the Cradle Mountain region reached its greatest Holocene extent during the middle Holocene with the highest percentage of the rainforest taxon *Nothofagus cunninghamii* between 8.5 and 6.5 ka, suggesting a higher amount of rainfall (Stahle et al., 2016, Fig. 6G). Similar comments mentioned earlier regarding Macphail (1979)'s findings equally apply to this work.

. Lynds Cave, central northern Tasmania **(**41°35′ S, 146°15’ E, 290 m asl) was studied by Xia et al. (2001) who examined a combination of δ^{18}O, δ^{13}C as well as stalagmite growth rate. These authors found that between 8.6 and 8 ka there was a period of stable and moderate precipitation and stable and high bio-productivity, associated with continuously rising temperatures. Later, between 8 ka and 7.4 ka, they identified that the warmest period was registered with high evaporation and low effective precipitation, and then between 7.4 ka and 7 ka, the wettest period with highest stalagmite growth, and finally between 7 ka and 6.6 ka.

5. Addition terrestrial archives/cores outside Australia worthy of comparison with the Australian data sets

5.1. . EPICA Dome C and other sites, Antarctica

Monnin et al. (2004) used a combination of three ice cores (EPICA Dome C (=EDC 75°06′S, 123°21′E; 3233 m asl), Dronning Maud Land (=DML 75°00′S, 65°01′ E, 2900 m a.s.l.), and Taylor Dome (= TALDICE 77°40′S 157°40′E; 2375 m a.s.l.) for the study of CO2 trapped in gas bubbles during the Holocene. They documented that there is a period of low CO_2 concentration levels between 8.2 and 6.2 ka (Fig. 3I).

In addition, Parrenin et al. (2013) reconstructed past atmospheric temperatures in Antarctica using a stack of 5 core records (EDC, TALDICE, EDML, as well as Vostok (78°27′ S 106°50′ E; 3489 m asl) and Dome Fuji (7°19′ S 39°42′ E; 3765 m asl) that were synchronised. These authors identify that the period spaning 8.2 to 6.4 ka was the warmest (Fig. 3I) before another phase towards the end of the Holocene, e.g. the last millennium.

6. Discussion

6.1. Marine cores and New Zealand glaciers

Fig. 2 displays the selection of three proxies (SST and assessment of the thermocline depth linked to the presence/absence of the westerlies over the core sites, as well as the prevalence of the westerlies) used in each of the two cores. There are some SST fluctuations recorded in both cores around the middle of the Holocene, but the highest SST are seen at ~6.2 ka. This timing coincides with the highest mean and maximum SST recorded in core Fr10-95/GC17 offshore North West Cape in NW Western Australia (De Deckker et al., 2014). However, in both cores, the SST were consistently high between 8.2 and 5.5 ka, the period which here is coined the marine hypsithermal offshore southern Australia. In addition, when SST were high, the percentage of *G. ruber* brought in to the core sites by the Leeuwin Current are diminished as this current is reduced as a result form the lack of westerly winds (Fig. 2. B, F).

The assessment of the thermocline depth in both Australian cores through the percentage of *G. truncatulinoides* (Fig. 2 C, G) is considered to be an indicator of the presence/absence or diminution of the westerlies south of Australia. It is noteworthy during the temperature hypsithermal, the thermocline depth was at the highest for the Holocene (Supp. Fig. 3).

Note also that Gingele et al. (2007) had examined in great detail the Holocene record of MD03-2611), and in particular commented on discharge of the nearby River Murray that drains a large part of eastern Australia (~$1{\cdot}10^6$ km^2). The pollen record of the adjacent core MD03-2607 was recently provided in De Deckker et al. (2021).

Already, Bostock et al. (2013) in their summary of marine records over the last 30 ka from the Australian-New Zealand region conducted for the Aus-INTIMATE project, referred to the MD03-2611 alkenone SST record by Calvo et al. (2007) and compared it against records from offshore New Zealand (see Fig 3 in Bostock, 2013). It is clear that the New Zealand records display a SST hike much earlier than the Australian record which is a surprise. In more detail, along the east coast of New Zealand cores MD97-2120 (45° 31′S, 174° 55′E), the alkenone SST reconstructions peak ~11 ka and Mg/Ca SST done on *G. bulloides* peak ~9 ka (Pahnke et al., 2003). In another nearby core MD97-2121 (40°22′S, 177° 59′E), the alkenone SST peak ~9 ka (Pahnke and Sachs, 2006). Along the west coast of New Zealand, alkenone SST reconstructions done on core SO136-GC11 (43° 26′S, 167° 51′E) peak at ~9 ka (Barrows et al., 2007). These discrepancies were later investigated in great detail by Prebble et al. (2017).

It is no surprise therefore to see that Denton et al. (2021)'s assessment of all the ages for glacial advances on mid-latitude mountain ice fields in the South Island of New Zealand display a good coincidence with changes in the southern Australian marine cores (Fig. 2D). Denton et al. (2021) had already postulated that there was a good link between glacial advances and the position of the westerlies, and the lack of upwelling (viz. a deep thermocline caused by a lack of westerlies in the region) as seen in both cores (2611 and GC15) further confirms this observation. In other words, as the position of the austral westerlies is crucial also for generating climatic conditions in New Zealand, when westerlies were close to New Zealand glacial condition were engendered on the South Island, and the opposite forcing more 'interglacial-mode' conditions. The striking feature is the lack of glacial advances between the 8.06 and 3.89 ka period, except for three episodes at 7.19, 6.89 and at 6.74 ka (Fig. 2D). The first one in the Pukaki main valley (Putnam et al., 2012), and the other two in the Cameron valley (Schaefer et al., 2009; Putnam et al., 2012). In fact, these three dates tend to overlap when error bars are taken into account, and also the two youngest dates match peaks in *G. truncatulinoides* % in at least core 2611 (Fig. 2C).

6.2. Lacustrine and speleothem cores

Fig. 3 displays those significant records from low to high latitudinal distribution. Description of changes that were recognised during the Holocene that coincided with either a higher temperature and/or precipitation have already been discussed in the results section above. Nevertheless, some generalisation is warranted on all those terrestrial archives.

Overall, in southeastern Australia, the mid-Holocene (~8.2 to 6 ka) is marked by increased wet elements in forests that indicate moister conditions. Lake levels were either high or salinities reduced because of the significant rainfall. These vary between locations, but those observations may result from low chronology levels, and/or local environmental conditions. Nevertheless, it is clear that the conditions that prevailed during those two millennia are quite different from those registered since. The additional important observation is that atmospheric temperatures registered at Lake McKenzie on Fraser Island, although few in numbers, where the highest for the entire Holocene. Equally, at Lynds Cave in Tasmania, Xia et al. (2001) identified that the warmest period was registered with high evaporation and low effective precipitation between 8.6 and 8 ka and then later, between 8 ka and 7.4 ka, the warmest period was registered with high evaporation and low effective precipitation. This coincides with similar high temperatures at sea, discussed in the previous section. Perhaps we may also assume that the proliferation of rainforest vegetation from northern Australia down to Tasmania would have occurred not only as a result of increased rainfall/moisture, but likely from warmer ambient temperatures (Mooney et al., 2017).

Despite the fact that at various sites like in Tasmania and in northern Australia discussed above and which all show significant vegetation changes during the hypsithermal, other lacustrine sites appear not have followed the trends such as in the Volcanic District of Western Victoria. At Lake Keilambete, Dodson (1974)'s pollen diagram indicates very little vegetation changes during the entire Holocene. Similarly, the vegetation spectra at the nearby Basin Lake (also a volcanic maar) show little change during the entire Holocene (Gell et al., 1994). Dodson (1974) provided the answer by stating that the 'volcanic soils may have been important, if not all-important, in determining the general type of the vegetation and thus did not allow other vegetation types to compete effectively … '. This implies that caution has to be taken when comparing vegetation records at a continental scale. On the other hand, the algal records at those two sites discussed above clearly show a freshening of both lake waters, coincident with the hyspsithermal (refer to Dodson, 1974, and Gell et al. 1994), but these records are not discussed any further as they rely on too few dates.

6.3. Rivers

The combination of fluvial records and valley fills between 30 and 42°S in southeastern Australia was assessed by Cohen and Nanson (2007). These authors examined 35 fluvial deposits (8 of which are <1 ka) and 35 upland swamp sites and relied on numerous radiocarbon dates, and identified a period of 'enhanced water discharges, stable well-vegetated catchments and low sediment yields'. These were represented by a clear distinct gap in the alluvial record, also repeated in the upland swamp spanning the 8 to 4 ka period. This very wet fluvial phase is coined the 'Nambucca Phase' (Cohen and Nanson, 2007) (Fig. 3E).

6.4. The position of the westerlies offshore southern Australia over the holocene

De Deckker et al. (2020), who drew a series of palaeoclimatic maps of Australia for every two millennia spanning the period of 34 to 14ka BP, clearly showed the waxing and waning of the Subtropical Front (STF) south of Australia. This was based on the percentages of specific planktic foraminifera *(Neogloboquadrina incompta* and *Globigerina bulloides*) that are both indicative of the position of the STF with respect to the core sites studied here (2611 and GC15). In addition, work by Perner et al.

(2018, Fig 6) estimated that when the percentages of *Globorotalia truncatulinoides* in the cores are low, the thermocline is deep as is often seen during La Niña phases. In contrast, when *G. truncatulinoides* are high, the thermocline is shallower as postulated during El Niño events (Middleton and Bye, 2007, Fig. 26). Therefore, the low percentages in both cores (Fig. 2 C, G) of *G. truncatulinoides* between 8.3 and 5.7 ka are interpreted to be indicative of a deep thermocline associated a continuous La Niña phase and also with low westerlies winds near the South Australian coast. During that period of time, the highest SSTs were recorded in both cores, but this period is extended to a slightly longer time frame: 8.5 to 5.3 ka (Suppl. Fig. 3).

Of interest is that Shulmeister et al. (2004) in their review two decades ago of the behavior of the westerlies in the Australasian region identified that the minimum of westerly winds activity was centered around 11 ka and that a maximum flow recommenced in the late Holocene. Our records now modify this view and is backed by ample samples in the two marine cores and backed by numerous radiocarbon dates. Prebble et al. (2017) who examined a vast numbers of cores east and southwest of New Zealand, clearly identified that SSTs were high and coincided with a much-reduced westerly wind. In our two main cores, the percentages of *G. truncatulinoides* were very high at the beginning of the Holocene (Fig. 2 C, F) but in contrast SSTs were much lower than during the hypsithermal in the Australian region. Obviously, the New Zealand sector of the Southern Ocean behaved differently to what was happening just south of Australia. The reason for this is that during the Holocene cores 2611 and GC15 were always located north of the Subtropical Front, whereas most of the studied New Zealand cores were not (core MD97-2121 being the exception).

The great wetness seen during the hypsithermal in eastern Australia is very likely to have been caused by the higher SSTs at the time, and a much warmer Tasman and Coral Seas (Fig. 1) would have been the major source of moisture as identified today during La Niña phases by Holgate et al. (2022).

6.5. Climatic implications for human activities in Australia during the Holocene before European arrival

Williams (2013) provided an assessment of human population in Australia covering the last 50 ka by examining al the radiocarbon-dated material found in association with human activity. He established a population curve that was low for the Late Pleistocene, followed by an increase at the beginning of he Holocene followed by three pulses (~8.3 to 6.6 ka, 4.4 to 3.7 ka, and 1.6 to 0.4 ka). He already stated that the demographic change appears to be in 'response to major climatic events'. This idea was further developed by Williams et al. (2015) who arbitrarily defined the Holocene 'climatic optimum' to have occurred between 9 and 6 ka for which time these authors state that the 'rapid expansion, growth and establishment of regional populations across ~75% of Australia, including much of the arid zone'. This period was followed by population fragmentation by the 'onset of El Niño-Southern Oscillation (=ENSO) that restricted low-level food production and resulted in population fragmentation'. Smith et al. (2008) further discussed archaeological records in Australian drylands and, using radiocarbon density plots, suggested 'a step-wise pattern of population growth and expansion, with significant thresholds at 19, 8 and 1.5 ka'. These authors commented on the fact at around 8 ka, the marine transgression provided very suitable and productive mangrove sites across northern Australia, but also that in the Murray Darling Basin there is a peak visibility (*sensu* Smith et al., 2008) associated with rivers sustaining major discharges.

Since then, Perner et al. (2018) defined more accurately and in great detail the waxing and waning of ENSO events, with the last 3.5 ka being more or less dominated by an El Niño state (with frequent shifts between El Niño and La Niña states, and this has been further confirmed by the work of Barr et al. (2019) on Minjerribah) and this should eventually be reassessed in conjunction with evidence of human population across Australia, as suggested by Smith et al. (2008).

Of interest also, Balme and Hope (1990), who examined midden sites in the Lower Darling River area of western NSW, had found that radiocarbon-dated middens during the period 8.6 to 6.6 ka (16 dates calibrated by this author with a mean of 8.34 ± 0.46 ka) were most localised along the Teryawynia Creek (Fig. 1) which is an offshoot of Talyawalka Creek (an anabranch of the Darling River) and associated lakes that runs parallel to the Darling River. On the other hand, younger middens were found mostly along the Darling River and associated lunette lakes such as Lake Menindee (Balme and Hope, 1990). It is thought here that the Darling River may have registered a very fast flow and rapidly shifting broad meanders, whereas its anabranch (Teryawynia Creek) saw flowing water between 8.6 and 6.6 ka being more suitable for human occupation along its margins during this period. This creek may have dried up after ~6.6 ka. This indicates that people shifted location depending on the suitability of the aquatic environments suitable for gathering resources.

Pardoe and Hutton (2021), who investigated mounds in the Barapa wetland in the River Murray floodplain (Fig. 1), identified some 153 mounds in the vicinity of Pollack Swamp that are distributed around the swamp and Barbers Creek. These mounds were built by people within the last 4 ka and are thought to be either burial grounds or 'kitchens' in which river clay was used as heat retainers in ground ovens used to cook food items. The result is a 'picture of people living in large groupings – villages and hamlets – around water bodies' *sensu* Pardoe and Hutton (2021). More recently, additional mounds in the River Murray valley near Renmark were investigated by Ross et al. (2019) using magnetometry to verify relatively subtle topographic variations in the landscape. Such mounds are considered to be the 'result of socio-demographic changes including population growth and increased sedentism, as well as an associated need to enhance food production through the use of more labour-intensive food-production systems' (Ross et al., 2019; but see also Lourandos, 1997). Thus far, no mounds found in southeastern Australia are older than 4.81–4.52 ka BP (Ian Moffatt, pers. com.) and therefore this suggests a significant change in human practices that led to sedentary behavior. These should be directly linked to an overall change in climate as postulated by Williams et al. (2015). Nevertheless, further dating is required from a variety of mounds to identify their antiquity, but this may be a culturally difficult question to address.

Concerning human occupation of today's driest part of Australia, Hughes et al. (2017) reviewed the published evidence and identified that between 12 and 5 ka, several sites registered stone artefacts in the northern Flinders Ranges and the Roxby dunefield as well as in the Lake Frome area, but overall there was 'very little archaeological material of early-mid Holocene age recovered from anywhere in the region' (sic Hughes et al., 2017). Postdating that phase, these authors clearly indicate that 'many thousands of archaeological sites are demonstrated by direct dating or inferred on the basis of artefact assemblage composition that are of late Holocene age in the same study area. However, these consist of surface clusters of stone artefacts, occasionally associated with hearths' (sic Hughes et al., 2017). Nevertheless, there is no evidence of any change in human habitation or practices.

7. Conclusions

Detailed investigations of well-dated sites all along eastern Australia, from The Atherton Tableland down to Tasmania, point to the following:

(1) at the very beginning of the Holocene when percentages of *G. truncatulinoides* were very high (see Fig. 2 C, G) a result of strong westerlies, there must have been a positive Southern Annular Mode (SAM).
(2) Following from that, the percentages of *G. ruber* were at their highest for the Holocene, and during that period, the FC would have progressively weakened as shown by the decreasing

percentages of *G. truncatulinoides*, and the entire region was affected by a continuous negative SAM. During that time, the westerlies must have retreated further south.

(3) During the Australian Hypsithermal (~8.2 to ~5.5 ka), on the other hand, the Subtropical Ridge would have been placed close to the Australian continent, and the entire region entered in a permanent negative SAM and the westerlies had seriously diminished.

(4) It is also evident that glacial conditions on the South Island of New Zealand were almost absent during that period, except for a few centuries around 7 ka when the westerlies may have migrated equatorward once more during that period.

(5) Later on, ENSO signals prevailed across the Pacific ENSO conditions with alternations between El Niño and La Niña phases. The timing of this period varies slightly between sites and this may result from different chronological controls as well as latitudinal locations and this affected climates on land and conditions at sea in the Australian region. Those conditions had already been addressed in great detail by Perner et al. in 2018 and will not be repeated here.

Nevertheless, the Antarctic ice core records shows that during the period of 8.2 to 6.5 ka, atmospheric CO_2 levels and ambient temperatures were the lowest recorded for the Holocene (except for temperature levels during the last millennium). It appears therefore that the terminology of 'Holocene Hypsithermal' is not suitable when comparing the Australian record with that of Antarctica. Regional differences are far too great and too variable to warrant at this stage a suitable general label like is done for the 'Atlantic Period' commonly used in Europe for the period spaning between 8 and 6 ka.

Human populations significantly increased in Australia during the Holocene, very likely as a result of climatic conditions having improved. It appears that a more sedentary life style and the occurrence of people in large groupings around water bodies such as along swampy areas of the River Murray, that are interpreted as villages/hamlets, only spread after the Holocene wettest and warmest period from ~4.5 ka onwards. In the more arid part of central and south central South Australia, there is no evidence of a change of human lifestyle. It will be necessary also to better define the impact of vegetation burning mostly caused by human activities) on hydrological and climatic conditions affecting the Australian continent, but this is not addressed in the present paper.

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.qsa.2022.100061.

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