SPCZ zonal events and downstream influence on surface ocean conditions in the Indonesian Throughflow region

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Abstract Seasonal surface freshening of the Makassar Strait, the main conduit of the Indonesian Throughflow (ITF), is a key factor controlling the ITF. Here we present a 262 year reconstruction of seasonal sea-surface-salinity variability from 1742 to 2004 Common Era by using coral δ18O records from the central Makassar Strait. Our record reveals persistent seasonal freshening and also years with significant truncations of seasonal freshening that correlate exactly with South Pacific Convergence Zone (SPCZ) zonal events >4000 km to the east. During these events, the SPCZ dramatically rotates ~15° north to near the equator and stronger westward flowing South Pacific boundary currents force higher-salinity water through the Makassar Strait in February–May halting the normal seasonal freshening in the strait. By these teleconnections, our Makassar coral δ18O series provides the first record of the recurrence interval of these zonal SPCZ events and demonstrates that they have occurred on a semiregular basis since the mid-1700s.

1. Introduction

In the far western Pacific there is a complex relationship between western boundary currents (WBCs), the Intertropical and South Pacific Convergence Zones (ITCZ and SPCZ, respectively) and the Indonesian Throughflow (ITF) [Hu et al., 2015; Vincent et al., 2009] (Figure 1). The ITF is an important ocean current that connects the Pacific and Indian Oceans and follows an intricate pathway through the Indonesian seafloor on the edge of the western Pacific warm pool (WPWP). The ITF is the only low-latitude intermediate oceanic conduit and annually transports a large amount of water (~15 sverdrups, where one sverdup equals 1×10^6 m^3/s) and heat (~0.5 PW, where 1 PW = 10^15 W) from the WPWP north of the equator to 12°S in the Indian Ocean. The ITF is thought to play a key role in modulating Indo-Pacific climate over a range of time scales [Gordon, 1986; Gordon et al., 2003; Linsley et al., 2010; Valsala et al., 2011; Holbourne et al., 2011; van Sebille et al., 2014]. The main conduit for the ITF is the Makassar Strait (Figure 2). The source water for the ITF originates primarily from two WBCs, the Mindanao Current and the New Guinea Coastal Current (NGCC) [Hu et al., 2015]. On average, ~80% of water comprising the ITF comes from the Mindanao Current in the North Pacific with the remaining 20% sourced from the South Pacific via the NGCC which in turn acquires water from the South Equatorial Current (SEC) [Gordon, 2005; Sprintall et al., 2014; Hu et al., 2015]. The ITF velocity is ~50% reduced during the winter monsoon (boreal winter) relative to the summer and has a high velocity core at ~100 m depth which appears to shoal during El Niño events [Gordon et al., 2003; Sprintall et al., 2014]. Recent discussions surrounding interannual ITF and WPWP variability have focused on the shoaling of the ITF high-velocity core since 2007 and the relative influence of North Pacific sources and the influence of the South China Sea as well as the Indian Ocean Dipole [Sprintall et al., 2014; Tozuka et al., 2007; Abram et al., 2009; Gordon et al., 2012]. However, still ambiguous is the relative influence of the South Pacific on the ITF across a range of time scales. Similar high-amplitude seasonal radiocarbon (Δ14C) variability in both Makassar Strait and Guam corals was interpreted to indicate a year-round North Pacific source for the ITF [Moore et al., 1997], but other oceanographic and coral-derived paleoceanographic data indicate that the South Pacific is an intermittent source of the ITF [Godfrey et al., 1993; Kashino et al., 1996; Morey et al., 1999; Ueki et al., 2003; Gordon, 2005; Fallon and Guilderson, 2008; van Sebille et al., 2014].
**Figure 1.** Sea surface salinity (SSS) data for the western tropical Pacific and Indonesia from the SODA SSS database [Carton and Giese, 2008] for (a) March 1982, (b) March 1983, (c) March 1991, (d) May 1992, (e) March 1997, and (f) March 1998. The right-hand column of three panels for March 1983, May 1992, and March 1998 are when the South Pacific Convergence Zone (SPCZ) was determined from Global Precipitation Climatology Project (GPCP) [Adler et al., 2003] data to be in a "zonal" orientation [Vincent et al., 2009]. The white box in the Makassar Strait indicates our study sites. The increase in SSS along the equator during the SPCZ zonal events (right column) coincides with increases in the South Equatorial Current (SEC), the New Guinea Coastal Current (NGCC), and New Guinea Coastal Under Current (NGCUC) and the truncation of seasonal freshening in the Makassar Strait (also see Figures S2–S5).
Figure 2. (a) Location of study sites at Kapoposang and Langkai in the Makassar Strait in relation to bathymetry and general flow vectors for the Indonesian Throughflow (ITF). (b) Vertical salinity profiles in the upper 500 m of salinity (from climatology) for the different seasons [Conkright et al., 1998]. (c) SODA SSS (blue) and IGOSS SST (black) data from grid box containing Kapoposang at study site in the Makassar Strait. (d) Kapoposang coral core KC4 $\delta^{18}O$ (black) and pseudo-coral forward model results using SST and SSS to estimate coral $\delta^{18}O$ (green). The red arrows indicate the years of previously identified zonal SPCZ events.
Easterly Pacific trade winds play an important role in driving the main westward flowing upper ocean currents that bifurcate into the western boundary currents upon approaching the far western Pacific [Hu et al., 2015]. In the South Pacific, a key atmospheric feature that is related to trade wind strength and location is the position of the SPCZ [Kiladis et al., 1989; Vincent et al., 2009; Cai et al., 2012; Tchilibou et al., 2015]. The SPCZ is a persistent rainfall band extending southeast from the WPWP, where it is merged with the ITCZ, into the subtropical South Pacific. It is the main feature regulating western South Pacific hydroclimate and South Pacific tropical cyclone genesis [Vincent, 1994; Vincent et al., 2009]. The rather unusual northwest-southeast orientation of the SPCZ has been suggested to be related to the anchoring of the SPCZ in the west to the WPWP with the southeastern portion controlled less by sea surface temperature (SST) but more by extratropical circulation, trade winds, and the dry zone in the southeast Pacific [Kiladis et al., 1989; Vincent et al., 2009]. Although the SPCZ is present throughout the year, it is most fully developed from November to April-May.

It has recently been observed that during some El Niño events the position of the SPCZ dramatically rotates ~15° of latitude northeast into a zonal orientation paralleling the equator in March to approximately May and merging with the ITZC just south of the equator when the ITZC is no longer observed west of 160°W [Vincent et al., 2009; Cai et al., 2012] (Figures 1 and S1 in the supporting information). These events have been termed SPCZ zonal events (or asymmetric events) [Vincent et al., 2009] and have only been documented in March-May of 1983, 1992, and 1998 near the end of El Niño events in those years (and also in January 2016 based on NOAA-National Centers for Environmental Prediction Climate Prediction Center Climate Anomaly Monitoring System precipitation data). The timing of the SPCZ zonal events are not correlated with the strength of each El Niño, as measured in the Niño 3.4 region, but are strongly correlated with the longitude of the eastern edge of the WPWP as defined by the 29°C isotherm [Vincent et al., 2009]. During these SPCZ zonal events, as the WPWP eastern edge shifts eastward to near 150°W, the SPCZ central axis rotates counterclockwise toward the equator. Model results of enhanced warming under future climate change scenarios indicate more frequent occurrences of these SPCZ excursions away from the standard climatological position with additional impacts on the location of tropical cyclone genesis [Cai et al., 2012; Widlansky et al., 2012; Borlace et al., 2014]. With limited satellite and ship-based observational data to identify past zonal SPCZ events before 1982, the recurrence interval of these SPCZ zonal excursions remains uncertain.

Here we show that coral oxygen isotope (δ18O) time series records from the central Makassar Strait in Indonesia have recorded these zonal SPCZ events due to an intermittent upper ocean teleconnection between the SPCZ, western boundary currents in the South Pacific and Indonesia (Figures 1 and 2). Thus, this site in the Makassar Strait is a unique location from which to remotely reconstruct the timing of these zonal SPCZ events. We use our coral δ18O record to identify years with zonal SPCZ events back to 1742 Common Era (C.E.). In turn, our work demonstrates the complexity of climatic linkages between seemingly disparate regions and supports the view that remote and maybe intermittent teleconnections need to be considered when interpreting climatic and paleoclimatic data.

2. The ITF and Makassar Strait Seasonal Surface Salinity Variability

The usually regular seasonal influx of low-salinity surface water from the South China and Java Seas into the southern Makassar Strait during the boreal winter-spring (January–May) lowers surface salinity by 2 to 3 g/kg and generates a northward pressure gradient in the strait (Figures 1 and 2 and see non-El Niño years in Figures S2–S5). The low-salinity “plug” seasonally inhibits the flow of warm surface water in the far western Pacific Ocean from freely flowing southward into the Indian Ocean [Gordon et al., 2003]. The ITF is cooler than it would be without the low-salinity surface layer and has the net effect of cooling and freshening of the Indian Ocean thermocline [Gordon et al., 2003]. El Niño events result in drought throughout Indonesia and anomalously higher mean annual surface salinity in the central Makassar. However, there is not a direct correlation between El Niño event strength based on Niño 3.4 region measurements and Makassar Strait salinity anomalies or ITF velocity anomalies [van Sebille et al., 2014], suggesting a more complicated relationship between rainfall anomalies, hydroclimate, and surface ocean currents in this central ITF passage.

3. Makassar Strait Coral δ18O: Amplitude of Seasonal Freshening Back to 1742 C.E.

Our composite coral δ18O record from the Makassar Strait is based on cores from three coral colonies at the islands of Kapoposang and Langkai in the central Makassar Strait (see Figure 2a and the Methods section in
the supporting information). Two of the cores were collected in 1990 and designated LAN1A (1990–1950) and KAP1A (useable from 1964–1742) with preliminary $\delta^{18}O$ data reported [Moore, 1995; Fairbanks et al., 1997]. The third core designated KC4 was collected in 2004 also at Kapoposang (see Figure S6). We analyzed $\delta^{18}O$ at 1 mm increments along core KC4 generating a near-monthly $\delta^{18}O$ time series extending from 2004 to 1938. For cores LAN1A and KAP1A we generated new age models based on the current information on the timing and amplitude of the seasonal freshening cycle in the Makassar Strait as the initial assigned topmost age of core KAP1A (with a dead top) was incorrect (see the Methods section in the supporting information). The final near-monthly resolved composite series spans the period of 1742–2004 C.E. All three $\delta^{18}O$ series exhibit robust intercolony correlations. For the standardized records, the Pearson product-moment correlation coefficient ($r$) between KC4-LAN1A is 0.83, KC4-KAP1A is 0.78, and LAN1A-KAP1A is 0.86 (Figure 3a). With the seasonal cycles removed (climatology 1950–2004), the correlation coefficient of the anomalies is 0.49 between KC4-LAN1A, 0.31 between KC4-KAP1A, and 0.48 between LAN1A-KAP1A (Figure 3b). The low 1σ error envelope over the replication period of the composite record provides additional confidence in these corals’ as accurate recorders of environmental surface ocean conditions in the Makassar Strait (Figure 3c).

The chronology was also verified over the last two centuries by cross-checking against the timing of El Niño events [Quinn and Neal, 1992; Cobb et al., 2013; Linsley et al., 2015]. The Makassar composite $\delta^{18}O$ record displays interannual (3–7 years) variability that is coherent with Niño 3.4 SST anomaly (SSTA) and multiple western Pacific coral records [Urban et al., 2000; Cobb et al., 2013] demonstrating the remote influence of El Niño–Southern Oscillation as observed from instrumental records [Meyers, 1996; England and Huang, 2005] (Figure S7).

Annual $\delta^{18}O$ variations of 1–1.5‰, density banding, and thin but distinct fluorescent banding coincident with each annual $\delta^{18}O$ minima indicate that the large coral skeletal $\delta^{18}O$ variations we observe are annual and in part related to seasonal variations in river discharge in the southern Makassar Strait (Figure S6). This is further supported by the high degree of agreement, based on least squares linear regression, between the Makassar coral composite $\delta^{18}O$ record and Simple Ocean Data Assimilation Sea Surface Salinity ver. 2.1.6 (SODA SSS) [Carton and Giese, 2008] ($r^2 = 0.72$; $p < 0.01$; 1986–2004) (see also Figure S8 [Gordon and Fine, 1996; Gordon et al., 1999, 2008]). This association indicates that seasonal coral $\delta^{18}O$ variability in the strait mostly reflects the large seasonal salinity changes with only minimal influence from the small (0.5°C) bimodal seasonal SST cycle in this region (Figures 2c, 2d, and S9a). Our Makassar coral $\delta^{18}O$ record also reveals a significant agreement with a forward model “pseudo-coral” [Thompson et al., 2011] based on the gridded SODA SSS and both the NOAA Optimum Interpolated SST [Reynolds et al., 2002] (1981–2004: $r^2 = 0.68$; $p < 0.01$; Figure 2d) and Extended Reconstructed SST (v.4) [Huang et al., 2015] (1980–2004; $r^2 = 0.63$; $p < 0.01$) (see the Methods in the supporting information). We also evaluated the SSS influence on coral $\delta^{18}O$ by another approach where we attempted to remove the temperature component of $\delta^{18}O$ variability over a calibration interval (2004–1980). We then applied different $\delta^{18}O$-SSS sensitivities to temperature corrected $\delta^{18}O$ and compared the result to SODA SSS (see Figure S9). The small-amplitude difference between SODA SSS and estimated relative SSS (pseudo-coral and composite coral $\delta^{18}O$ with SST component removed) can be attributed to uncertainties about the coral $\delta^{18}O$-SSS sensitivity at this location (see Figure S9). These comparisons support the interpretation that seasonal variations in our Makassar Strait coral $\delta^{18}O$ record are predominantly related to the seasonal freshening cycle in the central Makassar.

A peculiar feature of both the SODA SSS data and the Makassar coral $\delta^{18}O$ record are years when the seasonal freshening cycle is significantly truncated in magnitude measured against the average seasonal $\delta^{18}O$ cycle (Figures 2c, 3, and 4). Anomalously reduced seasonal freshening most recently occurred in 1998 and 1983 and to a lesser extent in 1992 (see Figures 2d and 3c). In these years the normal freshening cycle is almost completely missing (in 1998) or greatly reduced in amplitude (in 1983 and 1992). During February–March 1998, the coral $\delta^{18}O$ record indicates a +0.47‰ deviation from the climatological February–March average (Figure 2d). Annual $\delta^{18}O$ minima during the 1983 very severe (VS) El Niño deviated from the climatology by +0.31‰. However, both the SODA SSS data and Makassar coral $\delta^{18}O$ indicate that not all El Niño events result in truncated seasonal freshening (i.e., see 1986/1987 and protracted 2002–2005 El Niño).
Figure 3. Coral δ¹⁸O results of cores KC4, KAP1A, and LAN1A from the central Makassar Strait for the period 1930–2004. (a) Coral δ¹⁸O anomalies with the average seasonal cycle removed, (b) Standardized coral δ¹⁸O to adjust for δ¹⁸O offsets between cores (mean removed and per standard deviation), (c) Composite average coral δ¹⁸O from the 3 cores (green) with 1σ error envelope over the replication period (grey) and (d) number of cores used in the composite for different time periods. Prior to 1938 only core KAP1A extends back to 1742.
The specific years of anomalously high $\delta^{18}O$ in the Makassar coral record cannot be completely explained by local monsoon-related precipitation changes because Makassar coral $\delta^{18}O$ and local or regional SODA SSS from 1979 to 2004 do not show a robust relationship with precipitation (data from Global Precipitation Climatology Project (GPCP)) (Adler et al., 2003) (see Figures S10 and S11). Surface ocean advective processes appear to be the main source of SSS variability in the central Makassar Strait and also the primary driver of the truncated seasonal freshening events in the Makassar Strait (Figures 1, 2, and S2–S5).

Figure 4. (a) Makassar Strait composite coral $\delta^{18}O$ series with seasonal $\delta^{18}O$ minima (fresh season) highlighted in blue. (b) Makassar Strait coral $\delta^{18}O$ fresh season minima isolated from a 3 year band-pass-filtered and centered composite coral $\delta^{18}O$ series where all variability with periods greater than 36 months had been removed (c) Makassar Strait coral $\delta^{18}O$ peak seasonal fresh season (February–March) differences from average fresh season $\delta^{18}O$ using the 36 month filtered data. The top 10 and top 20 anomalously high $\delta^{18}O$ (higher salinity) fresh seasons were then determined by ranking the results. We interpret the top ~20 truncated freshening events in the Makassar Strait as times when the SPCZ was in a more zonal orientation during February–May of that year (see text).
4. Makassar Strait Truncated Seasonal Freshening and Linkage to SPCZ Zonal Events

During the last 30 years of the best instrumental calibration data, there is an apparent direct correlation between years with truncated seasonal freshening in the Makassar Strait and the years of zonal SPCZ events when the SPCZ collapses onto the equator (Figures 1–3). The timing of zonal SPCZ events has not been documented prior to 1979, but the zonal SPCZ events in 1983, 1992, and 1998 correspond exactly with the timing of the three most recent Makassar Strait freshening events based on our coral δ¹⁸O results and the SODA SSS data. A close examination of the monthly SODA SSA data for all of these years reveals that the normal west to east spreading of lower salinity surface water from the Karimata Strait into the central Makassar Strait is abruptly stopped on the western side of the Makassar Strait in February–March only in 1983, 1992, and 1998 when the SPCZ is in a zonal position (Figures 1 and S2–S5). Normally, the SSS minimum spreads eastward all the way across the Makassar Strait to Sulawesi, with a distinct annual SSS minima in the central Makassar Strait in February–March. During years with SPCZ zonal events, the low SSS front appears to be stopped (truncated) from crossing the Makassar by the inflow of higher SSS surface water from the north (see Figures S3–S5). The 1998 current mooring results in the Makassar Strait [Gordon et al., 1999, 2003] apply only to depths below ~200 m but help constrain anomalous southward flow of the ITF during the 1998 SPCZ zonal event to depths shallower than 200 m.

An important observation is that not all severe El Niño events result in significant reductions in seasonal Makassar Strait freshening. In addition to 1998, 1992, and 1983, other years with clear truncated seasonal freshening cycles are 1964, 1920, 1916, 1889, 1877, 1808, and 1805 (see Table S1). Of these, only 1998, 1983, and 1877 are ranked as VS El Niño events, while others are either moderate or severe events. During the severe El Niño events of 1957/1958 and 1972/1973 based on the amplitudes of Niño 3.4 SSTA, February–March SSS in the Makassar Strait was near climatology as recorded by Makassar coral δ¹⁸O with peak fresh seasonal δ¹⁸O departures from average climatology of <0.15‰. Several moderate strength El Niños (again based on the amplitude of Niño 3.4 SSTA), however, do result in significant reductions in Makassar Strait seasonal freshening. During the moderate El Niño’s of 1963/1964 and 1991/1992 there were greater reductions in seasonal freshening as recorded in Makassar coral δ¹⁸O than the previously mentioned severe El Niño events in 1957/1958 and 1972/1973 with the composite coral δ¹⁸O record indicating enrichment of 0.34‰ (March 1964) and 0.21‰ (March 1992).

We calculated and then ranked the peak February–March (fresh season) differences from the average fresh season δ¹⁸O using a 36 month band-pass filtered data (see Table S1 and Figure 4). To identify and rank the years when the central Makassar Strait experienced a truncated freshening seasonal SSS cycle, we first calculated the δ¹⁸O departures from the average fresh season δ¹⁸O for each year. Based on our pseudo-coral calibration, this represents the departure from the average degree of seasonal freshening since the bimodal SST annual cycle is extremely small and not clearly represented in coral δ¹⁸O series (Figures 2c and 2d). The Makassar coral composite δ¹⁸O series was first band-pass filtered to remove all modes of variability with recurrence intervals <3 years. This facilitated isolation of the seasonal freshening cycle in coral δ¹⁸O from interannual and lower frequency changes in SST and/or SSS. The probability (P) for the occurrence of a specific magnitude event occurring in any given year was calculated as follows: 

\[ P = \left[ \frac{M}{(n + 1)} \right] \]

where \( M = \text{rank} \) and \( n = \text{length of time series} \), in this case \( n = 262 \) years. The top 20 truncated seasonal freshening cycles since 1742 are listed in Table S1. This analysis indicates that the top 6 events occurred after 1876 (in order: 1998, 1916, 1964, 1889, 1983, and 1877) with probabilities of occurrence in any given year ranging from 0.4% for the 1998 event to 2.3% for 1877 event. However, in general, these anomalous truncated Makassar Strait freshening cycles are spread over the last 262 years with the exception of the period from 1837 to 1876 when there are no top 20 events.

Modeling and hydrographic monitoring studies have identified the far western South Pacific as a region of intermittently strong influence on the inflow pathways of the ITF [van Sebille et al., 2014; Hu et al., 2015]. In the region north and northeast of New Guinea, ocean currents link the tropics and the subtropics. Simulations and hydrographic data tracking the pathways of the ITF indicate that southern hemisphere source waters are an integral component of both the Molucca and Makassar Straits [Godfrey et al., 1993; Kashino et al., 1996; Morey et al., 1999; van Sebille et al., 2014]. Evidence for the anomalous western advection of salty South Pacific water just north of New Guinea during the 1997/1998 El Niño comes from a mooring study [Ueki et al., 2003]. These mooring results show abnormal year-round northwestward flow of the
NGCC and New Guinea Coastal Undercurrent (NGCUC) during 1997–1998 without the normal boreal winter southeastward change in flow due to weakened monsoonal winds. This is exactly when we observe truncated freshening in the Makassar Strait. The mooring observations [Ueki et al., 2003] are consistent with other results that showed the intensification of the NGCUC during or several months after the peak of an El Niño [Kessler and Cravatte, 2013]. Collectively, these observations suggest that the process that links the observed truncated freshening events of the southern Makassar Strait with a zonal SPCZ position involves changes in ITF strength and source possibly due to the northward shifts of both the North Equatorial Current and SEC [Hu et al., 2015] and intensification of the NGCC [Ueki et al., 2003]. A more northerly position and westward extension of the SEC at the same time as a strengthened NGCUC and northwestward flow of the NGCC likely inject higher-salinity South Pacific source waters into the upper water column in the Makassar Strait. We propose that our coral δ¹⁸O-reconstructed high SSS (truncated freshening) seasonal events in the southern Makassar are due to the increase in contribution from higher-salinity South Pacific source waters with a minor or negligible influence of precipitation on coral δ¹⁸O. The fact that modeling results [van Sebille et al., 2014] do not capture the short-lived enhanced influx of higher-salinity water into the Makassar Strait during the SPCZ zonal events may be due to the failure to include stronger anomalous NGCC and NGCUC northwest flow during the months when the SPCZ shifts north to near the equator.

In model simulations of SPCZ displacement to a more zonal position during El Niño events of various magnitudes, the moderate El Niño of 1991/1992 is coincident with a zonal SPCZ event where the northernmost latitude of the SPCZ that year was intermediate between its normal position during most El Niños and the extreme displacements that occurred during the VS El Niños of 1983 and 1998 [Cai et al., 2012; Borlace et al., 2014; Charles et al., 2014]. Our Makassar Strait coral δ¹⁸O record reflects this intermediate intensity zonal SPCZ event with a muted truncation of seasonal freshening (rank 14, see Table S1). In comparison, the 1998 and 1983 zonal SPCZ events were recorded in Makassar coral δ¹⁸O as the first and fifth ranked events, respectively, in line with the observed and modeled SPCZ northward displacement in those years [Vincent et al., 2009; Cai et al., 2012]. The accurate recording of the relative strengths of the 1983, 1992, and 1998 events attests to the fidelity of Makassar coral δ¹⁸O to record these poorly understood ocean-atmosphere events occurring ~4000 km to the east.

### 5. SPCZ Zonal Events and the Indonesian Throughflow

Our Makassar coral δ¹⁸O record provides the first multicentury length record of the recurrence interval of SPCZ zonal events and indicates the consistent but irregular occurrence of the SPCZ zonal events back to 1742. Zonal SPCZ events induce strong displacement of precipitation anomalies in the western equatorial Pacific in conjunction with the anomalous eastward expansion of the western Pacific warm pool (see Figure S1). This SPCZ repositioning also appears to result in the westward extension of the SEC, intensification of the NGCC and NGCUC, and the influx of higher-salinity water into the Makassar Strait in part from the South Pacific.

There is no clear increase in the recurrence interval of SPCZ zonal events in the later twentieth century. Although the largest amplitude truncated freshening event in the Makassar Strait occurred in 1998 near the end of the VS 1997/1998 El Niño, there is no conclusive evidence in the coral δ¹⁸O series that these years with anomalously high-salinity fresh seasons are more frequent or more intense (higher salinity) than in the 1700s or 1800s (Figure 4c).

Vincent et al. [2009] observed that SPCZ zonal events correlate with times when the WPWP eastern limit (defined by the longitude of the 29°C isotherm) has shifted far to the east (to between 160°W and 140°W). This suggests a relationship between WPWP dynamics and SPCZ position. Our results support this link to WPWP dynamics and show that the relationship between SPCZ zonal events and some El Niño events is persistent back to the 1740s. However, the exact triggering processes that drive the SPCZ into a zonal configuration require further investigation.

Collectively, the strong correlation between SPCZ zonal events and WPWP eastward extent, but not El Niño strength (as quantified in the Niño 3.4 and Niño 3 regions) suggests the possibility that the quantification of El Niño strength by just Niño 3 or Niño 3.4 SSTA is not a complete measure of the extent and influence of individual El Niño events in the western tropical Pacific. Finally, our results suggest that long-term changes
in the mean position of the SPCZ could affect the surface salinity of the Makassar Strait which would have forced changes in the mean temperature and salinity of the subsurface core of the ITF.

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\textbf{References}


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Supporting Information for

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**Figure S4**: Monthly maps of SODA Sea Surface Salinity (SSS) in Indonesia from January 1981 to March 1984 showing our study site.

**Figure S5**: Monthly maps of SODA Sea Surface Salinity (SSS) in Indonesia from January 1991 to May 1993 showing our study site.

**Dataset**

Dataset S1: Data file contains Kapoposang and Langkai 3 coral $\delta^{18}$O composite data for the period 1930-2004. The data file also contains detrended coral $\delta^{18}$O from 1742-2004 used to rank the years with interpreted anomalously high fresh season salinity. As discussed in main text, these are years of SPCZ zonal events.

**Introduction**

**Methods**

**Coral Core Sampling, $\delta^{18}$O Analyses, and Chronology Development**

Our Makassar coral $\delta^{18}$O composite record contains time series $\delta^{18}$O data from three individual coral colonies cored in the southern Makassar Strait near southwest Sulawesi. The most recently sampled colony was a live *Porites* sp. coral (KC4) with a continuous outer tissue layer collected at Kapoposang Atoll in September 2004 (4º41’32.27” S, 118º55’34.49” E; Figures 2, S2 – S5). The coral core was split and 6 mm thick slabs were produced at the Leibniz Center of Tropical Marine Ecology (ZMT) in Bremen, Germany and shipped to Lamont-Doherty Earth Observatory of Columbia University (LDEO) for micro-sampling and analysis.
The coral slabs from KC4 were cleaned with deionized (DI) water and ultrasonically cleaned with a high-energy (500 W, 20 kHz) probe sonicator in DI water bath for 15 minutes. The air-dried slabs were imaged by X-radiography (35 kV, 90 seconds) at LDEO revealing the horizontal density banding and growth increments (Figure S6). The X-radiograph density banding guided the micro-sampling carried out with a low-speed micro-drill at 1 mm intervals excavating a 2-3 mm wide and 2 mm deep sampling path perpendicular to the vertical growth axis. Coral powder samples of KC4 were analyzed for δ¹⁸O using both an Optima with Multiprep stable isotope ratio mass spectrometer and a Thermo Delta V-Plus with Kiel IV stable isotope ratio mass spectrometer. The individual isotope ratios are reported in ‰ deviation relative to the Vienna Pee Dee Belemnite (VPDB). On both the Optima and the Delta V-Plus, the average difference between duplicate δ¹⁸O analyzes of coral samples was 0.07‰. The isotope ratio values were verified against the international standard NBS-19. Long-term reproducibility of the δ¹⁸O values from repeated analyses of NBS-19 is better than ±0.06‰ (1σ).

The two other *Porites* sp. δ¹⁸O records used in our Makassar δ¹⁸O composite were generated from corals collected in July 1990 from Kapoposang Atoll (core KAP1A) near KC4 and from Langkai Island (LAN1A; 5°02’ S, 119°04’ E; Figure 2) 40 km south of Kapoposang. Details of sample collection and isotopic analyses of KAP1A and LAN1A have been previously described (Moore, 1995; Fairbanks et al., 1997). The internal precision of δ¹⁸O measurements for KAP1A was ±0.08‰, and for LAN1A was ±0.05‰ (Moore, 1995).
Core LAN1A was collected from a live coral with continuous growth surface while core KAP1A was collected from a colony with a dead top surface. Because the original age models presented in Moore (1995) were based on incorrect assumptions about the timing of sub-seasonal skeletal $\delta^{13}C$ for LAN1A and KAP1A and also on an incorrect top age for KAP1A (dead-topped colony), we elected to re-make the age models for both cores using the same approach we applied to core KC4. The age model for core KC4 and the new age models for KAP1A and LAN1A were based on the observed relationship between annual density banding, annual $\delta^{18}O$ minima, and seasonal SSS minima in the Makassar Strait as well as fluorescent bands in KC4. This supported the assumption that the annual $\delta^{18}O$ minima in all three corals coincided with annual SSS minima. The timing of seasonal and annual $\delta^{18}O$ anomalies in KC4 and LAN1A were used to determine that the core top in KAP1A was originally accreted in 1964 and assigned as the top age of KAP1A. For all three cores (KC4, KAP1A, and LAN1A) annual $\delta^{18}O$ minima were set to February/March and maxima to September/October, the climatologic freshest and saltiest times of the year respectively. Large climatic events, such as El Niño, were also used to crosscheck the overlapping chronology from 1950-2004 and to splice the individual records together for a composite $\delta^{18}O$ record. Coral skeletal $\delta^{18}O$ offsets between temporally overlapping sections of the three cores were observed. KC4 was -0.69‰ from KAP1A over 1938-1964 and -0.47‰ from LAN1A over 1950-1990.

Splicing Makassar Strait Coral Records

The final $\delta^{18}O$ chronologies from each core indicate that core KC4 spans 1938-2004, core LAN1A spans 1950-1990, and core KAP1A spans 1742-1964. The composite
Makassar coral δ¹⁸O series from these three cores extends continuously from 1742 to 2004 with near-monthly resolution. Before making the composite, we evaluated δ¹⁸O anomalies (average annual cycle removed; Figure 3A) from each core and standardized δ¹⁸O (mean removed divided by standard deviation; Figure 3B) over the period 1930-2004. This was done to: (A) verify the independently derived chronologies, (B) evaluate the inter-colony reproducibility of the climate signal, and (C) form the Makassar δ¹⁸O composite record (Figure 3C). The robust and significant correlation relationships (p < 0.001) between the three coral cores provide confidence in the regional environmental significance of the Makassar coral δ¹⁸O composite record. To make the Makassar δ¹⁸O composite (Figure 3C), we first removed the inter-laboratory offset from KAP1A and LAN1A to be in line with KC4. The 3 individual time series were then averaged over common periods changing between two or three colonies: 1964-1990 (KC4 and LAN1A), 1950-1964 (3 colonies), 1938-1950 (KC4 and KAP1A), then extended from 1742-1938 with KAP1A and 1990-2004 with KC4 (Figure 3C). The 1σ error envelope (gray bounding curves in Figure 3C) of the overlapping periods (standard error of mean) indicates the degree of inter-colony range and amplitude differences. This was calculated following established methods (Figure 3C)(Linsley et al., 2008).

Climate-Proxy Data Verification and Statistical Analyses

A forward-modeling approach (pseudo-coral)(Thompson et al., 2011) using instrumental OI-SST (Reynolds et al., 2002) and ERSST (Huang et al., 2015) and SSS (SODA SSS)(Carton and Giese 2008) data was taken to verify the observations in the Makassar corals. The forward model δ¹⁸O calculation determines the expected isotopic variations assuming that they are entirely due to the combined effects of SST and SSS,
with a SST-$\delta^{18}$O slope of -0.23 ‰ °C$^{-1}$ and the SSS-$\delta^{18}$O slope of 0.47 ‰ per salinity unit. Additional statistical analysis (Pearson product-moment correlation, least squares linear regression, and goodness of fit) of the Makassar $\delta^{18}$O composite time series and the pseudo-coral result was completed on the open source R-project (R Development Core Team, 2013) Stats package (see Figure 2D). The monthly-resolution SODA SSS data between 0-10m were used for evaluation of salinity variability in the Makassar Strait. In addition to the temporal overlap with the top ~25 years of our Makassar coral $\delta^{18}$O record, the choice of this reanalysis product (SODA SSS) rather than the shorter (2011-2015) surface sensing (1 cm) Aquarius satellite measurements is supported by good general agreement between 10m salinity data from CTD casts in the Makassar Strait and the corresponding SODA salinity data in the same grid cell (see Figure S8).
**El Niño strength** based on Nino 3.4 SSTa (ERSSTv.4) back to 1900 and based on a combination of ERSSTv4 and qualitative historical records (Quinn and Neal, 1992) before 1900.

$\text{Probability (P) calculated as follows: } P = \frac{M}{(n+1)}$, where $M =$ rank, and $n =$ length of time-series, in this case $n = 262$ years.

$\text{-- = no apparent El Niño event these years.}$

**Bold** = years where SPCZ zonal events have been identified in instrumental rainfall data (Janowiak and Xie 1999; Alder et al., 2003).

**Table S1:** List of the top 20 largest amplitude truncated freshening seasonal cycles in the Makassar Strait coral $\delta^{18}$O series: Column 1 is rank (largest to smallest), Column 2 is year, Column 3 is departure from average coral $\delta^{18}$O of peak fresh season in per mil ($\%$). The 1998, 1983 and 1992 events (in bold) correspond to the SPCZ zonal events documented in instrumental precipitation data (Vincent et al., 2009). Column 4 is the probability of occurrence in any given year. Column 5 is the relative El Niño strength that year.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Year AD</th>
<th>Departure from average ($%$)</th>
<th>Probability in any given year**</th>
<th>Relative El Niño strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1998</td>
<td>0.47</td>
<td>0.4</td>
<td>VS</td>
</tr>
<tr>
<td>2</td>
<td>1916</td>
<td>0.35</td>
<td>0.8</td>
<td>M+</td>
</tr>
<tr>
<td>3</td>
<td>1964</td>
<td>0.34</td>
<td>1.1</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>1889</td>
<td>0.33</td>
<td>1.5</td>
<td>M+</td>
</tr>
<tr>
<td>5</td>
<td>1983</td>
<td>0.31</td>
<td>1.9</td>
<td>VS</td>
</tr>
<tr>
<td>6</td>
<td>1877</td>
<td>0.31</td>
<td>2.3</td>
<td>VS</td>
</tr>
<tr>
<td>7</td>
<td>1805</td>
<td>0.27</td>
<td>2.7</td>
<td>M</td>
</tr>
<tr>
<td>8</td>
<td>1920</td>
<td>0.27</td>
<td>3.0</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>1808</td>
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<td>3.4</td>
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</tr>
<tr>
<td>10</td>
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<td>0.25</td>
<td>3.8</td>
<td>M+</td>
</tr>
<tr>
<td>11</td>
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<td>M+</td>
</tr>
<tr>
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<td>1965</td>
<td>0.22</td>
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<td>0.22</td>
<td>4.9</td>
<td>M</td>
</tr>
<tr>
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<td>1992</td>
<td>0.21</td>
<td>5.3</td>
<td>M</td>
</tr>
<tr>
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<td>1762</td>
<td>0.21</td>
<td>5.7</td>
<td>S</td>
</tr>
<tr>
<td>16</td>
<td>1891</td>
<td>0.2</td>
<td>6.1</td>
<td>VS</td>
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<tr>
<td>17</td>
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<td>--</td>
</tr>
<tr>
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<td>0.18</td>
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<td>7.2</td>
<td>M</td>
</tr>
<tr>
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<tr>
<td>21</td>
<td>1930/31</td>
<td>0.17</td>
<td>8.0</td>
<td>M</td>
</tr>
</tbody>
</table>

* = El Niño strength based on Nino 3.4 SSTa (ERSSTv.4) back to 1900 and based on a combination of ERSSTv4 and qualitative historical records (Quinn and Neal, 1992) before 1900.

** = Probability (P) calculated as follows: $P = \frac{M}{(n+1)}$, where $M =$ rank, and $n =$ length of time-series, in this case $n = 262$ years.

-- = no apparent El Niño event these years.

**Bold** = years where SPCZ zonal events have been identified in instrumental rainfall data (Janowiak and Xie 1999; Alder et al., 2003).
Rainfall Anomalies (in mm/month)

January 2006; SPCZ normal orientation

February 1998; SPCZ Zonal orientation

January 2016; SPCZ Zonal orientation

Figure S1: Rainfall anomalies in: (A) January 2006 with normal SPCZ orientation (B) February 1998 with zonal SPCZ orientation, and (C) January 2016 with zonal SPCZ orientation. Data from: NOAA NCEP CPC CAMS_OPI v0208 anomaly prcip (Janowiak and Xie, 1999).
Figure S2: Sea surface salinity (SSS) data for Indonesia from the SODA SSS database (Carton and Giese, 2008) for: (top left) March 1982, (top right) March 1983, (bottom left) March 1997, and (bottom right) March 1998. Blue dot is location in the Makassar Strait where corals KC4, KAP1A and LAN1A were collected. Every year relatively low salinity water spreads across the Makassar Strait from west to east. Under normal conditions the freshening in the strait peaks in March as in 1982 and 1997 above. During the SPCZ zonal events, the monthly SODA SSS data indicates that the seasonal west to east spreading of low salinity water is abruptly stopped on the west side of the strait (see 2 right hand panels) apparently by the inflow of higher salinity water from the north.
Please see separate files in this Supplement for Figures S3, S4 and S5. Figures S3, S4 and S5 are included as separate files in this supplement because they are series of monthly maps (animations) of SODA surface salinity variability in the Makassar Strait and Java Sea region spanning the 1997-1998, 1982-1983 and 1991-1992 El Niño events.

**Figure S3:** Monthly maps of SODA Sea Surface Salinity (SSS) in Indonesia from January 1996 to December 1999 showing our study site.

**Figure S4:** Monthly maps of SODA Sea Surface Salinity (SSS) in Indonesia from January 1981 to March 1984 showing our study site.

**Figure S5:** Monthly maps of SODA Sea Surface Salinity (SSS) in Indonesia from January 1991 to May 1993 showing our study site.
**Figure S6:** Presentation of coral core KC4 collected in 2004 from Kapoposang. (Left), Image of the top section of core KC4 taken under UV fluorescent light of a slab face from Kapoposang displaying annual and narrow high fluorescent bands. Core was collected in 2004. Note the narrow, annual, high fluorescent bands. (Middle), $\delta^{18}$O data versus depth down core aligned with the depth in the fluorescent image. Note that $\delta^{18}$O minima each year correspond with the narrow high fluorescent bands. Also note the missing fluorescent band in 1998 and the faint fluorescent band in 1992. The years 1998 and 1992 had documented SPCZ zonal events (Vincent et al., 2009). (Right), X-radiograph positive collage of core KC4 oriented with youngest live surface at the top.


Most negative $\delta^{18}$O value corresponds with UV band each year.
Figure S7: Coral $\delta^{18}$O data from our Makassar composite reconstruction (in blue) compared to equatorial Pacific coral $\delta^{18}$O records (in red). All $\delta^{18}$O data has been band-pass filtered to isolate the interannual ENSO variability between 3 and 9 years. The central Pacific data is a composite of $\delta^{18}$O results from Fanning (Cobb et al., 2013), Palmyra (Cobb et al., 2013) and Maiana (Urban et al., 2000) (composite previously presented in Linsley et al., 2015). Interannual coral $\delta^{18}$O variability in the Makassar Strait is closely related to the phase of ENSO in most years.
Figure S8; Southern Makassar Strait SODA upper 10m salinity versus 10m salinity from CTD casts in the same grid cells as the SODA results (units are g/Kg). CTD data collected on 10 different cruises: 1985 (Steve Murray pers. comm.); 1993 and 1994 (Gordon and Fine 1996); 1996 and 1998 (Gordon et al., 1999); 2004 and 2005 (Gordon et al., 2008). With the exception of February 1994 and one January data point in 2004 from the very southern Makassar, the CTD results supports the overall accuracy of the SODA salinity data in this very seasonally dynamic region. The agreement of our coral δ¹⁸O results with SODA SSS also supports our conclusion that seasonal changes in coral δ¹⁸O at our study sites near Kapaposang are recording seasonal SSS changes.
Figure S9. (A) Comparison of Makassar composite coral $\delta^{18}O$ record (black) and the same Makassar coral $\delta^{18}O$ record with SST component removed using the $\delta^{18}O$-SST sensitivity of -0.23‰ °C$^{-1}$ (blue). We used IGOSS SST as shown in Figure 2. (B) Comparison of reconstructed relative SSS change between the pseudo-coral $\delta^{18}O$ record (black), Makassar composite coral $\delta^{18}O$ record with SST component removed (blue), and SODA SSS record for the grid centered on Kapoposang (green). Conversion to relative SSS from published Porites sp. coral $\delta^{18}O$ to SSS relationship range, 0.27‰ per salinity unit (solid lines, black and blue) [Fairbanks et al., 1997] and 0.25-0.29‰ salinity unit (dash lines, black and blue) [Gagan et al., 2000]. The solid red line is the reconstructed SSS from the Makassar coral $\delta^{18}O$ record with SST component removed where an SSS-sensitivity of 0.47‰ per salinity unit was used. This sensitivity results in a better fit to SODA SSS.
Figure S10: Correlation between seasonally averaged monthly Makassar composite $\delta^{18}O$ and precipitation. Correlations determined for the 3-month seasonal average Makassar composite $\delta^{18}O$ record with gridded GPCP rainfall (ver. 2; Adler et al., 2003) over the period 1979-2004, (top) December-February, and (bottom) January-March. Zero correlation contour is between the orange and blue colors. Significant correlation at $p < 0.01$ are shown in bold contour. X symbol denotes location of Makassar composite $\delta^{18}O$. 
Figure S11: Correlations between seasonally averaged monthly SODA SSS (0-15m) and precipitation over the period 1979-2004. (A) Correlations determined from the average of gridded GPCP rainfall database (ver. 2; Adler et al., 2003) in the 2 grid cells nearest to a single SODA SSS grid from December-February, and (B) January-March. (C) Correlation between the SODA SSS grid centered on Kapoposang at our Makassar Strait study site (4.25°S, 118.75°E) and gridded GPCP rainfall from December-February, and (D) January-March. Zero correlation contour is between the orange and blue colors. Significant correlation at p < 0.01 are shown in bold contour. X symbol denotes location of Kapoposang study site in the Makassar Strait.
Figure S3: Monthly maps of Soda Sea Surface Salinity (SSS) in Indonesia from Jan. 1996 to Dec. 1999

Note that the normal west to east influx of relatively fresh water across the central Makassar Strait that occurs in Jan-April/May is truncated or stopped from reaching our study sites at Kapoposang in February-May 1998 when the SPCZ was in a zonal orientation. The SODA SSS data indicates the same truncated freshening response in Spring 1983 and Spring 1992 during the two other documented SPCZ zonal events.

Blue dot on figures indicates our Kapoposang site
Feb
1996
April 1996
June 1996
Mar 1997
July 1997
Feb 1998

Note
Truncated Freshening
Feb-May
March 1998
Feb 1999
Mar
1999
July 1999
Oct 1999
Nov 1999
Dec 1999
Figure S4: Makassar Soda SSS from January 1981 to March 1984

Note the truncated west to east freshening in the central Makassar Strait near our study site at Kapoposang in Feb-April 1983 during the SPCZ zonal event.

Blue dot on figures indicates our Kapoposang site.
Jan 1981

Kapoposang site
Feb 1981
July 1981

depth 5.01 meters time Jul 1981
Dec 1981

depth 5.01 meters
time Dec 1981
Mar 1982
May 1982
July 1982
Jan 1983
Feb 1983

Note
Truncated Freshening
Feb-April
Mar 1983

Note
Truncated Freshening
Feb-April
April 1983

Note: Truncated Freshening Feb-April
Aug 1983
Sept 1983
Nov 1983

[Image of a map with depth contours and geographic coordinates]

depth 5.01 meters time Nov 1983
Dec 1983
Mar 1984
Figure S5: Makassar Soda SSS from January 1991 to May 1993

Note the truncated west to east freshening in the central Makassar Strait near our study site at Kapoposang in December 1991 - February 1992 during the SPCZ zonal event

Blue dot on figures indicates our Kapoposang site
depth 5.01 meters time Jan 1991

Kapoposang site
depth 5.01 meters time Feb 1991
depth 5.01 meters time Apr 1991
depth 5.01 meters time Jul 1991
depth 5.01 meters time Sep 1991
depth 5.01 meters time Oct 1991
depth 5.01 meters time Nov 1991
depth 5.01 meters time Dec 1991
depth 5.01 meters time Jan 1992
depth 5.01 meters time Feb 1992
depth 5.01 meters time Mar 1992
depth 5.01 meters time Apr 1992
depth 5.01 meters time May 1992
depth 5.01 meters time Jun 1992
depth 5.01 meters time Sep 1992
depth 5.01 meters time Jan 1993
depth 5.01 meters time Feb 1993
depth 5.01 meters time Mar 1993
depth 5.01 meters time Apr 1993