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Heat export from the tropics drives mid to late Holocene palaeoceanographic changes offshore southern Australia

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A B S T R A C T

The Leeuwin Current (LC), an eastern boundary current, transports tropical waters from the Indo-Pacific Warm Pool (IPWP) towards southern latitudes and modulates oceanic conditions offshore southern Australia. New, high-resolution planktic foraminifer assemblage data and alkenone-derived sea surface temperatures (SST) provide an in-depth view on LC variability and mechanisms driving the current's properties during the mid to late Holocene (last *c.* 7.4 ka BP). Our marine reconstructions highlight a longer-term mid to late Holocene reduction of tropical heat export from the IPWP area into the LC. Mid Holocene (*c.* 7.4 to 3.5 ka BP) occurrence of high SSTs (>19.5 °C), tropical planktic foraminifera and a well-stratified water column document an enhanced heat export from the tropics. From *c.* 3.5 ka BP onwards, a weaker LC and a notably reduced tropical heat export cause oceanic cooling offshore southern Australia. The observed mid to late Holocene trends likely result from large-scale changes in the IPWP's heat storage linked to the El Niño-Southern Oscillation (ENSO) phenomenon. We propose that a strong and warm LC occurs in response to a La Niña-like state of ENSO during the mid Holocene. The late Holocene LC cooling, however, results from a shift towards an El Niño-like state and a more variable ENSO system that causes cooling of the IPWP. Superimposed on these longer-term trends we find evidence of distinct late Holocene millennial-scale phases of enhanced El Niño/La Niña development, which appear synchronous with northern hemispheric climatic variability. Phases of dominant El Niño-like states occur parallel to North Atlantic cold phases: the '2800 years BP cooling event', the 'Dark Ages' and the 'Little Ice Age', whereas the 'Roman Warm Period' and the 'Medieval Climate Anomaly' parallel periods of a predominant La Niña-like state. Our findings provide further evidence of coherent interhemispheric climatic and oceanic conditions during the mid to late Holocene, suggesting ENSO as a potential mediator.

1. Introduction

The Indo-Pacific Warm Pool (IPWP) redistributes heat and moisture that influence the global climate system via atmospheric convection and ocean currents (Mayer et al., 2014; Rippert et al., 2016). Variations in the IPWP's heat storage directly relate to the influence of the El Niño-Southern Oscillation (ENSO) phenomenon and consequent changes in the strength of the Pacific Walker circulation. During El Niño phases, oceanic heat discharges from the IPWP towards the central eastern Pacific. Consequently, the Walker circulation weakens and oceanic heat globally redistributes via atmospheric circulation (e.g., Klein et al., 1999; Trenberth et al., 2002; Mayer et al., 2013). On the contrary, during La Niña phases, a strong Walker circulation prevails in the Pacific Ocean and heat accumulates in the western IPWP. This greater heat accumulation leads to an enhanced heat export into the Indian and Atlantic Ocean via ocean currents (e.g., Mayer et al., 2014; McGregor et al., 2014),

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such as the South Equatorial Current and the Leeuwin Current (LC; Fig. 1).

The warm and saline LC is a southward flowing eastern boundary current that influences the oceanographic conditions, i.e. temperature, salinity and water column stratification, along Australia's western and southern shores (Fig. 1; Holbrook et al., 2012 and references therein). Oceanographic observations reveal that this region is sensitive to modern remote ENSO state changes in the Pacific and thus, to changes of the tropical heat export from the IPWP (Middleton and Bye, 2007; Feng et al., 2013). Prominent recent examples of this influence are the 1998 El Niño and the 2011 La Niña that effected regional oceanic and climatic conditions (e.g. Feng et al., 2013; Middleton and Bye, 2007). During El Niño (La Niña) phases the LC flow is weaker (stronger), SSTs are colder (warmer), the thermocline is shallower (deeper) and the sea-level height anomaly is negative (positive; Cirano and Middleton, 2004; Middleton et al., 2007; Middleton and Bye, 2007; Feng et al., 2013).

Despite of the known close coupling between ENSO and the LC in the instrumental data period, there is little information available on the currents palaeoceanographic evolutions offshore southern Australia. Last glacial palaeoceanographic reconstructions from this region present evidence that alternating warm and cold phases of the LC result from changes in the heat export from the IPWP, accompanied by latitudinal shifts of the Subtropical Front (STF; De Deckker et al., 2012). A previous study by Moros et al. (2009) identified that during the early Holocene (*c.* 10 to 7.5 ka BP); the STF was located close to the South Australian coast, compared to its present location at 45° S in winter. An early to mid Holocene poleward migration of the STF led to the establishment of the LC within the study area. Therefore, this region became susceptible to variations in the tropical heat export and thus to extra-tropical ENSO influence.

Here, we present new records of planktic foraminifer data and alkenone-derived SST from two marine sediment cores located along the flow path of the LC offshore southern Australia (Lincoln and Otway Shelf; Fig. 1). The planktic foraminifer assemblage allow a more detailed reconstruction of the LC's water mass characteristics, i.e., changes in stratification and the thermocline depth. Our reconstructions provide a more comprehensive view on longer-term and millennial-scale mid to late Holocene variations in the tropical heat export from the IPWP that link to ENSO state changes and the development of El Niño/La Niña events during these phases.

2. Modern oceanographic setting

The LC influences oceanographic conditions offshore western and southern Australia (Holbrook et al., 2012). This surface-water current (upper 200 m of the water column) carries tropical and low-saline waters that originate in the IPWP, driven westwards by the trade winds and channelled via the Indonesian Throughflow (ITF) into the eastern Indian Ocean (Rochford, 1986; Feng et al., 2003; Le Quéré et al., 2007). The LC flows southwards along the West Australian coast and mixes partly with salty subtropical waters from offshore (Cresswell and Peterson, 1993). After rounding Cape Leeuwin (Fig. 2A), the LC turns eastwards into the Great Australian Bight (Cresswell and Golding, 1980; Ridgway and Condie, 2004). Satellite images, instrumental data and modelling studies show seasonal variations in the strength of the LC (Cresswell and Peterson, 1993; Ridgway and Condie, 2004; Cirano and Middleton, 2004). During the austral summer (October to March), the current is relatively weak due to strong opposing winds (Smith et al., 1991; Feng et al., 2003), while during austral winter (April to September), the current increases in strength and carries a greater amount of tropical water (Cresswell and Peterson, 1993; Ridgway and Condie, 2004; Middleton and Bye, 2007). Fig. 2A presents the mean April SST for 2011, a La Niña year that illustrates such a phase of a strong/warm LC within the study area. This image is based on satellite data from MODIS (MOderate Resolution Imaging Spectro-radiometer) operated on the satellite Aqua, using a spatial resolution of 4 km (NASA Ocean Colour Web Page; https://oceancolor.gsfc.nasa.gov/atbd/sst/).

The LC has a persistent influence on oceanic conditions offshore southern Australia throughout the year with a stable thermocline-driven stratification (e.g. Holbrook et al., 2012) and SSTs that are *c.* 2–3 °C higher than the open Southern Ocean (Legeckis and Cresswell, 1981; Herzfeld and Tomczak, 1997). The Flinders Current (FC; Middleton and Cirano, 2002), a northern boundary current, originates in the Southern Ocean (Gordon et al., 2008) and carries Antarctic Intermediate Water that influences subsurface waters along Australia's southern shelf (Fig. 2A).

The modern position of the Subtropical Front (STF, also called the Subtropical Conversion) is found at *c.* 45° S in winter and at 47° S in summer, a few degrees south of our study area. Here, the summer 15 °C isotherm and winter 10 °C isotherm outcrop on the surface (Martinez, 1994, Fig. 1). The STF forms the southern limit of the subtropical surface waters and marks the latitudinal position of the westerlies in the Southern Ocean (Belkin and Gordon, 1996; Rintoul et al., 1997; Sikes et al., 2009).

On an inter-annual scale, ENSO influences the strength of the LC (Meyers, 1996; Middleton et al., 2007; Feng et al., 2009). During El Niño years, the ITF is weaker and the LC flow reduced. The sea-level height anomaly off Australia's western and southern coasts is lower (Fig. 2B; Feng et al., 2003; Holbrook et al., 2012). Observations show that the thermocline (approximated by the 11.5 °C isotherm) shallows by up to 170 m during El Niño summers from its mean depth of 250 m off Kangaroo Island (Fig. 2C; Middleton and Cirano, 2002; Middleton et al., 2007). During La Niña years, the ITF is stronger and the LC flow strengthens, and the sea level height anomaly off Australia's western and southern coasts increases (Fig. 2B and C; Feng et al., 2003; Wijffels and Meyers, 2004; Middleton and Bye, 2007; Middleton et al., 2007; Feng et al., 2013).

3. Ecological preference of planktic foraminifer

Ecological studies of planktic foraminifer (Phleger, 1960; Bé, 1977; Murray, 1991) demonstrate the close coupling of species to specific surface waters as their faunal signatures trace frontal movements (e.g., King and Howard, 2003, 2005). Several species prefer certain depth habitats in the water column. Therefore, variations in the relative species abundance document changes in the mixed-layer and thermocline (shallow or deep) properties, and thus provide indications of changes in regional water mass stratification (Cifelli and Smith, 1970; Bé and Tolderlund, 1971; Prell and Hutson, 1979; Howard and Prell, 1992; Niebler and Gersonde, 1998; Li et al., 1999; Peeters et al., 2004).

In the study area, the occurrence of shallow water species (<50 m) *Globoturborotalita rubescens* pink (Hofker, 1956), *Globoturborotalita tenella* (Parker, 1958), and *Globigerinoides sacculifer* (Brady, 1877) mark the presence of tropical-to-subtropical waters in the LC. In the following, we refer to these species as the 'Tropical fauna'. Occurrence of the subtropical surface-dweller (*c.* 50 m water depth) *Globigerinoides ruber* (d'Orbigny, 1839) and *Globigerinella siphonifera* (d'Orbigny, 1839) also links to the influence of the LC (e.g., Maxwell and Creswell, 1981; Li et al., 1999). The LC's warm tropical waters enable these species to survive further south than typically found and consequently limits their presence and latitudinal extent (e.g., Bé, 1977; Maxwell and Creswell, 1981; Li et al., 1999).