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

Braddock K. Linsley, Henry C. Wu, Tim Rixen, Christopher D. Charles, Arnold L. Gordon, Michael D. Moore

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Key Points:
- SPCZ zonal events are regular features of SPCZ variability
- SPCZ position can influence surface salinity in the Makassar Strait, the main conduit for the Indonesian Throughflow
- Paleoceanographers need to consider teleconnections and intermittent teleconnections when evaluating paleoclimatic data

Supporting Information:
- Data Set S1
- Supporting Information S1
- Figure S3
- Figure S4
- Figure S5

Correspondence to:
B. K. Linsley and H. C. Wu,
blinsley@ldeo.columbia.edu;
henry.wu@locean-ipsl.upmc.fr

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

Braddock K. Linsley[1], Henry C. Wu[2,3], Tim Rixen[4,5], Christopher D. Charles[6], Arnold L. Gordon[1,7], and Michael D. Moore[8]

[1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA, [2]IRD-Sorbonne Universités (UPMC, Université Paris 6), CNRS-MNHN, Laboratoire d'Océanographie et du Climat, IRD France-Nord, Bondy, France, [3]Laboratoire des Sciences du Climat et de l'Environnement/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France, [4]Leibniz Center for Tropical Marine Ecology (ZMT), Bremen, Germany, [5]Institute of Geology, University of Hamburg, Hamburg, Germany, [6]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA, [7]Department of Earth and Environmental Science, Columbia University, New York, New York, USA, [8]Redmond, WA

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 δ^{18}O 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 δ^{18}O 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 seas on the edge of the western Pacific warm pool (WPWP). The ITF is the only low-latitude interocean conduit and annually transports a large amount of water (10–15 sverdrups, where one sverdrup 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 (Δ^{14}C) 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].

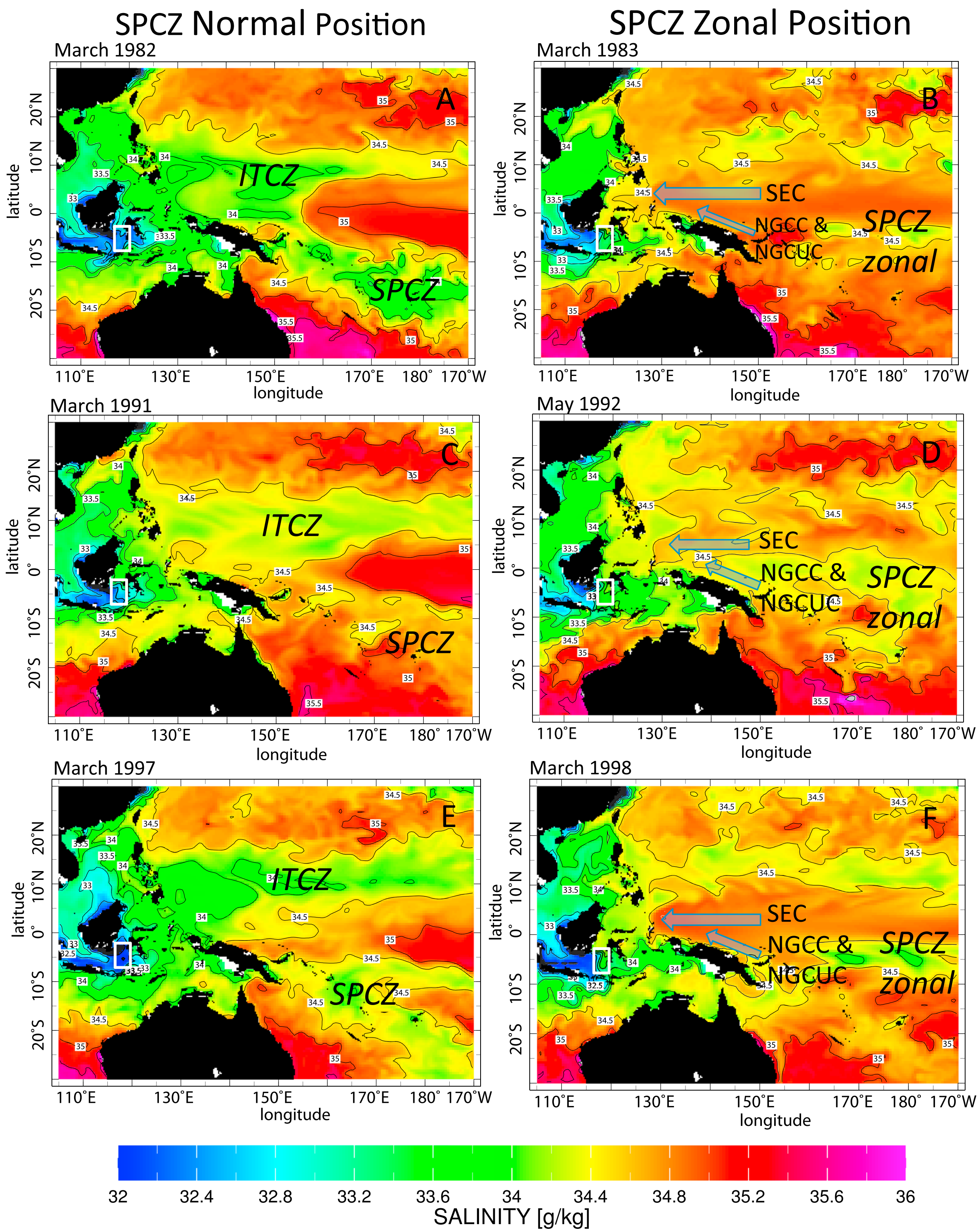

Figure 1. Sea surface salinity (SSS) data for the western tropical Pacific and Indonesia from the SODA SSS database [*Carton and Giese*, 2008] for (a) March 1982, (b) March 1983, (c) March 1991, (d) May 1992, (e) March 1997, and (f) March 1998. The right-hand column of three panels for March 1983, May 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).

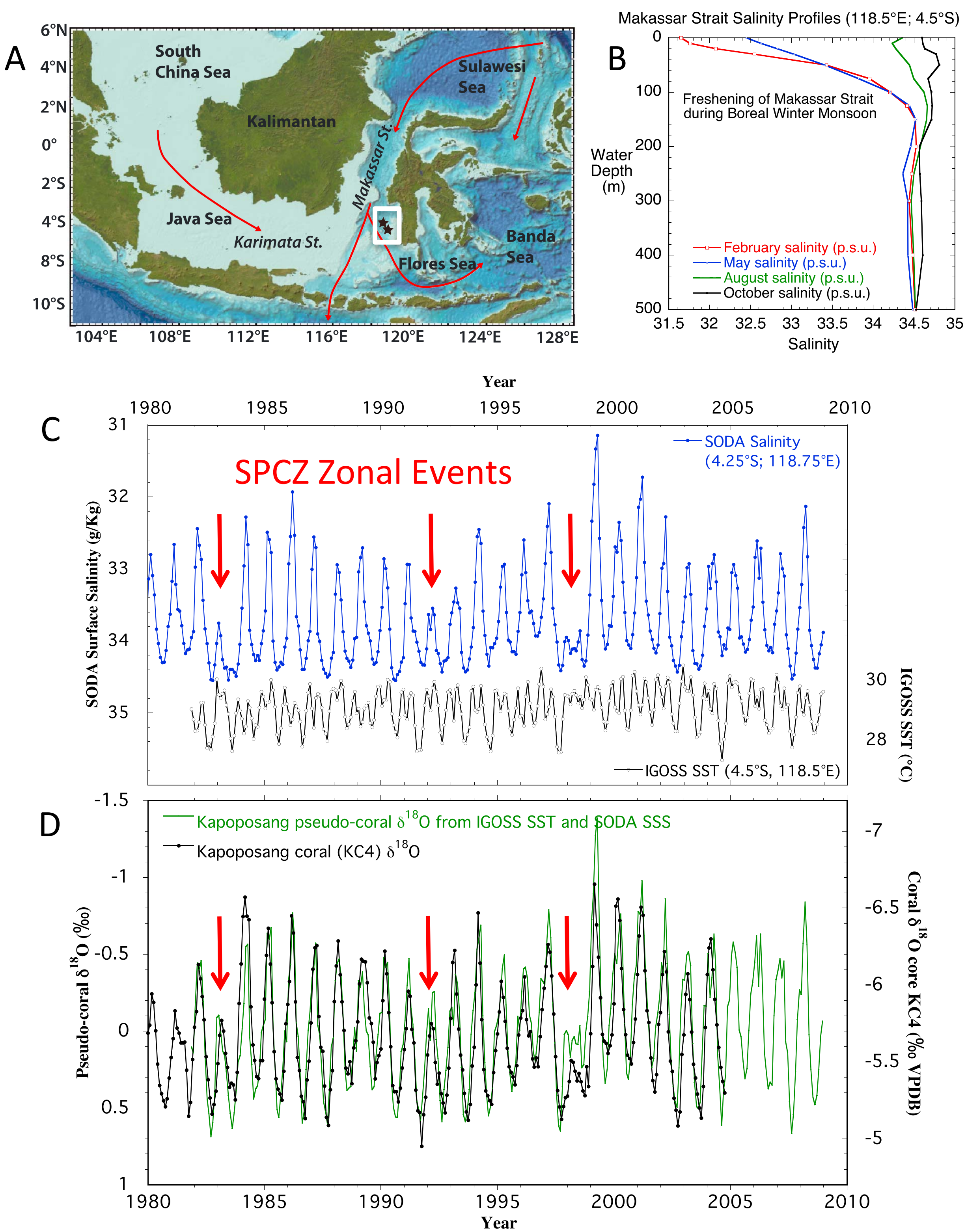

Figure 2. (a) Location of study sites at Kapoposang and Langkai in the Makassar Strait in relation to bathymetry and general flow vectors for the Indonesian Throughflow (ITF). (b) Vertical salinity profiles in the upper 500 m of salinity (from climatology) for the different seasons [*Conkright et al.*, 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 ITCZ just south of the equator when the ITCZ 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 (δ^{18}O) 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 δ^{18}O 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 δ^{18}O: Amplitude of Seasonal Freshening Back to 1742 C.E.

Our composite coral δ^{18}O 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).

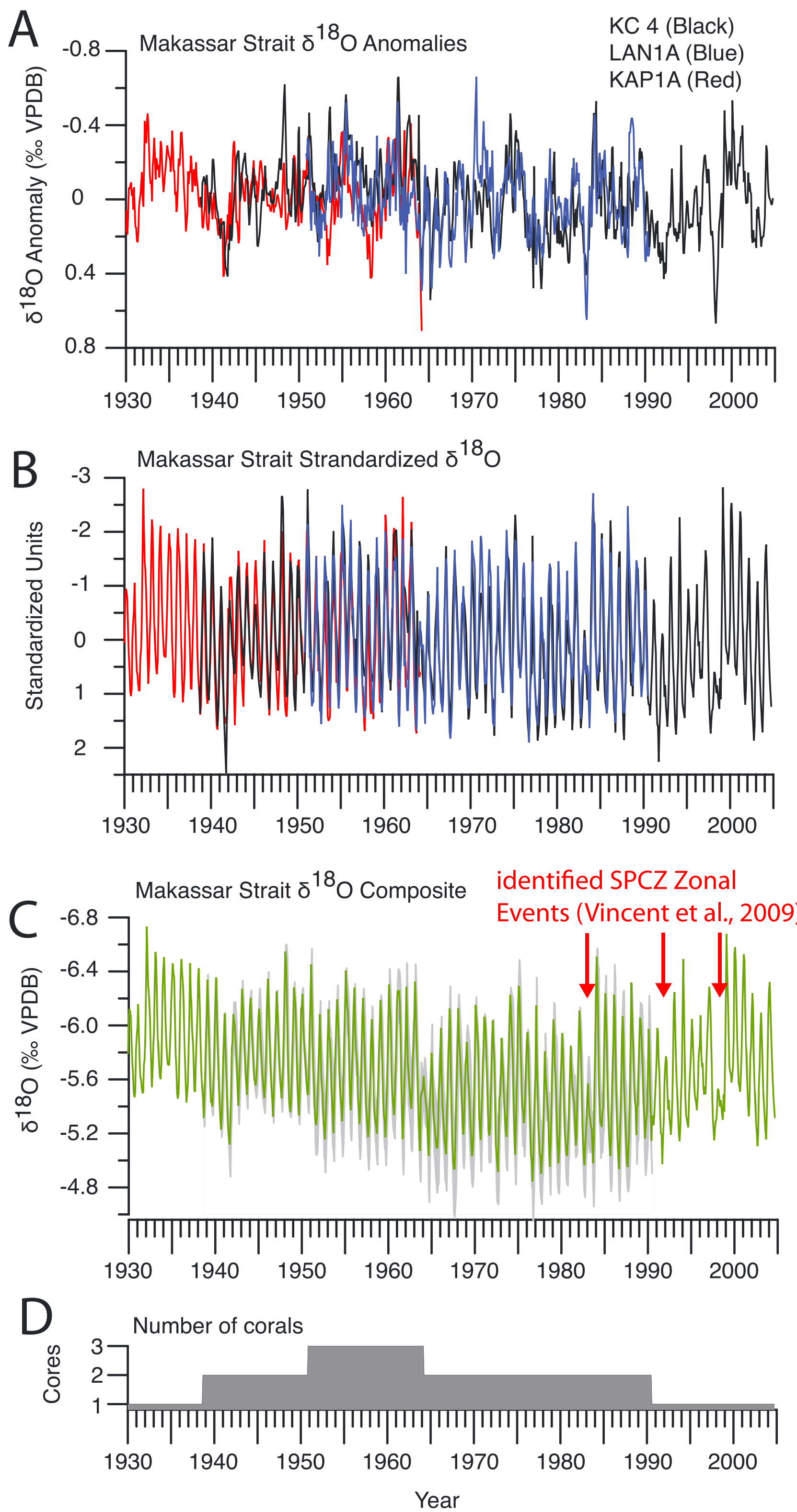

Figure 3. Coral $\delta^{18}O$ results of cores KC4, KAP1A, and LAN1A from the central Makassar Strait for the period 1930–2004. (a) Coral $\delta^{18}O$ anomalies with the average seasonal cycle removed, (b) Standardized coral $\delta^{18}O$ to adjust for $\delta^{18}O$ offsets between cores (mean removed and per standard deviation), (c) Composite average coral $\delta^{18}O$ 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.

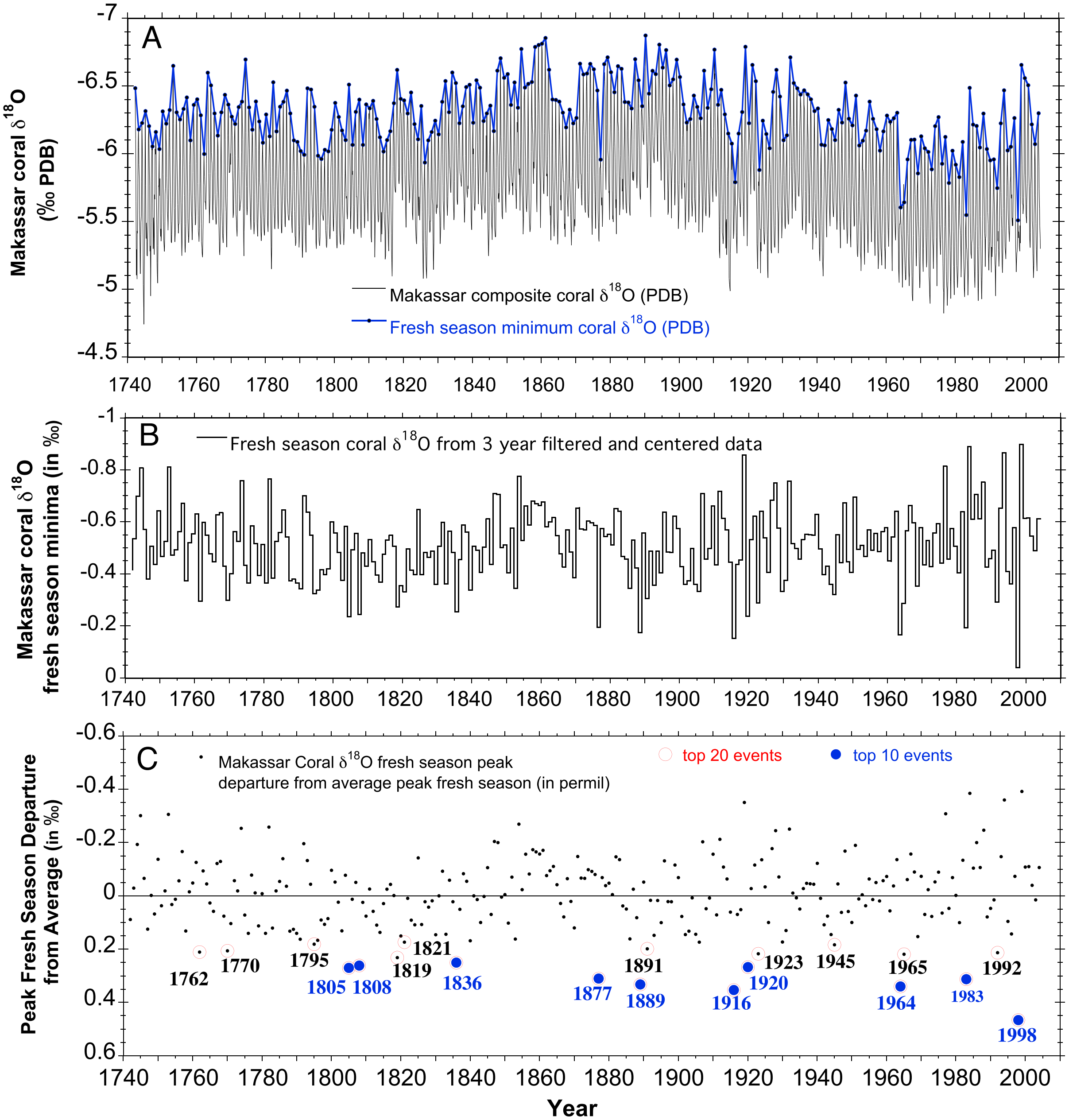

Figure 4. (a) Makassar Strait composite coral $\delta^{18}O$ series with seasonal $\delta^{18}O$ minima (fresh season) highlighted in blue. (b) Makassar Strait coral $\delta^{18}O$ fresh season minima isolated from a 3 year band-pass-filtered and centered composite coral $\delta^{18}O$ series where all 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).

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).

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 $\delta^{18}O$ 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 $\delta^{18}O$ with peak fresh seasonal $\delta^{18}O$ 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 $\delta^{18}O$ than the previously mentioned severe El Niño events in 1957/1958 and 1972/1973 with the composite coral $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ departures from the average fresh season $\delta^{18}O$ 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 $\delta^{18}O$ (Figures 2c and 2d). The Makassar coral composite $\delta^{18}O$ 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 $\delta^{18}O$ 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: $P = [M/(n+1)]$, where M = rank and n = 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 $\delta^{18}O$-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 $\delta^{18}O$. 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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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