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Abstract

We have explored surface water mixing in the Lombok Strait through a ~bimonthly resolved surface water $\Delta^{14}C$ time-series reconstructed from a coral in the Lombok Strait that spans 1937 through 1990. The prebomb surface water $\Delta^{14}C$ average is -60.5‰ and individual samples range from -72‰ to 134‰. The annual average post-bomb maximum occurs in 1973 and is 122‰. The timing of the post-bomb maximum is consistent with a primary subtropical source for the surface waters in the Indonesian Seas. During the post-bomb period the coral records regular seasonal cycles of 5-20‰. Seasonal high $\Delta^{14}C$ occur during March-May (warm, low salinity), and low $\Delta^{14}C$ occur in September (cool, higher salinity). The $\Delta^{14}C$ seasonality is coherent and in phase with the seasonal $\Delta^{14}C$ cycle observed in Makassar Strait. We estimate the influence of high $\Delta^{14}C$ Makassar Strait (North Pacific) water flowing through the Lombok Strait using a two endmember mixing model and the seasonal extremes observed at the two sites. The percentage of Makassar Strait water varies between 16 and 70%, and between 1955 and 1990 it averages 40%. During La Niña events there is a higher percentage of Makassar Strait (high $\Delta^{14}C$) water in the Lombok Strait.

Introduction

The western tropical Pacific plays an important role in the localization of deep atmospheric convective activity and is a major exporter of latent and sensible heat to both hemispheres (*e.g.,* Peixoto and Oort, 1992). On interannual (*e.g.*, El Niño- Southern

Oscillation or ENSO) and longer-timescales the transport of warm surface water into and out of the western equatorial Pacific is thought to play an important role in regulating the development and termination of warm ENSO events with links to the Asian Monsoon system, and in global climate through atmospheric teleconnections. Intense surface heating along the equator, combined with the mean easterly flow of the trade winds, causes warm surface waters to accumulate at the western margin of the Pacific Ocean, producing sea surface temperatures in excess of 29°C, and driving tropospheric circulation by creating deep convection aloft. Compensation of westward flowing currents occurs via the surface counter currents, eastward flowing undercurrents, and the Indonesian throughflow (*e.g.*, Fine *et al*., 1994). Our understanding of the interaction between the overlying wind-field, the observations of which have their own problems (*e.g*. Clarke and Lebedev, 1996), and the shallow circulation has historically relied upon ship drifts, drogues, and a relatively small number of current meter moorings (*e.g*. Reverdin *et al*., 1994). The paucity of data requires broadscale or coarse synoptic averaging and does not allow for more detailed questions regarding inter-annual to decadal scale variability. Satellite observations such as scatterometer winds and altimeter data provide higher spatial and temporal sampling (*e.g*., Lagerloef *et al*., 1999) but are relagated to only the last 15-25 years. Such a time-history is insufficient to look at longer time-scale variability.

The intimate coupling of the surface ocean and overlying atmospheric boundary layer implicitly links variations in atmospheric characteristics to the underlying sea surface temperature (SST) field. Warm ocean waters provide latent and sensible heat to the atmosphere that localizes convection and drives surface convergent winds. The convection exports moisture that eventually rains out providing a freshwater source to the surface and warming the atmosphere. The Indonesian Seaway is a conduit for cross-equatorial trans-ocean exchange between the western Pacific and Indian Ocean. Gordon (1986) recognized the importance of the Indonesian Throughflow (ITF) as an important contributor to the global thermohaline circulation (*perhaps*) ultimately contributing to the formation of North Atlantic Deep Water. Enhanced vertical mixing in the Indonesian Seas drives large fluxes of heat and freshwater into the water column which is ultimately incorporated into the ITF and contributes to the regional freshwater and heat budget (*e.g.*, Gordon and Fine, 1996; Hautala *et al.*, 1996). It is the redistribution of heat and salt which sets the stage for the global thermohaline circulation in addition to regional or basin-scale processes such as the El Niño-Southern Oscillation.

Although much of the thermocline and surface water driven by the trade winds is recirculated within the Pacific, some enters the Indonesian Seaway and flows into the Indian Ocean (Figure 1). This Indonesian throughflow (ITF) is driven by the difference in sea level between the two oceans (average 16 cm) and much of the flow is in the upper 200m (Wyrtki, 1987). Current meters in the Makassar Strait indicate reduced flow below ~400m (Gordon *et al.*, 1999). It is thought that variations in the transport and modification of water properties (heat and freshwater) due to vertical exchange within the Indonesian Seas have an impact on decadal climate (Ffield and Gordon, 1992; Ffield, 1994; Hirst and Godfrey 1993; Rodgers *et al.,* 1999). The principal path is considered to be through the Sulawesi and Java Seas via the Makassar Strait with the bulk of the throughflow derived from the North Pacific supplied by the Mindanao Current (Ffield and Gordon, 1992). Another path is via the Halmahera Strait which enters the Banda Sea, with throughflow derived from the South Pacific and supplied by the South Equatorial Current (Wajsowicz, 1993). Waters flowing southward through the Makassar Strait enter the Flores Sea. A portion of this water directly exits the Indonesian Seas into the Indian Ocean via the Lombok Strait (*e.g.,* Murray and Arief, 1988) and the remainder appears to flow eastward to the Banda Sea. Water that enters the Banda Sea is modified by vertical dynamic processes (*e.g*., upwelling) that when combined with exchanges of heat and freshwater with the atmosphere can alter the heat and salt content of the water masses prior to their export to the Indian Ocean via the Sumba, Savu, and Dao Straits, and the Timor Passage (Hautala *et al*., 1996; Hautala *et al*. 2001 and references therein.)

Estimates of the ITF span a wide range between -2Sv to 22Sv with *large* seasonal and interannual variability. Current meter measurements in the Makassar Strait during 1996 through 1998 document an average flow of 9.5±2.5Sv with much of the error derived from how the surface flow is accounted for (Gordon *et al*., 1999). Maximum flow is near 300db at the depth of the salinity minimum associated with North Pacific Intermediate Water with decreasing velocities below 400db (Gordon *et al*., 1999). In general, surface flow is weak in winter and strong (to the south) in austral summer during the southeast monsoon. During this short observation period all of the inter-ocean transport can be accounted for within the Makassar Strait, and there is a strong correlation with the state of ENSO with diminished flow observed during the 1997 El Niño event. Just how representative this ~2yr time-series is of the long-term mean flow is unknown. It is equally unknown how the surface flow is coupled with the flow within the thermocline.

Estimates of the (~100m) shallow flow derived from an array of pressure gauge pairs and ADCP profiles across the five principal straits that separate the eastern Indian Ocean from the interior Indonesian Seas for December 1995 – May 1999 (Hautala, *et al*., 2001) have shown that there can be large differences in the timing of the peak influx of water into the Indonesian Seas (as inferred from the Makassar Strait current meter data) and that exported to the Indian Ocean. A similar offset in maximum flow is also inferred from Lombok Strait current profile data in 1985-1986 (Murray and Arief, 1988). In an admittedly simple sensitivity test Hautala *et al.,* (2001) explore how the offset in timing of peak outflow (equivalent to a 5Sv imbalance) can lead to a ~5°C difference in thermocline temperature, and thus a significant change in the heat content, storage, and export in the Banda Sea. Therefore it is important to understand the processes within the Indonesian Seas governing the evolution and properties (heat, salt) of the inter-ocean exchange waters.

The pressure guage estimates of transport exhibit inter-annual variability that is of the same order as the long-term mean. Hautala *et al*., (2001) document intra-seasonal reversals where surface waters flow north from the Indian Ocean into the Indonesian Seas. It is thought that this reversal is a consequence of coastally trapped Kelvin waves generated on the west coast of Sumatra. The three ADCP (cruises) profiles indicate that when flow is to the south (March 1997, 1998) it occurs over the whole water column whereas when there is northward flow (December 1995), the north flow is constrained to the surface with no net flow at depth. Interestingly, although similar in mean transport, flow through the Lombok Strait had much larger variability than that in the Timor Passage with a strong correlation ($r^2 = 0.8$) between the Lombok Strait component and the total, as measured through all of the straits, shallow flow. Reconstructing the transport history of the Lombok Straits would go a long way in understanding the total shallow water transport between the Indonesian Seas and the Indian Ocean.

Atmospheric nuclear weapons testing in the late 1950s and early 1960s resulted in an excess of ^{14}C in the atmosphere and as this signature has penetrated the ocean it has augmented the natural gradient between the surface and deeper waters. Isotopic equilibration with atmospheric $^{14}C/^{12}C$ is on the order of a decade (Broecker and Peng, 1982) and thus $\Delta^{14}C$ in surface waters can be used as a quasi-conservative, passive advective tracer. Time-series such as those derived from archives such as hermatypic corals can augment historical, conventional (temperature, salinity) observations especially in times and regions where observations are sparse. Corals act like strip-chart recorders continuously recording the radiocarbon content of the waters in which they live. Ocean dynamics can be reconstructed and studied from these biogenic archives.

Measurements of coral skeletal material which accurately record the $\Delta^{14}C$ of ΣCO_2 (*e.g.,* Druffel, 1981 among others) have added important information to water sampling programs like GEOSECS (Östlund *et al.*, 1987) and the World Ocean Circulation Experiment (WOCE: Key *et al.* 1996). There are notable limitations to shipboard sampling, primarily the inability to continuously monitor ocean conditions. For ^{14}C in the deep ocean, this is not a problem because the transport is relatively slow and the gradients are relatively low. For the surface ocean, where ^{14}C gradients are highest and transport is rapid, it has been demonstrated that temporal variability in surface $\Delta^{14}C$ is of the same order as spatial variability (e.g., Guilderson *et al*. 1998), an observation which is lost in discrete analyses like GEOSECS or WOCE whose "snapshots" of bomb-radiocarbon are integrations of ~20 and ~40 years (respectively) of ocean dynamics.

We have chosen sites (Figure 1) to monitor variations in the transport of water out of the Pacific (Langkai, Bunaken) and into the Indian Ocean (Padang Bai). Our multi-decadal continuous $\Delta^{14}C$ records will complement the existing physical and chemical data sets from oceanographic expeditions of the Indonesian region and will prove to be a valuable tool for exploring circulation through the Indonesian Seas. Reconstructing the tracer history of the Lombok Strait would go a long way in understanding the total shallow water transport between the Indonesian Seas and the Indian Ocean. The results presented here are placed in a dynamic context through comparison with a new record from the Makassar Strait (Fallon and Guilderson, 2007), and a previously published record from the northwest coast of Sumatra in the Mentawai Islands (Grumet *et al*., 2004).

Methods

Coral cores were drilled in January 1990 from an exceptionally large *Porites* colony growing at a depth of 5 meters at Padang Bai, Bali (8°15'S, 115°30'E) on the southern edge of the Lombok Strait. The recovered coral cores span nearly 300 years of growth and a long (~1mm resolved) stable isotope record can be found in Charles *et al.,* (2003). We have focused our radiocarbon work on the upper-most ~70cm of the coral which mainly covers the pre to post-bomb period.

The cores were cut into ~9mm mm slabs, ultrasonically cleaned in distilled water, and air-dried. After identifying the major vertical growth axis, the coral was sequentially sampled at 2 mm increments with a low-speed drill. Where necessary, we overlapped parallel sample tracts in order to adequately splice sections together. Splits (~1 mg) were reacted in vacuo in a modified autocarbonate device at 90°C and the purified CO_2 analyzed on a gas source stable isotope ratio mass spectrometer. Stable isotope data are reported in standard per mil notation relative to Vienna Pee Dee Belemnite (Coplen, 1993). Analytical precision based on an in-house standard is better than ±0.05‰ (1s) for both oxygen and carbon. The remaining sample splits (8-9 mg) were placed in individual reaction chambers, evacuated, heated, and acidified with orthophosphoric acid at 90°C. The evolved CO_2 was purified, trapped, and converted to graphite in the presence of iron catalyst and a stoichiometric excess of hydrogen (Vogel *et al*., 1987). Graphite targets were measured at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Radiocarbon results are reported as age-corrected $\Delta^{14}C$ (‰) as defined by Stuiver and Polach (1977) and include a background correction using ^{14}C-free calcite, and the $\delta^{13}C$ correction obtained from the stable isotope results. Analytical precision and accuracy of the radiocarbon measurements is ±3.5‰ (1s sd).

Embedded in the oxygen isotopic composition of the coral's aragonite skeleton is information on temperature and the oxygen isotopic composition of the water (δ_w) in which the coral resided (*e.g.,* Epstein *et al*., 1951). The d_w of the water is directly related to salinity (*e.g.,* Craig and Gordon, 1965) with low salinities having low $\delta^{18}O$ and the converse true for high salinity waters. Thus salinity is often used as a proxy for δ_w. The average Lombok Strait sea surface temperature is ~28.7°C with an annual range on the order of 2°C (Sprintall *et al.*, 2003; Levitus and Boyer, 1998; Reynolds and Smith, 1994), but not what one would consider a clear annual cycle. Mean annual salinity is ~33.4 psu (Sprintall *et al.,* 2003; Levitus and Boyer 1998) with a solid seasonal cycle in excess of 2psu. In the Lombok Strait sea surface temperature maxima and salinity minima co-occur in late March-May and correspondingly highest salinities tend to occur during the lowest sea surface temperatures in September-October. At this location the seasonal signal in salinity and temperature are reinforced in the $\delta^{18}O_{coral}$ with the annual $\delta^{18}O_{coral}$ cycle being primarily driven by salinity (δ_w) variations.

Coral chronology has historically relied upon the presence of annual high- and low-density band couplets (*e.g*., Dodge and Vaisnys, 1980 and references therein) or the seasonal variability in coral $\delta^{13}C$ which is thought to reflect surface irradiance (*e.g*., Shen *et al*., 1992). Independent chronologies based on these two methods on the same coral specimen tend to agree within a few to 6 months (*e.g*., Shen *et al*., 1992). We created a preliminary age model based upon the seasonal structure within the $\delta^{13}C$ record and sclerochronology but in order to obtain the best timescale we have refined our age model by correcting the preliminary age model through coral $\delta^{18}O$ comparisons with instrumental records (*e.g.*, Guilderson and Schrag, 1999). Chronological assignments for the core were straightforward due to the clear seasonal cycle in $\delta^{18}O$. The seasonal extremes were anchored to April and September of each year consistent with instrumental observations of temperature, salinity, and cloudiness (Charles *et al.*, 2003). Age errors are estimated to be approximately one to two months.

Results

The $\Delta^{14}C$ time-series spans ~1937.5-1990. The ~14mm/year apparent linear growth rate yielded 7-8 $\Delta^{14}C$ samples per year with an average resolution of ~1.5 months. Individual ~bimonthly $\Delta^{14}C$ values range from -72‰ to 134‰ (Figure 2). The average $\Delta^{14}C$ pre-bomb (1937-1950) value is -60.5 ± 4.2‰, or 501 radiocarbon years. Over the pre-bomb interval the Lombok coral surface water $\Delta^{14}C$ is intermediate in value between Makassar Strait and lower $\Delta^{14}C$ Indian Ocean surface water as recorded at Mentawai. Between 1947 and 1954 the data trends to slightly more negative values: ~ -68‰ in 1951 and 1952. In 1954 values average -62.5‰ and are followed by a rise of ~30‰ during 1955. Values decrease slightly in 1956 and into 1957 before rising toward the post-bomb peak. The mean annual post-bomb maximum occurred in 1973 (122‰). Mean annual $\Delta^{14}C$ values remain between ~110‰ and ~120‰ through 1982 and then begin a slow decrease until the end of the record in 1990.

In the pre-bomb portion of the record seasonality is irregular. Seasonality is distinct in nearly all of the post-bomb (post 1955) years and ranges between ~5 and ~20‰, with most years ~10‰. Seasonal $\Delta^{14}C$ maxima occur coincident with warm temperatures and low salinity (more negative $\delta^{18}O_{coral}$) and conversely $\Delta^{14}C$ minima occur with more positive $\delta^{18}O_{coral}$ values (cooler, saltier water).

Discussion

Prior to atmospheric weapons testing and oceanic uptake of "bomb-^{14}C" the mid to low latitude surface water $\Delta^{14}C$ gradients were small. In the western equatorial Pacific and eastern Indian Ocean the gradient is on the order of 17‰: from a high of ~ -47‰ for the North Pacific subtropics (*e.g*., Druffel *et al*., 2001) to -64‰ at Penang Island (0° 0.8'S, 98° 31'E) off the northwest coast of Sumatra in the Mentawai Islands (Grumet *et al*., 2004). Where the time series overlap we use Makassar Strait (North Pacific) and Penang Island (Indian Ocean) as reference end-members to infer dynamic processes and potential transport through the Lombok Strait. Doing so grossly oversimplifies the complicated intraseasonal changes in surface currents that occur in the eastern Indian Ocean. The South Java Current only flows southeast during the monsoon transitions (May and November) whereas during the rest of the year it flows westward (*e.g*., Tomczak and Godfrey, 2003; Schott *et al*., 2001). The low ^{14}C water observed at Penang Island is brought to the surface by upwelling along the Sumatra coast which occurs when the South Java Current flows west. Using the Penang Isl record as a pseudo-endmember is probably reasonable during the pre-bomb interval where $\Delta^{14}C$ seasonality and gradients in the eastern Indian Ocean are small. In the post-bomb era we use the intrinsic seasonal $\Delta^{14}C$ in the Lombok Strait coral record in our assessment of the evolution and mixing of Lombok Strait surface water.

Between 1938 and 1944 the Lombok Strait $\Delta^{14}C$ data are 5-10‰ more negative than the corresponding Makassar Strait record. Between 1944 and 1947 Lombok and Makassar Strait coral $\Delta^{14}C$ are indistinguishable from each other and values are10-15‰ more positive than surface waters off the west coast of Sumatra at Penang Isl. From 1947-1954 Lombok $\Delta^{14}C$ values are equivalent to Penang Isl. and both records are 10-15‰ more negative than values recorded in the Makassar Strait. When Lombok and Penang Is $\Delta^{14}C$ are similar we infer enhanced upwelling on the west coast of Sumatra and Java. This enhanced upwelling may be accommodated by increased northward flow through the Lombok Strait. When Lombok and Makassar Strait $\Delta^{14}C$ are more similar we infer the converse: less upwelling, less potential influence of Indian Ocean water backfilling the Indonesian Seas through Lombok, and potentially more flow through Makassar and Lombok Straits.

The distinct ~30‰ transient $\Delta^{14}C$ in 1955 is a unique feature, until recently previously unrecognized in circum-Pacific coral-based $\Delta^{14}C$ reconstructions (Fallon and Guilderson, 2008). The feature occurs well before a significant rise in atmospheric-^{14}C concentrations (*e.g.*, Manning and Melhuish 1994; Stuiver and Quay, 1981) and is therefore unlikely to be the result of air-sea ^{14}C exchange given the ~decadal time-delay for isotopic equilibration (Broecker and Peng, 1982). Toggweiler and Trumbore (1985) documented a ^{90}Sr (a weapons fallout product) peak in the skeletal material corresponding to 1955 in a coral from Cocos Island in the Indian Ocean. Given the spatial distribution and timing of individual atomic weapons tests and the constraints of air-sea isotopic exchange, the path of least resistance to reconcile the ^{90}Sr and rapid ^{14}C increase is for waters from near Bikini Atoll where the early atmospheric weapons tests were conducted to be transported via the North Equatorial Current to the Mindanao Current to be transported into the Indian Ocean through the Lombok Straits. A similar well-defined transient with higher $\Delta^{14}C$ values at exactly the same time is observed in the Makassar Straits (Fallon and Guilderson, 2008).

The timing of the post-bomb $\Delta^{14}C$ peak is consistent with air-sea isotopic equilibration of ~10 years, relative to the atmospheric peak in the early 1960s, and a subtropical origin of much of the surface water. One could argue that there is not an individual single "peak" but that between 1973 and 1982 $\Delta^{14}C$ values are equivalent before they begin to turn down. The elevated value reflects the slow penetration and dilution of bomb-^{14}C with interior waters that upwell in only a few locations in the tropical Pacific and Indian Ocean. Penetration of bomb-^{14}C laden water into newly subtropical mode waters will (*eventually*) be entrained and upwelled at the equator to recycle its ^{14}C signature. The Lombok post-bomb peak is bracketed by the subtropical $\Delta^{14}C$ peak of the early 1970s (*e.g.*, Druffel 1987), 1982 observed at Nauru in the western equatorial Pacific (Guilderson *et al*., 1998), and 1985 in the Solomon Sea (Guilderson *et al*., 2004). The surface waters that eventually exit through the Lombok Strait have their origins in these locations and the stretched post-bomb 'peak' reflects the influence of these waters.

Spectral analysis of the $\Delta^{14}C$ time-series confirms the visually striking seasonal cycle and a two year periodicity. This two year periodicity is likely a reflection of the SE Asian monsoon, which has a strong biennial component [Meehl, 1997], and its influence on the passage of waters through the Lombok Strait. It is interesting that the $\Delta^{14}C$ record exhibits a biennial period because the Padang Bai $\delta^{18}O$ record does not (Charles *et al*., 2003). This is an example of the important and subtle difference between a true water mass tracer such as $\Delta^{14}C$ versus $\delta^{18}O$ in corals which is a combination of temperature and $\delta^{18}O_w$ (salinity): two tracers that over a few months (or less) can be significantly modified by air-sea processes and thus are not conservative water mass tracers. Although the Indonesian region is impacted by ENSO the $\Delta^{14}C$ (and $\delta^{18}O$) of Lombok Strait surface water is not, *sensu strictu*, a simple recorder of ENSO events. Interannual "events" do not bear a simple linear correspondence with for example the Southern Oscillation Index modulated by the SE Asian monsoon, or events in the Indian Ocean (see also Charles *et al*., 2003). This is because $\Delta^{14}C$ in the Lombok Strait reflects not only the mixing of Indonesian Seas and Indian Ocean water, but the temporal evolution of the $\Delta^{14}C$ at the source regions of the individual water masses.

To explore the relationship between surface waters in Makassar and Lombok Straits we passed the respective $\delta^{18}O$ and $\Delta^{14}C$ records individually through a Gaussian filter centered on the annual cycle (1±0.3 hz). The (visual) correspondence of the individual strait's $\delta^{18}O$ (temperature/salinity) and $\Delta^{14}C$ is confirmed: they are coherent and nearly always in phase (Figure 3). There are instances where the Lombok Strait's seasonal high $\Delta^{14}C$ value is lagged relative to the $\delta^{18}O$ by one sample. Not surprisingly and entirely due to the mechanics of creating the age-model, $\delta^{18}O$ between Makassar and Lombok Straits is in phase. The seasonal cycle in radiocarbon between the two sites is also highly coherent and in phase. Although we have *a priori* fixed the calendar month (using $\delta^{18}O$) there was no guarantee that the coral $\Delta^{14}C$ seasonal cycles would be in phase. If we make the logical first order assumption that Makassar and Lombok Strait share a common source of high $\Delta^{14}C$ surface water, then the fact that the $\Delta^{14}C$ seasonal cycles are in phase implies, within the resolution of our sampling, little to no lag in the transport through the two "coral-based observation platforms." The implicit assumptions used in the construction of the age-model does force some amount of correspondence at least within the sample resolution (~bimonthly). If we were able to derive a completely independent coral calendar age-model we might be able to tease out a lag smaller than several months.

Variability in the export of water out of Lombok Straits and the Indonesian Archipelago to the Indian Ocean is not stationary. In the Hautala *et al.,* SPGA (1995-1998) study only 20% of the variability was in the seasonal cycle, and 50% was intra-seasonal. In a modeling study forced with 14 years (1985-1999) of ECMWF (observed) 3-day winds, Poterma *et al*., (2003) estimate that over the 14 year span 48% of the variability is associated with the seasonal cycle. Within the bimonthly resolution, our record supports surface water mixing and or export that is dominated by the seasonal cycle. This indicates a strong link between the Δ^{14}C signature in Lombok Straits and Western Pacific surface winds.

Following the idea that the Makassar and Lombok Straits' high Δ^{14}C is sourced from the same North Pacific water that seasonally flows southward through the Makassar Strait (Fallon and Guilderson, 2008; Gordon *et al.*, 1999, 2003), we explore the influence of this North Pacific water on the waters at the south of the Lombok Strait. Admittedly the relative dilution of North Pacific (Makassar Strait high Δ^{14}C water) with lower Δ^{14}C "Eastern Indian Ocean" water is not a quantitative measure of the flux. It should however provide a sense of past fluxes and dynamics that would otherwise be unattainable. Indeed, if the Lombok Strait's Δ^{14}C looked exactly like that of the Makassar Strait this would imply no (local) Indian Ocean water at all, and the "transport" might not be anything but "sloshing" back and forth like the water in a bathtub going from end to end. To estimate the relative percent of Makassar Strait water we use the seasonal high Δ^{14}C from the Langkai coral record (MAK end member) and the corresponding seasonal high Padang Bai coral Δ^{14}C value (Lombok measured). The Eastern Indian Ocean endmember is selected from the preceeding seasonal low Δ^{14}C in the Padang Bai record. A potential confound to this analysis is the influence of Banda Sea water. Due to upwelling and vertical entrainment of subthermocline waters (*e.g.*, Ffield and Gordon, 1992; Hautala *et al*. 2001) we expect Banda Sea Δ^{14}C to be lower than that observed in the Makassar Strait, at least until significant incorporation of bomb-^{14}C into subthermocline waters in the Banda Sea has taken place. During the southwest monsoon Banda Sea surface water gives the appearance of "back filling" the Java Sea

(Gordon *et al*., 2003). If Banda Sea water passes through Lombok Strait it would influence the Padang Bai $\Delta^{14}C$ signal that we have measured, and our reference point would be Banda Sea water and not Eastern Indian Ocean water.

We do not estimate the percent of MAK water in 1961 and 1962; these are the years when atmospheric $\Delta^{14}C$ is rapidly increasing and surface water $\Delta^{14}C$ is strongly influenced by air-sea isotope exchange. Air-sea ^{14}C exchange during these years can confound using $\Delta^{14}C$ as a surface water mass tracer. For all other years we calculate the percent of MAK water in the measured Lombok water using the simple two end-member mixing model. The results of this simple mixing model experiment are presented in figure (4). The percent of MAK water averages 40% and ranges from a low of 16% to a high of 70%. Visually there is a hint of a long-term decrease in the (seasonal) influence of MAK water in the Lombok Strait, if not an outright change in mean state on either side of 1975. On either side of 1975 the average percentage of MAK water is not statistically different (44±15, n=18 versus 35±15, n =15). The record is too short to confirm a multi-decadal component to the variability. The interannual variability is expressed as increased influence of MAK water during nearly every La Niña event that in general terminate strong El Niño events. The sense of the influence of MAK water is consistent with our understanding of transport through the ITF based on present day observations. During strong La Niña events there is a build-up of water and sea level height in the western equatorial Pacific which can lead to increased transport through the ITF. Particularly important in modulating the transfer of water from the Pacific to Indian Ocean is the establishment of buoyant, low salinity plugs that provide resistance to flow

(Gordon *et al*., 2003). We know that the surface waters' characteristics (temperature and salinity) is a complex integration of Pacific, Indonesian, and Indian Ocean processes (*e.g*., Charles et al., 2003). This interplay between competing and complementary dynamics influences the shallow water mixing, and ultimately the heat and salt budget of the throughflow. We refrain from inferring what the mixing percentages mean with regards to the total throughflow, the majority of which is at depth.

Conclusions

To infer surface water mixing in the Lombok Strait over the last ~50 years we have reconstructed the surface water $\Delta^{14}C$ history using a reef-building hermatypic coral cored off Padang Bai, Bali. The ~bimonthly record exhibits strong seasonality that is coherent and in phase with a similar data set acquired in the Makassar Strait (Fallon and Guilderson, 2007). Using admittedly simplistic assumptions regarding the seasonal transport of high $\Delta^{14}C$ water through Makassar and Lombok Strait, we estimate the percentage of high $\Delta^{14}C$ water common to the two records. The percentage of high $\Delta^{14}C$ "Makassar Strait" water varies between 16 and 70% with a mean of 40%. In addition to interannual variability that projects itself as high MAK percentages during La Niña events (positive Southern Oscillation), there is a hint of multi-decadal variability. We caution strictly using ENSO as the means to explain the variability because the Indonesian throughflow is a union of Pacific, Indian Ocean, and local Indonesian Sea processes.

The Lombok Strait $\Delta^{14}C$ time-series is remarkably rich data set that also exhibits biennial variability. The biennial variability reflects the influence of the southeast Asian monsoon on the regional dynamics and the movement of surface waters through the Lombok Strait. In time, we plan to expand the spatial coverage of time-series such as the one presented here. These and similar time series provide a unique diagnostic and a very difficult benchmark for ocean circulation models that attempt to recreate the dynamics of the Indonesian region.

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Figure Captions

Figure 1. Map of the Indonesian region, and schematic representation of surface and near surface currents (adapted from Lukas *et al*., 1996; Gordon *et al.*, 1999, Hautala *et al.*, 2001). Coral locations (solid circles) discussed in the text are: Lombok Strait (Padang Bai, Bali), Makassar Strait (Langkai), Sumatra (Padang Is, Mentawai). Currents denoted in the figure include the North/South Equatorial Current (NEC/SEC), North/South Equatorial Counter Current (NECC/SECC), the Mindanao and Kuroshio Currents (MC, KC), and the seasonally reversing South Java Current (SJC).

Figure 2. Surface ocean $\Delta^{14}C$ as reconstructed from reef-building hermatypic corals from Lombok Strait (LOM: thick solid line), Makassar Strait (MAK: thin grey line), Sumatra (SJC: thin dotted line). The Lombok and Makassar data have a 1-sigma sd of ±3.5‰. Coral chronologies were derived from independent $\delta^{18}O$ records anchored to seasonal extremes in sea surface temperature and salinity ($\delta^{18}O_w$).

Figure 3. a) Lombok coral $\delta^{18}O$ (thin line) and $\Delta^{14}C$ (thick line) passed through a one-year Gaussian filter (1±0.3). Note that the $\Delta^{14}C$ and $\delta^{18}O$ are coherent and nearly always in phase. b) Similarly filtered Lombok (thick line) and Makassar (thin line) Strait $\Delta^{14}C$. There is little lag between the $\Delta^{14}C$ seasonal cycle at the two locations.

Figure 4. Seasonal influence of high $\Delta^{14}C$ "Makassar Strait" water in the Lombok Strait derived from a two-component mixing model. The average over the time-series is 40%

and ranges from 16 to 70%. The thin solid line is the seasonal Tahiti – Darwin sea level pressure anomaly (SLPa), the Southern Oscillation Index, with a 3 month running mean filter applied.

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Figure 1

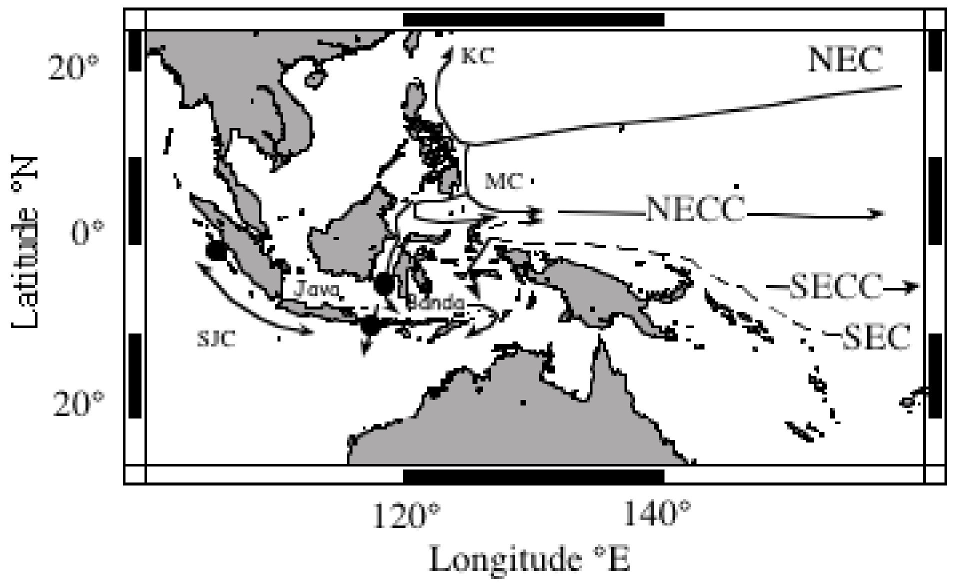
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Figure 2

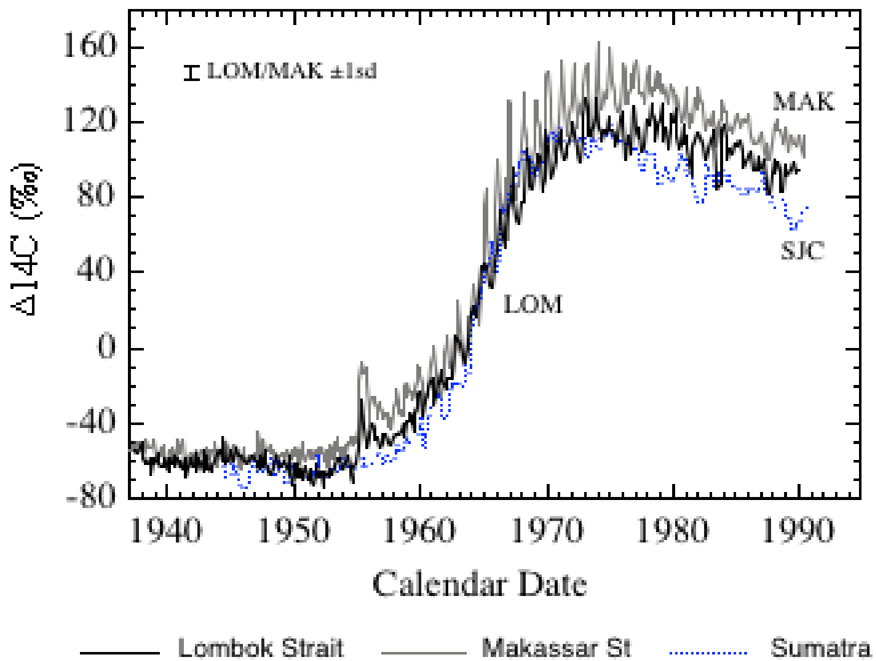
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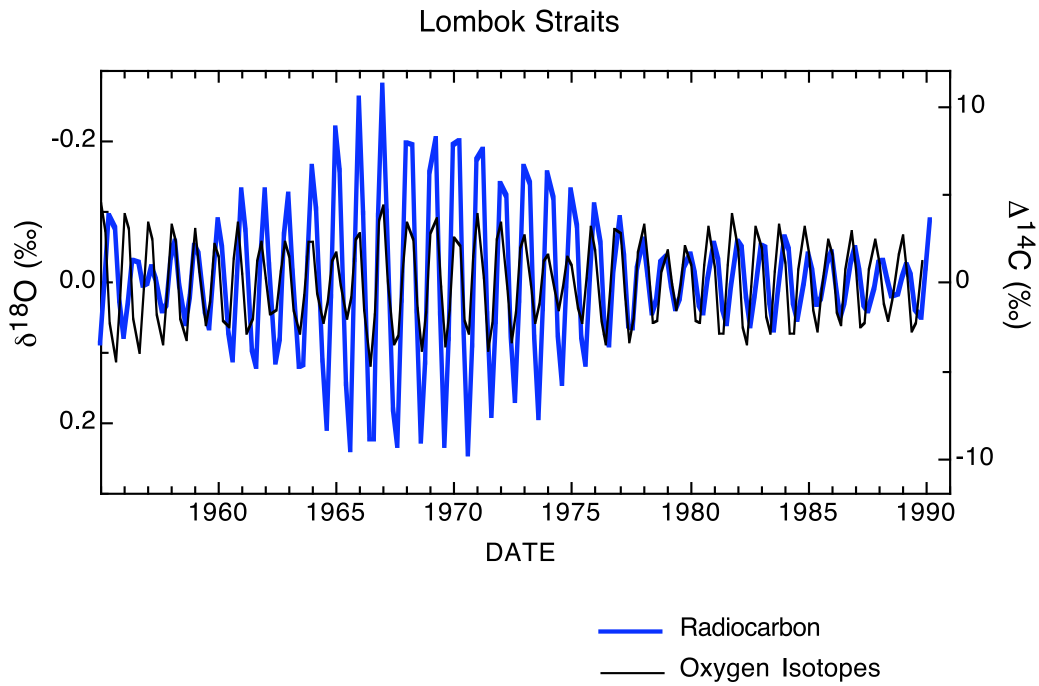
Figure 3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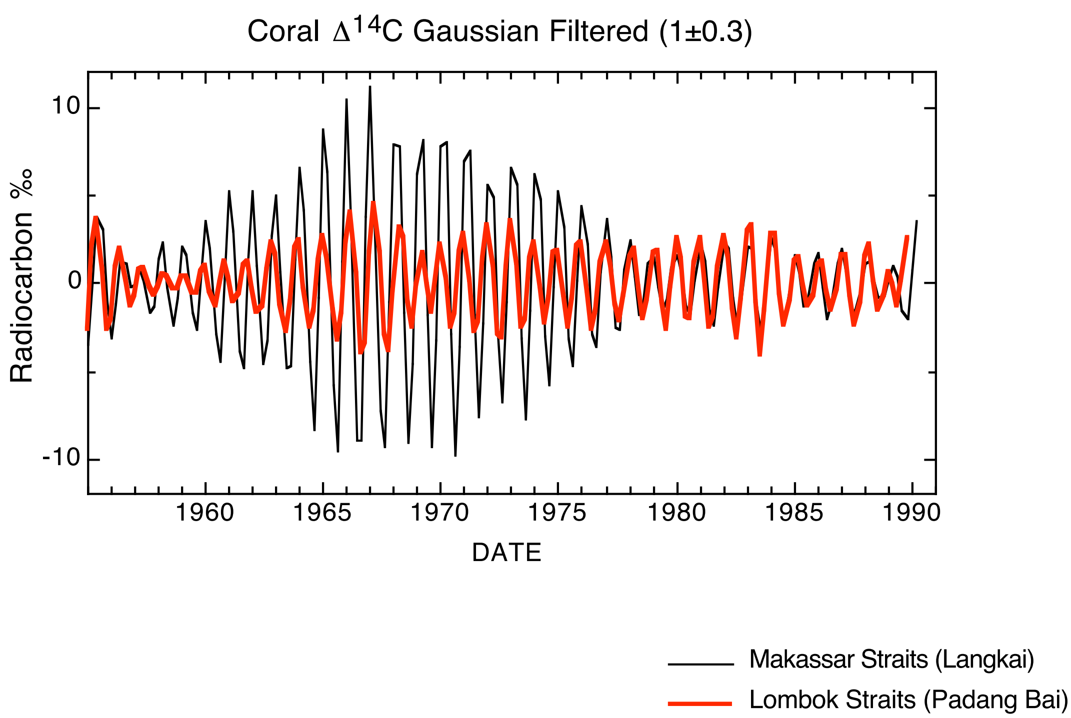
Oxygen Isotopes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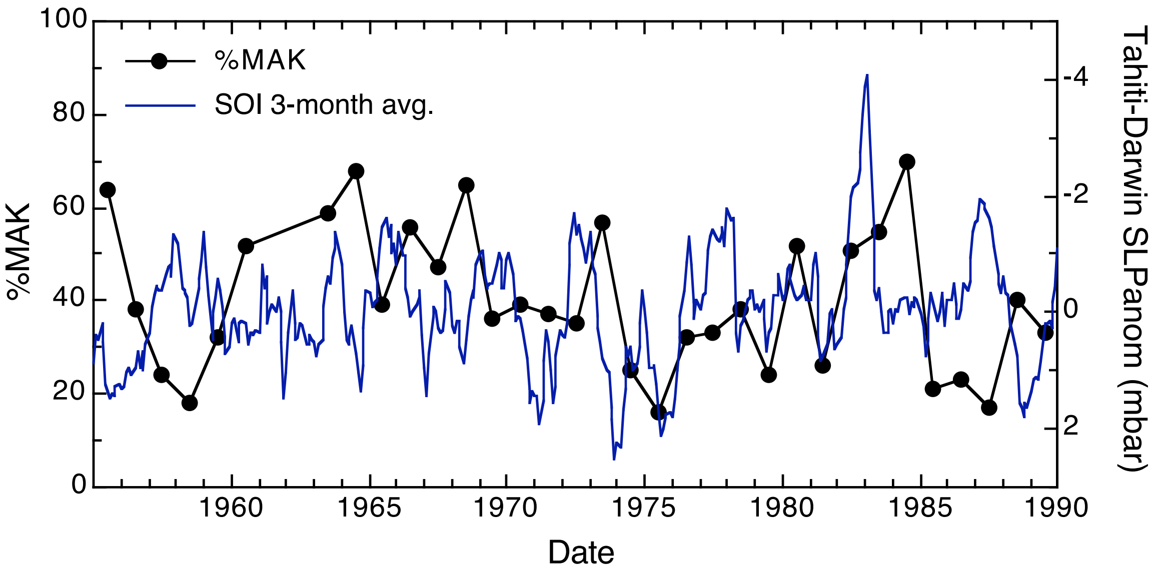
Makassar Straits (Langkai)
Lombok Straits (Padang Bai)

Figure 4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