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Supporting Information for

SPCZ Zonal Events and Downstream Influence on Surface Ocean Conditions in the Indonesian Throughflow Region

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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, 118°55'34.49" 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 $\delta^{18}O$ 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 $\delta^{18}O$ analyzes of coral samples was 0.07‰. The isotope ratio values were verified against the international standard NBS-19. Long-term reproducibility of the $\delta^{18}O$ values from repeated analyses of NBS-19 is better than ±0.06‰ (1σ).

The two other *Porites* sp. $\delta^{18}O$ records used in our Makassar $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ series from these three cores extends continuously from 1742 to 2004 with near-monthly resolution. Before making the composite, we evaluated $\delta^{18}O$ anomalies (average annual cycle removed; Figure 3A) from each core and standardized $\delta^{18}O$ (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 $\delta^{18}O$ 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 $\delta^{18}O$ composite record. To make the Makassar $\delta^{18}O$ 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 $\delta^{18}O$ 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 ‰ ºC^{-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).

Rank	Year AD	Departure from average (‰)	Probability in any given year**	Relative El Niño strength*
1	**1998**	**0.47**	**0.4**	**VS**
2	1916	0.35	0.8	M+
3	1964	0.34	1.1	M
4	1889	0.33	1.5	M+
5	**1983**	**0.31**	**1.9**	**VS**
6	1877	0.31	2.3	VS
7	1805	0.27	2.7	M
8	1920	0.27	3.0	M
9	1808	0.26	3.4	M
10	1836	0.25	3.8	M+
11	1819	0.23	4.2	M+
12	1965	0.22	4.6	S
13	1923	0.22	4.9	M
14	**1992**	**0.21**	**5.3**	**M**
15	1762	0.21	5.7	S
16	1891	0.2	6.1	VS
17	1945	0.18	6.5	--
18	1795	0.18	6.8	--
19	1821	0.17	7.2	M
20	1906	0.17	7.6	M
21	1930/31	0.17	8.0	M

* = 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= [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*).

Table S1: List of the top 20 largest amplitude truncated freshening seasonal cycles in the Makassar Strait coral δ^{18}O series: Column 1 is rank (largest to smallest), Column 2 is year, Column 3 is departure from average coral δ^{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.

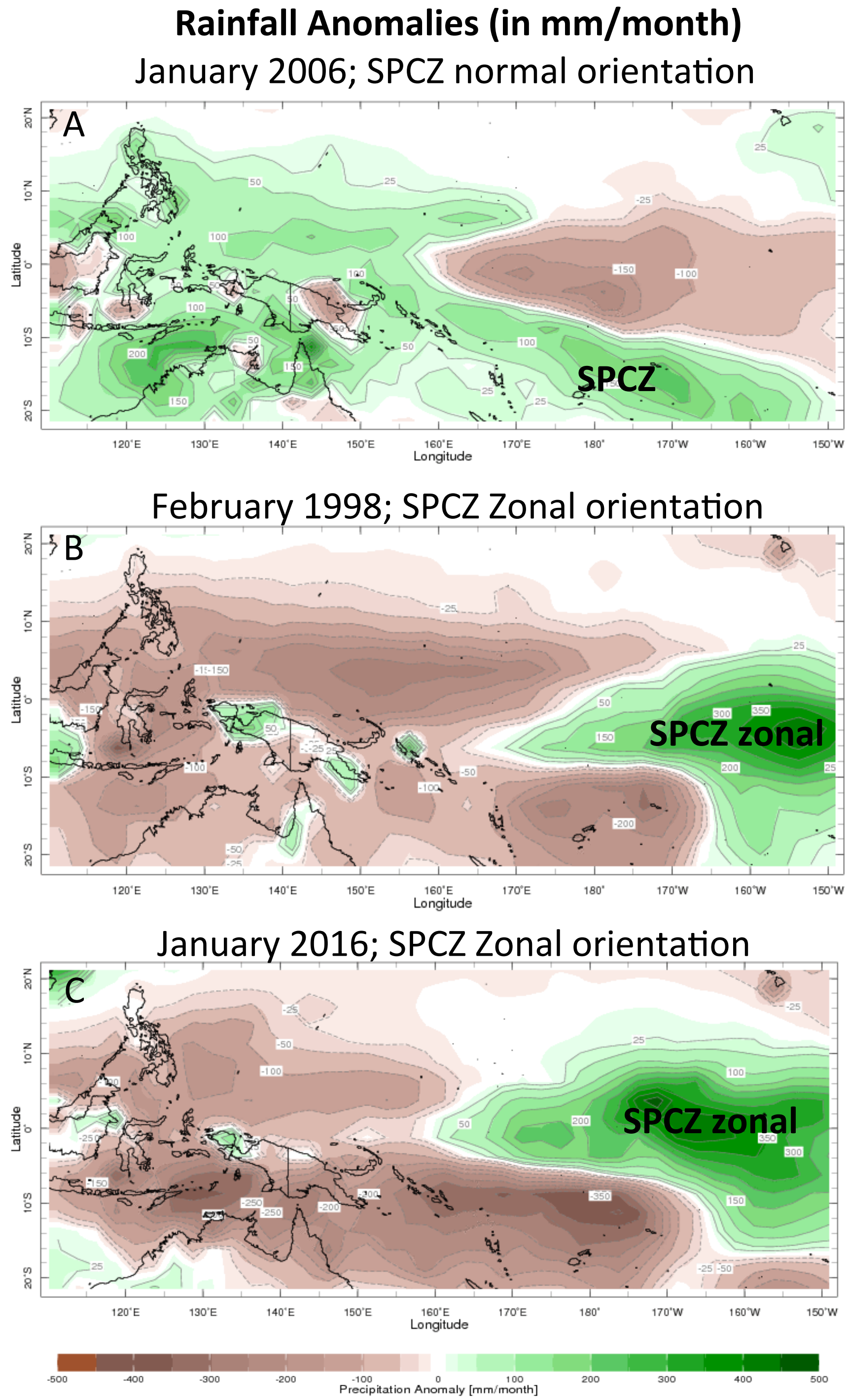

Figure S1: Rainfall anomalies in: (A) January 2006 with normal SPCZ orientation (B) February 1998 with zonal SPCZ orientation, and (C) January 2016 with zonal SPCZ orientation. Data from :NOAA NCEP CPC CAMS_OPI v0208 anomaly prcip (*Janowiak and Xie, 1999*).

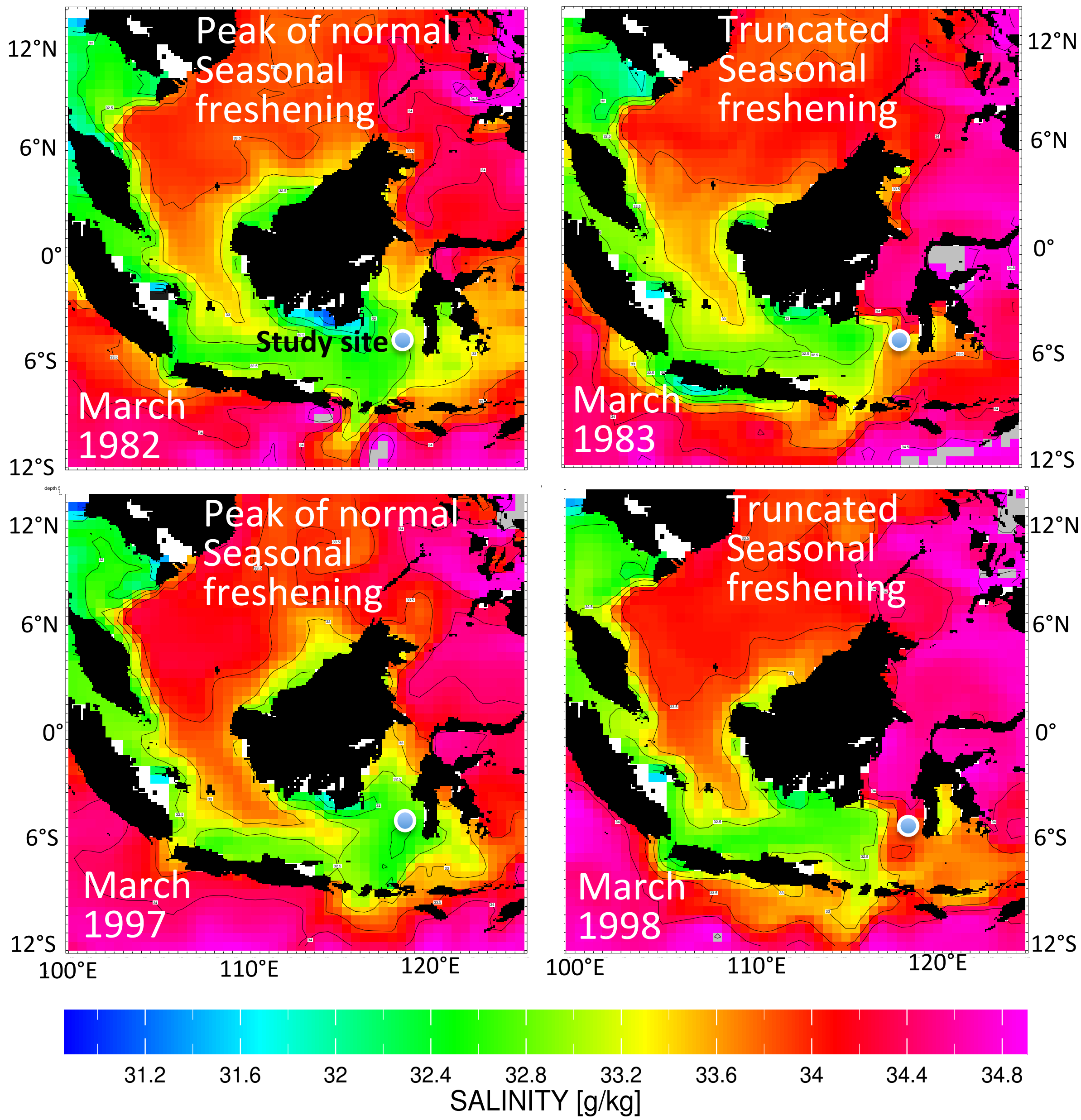

Figure S2: Sea surface salinity (SSS) data for Indonesia from the SODA SSS database (*Carton and Giese, 2008*) for: **(top left)** March 1982, **(top right)** March 1983, **(bottom left)** March 1997, and **(bottom right)** March 1998. Blue dot is location in the Makassar Strait where corals KC4, KAP1A 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 becasue 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.

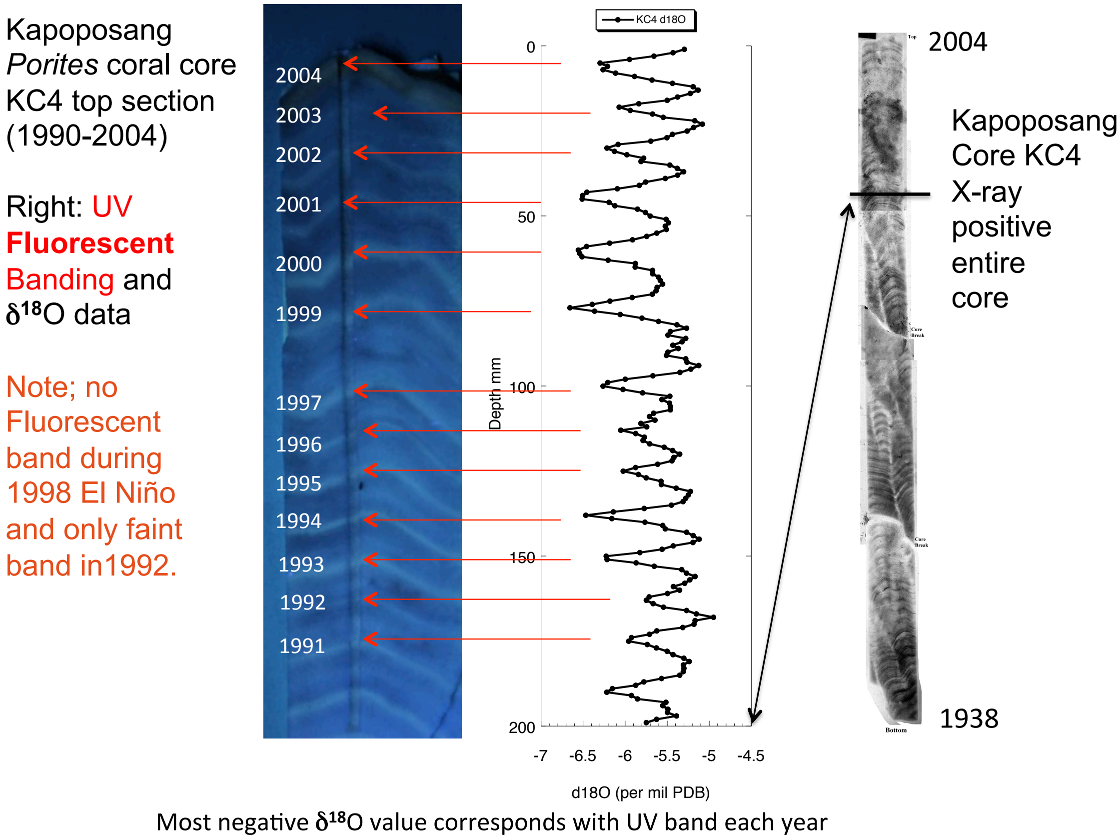

Figure S6: Presentation of coral core KC4 collected in 2004 from Kapoposang. **(Left)**, Image of the top section of core KC4 taken under UV fluorescent light of a slab face from Kapoposang displaying annual and narrow high fluorescent bands. Core was collected in 2004. Note the narrow, annual, high 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.

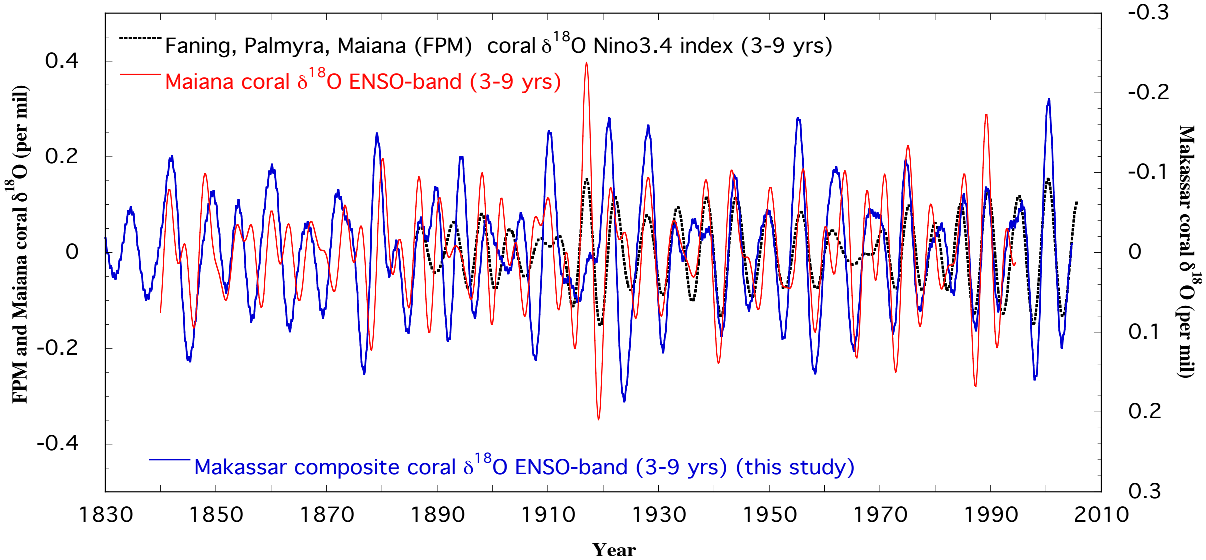

Figure S7: Coral δ^{18}O data from our Makassar composite reconstruction (in blue) compared to equatorial Pacific coral δ^{18}O records (in red). All δ^{18}O data has been band-pass filtered to isolate the interannual ENSO variability between 3 and 9 years. The central Pacific data is a composite of δ^{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 δ^{18}O variability in the Makassar Strait is closely related to the phase of ENSO in most years.

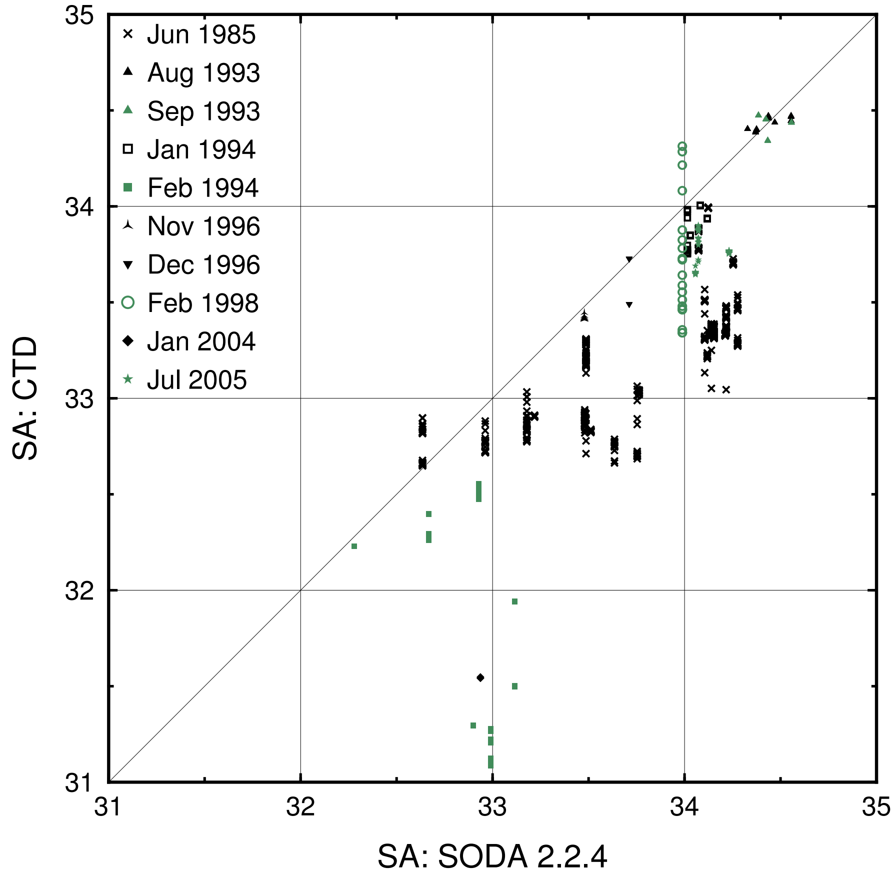

Figure S8; Southern Makassar Strait SODA upper 10m salinity versus 10m salinity from CTD casts in the same grid cells as the SODA results (units are g/Kg). CTD data collected on 10 different cruises: 1985 (*Steve Murray pers. comm.);* 1993 and 1994 (*Gordon and Fine 1996*); 1996 and 1998 (*Gordon et 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 $\delta^{18}O$ results with SODA SSS also supports our conclusion that seasonal changes in coral $\delta^{18}O$ at our study sites near Kapoposang are recording seasonal SSS changes.

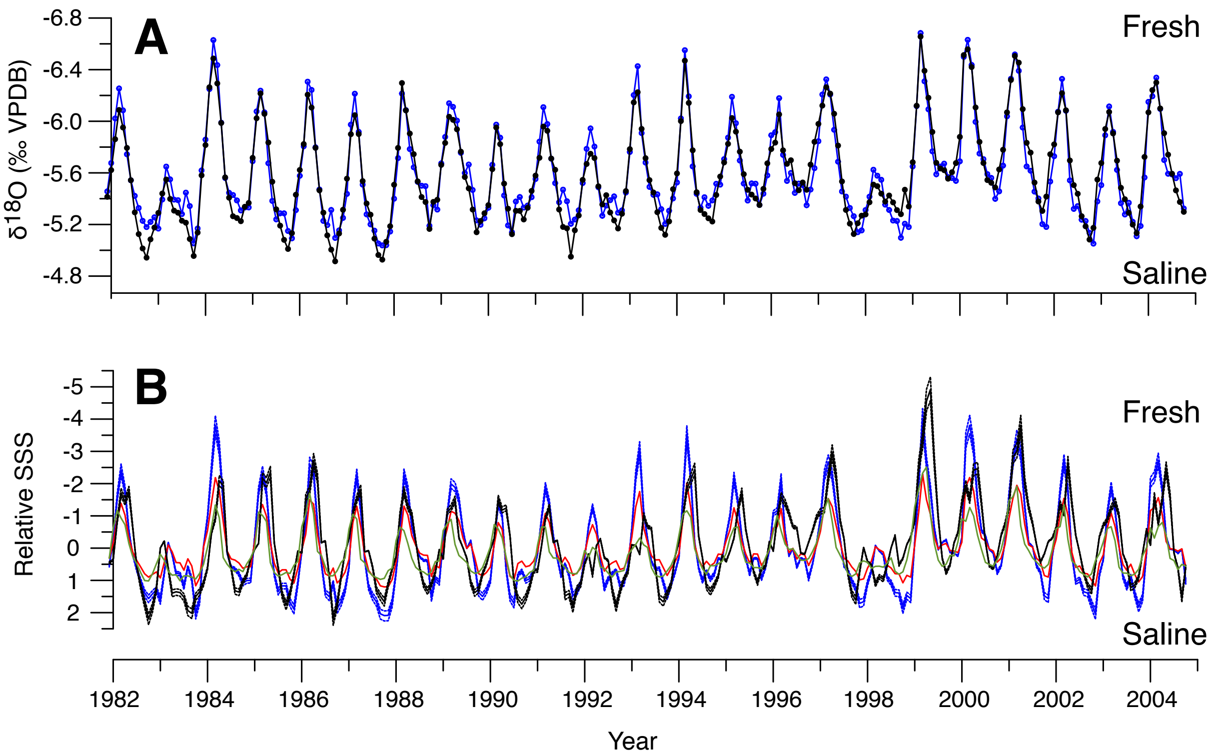

Figure S9. (**A**) Comparison of Makassar composite coral δ^{18}O record (**black**) and the same Makassar coral δ^{18}O record with SST component removed using the δ^{18}O-SST sensitivity of -0.23‰ °C^{-1} (blue). We used IGOSS SST as shown in Figure 2. (**B**) Comparison of reconstructed relative SSS change between the pseudo-coral δ^{18}O record (**black**), Makassar composite coral δ^{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 δ^{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 δ^{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.

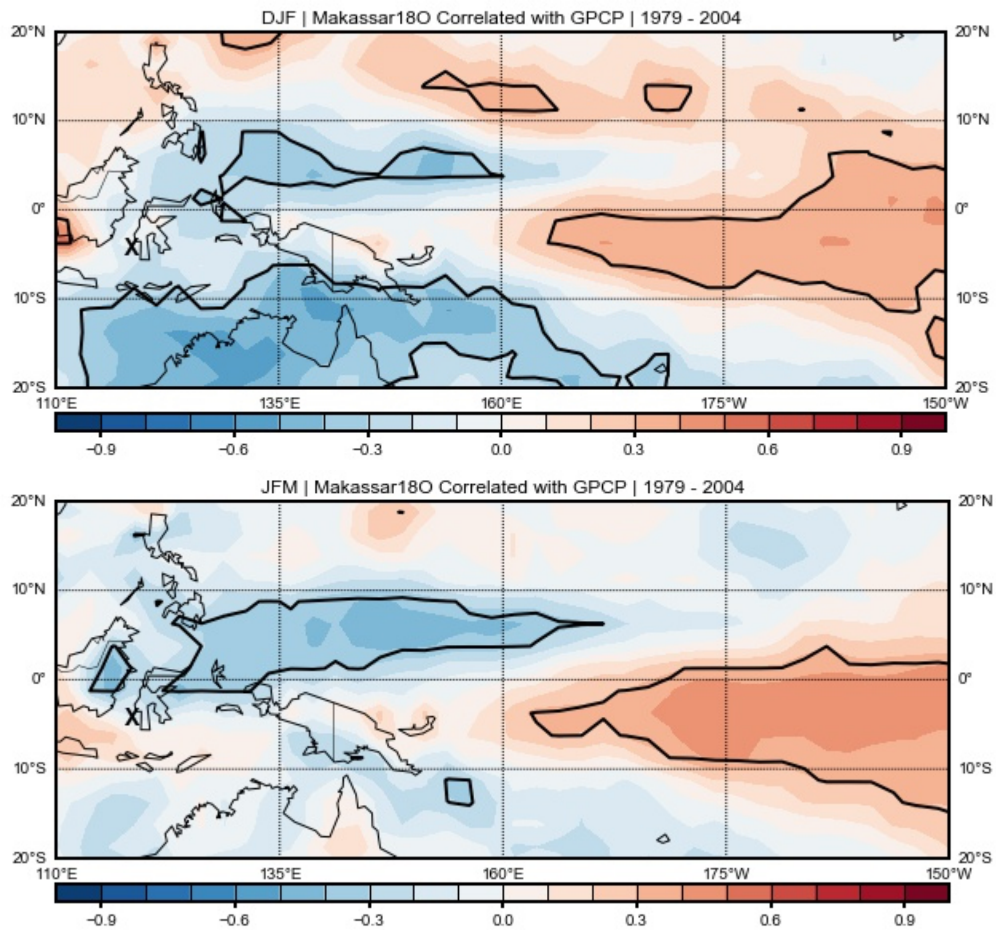

Figure S10: Correlation between seasonally averaged monthly Makassar composite $\delta^{18}O$ and precipitation. Correlations determined for the 3-month seasonal average Makassar composite $\delta^{18}O$ record with gridded GPCP rainfall (ver. 2; *Adler et al., 2003*) over the period 1979-2004, **(top)** 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 $\delta^{18}O$.

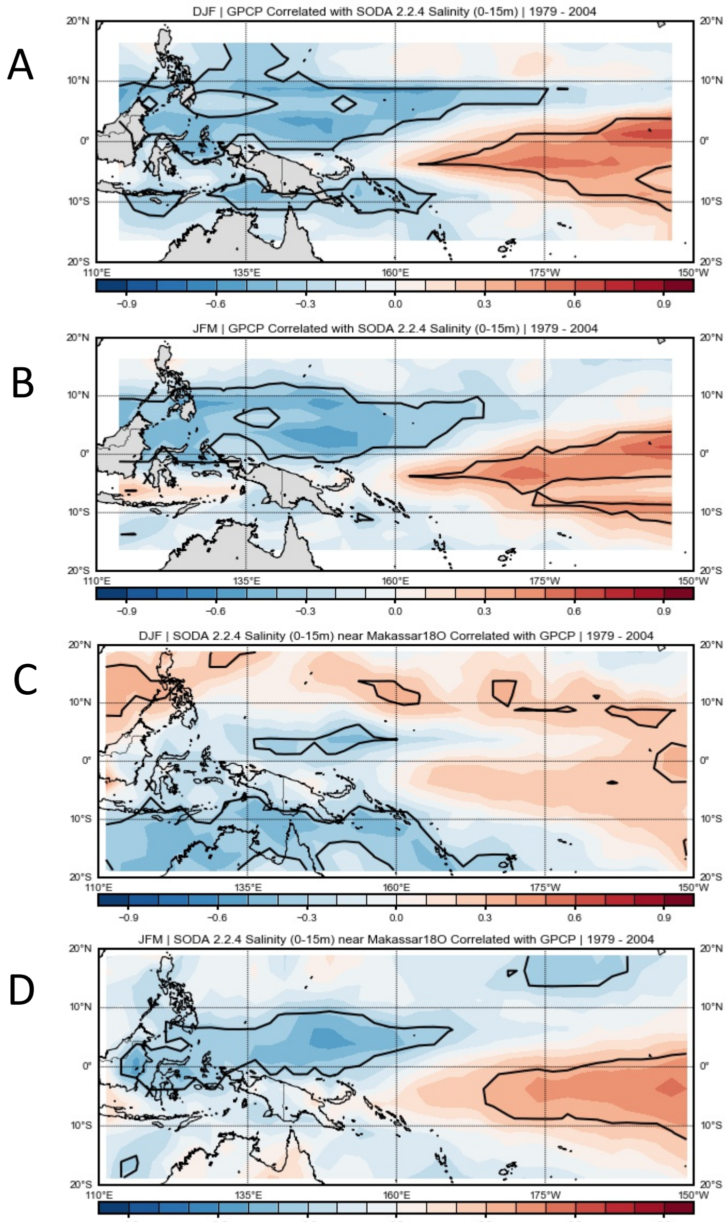

Figure S11: Correlations between seasonally averaged monthly SODA SSS (0-15m) and precipitation over the period 1979-2004. **(A)** Correlations determined from the average of gridded GPCP rainfall database (ver. 2; *Adler et al., 2003*) in the 2 grid cells nearest to a single SODA SSS grid from December-February, and **(B)** January-March. **(C)** Correlation between the SODA SSS grid centered on Kapoposang at our Makassar Strait study site (4.25ºS, 118.75ºE) 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.