Coral-based reconstruction of climatic and oceanographic variability across the Luzon Strait for the past ~230 years

Ramos Riovie Dela Pena

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**NANYANG
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SINGAPORE

**CORAL-BASED RECONSTRUCTION OF CLIMATIC AND
OCEANOGRAPHIC VARIABILITY ACROSS
THE LUZON STRAIT FOR THE PAST ~230 YEARS**

RAMOS RIOVIE DELA PEÑA

ASIAN SCHOOL OF THE ENVIRONMENT

2019

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OCEANOGRAPHIC VARIABILITY ACROSS
THE LUZON STRAIT FOR THE PAST ~230 YEARS**

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Asian School of the Environment
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A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2019

Candidate Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from 2 papers published in the following peer-reviewed journals which I am listed as an author.

Chapter 2 is published as: Ramos, R. D., Goodkin, N. F., Siringan, F. P., & Huguen, K. A. (2017). *Diploastrea heliopora* Sr/Ca and $\delta^{18}\text{O}$ records from northeast Luzon, Philippines: An assessment of interspecies coral proxy calibrations and climate controls of sea surface temperature and salinity. *Paleoceanography*, 32(4), 424-438. doi:10.1002/2017PA003098.

The contributions of the co-authors are as follows:

- I was the primary author.
- Assoc/Prof. Goodkin conceptualized the idea, its formalization and development with Dr. Huguen and Prof. Siringan. All the authors conducted the field sampling.
- I prepared all the samples and performed geochemical analysis and data synthesis in the lab.
- Assoc/Prof. Goodkin supervised the lab analysis, data interpretation, manuscript writing and overall progress of the project.
- Dr. Huguen and Prof. Siringan were critical in the review and editing of the manuscript.

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The contributions of the co-authors are as follows:

- I was the primary author.
- Assoc/Prof. Goodkin conceptualized the idea, its formalization and development with Prof. Druffel, Prof. Siringan and Dr. Fan.
- Assoc/Prof. Goodkin and Dr. Fan led the field sampling in Taiwan.
- Assoc/Prof. Goodkin, Prof. Siringan and I led the field sampling in the Philippines.
- I prepared subsamples for geochemical analysis.
- Prof. Druffel assisted with the geochemical analysis, data validation and interpretation.
- Assoc/Prof. Goodkin supervised the data interpretation, manuscript writing and overall progress of the project.

- Prof. Druffel, Prof. Siringan and Dr. Fan were critical in the review and editing of the manuscript.

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Summary

The Kuroshio-dominated water exchange across the Luzon Strait impacts the climate and oceanography of the South China Sea and the total transport of the Indonesian throughflow, inviting interest for research that will improve our understanding of the behavior and drivers of the Kuroshio Intrusion. However, continuous high-resolution observations of the Kuroshio intruding process are limited as comprehensive and systematic monitoring remain logistically challenging and complex. Massive corals provide an inexpensive means of extending high-resolution climatic and oceanographic records of the Kuroshio Intrusion and its drivers beyond the instrumental period, which is critical for evaluating long-term variability, regional trends and predictability under future change.

One *Diploastrea heliopora* and two *Porites* sp. coral cores were collected on either side of the Luzon Strait – Palaui, northwestern Philippines and Houbihu, southern Taiwan. The coral cores were slabbed and x-rayed to determine sub-annual bands allowing for precise age-control. The slabs were subsampled for Sr/Ca, $\delta^{18}\text{O}$ and $\Delta^{14}\text{C}$ as proxies for sea surface temperature (SST), sea surface salinity (SSS) and ocean circulation, respectively. Monthly-resolved SST and SSS reconstructions spanning the last 132 and 230 years were generated from Palaui and Houbihu, respectively. Seasonal and annual $\Delta^{14}\text{C}$ records from both Palaui and Houbihu cover the past ~68 years.

Sr/Ca-based records of SST reveal site-specific controls on observed SST variability. The Palaui paired *Diploastrea* and *Porites* winter Sr/Ca-SST records

exhibit similar sensitivity to the Pacific Decadal Oscillation (PDO). The extended *Porites*-based winter SST reconstruction since the late 19th century remained sensitive to the PDO, highlighting its potential long-term impact on tropical climate variability. Houbihu winter SST, on the other hand, exhibits hemispheric-scale SST patterns driven by global forcings (i.e. solar and volcanic radiative forcings). The additional ~100 years in Houbihu relative to the Palaui record allow for further examination of conditions at the end of the Little Ice Age (LIA), which indicates cooler SSTs relative to the most recent 30 years. Both coral sites exhibit significant recent rise in SSTs likely tied to anthropogenic warming. Collectively, these findings suggest a change in temperature and extent of the warm pool region in the past 230 years.

$\delta^{18}\text{O}_c$ -based records of SSS are robust allowing for investigating the advection signal across the Luzon Strait. Similar to Sr/Ca-SST, each of the Luzon Strait sites reveal site-specific controls on the observed surface salinity variability. The Palaui dry-season SSS record is sensitive to ENSO-related changes in hydrological processes. Seasonal difference between Palaui dry and wet season SSS record reveals the additional impact of the PDO in enhancing advection of Pacific waters to Palaui. In contrast, the Houbihu dry-season SSS record reflects East Asian Winter Monsoon (EAWM)-related changes in hydrological processes, modifying the surface salinity of the source waters. Examining the dry-season SSS difference between Palaui and Houbihu reveals the added influence of the PDO on the delivery of Pacific waters across the strait at decadal timescales. The additional ~100 years of dry-season SSS record in

Houbihu indicate high salinity surface water conditions (i.e. drier) at the end of the LIA relative to the present. Inferring from the strong modern relationships between the Houbihu SSS and the EAWM and the PDO, the Kuroshio intrusion at the end of the LIA is likely reduced. These conditions potentially resulted in an altered SCS climate and circulation.

Records of $\Delta^{14}\text{C}$ from both Palaui and Houbihu also reveal site-specific processes that control advection and water mixing at these sites, corroborating findings in the Sr/Ca and $\delta^{18}\text{O}$ -based climate records. Palaui $\Delta^{14}\text{C}$ relative to Pacific $\Delta^{14}\text{C}$ values is sensitive to the ENSO-forced migration of the North Equatorial Current (NEC) bifurcation latitude. Houbihu $\Delta^{14}\text{C}$ relative to SCS $\Delta^{14}\text{C}$ values reflects EAWM-mediated transport across the Luzon Strait and circulation of the SCS. Overall, the interannual $\Delta^{14}\text{C}$ difference between our sites and the surrounding seas reveal the dominant influence of ENSO in driving the Kuroshio Intrusion into the SCS at interannual timescales.

Across proxy records, this thesis has revealed site-specific drivers of observed climatic variability between sites in the Luzon Strait. This key finding underscores the importance of investigating and identifying processes that are related to EAWM, ENSO and PDO variability independently at each site. Collectively, this information is critical to understand their interaction that in turn controls the Kuroshio intruding process into the SCS.

Chapter 1

Introduction

1.1 Background and Research Aims

The northward flowing Kuroshio Current (KC) periodically intrudes across the Luzon Strait and into the South China Sea (SCS) as the Kuroshio Intrusion (KI) (Caruso et al., 2006; Centurioni et al., 2004; Hu et al., 2000; Jia & Liu, 2004; Nan et al., 2015; Wyrski, 1961) (Fig. 1.1). The KI delivers relatively warmer and higher salinity Pacific waters into the SCS, regulating heat, moisture and water exchange along its path (Caruso et al., 2006; Chen et al., 2001; Hu et al., 2015; Nan et al., 2015; Qiu & Lukas, 1996). While our understanding of the seasonality, intensity and drivers of the KI remain limited, it is linked to significant changes in the climate and circulation of the SCS (e.g. Hsin et al., 2012; Hu et al., 2000; Liang et al., 2008; Nan et al., 2013; Nan et al., 2015; Nan et al., 2016; Qu et al., 2004; Wyrski, 1961) and to the total transport of the Indonesian Throughflow (Wyrski, 1961; Yaremchuk & Qu, 2004). Continuous high-resolution records from corals, relating to the behavior and drivers of the KI are thus critical for evaluating long-term histories and future trends in regional climate variability.

Massive corals, especially of the genus *Porites*, are excellent recorders of high-resolution climate variability. Isotopes and trace metals, incorporated in coral aragonite (CaCO₃) skeleton, serve as indicators of past seawater properties

such as sea surface temperature (SST) and sea surface salinity (SSS) (Dunbar & Cole, 1999; Felis & Patzold, 2004; Gagan et al., 2000; Lough, 2010), as well as changes in ocean circulation patterns (Druffel, 1997a; Druffel & Griffin, 1993; Grottoli & Eakin, 2007). Annual banding identified in x-radiographs, acts as time markers, allowing for precise dating and sampling with bi-weekly to monthly resolution (Knutson et al., 1972; Lough, 2010; Weber et al., 1975). As massive corals are long-lived, they have the potential to generate multi-decadal to multi-centennial climate records, providing a tool to further assess future changes (Gagan et al., 2000; Lough, 2010).

The goals of this thesis are: 1) to investigate Sr/Ca (SST) and $\delta^{18}\text{O}$ (SST and/or SSS) proxies in corals collected from either side of the Luzon Strait, including an assessment of the paleo-utility of a slow-growing massive coral, *Diploastrea heliopora*; 2) to identify drivers of long-term changes in SST and SSS across the strait; and 3) to use coral $\Delta^{14}\text{C}$ to generate coral-based records of the Kuroshio transport across the strait and identify its driving mechanisms. The following subsections present a general overview of the current state of our knowledge regarding Kuroshio Intrusion variability and its drivers, and the resources and steps undertaken during the course of this research. Further details are discussed in the subsequent chapters.

Figure 1.1. The Luzon Strait located between southern Taiwan and northern Luzon, Philippines is the widest and deepest connection between the west Pacific Ocean and the SCS. Blue dashed line is a simplified schematic of the Kuroshio Intrusion path across the strait (modified from Caruso et al., 2006). Colors represent average salinity (Simple Ocean Data Assimilation – SODA, (Carton & Giese, 2008) between 1970 and 2010. Contour interval (black dotted lines) is 0.2 psu. (SODA Data source: http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4).

1.2 Overview of the Kuroshio Intrusion across the Luzon Strait and its drivers

Approximately 350 km wide with a sill depth of ~2500 m, the Luzon Strait is the widest and deepest channel connecting the SCS and the western Pacific Ocean (Chen et al., 2015; Jia & Chassignet, 2011; Liang et al., 2008; Metzger & Hurlburt, 2001; Peñaflor et al., 2007) (Fig. 1.1). Heat, salt and nutrients are exchanged across the strait, impacting marine ecology, climate and

circulation in the region (Caruso et al., 2006; Du et al., 2013; Hu et al., 2015; Nan et al., 2015; Qu et al., 2004; Xue et al., 2004).

Intermittent measurements of the water exchange across the strait reveal a spatially variable structure of the Luzon Strait transport (LST). Vertical profiles of the mean LST show that the upper (i.e. <500 m) and deep (i.e. 1500 m) layers flow into the SCS while the middle layer (i.e. 500 to 1500 m) flows out to the western Pacific (Nan et al., 2015; Qu et al., 2006; Qu et al., 2000; Shaw & Chao, 1994; Tian et al., 2006). In the upper layers, inflow to the SCS is commonly observed across the southern Luzon Strait (i.e. 19.5°N to 21°N), while outflow is detected across the northern end (i.e. north of 21°N, Chen et al., 2011; Hsin et al., 2012; Liang et al., 2008; Xue et al., 2004). The net flow into the SCS varies between 3 and 6.5 Sverdrups ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) annually (Nan et al., 2015 and references therein).

1.2.1 Seasonal variation of the KI into the SCS

The KI into the SCS varies in response to the reversing monsoon winds. Maximum intrusions of 2.75 to 13.7 Sv occur during winter when the northeast monsoon prevails (Centurioni et al., 2004; Metzger & Hurlburt, 1996; Nan et al., 2015; Qu et al., 2000; Wyrski, 1961; Yaremchuk & Qu, 2004). Conversely, minimal outflows of 0.2 to 2.75 Sv are commonly observed during summer when the southwest monsoon dominates (Centurioni et al., 2004; Metzger & Hurlburt, 1996; Nan et al., 2015; Qu et al., 2000; Wyrski, 1961; Yaremchuk & Qu, 2004). Model-derived LST estimates between seasons (i.e. 3.1 to 12.2 Sv and 0.7 to 8.2

Sv for winters and summers, respectively) confirm its strong link with the monsoons (e.g. Hsin et al., 2012; Nan et al., 2015) though the magnitude tends to be greater as a consequence of varying model assumptions. The path of the intrusion depending on the season also supports the difference in magnitude between seasons (Nan et al., 2011; Wu & Chiang, 2007). The probability of the looping path occurring during winter is higher, delivering more Pacific waters into the strait. In contrast, the KI leaping path occurs more frequently during summer (Nan et al., 2011; 2015).

1.2.2 Interannual variation of the KI into the SCS

Compared to seasonal LST variation, interannual variability and its controlling mechanisms are less understood due to the scarcity of continuous on-site observations (Nan et al., 2015; Wu, 2013). Numerical models show that the El Niño-Southern Oscillation (ENSO) influences the LST by means of shifting the position of the North Equatorial Current (NEC) bifurcation latitude (Qu et al., 2004) (Fig. 1.2). During El Niño years, a positive wind stress curl anomaly over the North Pacific tropical gyre results in a negative sea surface height anomaly that pushes the bifurcation latitude northward, leading to a weaker KC east of Luzon and Taiwan and enhancing the intrusion into the SCS (Gordon et al., 2014; Kim et al., 2004; Qiu & Chen, 2010; Qu & Lukas, 2003). The situation then reverses for La Niña periods. However, more recent numerical evidence shows that the mean flow across the strait is strongly linked to the Pacific Decadal Oscillation (PDO) and not ENSO (e.g. Nan et al., 2016; Wu, 2013; Wu et al.,

2016). Similar to ENSO-related wind forcing, PDO-driven anomalous cyclonic winds off the Philippine Sea induce northward (southward) NEC bifurcation during warm (cold) PDO phases, leading to enhanced (reduced) KI (Wu, 2013; Wu et al., 2016). Another study highlights the role of long-term changes in oceanic pressure gradients on the reduction of KI across the strait in the recent decades (e.g. Nan et al., 2013). Whether the intrusion is linked with the ENSO or PDO and driven by the local and large-scale wind forcing or pressure differences across the strait still remains a subject of disagreement (Nan et al., 2015).

Figure 1.2. Time-series of the mean position of the North Equatorial Current (NEC) bifurcation latitude (Qiu & Chen, 2010). Blue and black lines are the monthly and low-pass (annual) filtered time-series, respectively. Dashed gray line indicate the average NEC bifurcation latitude from 1960 to 2010.

ENSO and PDO for the most part, only explain the impact of local and large-scale wind forcing to the inter-annual variability of the KI. Apart from the wind, other factors such as the inter-basin pressure gradient (e.g. Metzger & Hurlburt, 1996; Qu et al., 2000), β -effect (e.g. Nan et al., 2015; Stommel & Arons, 1960) and eddy activity (e.g. Nan et al., 2015; Sheu et al., 2010; Yang et

al., 2013) also contribute to the Kuroshio intruding process, making the list of mechanisms and their interactions more complex (Nan et al., 2015). While direct measurements, satellite data and numerical models have advanced our present-day knowledge of water exchanges across the Luzon Strait, there is still a need for continuous interannual to multidecadal on-site records relating to the behavior and drivers of the Kuroshio intruding process. This information is critical for evaluating long-term histories and future trends in regional climate variability

1.3 Regional Climate

1.3.1 El Niño-Southern Oscillation (ENSO)

El Niño and the Southern Oscillation are periodic oscillations in SST and sea level pressure, respectively, associated with weakening and strengthening of the easterly trade winds across the equatorial Pacific Ocean (Wang et al., 2016). This self-sustained or stochastically forced coupled ocean-atmosphere system strongly drives global climate variability at interannual timescales (Philander & Fedorov, 2003; Wang et al., 2016). In normal conditions (Fig. 1.3), easterly winds along the equator drive warm surface waters towards the western Pacific region along with centers of atmospheric convection and rainfall while upwelling of cooler subsurface waters concurrently occurs in the eastern equatorial Pacific (Wang et al., 2016). During El Niño events (Fig. 1.3), trade winds associated with the Walker circulation weaken or reverse, extending the warm pool area towards the central and eastern tropical Pacific Ocean. Consequently, the western Indo-Pacific region experiences droughts while central and east Pacific experience

above normal rainfall conditions (Rasmusson & Carpenter, 1983; Ropelewski & Halpert, 1987). Conversely, during La Niña periods (Fig. 1.3), stronger trade winds and Walker Circulation results to greater convection over the western Pacific. SSTs in the central and east Pacific, on the other hand, are cooler as the thermocline shoals and upwelling intensifies during this period. Therefore, swings between El Niño and La Niña can induce severe droughts and floods across the Indo-Pacific region (Fig. 1.3).

Figure 1.3. Schematic diagram of the different ENSO phases: normal (top), El Niño (middle), and La Niña (bottom) phases. (Figure source: <http://www.bom.gov.au/climate/enso/history/ln-2010-12/three-phases-of-ENSO.shtml>).

Several indices have been developed to monitor ENSO mostly based on SST anomalies. Two of the most frequently used ENSO indices are the Niño 3.4 index and the Southern Oscillation Index (SOI) (Fig. 1.4). Niño 3.4 index

represents the average equatorial Pacific SSTs within 5°N to 5°S and 170°W to 120°W (Trenberth and Hoar, 1997). The index typically uses a 5-month running mean and individual El Niño/La Niña events are defined when SSTs exceed 0.4°C over a period of 6 months or more. SOI, on the other hand, is based on large scale air pressure differences across the Pacific (i.e. Tahiti minus Darwin) that changes in conjunction with the ENSO phases (Chen, 1982; Trenberth, 1984). These indices only span a few decades to up to a century, therefore elucidating ENSO variability at different time windows from the Holocene to the most recent centuries has often been a target of paleoclimate research. Paleoclimate evidence indicates that ENSO mean states have switched from La Niña-like conditions earlier in the past millennium to El Niño-like conditions in the 17th century (e.g. Cobb, 2002; Cobb et al., 2003; Jones, 2004). Throughout the Holocene, ENSO is suggested to be highly variable contrary to its expected response to solar insolation (Cobb et al., 2013). Coral-based SST reconstructions spanning the last 400 years in the western Pacific indicates that while 20th century warming is unprecedented, there is no clear evidence whether anthropogenic warming, or even natural forcings, can alter ENSO activity (Tierney et al., 2015). However, the Intergovernmental Panel on Climate Change (IPCC) identifies an El Niño-like future mean state despite any change in the average background conditions (Meehl et al., 2007; Christensen et al., 2013). These differences in future ENSO projections highlight the importance of generating multi-century high-fidelity paleorecords of ENSO variability.

Figure 1.4. (a) Niño 3.4 index from 1870 to present and (b) SOI from 1950 to present. Note that the SOI index is inverted to facilitate comparison between individual ENSO events. Red (blue) indicates El Niño (La Niña) years. (*Data source:* <https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni>; <https://climatedataguide.ucar.edu/climate-data/southern-oscillation-indices-signal-noise-and-tahitidarwin-slp-soi>).

1.3.2 Pacific Decadal Oscillation (PDO)

The PDO is the dominant mode of SST anomalies over the North Pacific poleward of 20°N at decadal timescales (Mantua & Hare, 2002; Mantua et al., 1997). It is often described as a long-lived ENSO-like pattern of Pacific climate variability (Deser et al., 2004; Mantua & Hare, 2002). A positive PDO is associated with warmer SSTs across the central and eastern tropical Pacific and colder anomalies in the western and central North Pacific, resembling SST anomaly patterns of ENSO (Deser et al., 2004; Mantua & Hare, 2002; Newman et al., 2016, Fig. 1.5). The key distinction between the PDO and ENSO is their

timescales: the PDO persists for multidecadal intervals (i.e. 20 to 30 years, Fig. 1.6) while ENSO persists every 2 to 7 years (Mantua & Hare, 2002; Mantua et al., 1997, Fig. 1.4).

Figure 1.5. Similarity in spatial structure of SST anomalies between the (a) PDO warm phase and (b) ENSO warm phase (El Niño). Cool (warm) colors represent cooler (warmer) SST anomalies. (Figure source: <https://climatedataguide.ucar.edu/climate-data/pacific-decadal-oscillation-pdo-definition-and-indices>).

Unlike ENSO, the driving mechanisms of the PDO remain complex and less understood (Mantua & Hare, 2002). This is due to the different atmospheric and oceanographic forcings of various timescales spanning the extratropical and tropical Pacific that contribute to PDO variability (Newman et al., 2016). The strength of the Aleutian Low, persistent oceanic memory closely dependent on ENSO-SST anomalies in the tropics and the Kuroshio Current system act in

unison to drive the spatial pattern of the PDO (Newman et al., 2016). As the varying influences change with time, so does the resultant SST pattern (Deser et al., 2004; Newman et al., 2016). Therefore, documenting and distinguishing the different processes that contribute to PDO variability is critical in understanding its long-term variability and predictability in the future (Newman et al., 2016).

Figure 1.6. The PDO index from 1900 to present. Red (blue) indicates warm/positive (cold/negative) phases. (Data source: <http://jisao.washington.edu/pdo/PDO.latest>).

1.3.3 East Asian Monsoon (EAM) system

The EAM system is one of the dominant climate features in Asia, including the SCS (Wang & Li, 2009). It is characterized by seasonally reversing winds driven by the unequal heating between the Pacific Ocean and the East Asian continent (Ha et al., 2012). During boreal summer, the East Asian landmass rapidly heats up relative to the surrounding seas, generating a pressure difference between the land (low pressure) and ocean (high pressure). This pressure gradient drives the East Asian Summer Monsoon (EASM) that induces

high rainfall conditions in East China and the surrounding region (Chen et al., 2004; Yihui & Chan, 2005). During boreal winter, on the other hand, colder landmass relative to the surrounding seas generate a pressure difference between Siberia (i.e. Siberian High) and the Aleutian seas (i.e. Aleutian Low), driving the East Asian Winter Monsoon (EAWM) winds (Wang & Chen, 2014; Wen et al., 2000). The EAWM is more intense and has more profound societal and economic impacts than the EASM, but more studies focus on understanding the latter (Ha et al., 2012). Cold air temperature can extend towards the SCS and the Maritime Continent, accompanied with intensified winter monsoon rains over the western Pacific, the SCS and the Maritime Continent (Wang & Chen, 2014, Fig. 1.7). Intense cyclones and severe snowstorms may also occur in East Asia, Korea and Japan during this period (Ha et al., 2012).

Figure 1.7. (a) Precipitation and (b) surface air temperature differences between strong EAWM conditions. Figure is adapted from (Wang & Chen, 2014).

The mean surface transport across the Luzon Strait, associated with the Kuroshio Intrusion, and the surface circulation in the SCS are also strongly

dependent on the Asian monsoon system. During winter, the prevailing northeast winds drive surface water flow westward across the strait (Centurioni et al., 2004; Hsin et al., 2012; Metzger & Hurlburt, 1996; Qu et al., 2004; Qu et al., 2000; Yaremchuk & Qu, 2004). The surface circulation in the SCS is cyclonic (anticyclonic) during the northeast (southwest) monsoon season (Wang & Li, 2009).

Indices of the EAWM and EASM (e.g. D'Arrigo et al., 2005; Li & Zeng, 2005, Fig. 1.8), based on zonal sea level pressure gradients, reveal interannual to decadal variability hypothesized to be influenced by both the ENSO and the PDO. In general, the EAM is weaker during El Niño events (Li, 1990; Zhang et al., 1996). Strengthening of the EAM due to La Niña, in contrast does not always hold true (Zhang et al., 1996). Other studies have suggested that the relationship between the monsoons (i.e. EAWM) and ENSO is modulated by the PDO. When ENSO and the PDO are in phase (i.e. El Niño and positive PDO phase and La Niña and negative PDO phase combine), the negative relationship between the EAWM and ENSO is stronger compared to when ENSO and the PDO are out of phase (Kim et al., 2014). In contrast, the relationship was found absent between ENSO and EAWM during warm PDO phases (Wang et al., 2008). This discrepancy may be due to methodical differences in calculating or defining the monsoon indices, which are highly variable (e.g. Kim et al., 2017; Wang & Chen, 2014) compared to the more established and widely used PDO and ENSO indices. Nonetheless, the time-varying response of the EAM to ENSO and/or the

PDO may be real and thus, understanding its forcings are crucial towards its predictability.

Figure 1.8. (a) The EAWM index from 1970 to present (D'Arrigo et al., 2005) and EASM index from 1950 to present (Li & Zeng, 2005). Positive (red) and negative (blue) anomalies indicate strong and weak monsoon, respectively.

1.4 Corals as climate archives

Massive corals provide a means to extend climate data beyond the availability of instrumental records and influence of anthropogenic causes. *Porites* sp. corals are the most targeted coral species for paleoclimate studies in the tropical Indo-Pacific region (Dunbar & Cole, 1999; Gagan et al., 2000; Sadler et al., 2014). Their rapid growth ($\sim 1 \text{ cm yr}^{-1}$) and massive forms allow for sub-seasonal to annual sampling resolution providing climate records of several decades up to centuries, making them an ideal climate archive. Two of the most extensively used geochemical tracers are Sr/Ca and $\delta^{18}\text{O}$ (Druffel, 1997a; Dunbar

& Cole, 1999; Eakin & Grottoli, 2006), generating SST and SSS records. Another coral-derived proxy is radiocarbon ($\Delta^{14}\text{C}$) that provides a record of surface ocean processes including upwelling (Druffel, 1997a, 1997b; Grottoli & Eakin, 2007). The following sections provide an overview of the utility and limitations of these geochemical proxies.

Porites-based climate reconstructions are restricted to the last several decades with few ($n < 20$) extending beyond the past 200 years (Tierney et al., 2015). Several coral species outside the genus *Porites* have been tapped as an alternative resource for paleoclimate studies. One alternate resource is the massive *Diploastrea heliopora*, commonly found in the Indo-Pacific region (Veron, 2000). The paleo-utility of this coral species lies in its slow growth (2 to 6 mm yr⁻¹), potentially generating 2 to 3 times the temporal coverage of a similar sized *Porites* core (Bagnato et al., 2004; Dassié & Linsley, 2015; Sadler et al., 2014; Watanabe et al., 2003; Damassa et al., 2006; Cantin et al., 2010); its dense skeletons that are resistant to marine grazers and burrowers, supporting a long life span (i.e. > 800 years, Bagnato et al., 2004) and its monospecific nature, potentially eliminating inter-specific offsets in geochemical variations (e.g. Grottoli, 1999; Watanabe et al., 2003). However, due to *Diploastrea*'s low extension rates and unique skeletal architecture, a few considerations must be made in sampling and interpreting geochemical data based on this coral species, that are not necessarily applicable to faster growing *Porites* corals as explained in Chapter 2. Lower extension rates (i.e. 4 to 6 mm yr⁻¹, e.g. Goodkin et al., 2005; Dassié & Linsley, 2015; Watanabe et al., 2013) may enhance kinetic effects (e.g.

McConnaughey, 1989a, 1989b) that may impact the validity of the *Diploastrea* geochemical data. Preferential enrichment of $\delta^{18}\text{O}$ in slow-growing corals, for example, may lead to $<2^\circ\text{C}$ SST difference relative to estimates derived from an adjacent *Porites* coral (Watanabe et al., 2003). Examining for growth rate effects is thus critical in evaluating the fidelity of the geochemical record (Bagnato et al., 2004; Dassié & Linsley, 2015; Goodkin et al., 2007; Goodkin et al., 2005; Watanabe et al., 2003). The skeletal structure of the corallites in *Diploastrea* also requires careful sampling techniques to maximize the quality of the geochemical data. Restricted sampling along the *columella*, a straight mesh-like structure in the center of a corallite, at 0.5 mm intervals for a growth rate of $\sim 4 \text{ mm yr}^{-1}$ (e.g. Dassié & Linsley, 2015), minimizes sampling artifacts and maximizes temporal resolution. Nonetheless, reproducibility between adjacent colonies of *Porites* and *Diploastrea* is remarkable (Bagnato et al., 2004; Dassié & Linsley, 2015; Watanabe et al., 2003), promoting its potential in improving long-term *Porites*-based climate reconstructions.

1.4.1 Sr/Ca as a sea surface temperature proxy

The ratio of strontium to calcium in coral aragonite skeletons is an established paleothermometer for several decades (Alibert & McCulloch, 1997; Beck et al., 1992; Smith et al., 1979; Weber, 1973). Cooler SSTs result in an increased Sr/Ca (and vice versa) as greater amounts of Sr^{2+} ions from the surrounding seawater substitute for Ca^{2+} in the coral aragonite crystal lattice (Weber, 1973; Smith et al., 1979; Corrège, 2006; Gaetani & Cohen, 2006).

Compared to $\delta^{18}\text{O}$ (discussed below), Sr/Ca allows for an independent SST reconstruction without the influence of any hydrological effects (i.e. evaporation-precipitation) thus, SST records based on Sr/Ca are more advantageous. However, some unresolved issues remain regarding Sr/Ca proxy validity. SST reconstructions based on coral Sr/Ca show 2°C to 4°C cooler estimates compared to other marine proxy-derived SST estimates over glacial cycles (Corrège, 2006; Quinn & Sampson, 2002). Sr/Ca-SST slopes (and intercepts) also vary widely (i.e. 0.03 to 0.08 mmol mol⁻¹ C⁻¹; Alibert & McCulloch, 1997; Corrège, 2006; Murty et al., 2018) depending on species and/or location (i.e. upwelling and other local effects, e.g. de Villiers et al., 1994; Goodkin et al., 2007; Murty et al., 2018; Shen et al., 1996). Non-SST related growth rate effects (i.e. slow-growing corals) can also influence monthly Sr/Ca-SST calibrations (e.g. Bagnato et al., 2004; Dassié & Linsley, 2015; Goodkin et al., 2007; Goodkin et al., 2005; Watanabe et al., 2003). These issues underscore the importance of investigating the applicability of Sr/Ca-SST proxy at a particular site including assessments of growth rate effects at inter-annual periods. This thesis presents high-resolution Sr/Ca records derived from fast and slow-growing corals, *Porites* and *Diploastrea*, respectively, to examine Sr/Ca-SST applicability across the Luzon Strait in the last ~230 years (Chapters 3 and 4).

1.4.2 $\delta^{18}\text{O}$ as a combined sea surface temperature and salinity proxy

Coral $\delta^{18}\text{O}$ is both sensitive to changes in SST and the $\delta^{18}\text{O}$ of the seawater as a function of hydrology (i.e. evaporation and precipitation, runoff

and water advection, e.g. Dassié & Linsley, 2015; Dunbar & Wellington, 1981; Gagan et al., 1994; Linsley et al., 2004; Lough, 2010). In regions where seasonal changes in SST are relatively larger, SST may have a stronger influence on the coral $\delta^{18}\text{O}$ signal. The coral $\delta^{18}\text{O}$ -SST relationship exhibits a range of slopes, from -0.15 to -0.21‰ °C⁻¹ (e.g. Grottoli & Eakin, 2007; Leder et al., 1996; Watanabe et al., 2003), that is dependent on coral species, growth rates, skeletal architecture, and/or location (e.g. McConnaughey, 1989a, 1989b) much like the coral Sr/Ca-SST proxy. Nearer the equator where seasonal SST changes are relatively small, coral $\delta^{18}\text{O}$ may better track fluctuations in seawater $\delta^{18}\text{O}$ variability due to hydrological changes (e.g. Linsley et al., 2017; Murty et al., 2017; Tudhope et al., 1995). Measured in tandem with coral Sr/Ca, Sr/Ca measurements also allow for isolating the $\delta^{18}\text{O}$ -SST contribution and deriving the residual seawater $\delta^{18}\text{O}$ which is a function of salinity (Corrège, 2006) and references therein). Independent reconstructions of SST and salinity have proven vital in assessing tropical climate variability under the recent warming period (e.g. Nurhati et al., 2009; Tierney et al., 2015). This thesis uses paired Sr/Ca- $\delta^{18}\text{O}$ records from two sites at either side of the Luzon Strait, to elucidate climatic controls on surface salinity (i.e. changes in hydrological balance and/or water advection due to Kuroshio transport variability) across the strait (Chapters 3 and 4).

1.4.3 Radiocarbon ($\Delta^{14}\text{C}$) as a tracer of ocean circulation

Radiocarbon (^{14}C) is naturally produced in the upper atmosphere through the collision of cosmic ray neutrons and ^{14}N (Anderson et al., 1947; (Broecker, 2014). The resultant ^{14}C rapidly oxidizes to $^{14}\text{CO}_2$ gas and is distributed in the Earth's carbon reservoirs.

In the surface ocean, atmospheric ^{14}C is incorporated into seawater and becomes part of the dissolved inorganic carbon (DIC) pool with a $\Delta^{14}\text{C}_{\text{DICsw}}$ that is lower than that in the atmosphere. Relative to the surface, deeper waters have lower $\Delta^{14}\text{C}$ values because of isolation from the atmosphere and subsequent radioactive decay. Consequently, upwelling or vertical mixing introduces older and deeper water to the surface resulting in an overall lowering of $\Delta^{14}\text{C}_{\text{DICsw}}$ values. During the late 1950s and early 1960s, thermonuclear bomb testing increased the difference between the surface and deep ocean $\Delta^{14}\text{C}$ values by $\sim 1000\%$ (Broecker et al., 1985), making ^{14}C a more sensitive tracer of ocean circulation and mixing (Broecker, 2014; Grottoli & Eakin, 2007).

Corals incorporate calcium and DIC in seawater for the production of aragonite (CaCO_3), hence changes in the $\Delta^{14}\text{C}_{\text{DICsw}}$ through time are proportional in the CaCO_3 skeleton of the corals (Druffel, 1997a; Grottoli & Eakin, 2007). Seasonal to decadal-scale changes in surface and subsurface circulation can thus be retrieved from annual banded coral skeletons (Druffel, 1987, 1989, 1996; Druffel et al., 2014; Gagan et al., 2000). Relative to other coral proxy records, $\Delta^{14}\text{C}_{\text{coral}}$ is not affected by biological process, thus providing a conservative tracer of ocean circulation (Dunbar & Cole, 1999). This thesis utilizes coral $\Delta^{14}\text{C}$

records derived from either side of the Luzon Strait, along with previously published coral $\Delta^{14}\text{C}$ records in the region (i.e. western Pacific Ocean, SCS, Indonesian Throughflow), to examine the interaction of western Pacific Ocean and the SCS across the strait and its drivers (Chapter 5).

1.5 Thesis structure

In this thesis, up to two-century long records of SST and SSS histories based on paired *Porites* Sr/Ca and $\delta^{18}\text{O}$, including that of a *Diploastrea heliopora* core, were generated to investigate the climatic and oceanographic changes across the Luzon Strait, the main conduit between the Pacific Ocean and the SCS.

Chapter 2 evaluates the reliability of a slow-growing coral *Diploastrea heliopora* against a nearby *Porites lobata* coral, both collected from Palau, northeastern Philippines – located at the southern end of the Luzon Strait. The evaluation is based on monthly-resolved Sr/Ca and $\delta^{18}\text{O}$ records from each coral core covering the period 1955 to 2012. The similarity in climate sensitivity between *Diploastrea* and *Porites* further strengthens the evidence for *Diploastrea* as an alternate Indo-Pacific climate archive. Moreover, the Palau corals' sensitivity to both the PDO and the ENSO is established in this chapter, providing a basis to further evaluate PDO-related variability in the region.

Chapter 3 investigates the long-term SST and SSS variability in Palau using paired *Porites* Sr/Ca and $\delta^{18}\text{O}$ records extending back to the late 19th century, building upon the results in Chapter 2. Climatic drivers across time frequencies including anthropogenic influences are further examined in this

chapter. The potential impacts of PDO-related variability on the tropical western Pacific climate are also identified.

Chapter 4 evaluates the reliability of paired *Porites* Sr/Ca and $\delta^{18}\text{O}$ records generated from Houbihu, southern Taiwan – located at the northern end of the Luzon Strait. The Houbihu wintertime Sr/Ca and $\delta^{18}\text{O}$ calibrations are robust, allowing for reconstruction of SST and SSS conditions extending at the end of the Little Ice Age (LIA). PDO-related variability in KI is evaluated in this chapter, building upon the results in Chapter 3. The influence of the EAWM is additionally evident in this chapter, proving to be another critical driver in regional climate variability.

Chapter 5 focuses on the interannual coral $\Delta^{14}\text{C}$ records generated on both Luzon Strait corals. Interannual $\Delta^{14}\text{C}$ differences between our sites and other $\Delta^{14}\text{C}$ records in the region reveal basin-specific process controlling ocean circulation, corroborating findings from the previous chapters. At this timescale, the dominant control of ENSO on the KI and associated transport across the strait is revealed.

1.6 References

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Chapter 2

***Diploastrea heliopora* Sr/Ca and $\delta^{18}\text{O}$ records from northeast Luzon, Philippines: an assessment of inter-species coral proxy calibrations and climate controls of sea surface temperature and salinity**

Ramos, R. D., N. F. Goodkin, F. P. Siringan, and K. A. Huguen (2017), *Diploastrea heliopora* Sr/Ca and $\delta^{18}\text{O}$ records from northeast Luzon, Philippines: an assessment of inter-species coral proxy calibrations and climate controls of sea surface temperature and salinity, *Paleoceanography* 32, 424-438. doi:10.1002/2017PA003098.

Abstract

The Indo-Pacific coral *Diploastrea heliopora* reveals regional multi-decadal to centennial scale climate variability using coral carbonate $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_\text{c}$) as a combined proxy for sea surface temperature (SST) and sea surface salinity (SSS). However, to assess the coral's full potential in resolving climatic events, an independent SST proxy would be more advantageous. We examined both Sr/Ca and $\delta^{18}\text{O}$ of *Diploastrea* against an adjacent *Porites lobata* core collected from northeast Luzon, Philippines. Winter Sr/Ca data from *Diploastrea* show a significant correlation to SST ($r = -0.41$, $p < 0.05$, RMSR = 0.81°C) and provide

a proxy with similar sensitivity as *Porites* ($r = -0.57$, $p < 0.05$, RMSR = 0.62°C). An inter-species SST record is shown to be robust and used for a reconstruction of the Pacific Decadal Oscillation (PDO) during boreal winter ($r = -0.70$, $p = 0.02$). While we were unable to generate a robust *Diploastrea* $\delta^{18}\text{O}$ -SSS calibration at inter-annual timescale, the freshening trend towards the present, commonly observed in the region, is qualitatively captured in *Diploastrea* $\delta^{18}\text{O}$. Comparison with *Porites* $\delta^{18}\text{O}$ and instrumental SSS records shows that the magnitude of freshening is consistent between coral species. Wet and dry season *Porites* $\delta^{18}\text{O}$ provide support for the relative influence of El Niño-Southern Oscillation (ENSO) events and local precipitation to SSS variability at our site. The multi-proxy, multi-species approach of this study further strengthens the evidence for *Diploastrea* as an alternate climate archive in the Indo-Pacific region, and seals its potential in helping resolve less understood global-scale climate phenomena.

2.1 Introduction

The relatively short length of observational climate records particularly in the tropics, limits our understanding of the natural drivers of long-term climate variability and our ability to constrain future changes (Gagan et al., 2000; Lough, 2004; 2010). Paleoclimate proxy reconstructions provide a means to extend climate data prior to both instrumental records and anthropogenic influences (Dunbar and Cole, 1999; Gagan et al., 2000).

Tropical massive corals are a key source of paleoclimate records (Dunbar

and Cole, 1999; Gagan et al., 2000; Felis and Patzold, 2004; Lough, 2010). Coral skeletons incorporate isotopic and geochemical tracers, which vary based on the environment, allowing for sub-annual reconstruction of climate parameters such as sea surface temperature (SST) and salinity (SSS) (Dunbar and Cole, 1999; Gagan et al., 2000). Visible banding in coral x-radiographs reflect changes in climate systems including El Niño-Southern Oscillation (ENSO), Asian Monsoon and ocean circulation (Druffel, 1997; Dunbar and Cole, 1999; Gagan et al., 2000; Felis and Patzold, 2004; Grottoli and Eakin, 2007).

Two of the most extensively used geochemical tracers are the ratios of Sr/Ca and $\delta^{18}\text{O}$ (Druffel, 1997; Dunbar and Cole, 1999; Eakin and Grottoli, 2006). Coral Sr/Ca is an exceptional paleothermometer where the elemental ratio of strontium-to-calcium is inversely related to the SST in which a coral grew (Smith et al., 1979; Beck et al., 1992; Alibert and McCulloch, 1997). Coral $\delta^{18}\text{O}$ is influenced by both SST variations and the $\delta^{18}\text{O}$ of the ambient seawater, which is a function of the hydrological balance between evaporation, precipitation, runoff and water mass advection (Dunbar and Wellington, 1981; Gagan et al., 1994; Linsley et al., 2004; Lough, 2010; Dassié et al., 2014). Sr/Ca and $\delta^{18}\text{O}$ measurements when combined allow for isolation of SSS (e.g. Gagan et al., 1998; Hendy et al., 2002; Ren et al., 2003; Correge et al., 2004; Kilbourne et al., 2004; Linsley et al., 2004; Shen et al., 2005; Cahyarini et al., 2008; Felis et al., 2009; Nurhati et al., 2011).

Porites spp. are the most targeted massive coral for reconstructing climate variability (e.g. Dunbar and Cole, 1999; Gagan et al., 2000; Sadler et al., 2014).

However, few ($n < 20$) *Porites*-based proxy records extend beyond the past 200 years in the Indo-Pacific (Gagan et al., 2000; Lough, 2004; 2010; Corrège, 2006; Grottoli and Eakin, 2007; Tierney et al., 2015). In addition, most of these records are based on a single core where non-climatic influences such as vital and kinetic effects or bleaching events may be difficult to detect and may compromise the quality of the geochemical record (McConnaughey, 1989b; Lough, 2004; 2010; Suzuki et al., 2003). Hence, replication of coral geochemical records is important in discriminating localized non-climatic influences from regional climatic signals (Lough et al., 2004; DeLong et al., 2007; Dassié et al., 2014).

Diploastrea heliopora, common in the Indo-Pacific region (Veron, 2000), offers an alternative resource for paleoclimate studies. Due to extension rates of 2 to 6 mm/year, roughly half that of *Porites lobata*, *Diploastrea* cores contain approximately two to three times longer temporal coverage than a similarly-sized *Porites* core (Watanabe et al., 2003; Bagnato et al., 2004; 2005). *Diploastrea*'s dense skeletons are resistant to boring organisms, grazing fish and damaging crown-of-thorns starfish (Veron, 2000) supporting a longer life span (i.e. >800 years, Bagnato et al., 2004). Limited studies on *Diploastrea* have demonstrated high reproducibility relative to a *Porites* collected at the same site and across study sites within the same geographic region (e.g. cores collected at New Caledonia and Alor, Indonesia (Watanabe et al., 2003) and cores collected at Fiji Islands (Bagnato et al., 2004; Dassié and Linsley, 2015). Therefore, utilizing *Diploastrea* as a climate archive to replicate and extend *Porites*-based records will help improve reconstructions of long-term regional climate variability.

Inherent to *Diploastrea*'s slow extension rates and complicated skeletal architecture are concerns regarding the reliability of its geochemical records. Kinetic effects were observed in offsets between the coral $\delta^{18}\text{O}$ records of *Diploastrea* and *Porites* (Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015). For example, kinetic isotope disequilibrium models predict that slow growing corals should reach close to isotopic equilibrium, and thus have preferential enrichment of ^{18}O compared to fast-growing corals (McConnaughey, 1989a; 1989b). Absolute values of *Diploastrea* $\delta^{18}\text{O}$ are consistently enriched compared to those of *Porites* with the offset equivalent to about $\sim 1.69^\circ\text{C}$ (Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015). However, the mean $\delta^{18}\text{O}$ offset was considered small, likely because while extension is slow, *Diploastrea* has high calcification rates leading to high skeletal bulk density (Watanabe et al., 2003). Consequently, recognition of kinetic effects is crucial in evaluating the accuracy of isotopic reconstructions (McConnaughey, 1989a; Guilderson and Schrag, 1999).

Another factor that may influence the geochemistry of corals is skeletal architecture. *Diploastrea* corallites have a straight inner mesh-like structure called the *columella*, surrounded by denser teeth-like radial structures called the *septa*. Based on previous studies, isotopic offsets from simultaneous subsampling of both *columella* and *septa* could reach up to 0.5‰ difference which may lead to erroneous climate reconstructions as these skeletal materials are deposited at different times throughout their growth (Watanabe et al., 2003; Bagnato et al., 2004; Damassa et al., 2006). Experiments on subsampling

Diploastrea exclusively on either part favored reconstructions from the *columella* as it yielded more robust inter-annual records (Watanabe et al., 2003; Bagnato et al., 2004; Damassa et al., 2006). Exclusive sampling of the *columella* at 0.5 mm intervals to yield bi-monthly records was found to be the optimal temporal resolution given their growth rates of ~ 4 mm/year, enough to capture the full annual $\delta^{18}\text{O}$ cycle and minimizing the effects of any sampling artifacts introduced either by the coral's intricate skeletal architecture or slow extension (Dassié and Linsley, 2015).

While the above challenges in sampling *Diploastrea* are well constrained for its $\delta^{18}\text{O}$ records, the reliability of its Sr/Ca composition has not been thoroughly investigated. Here, we further investigate the paleo-utility of both Sr/Ca and $\delta^{18}\text{O}$ proxies in *Diploastrea* relative to an adjacent *Porites*, to evaluate the coral's ability to reconstruct regional climate behavior.

2.2 Coral sampling and analytical methods

2.2.1 Core sites and sampling

Palaui Island (18.54°N, 122.15°E) lies along the northeastern coast of the Philippines facing the Pacific Ocean (Fig. 2.1). The island is surrounded by warm waters and receives rainfall throughout the year. Based on satellite-derived data products (See section 2.2.3 for details), the average annual SST range here is 27.4°C to 28.8°C. The average annual rainfall is ~ 2000 mm (Philippine Atmospheric, Geophysical and Astronomical Services Administration, PAGASA) whereas the mean annual salinity ranges from 33.9 to 34.7 psu. At

seasonal timescales, the amount of rainfall is controlled by the direction of the dominant monsoon winds, such that northeasterly (southeasterly) monsoon winds, prevailing during boreal winter (summer), bring in dry (wet) conditions (Chang et al., 2005). At inter-annual and decadal timescales, temperature and rainfall variability is primarily controlled by ENSO- and Pacific Decadal Oscillation (PDO)-related changes in the temperature, position and size of the Indo-Pacific Warm Pool (Yan et al., 1992; Gagan et al., 2000; Lin et al., 2013).

Figure 2.1. Coral colonies of *Diploastrea heliopora* and *Porites lobata*, approximately 2 km apart, were collected off the coast of Palaui Island in May 2012. Palaui island lies along the northeastern coast of the Philippines facing the Pacific Ocean (inset).

Vertical cores of *Diploastrea heliopora* and *Porites lobata*, approximately 2 km apart, were collected from 4 to 5 m water depth off the coast

of Palau Islands in May 2012 (Fig. 2.1). The cores were drilled using a pneumatic drill and the coring holes were plugged with cement to protect the inner parts of the corals from burrowing organisms. Following the procedures outlined in Bolton et al., (2014), the drilled cores were cleaned with freshwater and subsequently cut along their maximum growth axes into 7 mm thick slabs. Prior to subsampling and chemical analyses, each slab was cleaned thrice in an ultrasonic bath of deionized water for 15 minutes to remove any surface contaminants. The cleaned slabs were oven dried at 50°C for a minimum of 48 hours. The dried slabs were then X-rayed (See Appendix A) to visualize the banding pattern and to delineate the major growth axis along which subsamples were micro-drilled. The x-rays were taken at 50 kV, 10 mA with a source-to-object distance of 1 m and an exposure time of <1 second at the Diagnostic Imaging Lab, National University Hospital, Singapore.

Our *Diploastrea* slabs were subsampled for Sr/Ca and $\delta^{18}\text{O}$ exclusively along the *columella* following previous works (Watanabe et al., 2003; Bagnato et al., 2004; Damassa et al., 2006; Dassié and Linsley, 2015). Due to the porous structure of the *columella*, we set a manual drill press to a low speed of ~500 rpm to avoid any breakage or sample contamination during sampling. The slabs were drilled with a 1 mm diameter tungsten carbide burr at 0.4 mm intervals at a constant sampling depth of 1 mm, yielding a sampling resolution of ~10 samples per year. The subsamples from the *Porites* slabs were drilled at a similar sampling depth along its maximum growth axis but on a wider interval of 0.5 mm (about 26 samples per year) and at faster drilling speed of 1400 rpm.

2.2.2 Sr/Ca and $\delta^{18}\text{O}$ measurements

For Sr/Ca measurements, approximately 200 μg from each subsample was dissolved in 2 ml of 5% HNO_3 overnight. Strontium and calcium were measured thrice per sample using an inductively coupled plasma – optical emission spectrometry (ICP-OES, Thermo iCAP 6000 Series) at the Earth Observatory of Singapore (EOS). Solution standards were routinely measured to correct for instrument drift and matrix effects from varying calcium concentrations (Schrag, 1999). To evaluate measurement precision, bulk coral powder reference material JCp-1 (Okai et al., 2001) with a consensus Sr/Ca value of 0.01932 (± 0.0002) ppm or 8.838 (± 0.089) mmol/mol (Hathorne et al., 2013) was analyzed throughout each run. Repeat measurements of JCp-1 showed good reproducibility (0.019315 ± 0.00005 ppm, 1σ , RSD = 0.26%, $n = 2125$).

From the same subsample, $\delta^{18}\text{O}$ analyses were performed at the Australian National University (ANU) and EOS. At ANU, 150-200 μg samples were acidified with 105% H_3PO_4 at 90°C in an automated individual-carbonate reaction Kiel device and the resulting CO_2 gas was analyzed in a Finnigan MAT-251 isotope ratio mass spectrometer (IRMS). At EOS, 40-90 μg samples were acidified with 105% H_3PO_4 at 70°C in an automated Kiel IV carbonate device coupled with a ThermoFisher MAT-253 IRMS. All isotopic measurements in both labs were calibrated relative to Vienna Pee Dee Belemnite (VPDB) using National Bureau of Standards (NBS) 19 ($\delta^{18}\text{O} = -2.20\text{‰}$) and NBS 18 ($\delta^{18}\text{O} = -23.2\text{‰}$) (Stichler, 1995). The reproducibility of NBS 19 is $\pm 0.04\text{‰}$ (1σ , $n = 165$) at ANU and $\pm 0.03\text{‰}$ (1σ , $n = 10$) at EOS. We also used two standards to cross-

calibrate the instruments in both laboratories and results show no measurable offsets between laboratories or against published values. In addition, Estremoz, Carrara and TSF standards were routinely measured at EOS yielding the following average values and errors: $\delta^{18}\text{O}_{\text{Estremoz}} = -5.956 \pm 0.08\text{‰}$; $\delta^{18}\text{O}_{\text{Carrara}} = -1.938 \pm 0.05\text{‰}$; $\delta^{18}\text{O}_{\text{TSF}} = -2.281 \pm 0.07\text{‰}$ (total of all standards, $n = 688$).

2.2.3 Data sources

In the absence of *in-situ* SST measurements in the study area, monthly 1° by 1° grid resolution ($1^\circ \approx 111$ km) SST data from the Integrated Global Ocean Services System Products Bulletin (IGOSS), also referred to as Optimum Interpolation SST (OISST v.2, http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/, Reynolds et al., 2002) was used for SST calibration over the 30-year period of 1982-2012. We chose this SST dataset for calibration and comparison, rather than e.g. 4-km resolution AVHRR Pathfinder v.5 (Kilpatrick et al., 2001), because IGOSST SST data covers a longer time period and is more continuous.

Monthly gridded 0.25° by 0.25° resolution SSS data was acquired from Simple Ocean Data Assimilation (SODA, http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4, Carton and Giese, 2008) and monthly gridded 2.5° square resolution precipitation data from Global Precipitation Climatology Project v.2.2 (GPCP, <http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html>, Adler et al., 2003) covering the same time period to investigate the relative influence of salinity in

the coral $\delta^{18}\text{O}$ record. We found that other commonly used SSS datasets available for the tropical Pacific show opposite trends to the expected and observed climatology over our study site (e.g. Delcroix et al., 2011) and have limited temporal coverage (e.g. Aquarius, 2011-present, Lagerloef et al., 2008).

2.2.4 Chronology development

Age-depth models for all cores were developed using the annual density bands and fine-tuned using the seasonal cycles of Sr/Ca ratios in each core. Coral Sr/Ca profile minima, maxima and inflection points were aligned with their respective SST points each year using the Analyseries software (Paillard et al., 1996) to anchor the age-depth model. The Sr/Ca depth-series was then resampled into a monthly time-series by linear interpolation. The Sr/Ca-SST age model was similarly applied to the coral $\delta^{18}\text{O}$ record, which was then interpolated at monthly resolution.

2.2.5 Determination of extension rates and effects

The annual extension rates of each coral were measured along the distance of two consecutive Sr/Ca maxima, which marks the start of each year, from the Sr/Ca age model. The extension rates were then compared to their respective annual Sr/Ca and $\delta^{18}\text{O}$ records to check for growth rate effects.

2.3 Coral Sr/Ca and SST

2.3.1 Monthly calibration

Least squares linear regressions (LSLR) of monthly Sr/Ca to IGOSS SST from 1982 to 2012 show significant inverse relationship in both corals (Fig. 2.2a).

The regression equations are summarized in equations 2.1 and 2.2:

$$\text{Diploastrea Sr/Ca} = 10.657 (\pm 0.050) - 0.057 (\pm 0.002) \times \text{SST} (^{\circ}\text{C})$$

$$r = -0.86, r^2 = 0.74, p \ll 0.0001, \text{RMSR} = 0.86 ^{\circ}\text{C}, n = 365 \quad (2.1)$$

$$\text{Porites Sr/Ca} = 10.790 (\pm 0.043) - 0.068 (\pm 0.002) \times \text{SST} (^{\circ}\text{C})$$

$$r = -0.92, r^2 = 0.84, p \ll 0.0001, \text{RMSR} = 0.61 ^{\circ}\text{C}, n = 365 \quad (2.2)$$

where root mean square of the residual (RMSR) measures the difference between the instrumental and reconstructed SST.

Figure 2.2. SST calibrations and reconstructions. (a) Monthly *Diploastrea* (blue) and *Porites* (red) Sr/Ca lineary regressed against IGOSS SST. The regression

results are highly correlated, $r = -0.86$ and $r = -0.92$ for *Diploastrea* and *Porites*, respectively (both $p < 0.0001$). (b) SST reconstruction from *Diploastrea* (blue), *Porites* (red) and IGOSS SST (black). IGOSS SST is centered at 18.5°N, 122.5°E. (c) Coral SST anomalies from IGOSS SST, *Diploastrea* (blue circles), *Porites* (red circles).

Diploastrea Sr/Ca values are consistently higher than *Porites* Sr/Ca (Fig. 2.2a) as detected in Bagnato et al., (2004) and Correge et al., (2004) (Table 2.1). This inter-species offset is similarly observed in other paired *Diploastrea* – *Porites* studies (e.g. Watanabe et al., 2003; Bagnato et al., 2004; Table 2.1) investigating $\delta^{18}\text{O}$ as discussed later. The offsets are suspected to result from kinetic effects (McConnaughey, 1989a; 1989b; de Villiers et al., 1994; Cohen et al., 2001; Watanabe et al., 2003; Bagnato et al., 2004). Our mean Sr/Ca offset is ~ 0.182 mmol/mol or equivalent to $\sim 2.6^\circ\text{C}$ calculated using our *Porites* calibration slope, 0.068 mmol/mol $^\circ\text{C}^{-1}$ (Equation 2.2). This value is comparable with mean offsets estimated from *Diploastrea* – *Porites* Sr/Ca from Alor, Indonesia and New Caledonia (e.g. ~ 0.135 mmol/mol or $\sim 2.2^\circ\text{C}$, Correge et al., 2004), but higher compared with offsets reported from Fiji corals (e.g. 0.07 mmol/mol or 1.2°C ; Bagnato et al., 2004). In the Fiji study, *Diploastrea* Sr/Ca was only sampled along the *septa*, which may explain its discrepancy relative to the other studies above. The direction in which Fiji *Diploastrea* Sr/Ca is offset from *Porites* Sr/Ca is also different from what the kinetic equilibrium model predicts (McConnaughey et al., 1989a), such that Fiji *Diploastrea* Sr/Ca values are lower than paired *Porites* Sr/Ca. The Fiji *Diploastrea* Sr/Ca samples were also taken from septal material extending at an angle with respect to the major

growth direction, which is along the *columella* (Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015).

Our *Diploastrea* and *Porites* calibration slopes are slightly different, likely due to a greater Sr/Ca signal aliasing when sampling the slow-growing *Diploastrea* (*t*-test, *df* = 726, *p* < 0.0001). Nonetheless, both species generated SST reconstructions that are within error of each other (Fig. 2.2b and 2.2c). Both calibration slopes are within the range of slopes reported in other paired *columella Diploastrea* Sr/Ca records (e.g. -0.054 to -0.062 mmol/mol °C⁻¹, Bagnato et al., 2004 and Corregge et al., 2004), other *Porites*-based studies from the same region as our site (e.g. -0.042 to -0.061 mmol/mol °C⁻¹, Mitsuguchi et al., 1996; Shen et al., 1996; Sun et al., 2005; Yu et al., 2005; Wei et al., 2000); and other slow-growing corals, i.e. less than 0.8 cm/year (e.g. -0.045 to -0.059 mmol/mol °C⁻¹, Cardinal et al., 2001; Goodkin et al., 2005; 2007; DeLong et al., 2011; Xu et al., 2015). These results give indication that *Diploastrea* Sr/Ca has SST sensitivity similar to that of *Porites*.

Table 2.1. Palaui *Diploastrea*-*Porites* mean Sr/Ca and δ¹⁸O offsets.

	Mean Sr/Ca (mmol/mol)	Mean δ ¹⁸ O (‰)
<i>Diploastrea</i>	9.04	-4.66
<i>Porites</i> sp.	8.86	-4.91
inter-species offset	0.18	0.25
°C equivalent	2.6*	1.6**

* Calculated from our *Porites* Sr/Ca-SST calibration slope of 0.068 mmol/mol °C⁻¹

** Calculated from our *Diploastrea* δ¹⁸O-SST calibration slope of 0.16‰ °C⁻¹

2.3.2 Inter-annual calibrations

To further evaluate the reliability of our proxy calibrations, we derived inter-annual Sr/Ca-SST relationships by applying the monthly calibration equations (Equations 2.1 and 2.2) to 4-month summer (JJAS – June to September) and 4-month winter (DJFM – December to March) average Sr/Ca, which are based from the mean monthly climatology. We used the monthly calibration equations, instead of the statistically significant mean annual or winter SST calibrations (See Appendix D1), to minimize reconstructions errors that may result from the limited SST variability at inter-annual timescale at our site (i.e. mean annual SST range of $\sim 1.3^{\circ}\text{C}$). Using the mean annual and winter Sr/Ca-SST relationships ($p < 0.04$), for example, increase errors to 55% to 86% more, respectively, compared to the monthly calibration equations as discussed below.

Diploastrea summer SST reconstructions show no relationship to instrumental summer SST ($r = 0.17, p = 0.45$). *Porites* summer SST, on the other hand, significantly captures summer SST variability ($r = -0.53, p = 0.003$) with an RMSR of 0.42°C , or equivalent to $\sim 25\%$ of mean annual summer range, 1.66°C . *Diploastrea* and *Porites* winter SST reconstructions capture SST variability significantly with an RMSR of 0.81°C and 0.62°C , respectively ($r_{\text{Diploastrea}} = -0.41, r_{\text{Porites}} = -0.57, p < 0.05$; Fig. 2.3a). Winter RMSRs are equivalent to 40% and 31% of the mean winter SST range of 2.03°C for *Diploastrea* and *Porites*, respectively.

Building composite records from two or more individual corals minimizes local effects that are not climate related (Lough, 2004; DeLong et al., 2007), and thus, increases our confidence in reconstructing longer climate records. Palaui *Diploastrea* and *Porites* Sr/Ca winter SST reconstructions are not statistically different with each other (t-test, $df = 56$, $p = 0.50$). This indicates that while *Diploastrea* and *Porites* are distinctive species and have contrasting growth rates and patterns, both are recording the same SST conditions in which they lived. For this reason, we derived an inter-species composite record from the two coral time-series. We averaged the winter *Diploastrea* and *Porites* reconstructed SSTs, now referred to as the Palaui inter-species record, and compared with IGOSS SST.

The Palaui inter-species winter SST record shows a higher regression coefficient and lowered RMSR value than the individual calibrations over the same period ($r = 0.57$, $p = 0.001$, $n = 10$, $\text{RMSR} = 0.59^{\circ}\text{C}$). Compared with the instrumental mean annual winter SST, the inter-species winter SST reconstruction shows greater variability (Fig. 2.3b). The reconstructed winter SST has twice the range of the instrumental record. In particular, the large range was due to higher coral Sr/Ca (colder) in 1986-1987 and 2005 to 2008, and lower coral Sr/Ca (warmer) in 1990 to 1994.

Figure 2.3. (a) Winter SST reconstruction for *Diploastrea* (blue) and *Porites* (red) against IGOSS SST (dashed). Shaded areas represent $RMSR_{Diploastrea} = 0.81^{\circ}\text{C}$ and $RMSR_{Porites} = 0.62^{\circ}\text{C}$. (b) The winter inter-species record (black), derived by taking the average of the two coral time-series, shows higher regression coefficient ($r = 0.57$, $p = 0.001$) and lowered RMSR value (0.59°C , gray shaded area) than the individual coral reconstructions.

One possible source of the observed discrepancy between the reconstructed winter SST and instrumental record are ENSO years. The years contributing to greater SST variability correspond to El Niño events that may introduce skeletal growth anomalies such as slowed growth or die-offs due to bleaching (e.g. Suzuki et al., 2003). In general, *Porites* Sr/Ca records show no significant correlation between annual extension rates and Sr/Ca ratios at any season ($r < 0.10$, $p > 0.50$). The *Porites* coral extended ~ 1.3 cm/year, which is

within the range of rates with minimal growth rate effects (McConnaughey, 1989a; 1989b; Felis and Patzold, 2004; Sadler et al., 2014). In contrast, *Diploastrea*, with extension rate of ~ 4 mm/year, shows averaged annual and winter Sr/Ca ratios that are significantly correlated to annual extension rates (Sr/Ca vs. growth: annual $r = -0.46$, winter $r = -0.56$, $p < 0.04$) with similar significance to SST correlation (Sr/Ca vs. SST: annual $r = -0.36$, winter $r = -0.37$, $p < 0.04$). We found, however, that the coral Sr/Ca anomalies are neither consistent among ENSO events nor associated with unusual extension rates in each coral indicating that the high variability is not caused by growth effects.

Another possible source are errors associated with conventional microsampling of our corals impacting the resolution of our records through time and artificially dampening the calibration slope (Goodkin et al., 2005; 2007; Maupin et al., 2008; Dassié and Linsley, 2015). However, the possibility of sampling (or analytical) errors as sources of discrepancies also disagrees with the directionally consistent inter-annual signals in both corals (Fig. 2.2c). A more plausible explanation of the discrepancy may lie in the spatial range each record is able to resolve. Gridded SSTs average multiple observations over a large area (1° by 1°) and it is possible that this grid misrepresents local SST experienced by the corals. The Palaui cores were collected on a shallow coastal platform where greater SST variability than the open ocean can be expected. The coral record shows high variability both before and within the calibration period and still shows strong correlations to instrumental data, indicating support for local SST variations greater than regional variations. The above concerns may imply an

overestimation in the winter SST variability back in time, though relative variability compared to present should be consistent. Nevertheless, the individual coral and overall means of the records are consistent (26.3°C) and the trends are in good agreement with each other ($r = 0.54$, $p = 0.01$).

2.3.3 Decadal SST trends

We compared our inter-species coral winter (DJFM) SST record to the Pacific Decadal Oscillation (PDO), defined as the leading mode of SST anomalies over the North Pacific poleward of 20°N at decadal timescales (Mantua et al., 1997). Prominent PDO variability is commonly detected in boreal winters (Felis et al., 2010), as atmospheric circulation variability over the North Pacific is the strongest during this season (Trenberth et al., 1998; Deser et al., 2004). The Palau inter-species winter SST record is significantly correlated with the PDO index for DJFM months (<http://research.jisao.washington.edu/pdo/PDO.latest>; Mantua et al., 1997) ($r = -0.43$, $p = 0.02$, $n = 30$) over our calibration period. The inverse correlation indicates that warm (positive phase) PDO events are characterized by anomalously cool SSTs in the western Pacific and in the central North Pacific Ocean (Mantua et al., 1997; Felis et al., 2010; Gedalof and Smith, 2001). The coral records represent regional winter SST variability in the western tropical Pacific and the PDO index represents SST anomalies averaged over a larger area in the North Pacific. Therefore, we averaged 3-year bins in both time series to suppress local high frequency variability in our coral SST reconstructions and to

enhance signal-to-noise ratio in comparison to the PDO without artificially increasing the correlation coefficient. The correlation between the binned data is higher and remains statistically significant even after reducing the degrees of freedom ($r = -0.70$, $p = 0.02$, $n=10$). Coral winter SST correlates to the inter-decadal PDO index better than IGOSS SST data does at both time scales (IGOSS-PDO $r_{\text{annual}} = -0.19$, $p = 0.32$, $n = 30$; $r_{3\text{-yr_bin}} = -0.45$, $p = 0.19$, $n = 10$).

Beyond the calibration interval (back to 1955), the correlation between the 3-year binned Palau winter SST and PDO index remains statistically significant ($r = -0.56$, $p = 0.01$, $n = 19$; Fig. 2.4). Temporally, our winter SST record reflects known PDO regime shifts. In particular, the well-known 1976-1977 PDO regime shift to warm (positive) phase (e.g. Newman et al., 2016) is captured by our coral record as anomalously colder winters in the region. The 1988-89 and 1997-98 shifts to cool (negative) PDO phases (e.g. Newman et al., 2016) are likewise captured as positive excursions in our coral record. Compared with the only available coral-based PDO reconstruction in the subtropical northwestern Pacific (e.g. Felis et al., 2010), our results are of the same order of correlation at both annual and inter-annual timescales i.e. $r_{\text{annual}} = 0.30$ and $r_{3\text{-yr_running}} = 0.50$ from Ogasawara coral Sr/Ca and U/Ca. The PDO is one of the most significant climate phenomena influencing climate and ocean circulation in the western Pacific region (Mantua et al., 1997; Newman et al., 2016). Our understanding of drivers and mechanisms of the PDO is limited, especially its link with tropical climate (Gedalof and Smith, 2001; D'Arrigo et al., 2006; Newman et al., 2016). We find that the endemic *Diploastrea* corals have the

ability to record inter-decadal climate phenomena similar to *Porites*. In addition, the inter-species approach of this study has demonstrated its advantage by generating more reliable reconstructions. With *Diploastrea*'s longer lifespan than *Porites*, it has the potential to resolve centennial-scale variability in this important climate system.

Figure 2.4. Palau inter-species winter SST record (black) is significantly correlated to the Pacific Decadal Oscillation (dashed) over DJFM months at annual and 3-year binned timescales (3-year binned data shown; $r = -0.56$, $p = 0.01$, $n = 19$). Gray shaded area represents $\text{RMSR} = 0.59^{\circ}\text{C}$ based on the inter-species winter SST calibration.

2.4 Coral $\delta^{18}\text{O}$ and SSS

2.4.1 Monthly calibration

Monthly *Diploastrea* coral carbonate $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_c$) records are positively correlated with SSS ($r = 0.34$, $p < 0.0001$) and negatively correlated with SST ($r = -0.62$, $p < 0.0001$). *Porites* monthly $\delta^{18}\text{O}_c$ shows statistically significant correlations to SSS ($r = 0.67$, $p < 0.0001$) and to SST ($r = -0.66$, $p < 0.0001$) with higher r -values compared to *Diploastrea*. The monthly $\delta^{18}\text{O}_c$ records are also

strongly correlated with their paired monthly Sr/Ca values (*Diploastrea* $r = 0.63$ and *Porites* $r = 0.61$; $p < 0.0001$), which is expected as both proxies are a function of SST (See Appendix D1, Fig. D1.1). Additionally, monthly SODA SSS and IGOSS SST are correlated over the calibration period ($r = 0.51$, $p < 0.0001$), indicating that they impact $\delta^{18}\text{O}_c$ in opposite directions, serving to dampen the seasonal $\delta^{18}\text{O}_c$ signal.

To compare our data to the literature, we first calibrated our coral $\delta^{18}\text{O}_c$ directly to SST. Our columellar *Diploastrea* and *Porites* $\delta^{18}\text{O}_c$ records yield an SST dependence of -0.16 and $-0.14\text{‰ } ^\circ\text{C}^{-1}$, respectively. This lies on the lower end of the range of calibration slopes reported for other columellar *Diploastrea* $\delta^{18}\text{O}_c$ studies, (e.g. -0.16 to $-0.19\text{‰ } ^\circ\text{C}^{-1}$, Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015) and to typical *Porites* $\delta^{18}\text{O}$ -SST sensitivity (e.g. -0.15 to $-0.22\text{‰ } ^\circ\text{C}^{-1}$, Gagan et al., 2000; Lough, 2004; Corrège, 2006). This agrees with the instrumental data suggesting that our coral $\delta^{18}\text{O}_c$ records should have an attenuated seasonal signal due to the combined effects of SST and SSS.

The disequilibrium offsets we observed between *Diploastrea* and *Porites* Sr/Ca are also evident in their $\delta^{18}\text{O}_c$ records. The mean $\delta^{18}\text{O}$ offset is $\sim 0.25\text{‰}$ or equivalent to 1.6°C using our *Diploastrea* calibration slope and is comparable with offsets reported from *Diploastrea* – *Porites* $\delta^{18}\text{O}$ pairs in Fiji (e.g. 0.31‰ or 1.7°C ; Bagnato et al., 2004) and Alor, Indonesia and New Caledonia (e.g. 0.32‰ or 1.8°C ; Watanabe et al., 2003) (Table 2.1).

2.4.2 Inter-annual calibrations

Similar to our Sr/Ca data, we further evaluated our $\delta^{18}\text{O}_c$ records at inter-annual timescales over the same calibration period to better constrain the limits of our proxy calibration. The wet season in this region coincides with boreal summer (JJAS) and the dry season coincides with winter (DJFM). *Porites* $\delta^{18}\text{O}_c$ shows significant relationships with SSS for both wet and dry seasons. Wet season *Porites* $\delta^{18}\text{O}_c$ is strongly correlated to wet SSS ($r = 0.60$, $p = 0.0006$) but it is not correlated to either wet SST or Sr/Ca ($p > 0.40$, Fig. D1.2b, See Appendix D1). Dry *Porites* $\delta^{18}\text{O}_c$ is significantly correlated with both dry SST ($r = -0.58$, $p = 0.0002$) and SSS ($r = 0.48$, $p = 0.01$) but not with its dry Sr/Ca pair ($p > 0.20$, Fig. D1.3b). On the contrary, wet season *Diploastrea* $\delta^{18}\text{O}_c$ is neither correlated to wet SST ($r = 0.24$, $p = 0.20$) nor wet SSS ($r = 0.03$, $p = 0.85$) but is significantly correlated to its Sr/Ca pair ($r = 0.46$, $p = 0.01$, Fig. D1.2a, Table D1.1). Dry season *Diploastrea* $\delta^{18}\text{O}_c$ is not correlated to either SST or SSS, nor to its paired Sr/Ca ($r < 0.15$, $p > 0.50$, Fig. D1.2a). These results indicate that SSS records from *Porites* may be isolated by examining $\delta^{18}\text{O}_c$ during the wet and dry seasons separately, as will be discussed later.

As previously described in the inter-annual Sr/Ca relationships, summer *Diploastrea* Sr/Ca is not correlated to summer SST. One possible reason is the small summer SST range in Palau, $\sim 1.5^\circ\text{C}$, making it difficult to identify a significant relationship during this period. However, we were able to determine a significant summer Sr/Ca-SST relationship for the adjacent *Porites* core, and therefore, the small summer mean SST range cannot be the only explanation. If

we consider the wet season, which is also coincident with the summer period, *Diploastrea* $\delta^{18}\text{O}_c$ is found to have no relationship with SSS, while the SSS range for this season is larger than the dry SSS range (0.94 psu versus 0.73 psu). We would expect to determine a significant and more robust relationship between wet $\delta^{18}\text{O}_c$ and SSS than during the dry season, similar to what we have obtained for our *Porites* record, but the relationship is absent.

Although skeletal extension rates may also impact Sr/Ca (see discussion in Section 2.3.2), we found no relationship between summer *Diploastrea* Sr/Ca and linear extension ($r = -0.26$, $p = 0.16$). However, we hypothesize that, similar to *Diploria labyrinthiformis* (a slow-growing coral from the tropical Atlantic), the summer growth in *Diploastrea* extends quickly and is subsequently in-filled by secondary calcification during the following winter, mixing the Sr/Ca and $\delta^{18}\text{O}_c$ signals (Cohen et al., 2004; Goodkin et al., 2005). Hence, the full amplitude of the annual cycle in *Diploastrea* $\delta^{18}\text{O}_c$, may be attenuated and harder to resolve, a problem compounded by conventional microsampling. Moreover, in places of low SSS range like our study site, i.e. annual range of ~ 0.66 psu, and where SST and SSS dampen the $\delta^{18}\text{O}_c$ amplitude, both SST and SSS signals will be harder to isolate from $\delta^{18}\text{O}_c$ data. Therefore, *Diploastrea* $\delta^{18}\text{O}_c$ may be more useful in places where SST and SSS signals combine to enlarge the $\delta^{18}\text{O}_c$ amplitude, as previously investigated throughout the Pacific (Hughen et al., 1999; Watanabe et al., 2003; Bagnato et al., 2004; 2005; Correge et al., 2004; Damassa et al., 2006; Dassié and Linsley, 2015).

2.4.3 SSS variability using *Porites* $\delta^{18}\text{O}_c$

Annual and 3-year binned $\delta^{18}\text{O}_c$ for the wet and dry seasons are statistically and significantly correlated to SSS (Equations 2.3 and 2.4, Fig. 2.5):

$$\begin{aligned} & \text{Porites } \delta^{18}\text{O}_{c_annual_wet\&dry} \\ &= -33.776 (\pm 3.003) \\ &+ 0.843 (\pm 0.089) \times \text{SODA SSS}_{annual_wet\&dry} \\ r = 0.78, r^2 = 0.62, p < 0.0001, \text{RMSR} = 0.22 \text{ psu}, n = 57 \end{aligned} \quad (2.3)$$

$$\begin{aligned} & \text{Porites } \delta^{18}\text{O}_{c_3yr_wet\&dry} \\ &= -41.722 (\pm 3.792) \\ &+ 1.075 (\pm 0.111) \times \text{SODA SSS}_{3yr_wet\&dry} \\ r = 0.93, r^2 = 0.86, p < 0.0001, \text{RMSR} = 0.09 \text{ psu}, n = 18 \end{aligned} \quad (2.4)$$

where RMSR of 0.22 and 0.09 psu are equivalent to ~33% and ~14%, respectively, of the mean annual SSS range, ~0.66 psu. The 3-year binned record has a higher correlation coefficient as a result of suppressing mismatched high-frequency SSS variability that is expected from comparing a single data point to a large spatial average.

Figure 2.5. Three-year binned *Porites* $\delta^{18}\text{O}_c$ values for the combined wet (green) and dry (brown) seasons are statistically and significantly correlated to SODA SSS ($r = 0.93$, $p < 0.0001$). $\delta^{18}\text{O}_c$ values for the wet and dry seasons separately also show strong correlations with SSS ($r_{3\text{yr_wet}} = 0.69$, $p = 0.03$ and $r_{3\text{yr_dry}} = 0.73$, $p = 0.02$).

The SSS reconstructions for the wet and the dry seasons show comparable correlation strength with SODA SSS ($r_{3\text{yr_wet}} = 0.69$, $p = 0.03$ and $r_{3\text{yr_dry}} = 0.73$, $p = 0.02$; Fig. 2.5) and the associated reconstruction errors between seasons are consistent (RMSR ≈ 0.09 psu). However, a few anomalies are notable. The 3-year binned wet season SSS reconstruction shows higher salinity estimates, ~ 0.14 psu, than SODA SSS for the period 1994-1996 (Fig. 2.6a). The dry season reconstruction conversely shows large departures from SODA SSS of about ~ 0.19 and ~ 0.15 psu for the periods 1988-1990 and 1997-1999, respectively (Fig. 2.6b).

Figure 2.6. (a) Wet season Porites SSS reconstruction (green) against SODA SSS (gray). (b) Dry SSS reconstruction (brown) against SODA SSS (gray). (c) Differences between the SSS reconstructions in A and B may be explained by changes in SOI (dashed lines), an indicator of ENSO events, and rainfall patterns from GPCP (gray bars). Shaded areas represent RMSR = 0.09 psu, based on the 3-year binned wet and dry season SSS calibrations.

We compared our SSS reconstructions with satellite-derived precipitation data (GPCP, Adler et al., 2003) and the Southern Oscillation Index (SOI, <https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/>), together with SODA SSS to assess the factors controlling our reconstructions. Over our calibration period, the reconstructed SSS for both wet and dry seasons shows

good agreement with the SOI ($r_{3\text{yr_wet}} = -0.82$; $p = 0.007$ and $r_{3\text{yr_dry}} = -0.74$, $p = 0.02$, Fig. 2.6c). The SOI is a measure of large-scale variability in air pressure across the Pacific that changes during ENSO episodes, and thus, provides a good test of ENSO impacts on the monsoon strength and fluctuations in the Inter-tropical Convergence Zone (ITCZ) over our study site. A negative (positive) SOI indicates El Niño (La Niña) phase. In the western Pacific, El Niño (La Niña) is characterized by anomalously cooler (warmer) SSTs and drier (wetter) conditions leading to droughts (above normal rainfalls) as the warm pool moves towards the central equatorial Pacific (western Pacific), together with atmospheric convection and rainfall centers (Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987). The 1997-1999 period covers one of the strongest back-to-back El Niño – La Niña phase changes for the past 30 years. The wet season $\delta^{18}\text{O}_c$ record for the 1997-1999 period captures the wet phase SODA SSS well (Figure 2.6a) while the dry season $\delta^{18}\text{O}_c$ anomaly reflects “wetter” (less dry) conditions (Figure 2.6b). The wetter than average condition coincides well with SOI (Fig. 2.6c) indicating that our site received above average rainfall expected during strong La Niña episodes. The strong La Niña in 1998-1999 developed during the winter/dry months, explaining the observed signal strength during this season.

An offset in timing between minimum salinity and precipitation may explain some of the differences between our reconstructions and SODA SSS (Figure 2.6c). The years 1994-1996 in our reconstruction show higher salinity estimates than SODA SSS during the wet season (Fig. 2.6a). GPCP rainfall data

shows that this period received one of the least amounts of rainfall over our calibration period that may not be ENSO-related. ENSO for these years is considered weak to moderate, thus impacts on rainfall variability may be minimal.

2.4.4 Application of calibration equation and comparison to SOI variability

Beyond the calibration period of 1982-2012, the 3-year binned *Porites* wet SSS reconstructions remained significantly correlated with SODA SSS when including data back to 1955 ($r = 0.56$, $p = 0.015$), allowing for robust SSS reconstruction (Fig. 2.7a). However, the *Porites* dry SSS to SODA SSS did not remain significant ($r = 0.14$, $p = 0.55$, Fig. 2.7b). The SOI is not correlated to wet SSS ($r = -0.08$, $p = 0.75$) but is significantly correlated to dry SSS ($r = -0.48$, $p = 0.04$, Fig. 2.7b). These results may be the outcome of less reliable SODA SSS data before ~1970s due to the limited number of observations (Delcroix et al., 2011) or may indicate that salinity variability between seasons is governed by different factors.

Figure 2.7. (a) Wet season *Porites* SSS reconstruction back to 1955 is significantly correlated to SODA SSS observations ($r = 0.56$, $p = 0.015$). (b) Dry season $\delta^{18}\text{O}_c$ may be better at recording SOI at longer timescales ($r = -0.64$, $p = 0.003$). Shaded areas represent RMSR = 0.09 psu, based on the 3-year binned wet and dry season SSS calibrations.

Porites wet SSS generally tracks local salinity (Fig. 2.7a). However, “drier” (less wet) excursions in the record, e.g., 1958-1960, 1964-1966 and 1976-1978, not reflected in the SODA time-series, may be explained by SOI. These years are predominantly weak to moderate El Niño years (with the year 1965-1966 as one of the strong El Niño events in the past ~65 years), resulting in drier conditions at our site. *Porites* dry SSS, on the other hand, may record more

regional changes in salinity based on its sustained relationship with SOI on longer timescales (Fig. 2.7b). The annual SOI averages are essentially a combined signal from the two seasonal extremes and therefore, defining each season separately may be more advantageous. ENSO onset begins during the dry season. If SOI values are averaged for DJFM months and compared to our dry SSS reconstruction, the correlation strength between the time-series becomes stronger ($r = -0.64$, $p = 0.003$).

While we are unable to generate a robust *Diploastrea* $\delta^{18}\text{O}_c$ –SSS reconstruction for the wet and dry seasons, long-term records indicate a freshening trend towards the present (Fig. 2.8). *Diploastrea* $\delta^{18}\text{O}_c$ has a decreasing slope of -0.0174‰/year ($r = 0.81$, $p = 0.002$) from the early 1950's to the present. If this is partly due to warming, we expect to see a significant increase in *Diploastrea* Sr/Ca and in the adjacent *Porites* record. Both coral Sr/Ca records are essentially flat ($m_{\text{Diploastrea}} = 0.0008$ mmol/year and $m_{\text{Porites}} = 0.0007$ mmol/year) hence, the *Diploastrea* $\delta^{18}\text{O}_c$ trend is likely due to freshening. *Porites* wet SSS reconstructions and SODA SSS show a freshening trend equivalent to ~ 0.007 and ~ 0.009 psu/year. If we convert the slope of *Diploastrea* $\delta^{18}\text{O}_c$ to salinity using Equation 2.4, it will result in a comparable magnitude of freshening of $0.016 (\pm 0.00464)$ psu/year.

Lower salinity towards the present is a common trend in the western and central Pacific (Cobb et al., 2003; Delcroix et al., 2007; Gagan et al., 2000; Nurhati et al., 2009; 2011), pointing to the intensification of the hydrological patterns (Cobb, 2003; Nurhati et al., 2009; 2011; Osborne et al., 2014) since the

start of the 20th century as the cause. Freshening trends obtained from both coral and instrumental records have been estimated to be on the order of 0.1 to 0.3 psu/decade (e.g. Delcroix et al., 2007) to up to 0.6 to 1.2 psu/century (Cobb, 2003; Nurhati et al., 2009; 2011). *Porites* wet SSS and instrumental data have the same magnitude of freshening approximately ~0.35 psu and ~0.30 psu, respectively, for the past six decades. The wet *Diploastrea* SSS record, in contrast, shows a greater amount of freshening, ~0.85 psu, which likely arises from the uncertainties in the *Diploastrea* calibrations as previously discussed.

Figure 2.8. Long-term freshening trend observed from decreasing *Diploastrea* $\delta^{18}O_c$ values.

2.5 Conclusions

This study investigated a *Diploastrea heliopora* coral relative to an adjacent *Porites* from northeast Luzon (Palau), Philippines, to evaluate both Sr/Ca and $\delta^{18}O$ paleoclimate proxies and *Diploastrea*'s ability to reconstruct regional climate behavior. Sr/Ca from *Diploastrea* has only been used as a chronological marker in previous studies (eg. Bagnato et al., 2004; 2005). Winter

Sr/Ca data from *Diploastrea* is an excellent SST proxy and has a similar sensitivity to an adjacent *Porites* core. The inter-species SST (averaged *Diploastrea-Porites* SST) record reflects the PDO and allows for a reconstruction of long-term PDO variability.

Salinity variability for the past half-century is qualitatively captured in the Palau *Diploastrea* $\delta^{18}\text{O}_c$, showing a freshening trend consistent with *Porites* $\delta^{18}\text{O}_c$, instrumental SSS and coral-based records within the Indo-Pacific region. However, a robust *Diploastrea* $\delta^{18}\text{O}_c$ and SSS calibration at inter-annual timescales was not achieved as a result of the competing SST and SSS influences dampening the $\delta^{18}\text{O}_c$ signal and compounding effects of continuing coral calcification during different seasons. *Diploastrea* $\delta^{18}\text{O}_c$ should be useful in places where there is high salinity range (mean annual salinity $> \sim 1.5$ psu) and where SST and SSS signals combine to enlarge the $\delta^{18}\text{O}_c$ amplitude as previously investigated in the central and south Pacific regions.

The multi-proxy, multi-species approach of this study further strengthens justification for the use of *Diploastrea* as an alternate climate archive in the Indo-Pacific region, and demonstrates its potential in helping resolve global-scale climate phenomena we poorly understand.

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Chapter 3

Late 19th century coral record of the Pacific Decadal Oscillation and its possible climatic control on the tropical western Pacific salinity variability

Abstract

The Pacific Decadal Oscillation (PDO) is a complex aggregate of different atmospheric and oceanographic forcings spanning the extratropical and tropical Pacific. The PDO has widespread climatic and societal impacts, thus understanding the processes contributing to PDO variability is critical. Distinguishing PDO-related variability is particularly challenging in the tropical Pacific due to the dominance of the El Niño-Southern Oscillation (ENSO) and influence of anthropogenic warming signals. Century-long western Pacific records of interannual sea surface temperature (SST) and sea surface salinity (SSS), derived from coral Sr/Ca and $\delta^{18}\text{O}$ profiles, respectively, allow for evaluating different climatic sensitivities and identifying PDO-related variability in the region. The summer Sr/Ca-SST record provides evidence of significant SST increase that commenced in the 1970s, likely tied to greenhouse gas emissions. Anthropogenic warming is masked in the winter Sr/Ca-SST record by interannual to multidecadal scale changes driven by the East Asian Winter Monsoon (EAWM) and the PDO. Decadal climate variability in winter SST is

strongly correlated to the PDO, in agreement with other PDO records in the region. At high frequencies, the PDO and EAWM exhibit reversing modulation on winter SSTs, providing insights on their interaction through time. The PDO also exerts influence on the SSS difference between the dry and wet season $\delta^{18}\text{O}$ -SSS records through water advection. The PDO and ENSO constructively combine to enhance/reduce advection of more saline Kuroshio waters at our site. Overall, we were able to demonstrate that climate records from a tropical reef environment significantly capture PDO variability and related changes over a century. This implies that the tropical western Pacific is a key site in understanding multifrequency climate variability including its impact on tropical climate at longer timescales.

3.1 Introduction

The Pacific Decadal Oscillation (PDO) is the dominant mode of sea surface temperature (SST) anomalies over the North Pacific poleward of 20°N at decadal timescales (Mantua & Hare, 2002; Mantua et al., 1997). The PDO rapidly transitions between prolonged periods of warm (positive) and cold (negative) phases every few decades (Mantua et al., 1997; Minobe, 1997; Newman et al., 2016), altering rainfall patterns and ocean productivity in the region. During warm (positive) PDO phases, SSTs are anomalously warm along the northwest coast of North America coincident with increased rainfall along its coast including the southwest United States (US) and Central America, and decreased rainfall and streamflow along the western US (Felis et al., 2010; Mantua & Hare,

2002; Miller et al., 1994; Nigam et al., 1999). Over the western and central Pacific, SSTs are anomalously cooler coincident with decreased rainfall in the western Pacific and increased extratropical storm intensities in the northwestern Pacific (Felis et al., 2010; Mantua & Hare, 2002; Miller et al., 1994). The SST anomalies and precipitation impacts reverse during a cold (negative) PDO phase (Felis et al., 2010; Mantua & Hare, 2002). Changes in ocean productivity in Alaska and the western coast of the US are correlated with the phase shifts of the PDO, significantly impacting the marine ecosystems and fishing industries (Mantua et al., 1997; Overland et al., 2008). While less constrained, PDO's influence extends to the tropics (Newman et al., 2016). The PDO interacts with the interannually dominant El Niño-Southern Oscillation (ENSO) in the tropics resulting in decadal SST and sea surface salinity (SSS) trends being broadly similar to ENSO patterns (Delcroix et al., 2007; Deser et al., 2004). The PDO also influences the Asian monsoon system by modulating the response of the East Asian Winter Monsoon (EAWM) to ENSO (e.g. Kim et al., 2014; Wang et al., 2008). Understanding the mechanisms driving PDO variability therefore is critical to the mitigation of its impacts and their predictability in the future.

More than just a single mode of climate variability, the PDO is presently considered a combination of extratropical and tropical atmospheric and oceanographic processes operating at varying timescales (Liu & Di Lorenzo, 2018; Newman et al., 2016). The strength of the Aleutian Low, persistent oceanic memory closely dependent to ENSO-SST anomalies and the Kuroshio Current system act together to drive the spatial pattern of the PDO (Newman et al., 2016).

Each PDO shift may then be a result of different combinations of the above processes (Deser et al., 2004; Newman et al., 2016), confounding our understanding of its mean climatic behavior. Adding more complexity in constraining its predictability is anthropogenic warming, where the shift of the PDO in 1976-77 from cold to warm phase is hypothesized to be linked to greenhouse gas emissions (Cole et al., 2000; Graham, 1995; Miller et al., 1994; Nurhati et al., 2011). One approach to overcome these challenges is to target documenting the different processes that contribute to PDO variability that extends beyond the instrumental period and anthropogenic influence, allowing to identify dependent and independent forcing mechanisms of the PDO and how their inter-relationships varied back in time (Newman et al., 2016).

Networks of tree-ring records from continental East Asia and northwestern America provide multi-century to millennial scale histories of PDO variability (e.g. Biondi et al., 2001; D'Arrigo & Wilson, 2006; Gedalof & Smith, 2001; MacDonald & Case, 2005; Minobe, 1997). However, terrestrial data do not fully represent oceanic processes linked to the PDO. Coral-based records documenting interannual to multidecadal SST patterns are concentrated in the central and south Pacific regions (e.g. Cobb et al., 2001; Linsley et al., 2000; Nurhati et al., 2011; Urban et al., 2000) but are extremely rare in the tropical and subtropical western Pacific (e.g. Asami et al., 2005; Felis et al., 2010). Most of these records are based on $\delta^{18}\text{O}$ profiles preventing independent estimates of SST anomalies in the region. Because the PDO is an aggregate of several processes and remotely influences the ENSO-dominated tropical region, combined records

of Sr/Ca and $\delta^{18}\text{O}$ are more advantageous to accurately estimate PDO-related climate variability.

Our previous study using corals from Palaui, northeastern Luzon (Ramos et al., 2017) shows that interspecies (i.e. averaged *Diploastrea heliopora* and *Porites lobata*) wintertime Sr/Ca-SST is sensitive to PDO variability. In addition, *Porites* dry (winter) season $\delta^{18}\text{O}$ -SSS record, compared with the wet (summer) season $\delta^{18}\text{O}$ -SSS reconstruction, reflects regional changes in salinity driven by ENSO at interannual timescales. In this paper, we present an extended record of SST and SSS histories derived from paired *Porites* Sr/Ca and $\delta^{18}\text{O}$ proxies for the past ~132 years using previously published calibrations (Ramos et al., 2017). We further assess these climatic drivers across different time-frequencies to examine their relative influence on SST variability and possible inter-relationships through time. We also evaluate the potential impacts of the PDO on the tropical western Pacific climate, which is considered to weakly correspond to decadal climate variability (Deser et al., 2004; Mantua & Hare, 2002; Newman et al., 2016).

3.2 Methods

3.2.1 Study site and coral sampling

In May 2012, a 3 m long coral core of *Porites lobata* was collected from 4-5 m water depth off the coast of Palaui Islands, Philippines (18.5°N, 122.2°E, Fig. 3.1). The core was drilled using a pneumatic drill with ~55 mm diameter core bit. Monthly instrumental SST (Integrated Global Ocean Services System –

IGOSS, centered at 18.5°N, 122.5°E, Reynolds et al., 2002) and SSS records (Simple Ocean Data Assimilation – SODA, centered at 18.8°N, 122.3°E, Carton & Giese, 2008) from 1982 to 2012, indicate that the warmest and wettest months occur from June to September (JJAS) while the coldest and driest months occur from December to March (DJFM). Mean annual SST and SSS both exhibit limited annual variability (i.e. 1.4°C and 0.66 psu, respectively). Annual rainfall is on average $2000 \pm 500 \text{ mm yr}^{-1}$ (1σ , Philippine Atmospheric Geophysical and Astronomical Services Administration-PAGASA).

Palau Island is located at the northeastern tip of Luzon facing the western Pacific Ocean to its east and the Luzon Strait to its north. It lies on the northern tip of the Western Pacific Warm Pool (WPWP) where the Asian monsoon, ENSO and the PDO exert influence on the regional SST, salinity and rainfall variability at seasonal to multidecadal timescales (e.g. Delcroix et al., 2007; Wang & Mehta, 2008; Yan et al., 1992).

3.2.2 Coral subsampling

The coral core was cleaned, cut into 7 mm thick slabs, and x-rayed (See Appendix A) according to methods previously outlined (Ramos et al., 2017). Using a micrometer-controlled drill press, subsamples were drilled along the major growth axis at 0.5 mm increments and at constant sampling depth of 1 mm, yielding a biweekly sampling resolution. Each individual sample weighed <300 µg, where 40 to 90 µg powder splits were set aside for stable isotope analysis. The remaining powder was used for Sr/Ca measurements.

Figure 3.1. A coral core of *Porites lobata* was drilled offshore Palaui island in May 2012. Palaui island is located at the northeastern tip of Luzon, facing the Luzon Strait and the Pacific Ocean (inset).

3.2.3 Sr/Ca analysis

Approximately 200 μg of subsample was dissolved in 2.5 mL of 5% HNO_3 overnight. Sr and Ca were simultaneously measured thrice per sample using an inductively coupled plasma - optical emission spectrometer (ICP-OES, Thermo iCAP 6000 Series) at the Asian School of the Environment (ASE), Nanyang Technological University (NTU). Solution standards (0 to 80 ppm) were routinely measured to correct for instrumental drift and matrix effects from varying calcium concentrations (Schrage, 1999). Bulk coral powder reference material JCp-1 (Okai et al., 2001) with a consensus Sr/Ca value of 0.01932 (± 0.0002) ppm or 8.838 (± 0.089) mmol mol^{-1} (Hathorne et al., 2013) and an in-

house powder standard (*Porites* sp.) were analyzed throughout each run to evaluate measurement precision. Repeat measurements of JCp-1 and in-house coral powder standard analyzed over a period of two years showed good reproducibility, 0.019291 (± 0.00004) ppm (1σ , relative standard deviation (RSD) = 0.18%, $n = 1074$) and 0.019289 (± 0.00005) ppm (1σ , RSD = 0.25%, $n = 396$), respectively.

3.2.4 $\delta^{18}\text{O}$ analysis

Oxygen stable isotope, $\delta^{18}\text{O}$, was analyzed in an automated Kiel IV carbonate device coupled with a ThermoFisher MAT-253 isotope ratio mass spectrometer (IRMS) at ASE, NTU. Powdered samples were acidified with 105% H_3PO_4 at 70°C. Measurements were calibrated relative to Vienna Pee Dee belemnite (VPDB) using external standards including National Bureau of Standards (NBS) 19 ($\delta^{18}\text{O} = 2.20\text{‰}$) and NBS 18 ($\delta^{18}\text{O} = 23.2\text{‰}$) (Stichler, 1995). Repeat measurements of NBS 19 analyzed over a two-year period is $\pm 0.07\text{‰}$ (1σ , $n = 103$). In addition, Estremoz, Carrara, and TSF standards were routinely measured yielding the following average values and standard deviations: $\delta^{18}\text{O}_{\text{Estremoz}} = 5.957 \pm 0.08\text{‰}$; $\delta^{18}\text{O}_{\text{Carrara}} = 1.966 \pm 0.07\text{‰}$; $\delta^{18}\text{O}_{\text{TSF}} = 2.276 \pm 0.07\text{‰}$ (total of all 3 standards, $n = 3586$).

3.2.5 Chronology development

Age-depth models were developed using the annual density bands and fine-tuned using the seasonal cycles of Sr/Ca. Beyond the instrumental and

calibration period previously reported (Ramos et al., 2017), time was assigned using the averaged IGOSS SST climatology, aligning Sr/Ca profile minima, maxima, and inflection points with their respective SST points each year using the Analyseries software (Paillard et al., 1996). The Sr/Ca depth series was then resampled into a monthly resolution by linear interpolation. The Sr/Ca-SST age model was similarly applied to the corresponding $\delta^{18}\text{O}$ record, which was then interpolated at monthly resolution.

3.2.6 SST and SSS reconstructions

Records of SST and SSS variability extending back to 1880 were generated using previously published calibration equation for this coral for SST:

$$\begin{aligned} \text{Sr/Ca} &= 10.790 (\pm 0.043) - 0.068 (\pm 0.002) \times \text{SST } (^{\circ}\text{C}) \\ r &= -0.92, p < 0.0001, \text{RMSR} = 0.61^{\circ}\text{C}, n = 377 \end{aligned} \quad (3.1)$$

and three-year binned annual wet (JJAS) and dry (DJFM) season for SSS:

$$\begin{aligned} \delta^{18}\text{O}_{\text{c}_{3\text{yr_wet\&dry}}} &= -41.722 (\pm 3.792) - 1.075 (\pm 0.111) \\ &\times \text{SSS}_{3\text{yr_wet\&dry}} (\text{psu}) \\ r &= 0.93, p < 0.0001, \text{RMSR} = 0.09 \text{ psu}, n = 18 \end{aligned} \quad (3.2)$$

(Ramos et al., 2017), where RMSR is the root-mean-square of the residual describing the difference between the instrumental and reconstructed records. These equations were applied to interannual reconstructions (i.e. summer/3-yr wet and winter/3-yr dry SST/3-yr SSS) to effectively increase the signal to noise ratio that may otherwise be dampened by the limited SST and SSS variability at our site (Ramos et al., 2017).

3.2.7 Data analysis

We estimated the power spectral density on our records and climate indices using a simple fast Fourier transform (FFT) algorithm. Significance level (90%) was estimated using 10,000 Monte Carlo simulations. We also performed coherence and phase analysis using a non-parametric multitaper (MTM) method with bias correction (<http://www.people.fas.harvard.edu/~phuybers/Mfiles/index.html>, e.g. Huybers & Denton, 2008) to evaluate the significant frequencies shared by our reconstructions and climate indices. Spectral coherence was estimated with 2 windows and 50 iterations on Monte Carlo error estimates. To further isolate and observe variability specific to coherent frequencies between records, we applied a Gaussian filter using the Analyseries software (Paillard et al., 1996).

3.3 Results

The paired Sr/Ca and $\delta^{18}\text{O}$ records show distinct annual cycles throughout the reconstruction period extending back to 1880 (Fig. 3.2), consistent with our previous calibration work (Ramos et al., 2017). The extended proxy records add

75 years of climate data allowing for further examination of the climatic controls on both SST and SSS reconstructions.

Figure 3.2. Palaui monthly Sr/Ca and $\delta^{18}\text{O}$ timeseries extending back to 1880.

3.3.1 Sr/Ca – SST reconstruction

The summer and winter SST reconstructions exhibit interannual to multidecadal scale variability over a 3.4°C and 3.1°C SST range, respectively (Fig. 3.3a). Warmest summer and winter SSTs of $\sim 1.5^{\circ}\text{C}$ above average were recorded during one of the strongest ENSO events, El Niño/La Niña of 1998/99. The coldest period was recorded in 1939, about 1.9°C and 1.1°C below the winter and summer SST means, respectively. Both reconstructions show similar trends at the beginning of the record indicated by their significant positive 15-year running correlation (Fig. 3.3b). Around the mid-1920s, both records start to exhibit different trends with a negligible relationship recorded between 1925 and 1935, 1947 and 1974, 1979 and 1983 and 1994 and 2012. This change in decadal

behavior between records through time is confirmed by applying a 50-yr running variance on each record (Fig. 3.3c). Summer SST exhibits a gradual decrease in variance that reverses in direction in the early 1970s. Winter SST shows similar variance to that of the summer record until the late 1920s when it began to steeply increase around 1950 and in the more recent years of comparable magnitude (Fig. 3.3c). There is no discernible long-term trend in either SST record ($m_{summerSST} = 0.0029^{\circ}\text{C yr}^{-1}$ and $m_{winterSST} = 0.0014^{\circ}\text{C yr}^{-1}$; $r < 0.2$, $p < 0.05$), indicating minimal SST change over the past century. However, from 1970 to present, the summer record shows an SST increase of $0.03^{\circ}\text{C yr}^{-1}$ or 1.23°C over the past ~4 decades ($r = 0.66$, $p < 0.0001$), indicating a significant recent summer warming.

The PDO has previously been shown to exert influence on the Palau winter SST variability (Ramos et al., 2017). Over the calibration period (1981 to 2012), the multi-species composite winter SST is significantly correlated with the PDO at DJFM months ($r = -0.43$, $p = 0.02$, $n = 30$). The correlation is negative indicating that warm (positive) PDO events are characterized by anomalously cool SSTs in the western Pacific and central North Pacific Ocean (Felis et al., 2010; Gedalof & Smith, 2001; Mantua et al., 1997; Ramos et al., 2017). The interspecies winter SSTs also show improved correlation with the winter PDO when binned at 3-yr timescales over both the calibration and reconstruction periods spanning from 1954 to 2012 ($r = -0.56$, $p = 0.01$, $n = 19$, Ramos et al., 2017). This approach effectively suppressed higher frequency variability present in the interannual timeseries and increased the signal to noise ratio between records of different spatial coverages. The extended winter SST records

continued to exhibit significant correlation with the PDO at 3-yr interannual timescales ($r = -0.55$, $p < 0.001$, $n = 38$, not shown) suggesting that interannual to multidecadal SST changes may be evident in our winter SST reconstruction.

Figure 3.3. (a) Interannual summer (red) and winter (blue) Sr/Ca-SST reconstructions. Shading represents $\text{RMSR} = 0.61^\circ\text{C}$. (b) Fifteen-year running correlation between the summer and winter SSTs record. Dashed lines represent 95% significance level. (c) Fifty-year running variance of summer (red) and winter (blue) SSTs.

To further evaluate the robustness of this relationship and quantify the significant frequencies shared between our records and climate indices, we generated power spectral densities and coherence between our summer and

winter SST reconstructions and the PDO index over the same time period between 1901 and 2010. We similarly performed this analysis on both ENSO (i.e. Niño 3.4) and EAWM (D'Arrigo et al., 2005) indices over the same time period and compared them to the SST records.

Results of the spectral analysis reveal significant variance at multidecadal periods of 55 years and interannual periods of 2.1 years in the winter SST record and the PDO index (Fig. 3.4a and 3.4b.1). Coherence between these records also reveals statistical significance ($> 90\%$) during the above time intervals, including interannual periods of ~ 10 and 2.1 years (Fig. 3.4b.2), suggesting that our winter SST record is sensitive to PDO variability at multiple frequencies. Between the winter SST and the EAWM, the records show significant power and coherence at 2.8 years (Fig. 3.4c.2), indicating the additional influence of the EAWM on the winter SST variability at high frequencies. The winter SST also reveals significant spectral power at interannual periods of 2.6, 3.1 and 3.7 years (Fig. 3.4a) but are incoherent with the Niño 3.4 index (Fig. D2.1, See Appendix D). Summer SST, on the other hand, exhibit significant power at 2.3, 2.5, 3.7 and 5.2 years (Fig. D2.2, See Appendix D). Compared with the PDO, EAWM and Niño 3.4 indices (Fig. D2.2), these time frequencies show no significant coherence between records, indicating that the impact of these climatic forces on the summer SST record is limited or absent. Therefore, we further investigate the drivers of SST variability using our winter SST reconstruction and the PDO and EAWM indices.

The winter SST record and the PDO and EAWM indices were subsequently filtered to observe time-varying modulation at specific frequencies. The central frequency for filtering both the winter SST and EAWM is 0.359 ± 0.0045 cycles yr^{-1} , isolating 2.8-year period in the records. Between winter SST and the PDO, we used central frequencies of 0.018 ± 0.0045 , 0.105 ± 0.0045 and 0.473 ± 0.0045 cycles yr^{-1} , isolating ~ 55 -year, ~ 10 -year and 2.1-year periods, respectively. We isolated for 10-yr periods to additionally account for decadal changes occurring in our 132-yr long record.

Figure 3.4. Spectral analysis (upper panel) of detrended winter Sr/Ca-SST records (a) and climate indices, PDO (b.1) and EAWM (c.1). Significance level greater than 90% (red lines) are labelled. Spectral coherence with phase analysis (lower panels) is also performed to account for variances shared between winter SST and the PDO (b.2) and EAWM (c.2) indices. Red lines indicate 90% significance level while the gray dashed lines represent confidence intervals. Black labels are the periods further analyzed.

The 2.1-yr filtered winter SST and PDO records show a significant but low negative correlation ($r = -0.30$, $p = 0.002$, Fig. 3.5), likely resulting from the observed change in phase over time. This phase relationship is insignificant in the 10- and 55-yr filtered records, which in contrast exhibit strong antiphase relationships ($r_{10\text{-yr}} = -0.96$ and $r_{55\text{-yr}} = -0.90$, $p < 0.0001$, Fig. 3.6a and 3.6b), consistent with the known spatial structure of the PDO-related SST anomalies across the Pacific. In the 10-yr filtered timeseries, the amplitudes were attenuated between 1920 and 1940 and became gradually amplified towards the present (Fig. 3.6b), suggesting a more active PDO in recent years. On the basis of these results, we applied a 10-yr moving average on the winter SST record to reconstruct the winter PDO (Fig. 3.6c). Compared with the similarly averaged PDO index, the records show a strong negative relationship ($r = -0.75$, $p = 0$, $n = 101$, Fig. 3.6c), highlighting that our site is sensitive to decadal scale SST variability.

Figure 3.5. (a) 2.8-year filtered winter SST (blue) and EAWM record (black). (b) 10-yr running correlation reveals significant relationship from early 1960s. Horizontal dashed lines represent 95% significance level. (c-d) is the same as (a-b) but for the 2.1-year filtered winter SST and PDO records. Vertical dashed lines indicate the time when the PDO and EAWM inversely modulates SST variability.

Figure 3.6. (a) 55- and (b) 10-yr filtered winter SST (blue) and PDO index (black). (c) Interannual (dashed) and 10-yr moving averaged (solid) winter SST reconstruction (blue) compared to the PDO (black) and coral Sr/Ca record from Ogasawara, Japan (d, red).

Our winter SST record exhibits known regime shifts since the start of the 20th century: shifts from cold to warm phase in 1924 and 1976 and shifts from warm to cold phase in 1945 and 1998, represented by colder and warmer

excursions in our record, respectively (Fig. 3.6c). Beyond 1900, when the PDO index is no longer available, we found good agreement in the SST fluctuations between our record and the only available coral Sr/Ca-based PDO reconstruction in the western Pacific, Ogasawara coral from southern Japan (Felis et al., 2010, Fig. 3.6d). Both coral records exhibit “warmer” (i.e. less cold) winter SST anomalies between 1885 and 1895, indicative of a cold (negative) PDO phase during this period (Fig. 3.6c and 3.6d). While the climatological winter SST averages were slightly different for Palaui and Ogasawara (i.e. DJFM and NDJF, respectively), the two coral records exhibit good overall reproducibility ($r = 0.50$, $p < 0.0001$, $n = 106$) over 10-yr timescales, suggesting that marine-based proxy reconstructions in different geographical locations are consistent.

The 2.8-yr filtered winter SST and EAWM records, on the other hand, show a significant negative correlation ($r = -0.43$, $p < 0.0001$, Fig. 3.5), consistent with regional cooling during strong EAWM periods. The relatively low correlation strength between records is likely due to the change in sign through time, only showing significant negative relationships around the mid-1960s towards the present (Fig. 3.5). The observed gradual increase in amplitude in the EAWM record reaching maximum values in the 1960s is not evident in our winter SST reconstruction but may explain the change in phase and correlation strength between records, which occurred about the same time.

3.3.2 Dry and wet season $\delta^{18}\text{O}_c$ -SSS reconstruction

Variability between the reconstructed wet and dry season salinities from 1955 to 2012 has previously been shown to be governed by different factors (Ramos et al., 2017). Wet season $\delta^{18}\text{O}_c$ -SSS tracked local salinity patterns but excursions in the record responded to the ENSO phase. Dry season $\delta^{18}\text{O}_c$ -SSS reconstruction, on the other hand, reflected regional changes in salinity driven by ENSO (i.e. SOI) with some excursions explained by local precipitation. The correlation is negative such that negative (positive) SOI, indicative of El Niño (La Niña) episodes, coincides with drier (wetter) conditions as the WPWP and atmospheric convection centers moves eastward (westward). In addition, the comparison between the dry season SSS reconstruction and the dry season SOI months resulted in a stronger relationship due to mature ENSO phases occurring during this season.

The extended dry and wet season salinity reconstructions continued to show distinct patterns (Fig. 3.7a). The dry season $\delta^{18}\text{O}_c$ -SSS varies between 34.2 and 34.9 psu, with a mean amplitude of 0.76 psu. Since the late 19th century, the dry season SSS record exhibits a long-term decreasing trend of 0.003 psu yr⁻¹ ($r = 0.72$, $p < 0.0001$), indicative of freshening. The wet season $\delta^{18}\text{O}_c$ -SSS, on the other hand, varies between 33.8 and 34.5 psu, showing a slightly smaller range than the dry season record, 0.71 psu. There is no observable long-term trend (slope, $m_{wet(1880-2012)} = -0.0002$ psu yr⁻¹) but a prolonged “drier” (i.e. less wet) wet season salinity anomaly is evident between 1950 and 1980. Around 1976, the wet

season SSS record shows a decreasing trend that resumes to SSS values prior to the anomalous “drier” period, indicative of recent freshening.

Figure 3.7. (a) Reconstructed dry (brown) and wet (green) season $\delta^{18}\text{O}_c$ -SSS. Brown and green shading indicate RMSR = 0.09 psu. (b) SSS difference between the dry and wet season salinity records (thick black line) is significantly correlated to the PDO with 0 (solid gray line) to 6-yr lag (not shown). Hollow circles indicate times when the dry and wet season SSS values are statistically equivalent. Significant difference was calculated by propagating the reconstruction errors between the SSS records.

While the seasonal salinity variations appear independent, there are periods when the salinity values in both seasons are statistically equivalent. Between 1958 and 1976, the salinity difference between the dry and wet season

SSS records is small to negligible (<0.15 psu, Fig. 3.7b), indicating the loss of seasonality. Before and after this time period, the salinity difference is greater than 0.15 psu, reaching a maximum of 0.72 psu in the early 1930s (Fig. 3.7b). The similarity in SSS values between 1958 and 1976 could be due to the observed excursions in the data responding to either ENSO or local rainfall at our site as previously reported (Ramos et al., 2017). However, we hypothesize that the overall decadal trend in the SSS difference at longer timescales is additionally controlled by larger scale processes.

To evaluate the controlling factors in the SSS reconstructions at longer time periods, we compared the SSS difference to the PDO index. The PDO is significantly correlated to the dry-wet season SSS difference ($r = 0.39$, $p = 0.02$, $n = 37$, Fig. 3.7b) such that the period of small SSS seasonality coincides with the predominant cold (negative) PDO phase while periods of larger SSS differences coincide with the predominant warm (positive) PDO phases. The correlations remained significant and even stronger when we applied a 3- and 6-yr lag on the PDO time series ($r_{3yr_lag} = 0.57$, $p < 0.0001$, $n = 36$ and $r_{6yr_lag} = 0.72$, $p < 0.0001$, $n = 35$).

Spectral power and coherence analyses between the salinity difference and climate indices were performed using a time resolution of 3 years. Hence, the high frequency spectrum is excluded and only low frequencies (i.e. PDO) were identified. Spectral analysis analysis reveals significant power at periods of 6.7 and 6.4 years in the SSS difference and PDO records, respectively (Fig. 3.8a). Spectral coherence, on the other hand, reveals significant coherence at periods

>27 years between records (Fig. 3.8b). Because we are interested in low frequency variability, we filtered our data using a central frequency of 0.018 ± 0.0045 to isolate for 55-yr periods, coherent in both records. The 55-yr filtered records show a strong positive relationship annually ($r = 0.99$) with the PDO leading by 6 years ($r = 0.70$, Fig. 3.8c), suggesting a strong PDO-related control on salinity variability at longer timescales.

Figure 3.8. (a) Spectral analysis of the detrended SSS difference (black) and PDO (gray) records. Significance level greater than 90% (red line for the SSS difference, pink line for PDO) are labelled. (b) Spectral coherence with phase analysis between records reveal significant coherence at periods > 27 years. Red lines indicate 90% significance level while the gray dashed lines represent confidence intervals. (c) 55-yr filtered SSS difference (black) and PDO (gray) records with a 6-yr PDO lead.

3.4 Discussion

3.4.1 Climatic controls on SST variability

Both the summer and winter Sr/Ca-SST records significantly capture SST variability, each providing records of different SST behaviors. Our SST reconstructions are significantly correlated at the beginning of the records (Fig. 3.3b) suggesting that mean SST changes are governed by similar factors. However, towards the present, the summer SST record indicates a significant warming trend that started in the 1970s, but the winter SST record shows a different response (Fig. 3.3a). Beginning in the 1970s, both records exhibit increasing variance (Fig. 3.3c). However, the winter SST variance is consistent with decadal scale changes in variance throughout the record whereas previously, summer SST variance only had a decreasing trend. A 4-century long coral-derived SST record in the western Pacific (Tierney et al., 2015) shows evidence of 20th century warming associated with greenhouse gas emissions over the most recent ~50 years. However, compared to the magnitude of coral-derived SST rise in the western Pacific (i.e. 0.02°C per decade, Tierney et al., 2015) and a 1° by 1° gridded instrumental summer SST record at our site (i.e. 0.17°C per decade, Rayner et al., 2003), our warming estimate is ~16 and ~2 times higher, respectively. This disagreement in magnitude is expected due to differences in spatial coverage of the above records. Nonetheless, the onset of SST rise in our summer record is close to the timing of regional warming onset, likely tied to anthropogenic warming. Winter SST, on the other hand, exhibits greater

sensitivity to the PDO- and EAWM-related SST changes, potentially masking anthropogenic warming, as discussed below.

Interannual to multidecadal scale variability (i.e. 50 to 70 years) are known climatic oscillations in the North Pacific during the 18th and 19th centuries (Mantua & Hare, 2002). Multidecadal scale oscillations are present in coral records from Ogasawara (Felis et al., 2010) and Koshiki (Watanabe et al., 2014) islands in Japan, reflecting PDO variability in their SST (Sr/Ca) and summer monsoon ($\delta^{18}\text{O}$) reconstructions, respectively. Tree-ring climate reconstructions from continental Asia and northwest America (e.g. D'Arrigo & Wilson, 2006; MacDonald & Case, 2005; Minobe, 1997), also exhibit strong periodicities of 50 to 70 years. Causes of multidecadal scale variability are still unclear (MacDonald & Case, 2005; Mantua & Hare, 2002), but are likely forced by ocean-atmosphere interaction and modulated by solar radiation (Minobe, 1997).

To compare the spatio-temporal behavior of the PDO, we applied a 55-year Gaussian filter (0.018 ± 0.0045) on the above PDO reconstructions (excluding the non-SST-related record from Koshiki, Fig. 3.4 and 3.5). Our winter SST shows a strong correlation with the PDO index and in both coral- and tree-ring-based reconstructions from the western Pacific showing the expected phase relationship (Table 3.1, Fig. 3.9). Significant but relatively low correlations, on the other hand, are observed between the western Pacific records and the strongly correlated records from northwest America (Table 3.1, Fig. 3.9). Due to the clustering of strong relationships between different proxies within a geographic area but a reduced correlation across regions, a change in the spatial

pattern of the PDO over time is a likely cause. Because the PDO is a sum of several atmospheric and oceanic processes that are spatio-temporally dynamic (Newman et al., 2016), the observed inconsistency between regions can be expected as proxy sensitivity changes with location (D'Arrigo & Wilson, 2006; Newman et al., 2016). Reduced correlations may also lead to increased proxy sensitivity to other local climatic or environmental influences such as ENSO, monsoon failures, volcanic eruptions, and other extreme events, resulting in disagreement between records (e.g. D'Arrigo & Wilson, 2006). Nonetheless, the good reproducibility between proxies within a region highlights an advantage to understanding similar processes that contribute to PDO variability.

Interannual oscillations observed in the western Pacific PDO records likely originate from ENSO signals known to imprint PDO variability (D'Arrigo & Wilson, 2006; Felis et al., 2010; Watanabe et al., 2014). However, coherence between our SST records and Niño 3.4 is absent. The interannual frequency of the EAWM is evident in our record but changes in its phase and amplitude are not reflected in our reconstruction, resulting in an obscured winter SST and EAWM relationship. This may be due to the strong multidecadal component driving our SST variability and masking the interannual signals. When compared with the 2.1 year filtered winter-SST and PDO records, the time when the relationship of the above records is negligible coincides with the period when the EAWM influence on winter SST is more significant (Fig. 3.5a and 3.5b). Because the PDO and EAWM impact SSTs at our site in the same direction, it can be hypothesized that these climate systems inversely modulate SST variability at

higher frequencies. Longer records are needed to verify these changes and formulate mechanisms describing the inter-relationship between the PDO and EAWM back in time.

Table 3.1. Correlation between marine and terrestrial PDO reconstructions. All numbers are 95% significant.

	PDO index	Ogasawara coral Sr/Ca (Felis et al., 2010)	East Asia tree rings (D'Arrigo and Wilson, 2006)	Northwest America tree rings (MacDonald and Case, 2005)	Northwest America tree rings (Biondi et al., 2001)
Palaui Winter SST	-0.90	-0.90	-0.92	-0.39	-0.36
PDO index		0.97	0.97	0.83	0.83
Ogasawara coral Sr/Ca (Felis et al., 2010)			0.99	0.67	0.63
East Asia tree rings (D'Arrigo and Wilson, 2006)				0.62	0.60
Northwest America tree rings (MacDonald and Case, 2005)					0.99

Figure 3.9. Fifty-five-yr filtered winter SST and other marine and terrestrial PDO reconstructions across the Pacific.

3.4.2 Climatic controls on SSS variability

The PDO impacts surface salinity by modifying the hydrological balance (i.e. evaporation/precipitation) and/or water advection (Delcroix et al., 2007). During warm (cold) PDO phases, *in-situ* salinity observations over the tropical Pacific indicates higher (lower) salinity values in the western Pacific due to decreased (increased) rainfall (Delcroix et al., 2007). However, we found opposite relationships between the PDO and salinity reconstructions during the wet season at our site when maximum annual rainfall occurs. This suggests that PDO dominantly impacts the SSS difference through water advection instead of precipitation. The Kuroshio current, a northward flowing western boundary current in the Pacific, transports high salinity western Pacific water to Luzon as it impinges its coast and intrudes into the Luzon Strait (Hu et al., 2015; Nan et al., 2015; Qu et al., 1998). During warm (positive) PDO phases, the Kuroshio transport is slower, increasing Kuroshio intrusion across the Luzon Strait (Wu,

2013) and advecting more saline western Pacific waters to Palaui during this period. Similarly, El Niño/La Niña events enhance/reduce Kuroshio intrusion across the strait (Qu et al., 2004). Changes in Kuroshio transport are more pronounced during the winter (dry) season when ENSO events mature and prominent PDOs are detected (Deser et al., 2004; Trenberth et al., 1998). Therefore, the significant difference between the dry and wet season salinity records during the predominant positive PDO phases is due to the advection of high salinity waters to our site in the dry season (Fig. 3.7b).

Between 1958 and 1976 when SSS difference is small to negligible, the dry season SSS reconstruction indicates predominance of La Niña periods as previously reported (Ramos et al., 2017). La Niña-related increase in rainfall and reduced Kuroshio intrusion during this period positively combine to decrease dry season salinity at Palaui. This period also coincides with the predominant cold PDO phase (Fig. 3.7b) similarly reducing the Kuroshio and hindering advection of more saline waters to our site during this period. Thus, the predominant cold PDO phase between 1958 and 1976 combined with ENSO-related freshening lead to insignificant changes in salinity between seasons.

Overall, salinity variability at our site implies interaction between the PDO and ENSO. Warm/cold PDO and El Niño/La Niña phases constructively combine to enhance/reduce advection of more saline waters at our site. Because the PDO is viewed as a reddened ENSO reaction (Newman et al., 2016) where warm/cold phases are analogous to El Niño/La Niña episodes, salinity as a function of PDO-related Kuroshio water advection shows consistent response to

the ENSO-related Kuroshio transport and drought/above-normal rainfall anomalies associated with El Niño/La Niña events. This suggests that the mechanisms driving ENSO-related salinity changes similarly contributes to the PDO-related SSS variability.

We also compared our salinity records with previously published SSS reconstructions in close proximity to our study site – Ogasawara (Felis et al., 2009) in the Western Pacific, and Hainan Island (Deng et al., 2013) in the northern SCS. The above records show significant freshening trends since the late 19th century of variable magnitude and timing. In Ogasawara, the abrupt freshening trend in the early 1990s by as much as 0.35‰ or 0.82 psu is attributed to a combined forcing of atmospheric changes and oceanic advection (Felis et al., 2009). Weakened westerlies together with reduced Kuroshio transports lead to pronounced freshening during this period. In contrast, a gradual freshening trend of ~0.4‰ since 1900 is observed in Hainan, northern SCS, attributed to PDO-related changes in rainfall over South China and terrestrial runoff (Deng et al., 2013). In Palau, our dry season salinity record shows a similar freshening trend of 0.4‰ (0.39 psu) since the late 1800s. While the impact of PDO on Hainan and Palau records are evident, the responses and mechanisms by which PDO affects climate patterns at these sites are variable even within the same geographic location. Thus, isolating PDO's impact on the overall freshening trend remains complex. This is expected due to the several atmospheric and oceanic processes involved in the PDO, hence distinguishing PDO-related impact is critical. In Palau, reconstructing salinity variability in different seasons presented a unique

opportunity to distinguish PDO's added impact on significant changes in salinity through time.

3.5 Conclusions

Century-long records of Sr/Ca and $\delta^{18}\text{O}$ in Palaui allow reconstruction of SST and SSS variability and evaluation of their climatic drivers. Our SST records significantly captures SST variability with the summer and winter records exhibiting different climate sensitivities. The summer SST record provides evidence of significant warming that commenced in the 1970s. This warming is likely tied to the rise in western Pacific SSTs associated with greenhouse warming. Our winter SST, on the other hand, is sensitive to interannual to multidecadal scale changes driven by the EAWM and the PDO. Similar to other terrestrial and marine-based PDO records in the northwestern Pacific, our record exhibits decadal climate variability strongly correlated to the PDO. Compared to PDO records in the eastern Pacific, reduced correlation across basins may indicate a change in the spatial pattern of the PDO. Because the PDO and EAWM affect SST at our site in a similar direction, the dominance of PDO-related changes in our winter SST record obscures the monsoonal impact. However, their interrelationship through time may provide clues on the reversing modulation of the PDO and EAWM to winter SSTs at high frequencies.

Reconstructing salinity variability at different seasons similarly allowed for identifying distinct salinity controls between the wet and dry seasons. Both ENSO and non-ENSO related rainfall patterns are evident in our salinity records.

By determining the seasonal salinity difference through time, PDO's control on salinity is additionally revealed. The PDO and ENSO constructively combine to enhance/reduce advection of more saline Kuroshio waters at our site. Overall, we were able to demonstrate that climate records from a tropical reef environment like Palaui significantly captures PDO variability and related changes over a century. This implies that the tropical western Pacific is a key site in understanding multi frequency climate variability including its impact on tropical climate at longer timescales.

3.6 References

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Chapter 4

Coral-based records of sea surface temperature and salinity variability in the Luzon Strait since the end of the Little Ice Age

Abstract

Reconstructions of key climate parameters prior to anthropogenic influences serve to constrain decadal to multi-century natural climate variability. In the western Pacific region, relatively few reconstructions exist north of the Western Pacific Warm Pool (WPWP), a region critical to global climate. In this study, we collected a coral core from Houbihu, southern Taiwan and generated a 225-year reconstruction of wintertime sea surface temperature (SST) and sea surface salinity (SSS) records derived from paired *Porites* Sr/Ca and $\delta^{18}\text{O}$ profiles extending back to the end of the Little Ice Age (LIA, 1850 CE). Multidecadal winter SST trends generally track regional surface temperature reconstructions, indicating the dominant influence of solar and volcanic radiative forcings. A three-year binned SSS record, on the other hand, reflects an advection signal linked to the East Asian Winter Monsoon (EAWM) and the Pacific Decadal Oscillation (PDO), both influencing variations in the Kuroshio Intrusion (KI) across the Luzon Strait. Relative to the late 1900s, our SST and SSS reconstructions document $<1^{\circ}\text{C}$ cooler and <0.5 psu drier (higher salinity) conditions, respectively, during the end of the LIA, supporting other lines of

evidence of a retracted WPWP region during this period. In the late 20th to early 21st century, SST and SSS record warming of 0.16°C per decade and 0.15 psu per decade, respectively, highlighting the potential impact of anthropogenic forcing in the extension of the WPWP.

4.1 Introduction

Understanding long-term climate variability and constraining future changes rely on reconstructions of key climate parameters beyond the limits of observational data and anthropogenic influences (Dunbar & Cole, 1999; Gagan et al., 2000; Lough, 2010). Massive corals provide a means of generating high-resolution multi-century climate records, such as sea surface temperature (SST) and sea surface salinity (SSS) (Dunbar & Cole, 1999; Gagan et al., 2000), where influences of the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and East Asian monsoon systems may be examined.

One of the recent climate intervals that is of relevance in understanding widespread and naturally-forced climatic change is the Little Ice Age (LIA) (Bradley & Jones, 1993; Dunbar & Cole, 1999). The LIA is a 400- to 500-year cold interval (1300s to 1800s Common Era-CE) that is primarily identified in the high latitude Northern Hemisphere (e.g. D'Arrigo et al., 2006; Goodkin et al., 2008; Mann et al., 1999; Overpeck et al., 1997), but extensive evidence exists for cooling in the tropics (e.g. Chen et al., 2018; Deng et al., 2017; Newton et al., 2006; Oppo et al., 2009; Watanabe et al., 2001; Yan et al., 2015) and the Southern Hemisphere (e.g. Bradley & Jones, 1993; DeLong et al., 2014; 2016). LIA

conditions, in which terrestrial and ocean cooling were estimated to be between 0.4°C and 4°C relative to the present (Bradley & Jones, 1993), are linked with minimum solar forcing and higher volcanic activity during this period (Bradley & Jones, 1993; Crowley, 2000; Mann et al., 1999).

In the western Pacific region where the East Asia-Australia monsoon system prevails, LIA cooling is associated with a gradation of a drier southeast China – a wetter Western Pacific Warm Pool (WPWP) – and a drier north Australia region relative to the present (Yan et al., 2015 and references therein). This spatial variability is hypothesized to be driven by the expansion or contraction of the monsoon area or the Intertropical Convergence Zone (ITCZ) rain belt (Griffiths et al., 2016; Yan et al., 2015), in response to reduced solar forcing during this period.

As the greatest source of heat and moisture, the WPWP impacts critical ocean-atmosphere interactions worldwide (D'Arrigo et al., 2006; Webster & Lukas, 1992). Changes in its temperature, size and position thus have considerable effects in regional and global climate variability (Abram et al., 2009; Cravatte et al., 2009; Emanuel, 2005; Oppo et al., 2009; Yan et al., 1992). Paleoreconstructions based on networks of various climate archives are increasingly generated in various time spans to investigate large-scale atmosphere-ocean interactions related to the WPWP. For example, several coral-derived climate reconstructions beyond the LIA (e.g. Calvo et al., 2007; D'Arrigo et al., 2006; DeLong et al., 2012; Hendy et al., 2002; Lough, 2011) have complemented other marine and terrestrial-derived reconstructions in the region

(e.g. D'Arrigo et al., 2006; Deng et al., 2017; Yan et al., 2015) to examine the drivers of spatio-temporal changes in hydrological processes in the western Pacific. However, most of these coral-derived records are concentrated in the south equatorial western and central Pacific regions, potentially creating a bias in the observed variability (Tierney et al., 2015).

In this paper, we present a 225-year reconstruction of wintertime SST and SSS histories derived from paired *Porites* Sr/Ca- $\delta^{18}\text{O}$ records from Houbihu, southern Taiwan. We examine the climatic drivers of the observed SST and SSS variability since the end of the LIA in this region at the northern edge of the WPWP expected to be variably influenced by ENSO cycles and the East Asian monsoon system.

4.2 Methods

4.2.1 Study site and coral sampling

In May 2013, a *Porites* sp. core was collected from 6 m water depth off the coast of Houbihu, southern Taiwan (21.9°N, 120.7°E, Fig. 4.1). The core was drilled using an underwater hydraulic drill with an ~85 mm diameter core bit. Houbihu faces Nanwan Bay and the Luzon Strait to its south. The subtropical climate of southern Taiwan is affected by the East Asian Monsoon, in which maximal rainfall occurs during the southwest monsoon season (May to October) and cold fronts propagate from Siberia during the northeast monsoon season (November to April) (Shen et al., 2005). No major input of freshwater from rivers drains into the bay (Shen et al., 2005; Shen et al., 2005) but tidally-induced

upwelling delivers cold intermediate water into the bay daily (Lee et al., 1999a; Lee et al., 1999b; Lee et al., 1997).

Instrumental SST and salinity records (See Section 4.2.4) from 1982 to 2013 indicate that June to September (JJAS) are the warmest and wettest months while December to March (DJFM) are the coldest and driest months. Annual SST ranges from 26.1°C to 27.9°C with a mean amplitude of 1.8°C and annual SSS ranges from 33.8 to 34.5 psu with a mean amplitude of 0.69 psu. Annual rainfall averages 2000 ± 500 mm/yr (1σ , Climate Weather Bureau (CWB) at Hengchun County, (Shen et al., 2005).

Figure 4.1. A coral core of *Porites lobata/lutea* was collected offshore of Houbihu, southern Taiwan (21.9°N, 120.7°E) in May 2013. Houbihu faces Nanwan Bay and Luzon Strait to its south (inset).

4.2.2 Coral subsampling

Following the procedures outlined in (Ramos et al., 2017), the coral cores were cleaned, cut into 7 mm thick slabs, and x-rayed (See Appendix A) prior to subsampling. A micrometer-aided drill press was used in subsampling at 0.5 mm increments along the major growth axis. Around 24 subsamples were drilled per year of extension, yielding a near-biweekly resolution. Approximately 200 µg and 40 to 90 µg powder sample splits were set aside for Sr/Ca and stable isotope measurements, respectively.

4.2.3 Sr/Ca and $\delta^{18}\text{O}$ measurements

Sr/Ca subsamples were dissolved in 2.5 mL of 5% HNO₃ overnight. An inductively coupled plasma - optical emission spectrometry (ICP-OES, Thermo iCAP 6000 Series) at the Asian School of the Environment (ASE), Nanyang Technological University (NTU) was used to measure Sr and Ca simultaneously. Instrument drift and matrix effects resulting from varying calcium concentrations (Schrage, 1999) were corrected using solution standards (0 to 80 ppm) run at constant intervals. Sample unknowns, blanks and powder standards JCp-1 (Okai et al., 2001) with a consensus Sr/Ca value of 0.01932 ppm (± 0.0002) or 8.838 mmol/mol (± 0.089) (Hathorne et al., 2013) and an in-house powder standard (*Porites* sp.) were simultaneously prepared. Repeat measurements of JCp-1 and in-house coral standard analyzed over a two-year period showed good reproducibility: 0.019291 ± 0.00004 ppm (1σ , relative standard deviation (RSD))

= 0.18%, $n = 1074$) and 0.019289 ± 0.00005 ppm (1σ , RSD = 0.25%, $n = 396$), respectively.

Oxygen stable isotope, $\delta^{18}\text{O}$, was measured using a ThermoFisher MAT-253 isotope ratio mass spectrometer (IRMS) at ASE, NTU. Prior to measurement, powdered subsamples were acidified with 105% H_3PO_4 at 70°C in an automated Kiel IV carbonate device. Measurements were calibrated relative to Vienna Peedee belemnite (VPDB) using external standards including National Bureau of Standards (NBS) 19 ($\delta^{18}\text{O} = 2.20\text{‰}$) and NBS 18 ($\delta^{18}\text{O} = 23.2\text{‰}$) (Stichler, 1995). Repeat measurements of NBS 19 analyzed over a two-year period is $\pm 0.06\text{‰}$ (1σ , $n = 103$). In addition, Estremoz, Carrara, and TSF standards were routinely measured yielding the following average values and standard deviations over a two-year period: $\delta^{18}\text{O}_{\text{Estremoz}} = 5.957 \pm 0.08\text{‰}$; $\delta^{18}\text{O}_{\text{Carrara}} = 1.966 \pm 0.07\text{‰}$; $\delta^{18}\text{O}_{\text{TSF}} = 2.276 \pm 0.07\text{‰}$ (total of all 3 standards, $n = 3586$).

4.2.3.1 Dry-season $\delta^{18}\text{O}$ measurements

During the calibration period (1982 to 2013), $\delta^{18}\text{O}$ was measured on all samples. Prior to this period, $\delta^{18}\text{O}$ was only measured on dry season samples. The dry season $\delta^{18}\text{O}$ samples were selected on the basis of the winter-time Sr/Ca depth- and time-series data, in which $\delta^{18}\text{O}$ and Sr/Ca maxima coincide interannually. Dry season was selected because $\delta^{18}\text{O}$ -SSS during this season has regional rather than local drivers (See Appendix E and Sec. 4.3.2.). The reduction in $\delta^{18}\text{O}$ sample points is unlikely to create a bias across time periods as we consistently examine seasonal extremes (i.e. winter/dry versus summer/wet) at

interannual to multidecadal timescales. Time assignment for the interannual dry season $\delta^{18}\text{O}$ followed that of the paired Sr/Ca data (See Sec. 4.2.5).

4.2.4 Instrumental data

Monthly 1° by 1° grid resolution ($1^\circ \approx 111$ km) SST data from the Integrated Global Ocean Services System Products Bulletin (IGOSS, http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/, centered at 21.5°N , 120.5°E , Reynolds et al., 2002) was used for SST calibration over a 31-year period, 1982 to 2013. We chose this dataset for calibration and comparison, rather than the highly-resolved SST datasets (e.g. Advanced Very High-Resolution Radiometer Pathfinder-AVHRR v.5, Kilpatrick et al., 2001), because IGOSS SST provides a more continuous record over a longer time period.

SSS and precipitation data were also acquired to evaluate the relative influence of salinity in the coral $\delta^{18}\text{O}$ record. Monthly gridded 0.25° square resolution SSS data was obtained from Simple Ocean Data Assimilation (SODA v. 2.2.4, http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4, Carton & Giese, 2008) dataset centered at 21.75°N , 120.75°E at a depth of 5 m. We chose this dataset due to its record length and availability in the region. We found that other salinity products are spatially (e.g. Delcroix et al., 2011) and temporally (e.g. Aquarius, Lagerloef et al., 2008) limited. We note, however, that SODA SSS data earlier than the 1960s should be used with caution due to the sparse hydrographic observations during this period (Giese & Ray, 2011). Local

rainfall data from 1897 to 2013 provided by Taiwan Climate Weather Bureau at Hengchun County was used for comparison.

4.2.5 Chronology development

Distinct annual density bands visible in x-radiographs and seasonal cycles of Sr/Ca were used in developing age-depth models. Over the 31-yr instrumental and calibration periods, coral Sr/Ca profile minima, maxima, and inflection points were aligned with their respective SST points each year using the Analyseries software (Paillard et al., 1996). Beyond the calibration period, time was assigned using the averaged SST climatology, similarly aligning Sr/Ca and SST minima, maxima and inflection points. The same pointers in the Sr/Ca-SST age model was applied to the corresponding $\delta^{18}\text{O}$ record. Linear interpolation was then used to convert the proxy depth series into monthly time series.

4.2.6 Data analysis

The spectral characteristics of the proxy records were estimated using a simple fast Fourier transform (FFT) algorithm. Significance level (90%) was estimated using 10,000 Monte Carlo simulations. Non-parametric coherence multitaper method and phase analysis with bias correction (<http://www.people.fas.harvard.edu/~phuybers/Mfiles/index.html>, e.g. Huybers & Denton, 2008) were also performed to evaluate the significant frequencies shared between proxy reconstructions and key climatic indices. Spectral coherence was estimated with 8 windows and 50 iterations on Monte Carlo error

estimates. A Gaussian filter centered at significant frequencies was also applied using the Analyseries software (Paillard et al., 1996), to further isolate and observe specific frequencies through time.

4.3 Results

4.3.1 Sr/Ca-SST

4.3.1.1 Monthly calibration

Least squares linear regression (LSLR) of monthly Sr/Ca to IGOSS SST from 1982 to 2013 (Fig. 4.2a) shows a significant inverse relationship:

$$\text{Sr/Ca} = 10.604 (\pm 0.029) - 0.064 (\pm 0.001) \times \text{SST } (^{\circ}\text{C}) \quad (4.1)$$

$$r = -0.95, p < 0.0001, n = 377, \text{RMSR} = 0.59^{\circ}$$

where the root-mean-square of the residual (RMSR) is the difference between the instrumental and reconstructed SSTs. The calibration slope is within the range of slopes reported in *Porites*-based Sr/Ca-SST calibration studies (i.e. 0.042 to 0.080 mmol mol⁻¹ °C⁻¹; e.g. Alibert & McCulloch, 1997; Corrège, 2006; Murty et al., 2018). Compared with previous calibrations in Nanwan Bay (i.e. 0.051 and 0.053 mmol mol⁻¹ °C⁻¹, Shen et al., 1996; Shen et al., 2005), our calibration slope is steeper. The difference in the slopes may be explained by the differences in sampling location and resolution. Earlier Sr/Ca-SST calibrations were generated from corals collected at the mouth of the water intake pond of a nuclear power plant facility along the coast of Kenting. The collection depth is shallower, 2 and

4 m, compared to our offshore site which is about 2000 m away from the coast. Presumably, warmer SSTs inside the shallower water intake pond compared to the well-mixed offshore reef waters at our sampling site resulted in a dampened Sr/Ca-SST slope (e.g. Murty et al., 2018). Previous calibrations were also based on lower sub-sampling resolution, approximately 10 to 15 samples per year. This resolution is lower by half compared to our sampling yield of 20 to 28 samples per year. The shallower sampling location (i.e. presumably warmer ambient temperatures) and coarser sampling resolution both serve to dampen previous Sr/Ca-SST slopes compared to this study.

Figure 4.2. (a) Houbihu monthly Sr/Ca linearly regressed against IGOSS SST. (b) Sr/Ca-SST reconstruction (solid blue line) compared with IGOSS SST (dashed gray line). (c) Winter season Sr/Ca-SST reconstruction (solid blue line) compared with IGOSS SST (dashed gray line). Shaded areas represent RMSR = 0.59°C.

4.3.1.2 Inter-annual calibrations

We derived interannual Sr/Ca-SST relationships by averaging 4-month summer (JJAS-June to September), 4-month winter (DJFM-December to March) and interannual Sr/Ca and SSTs (Table D3.1, See Appendix D). The resultant interannual calibration equations are statistically significant (Table D3.1, See Appendix D). However, in all instances, the individual calibration equations exhibit less steep slopes (i.e. $m_{annual} = -0.054$; $m_{winter} = -0.058$; $m_{summer} = -0.049$ mmol mol⁻¹ °C⁻¹, Table D3.1, See Appendix D) compared with the monthly calibration equation ($m_{monthly} = -0.064$ mmol mol⁻¹ °C⁻¹), likely reflecting the limited interannual SST variability at our site (i.e. 1.8°C). This reduction in Sr/Ca-SST slope may also result in high reconstruction errors (RMSRs). We then applied the monthly calibration equation (Equation 4.1) to 4-month summer, 4-month winter and annual averaged Sr/Ca to best minimize reconstruction errors. The RMSRs calculated from applying the monthly calibration equation are smaller than RMSRs calculated using the independent SST calibrations (Table D3.1, See Appendix D), less than 30% of the mean annual, winter and summer SST ranges, indicating higher signal-to-noise ratios.

However, among the interannual SST reconstructions, the correlation between the summer Sr/Ca-SST and IGOSS SST is relatively moderate ($r = 0.48$, $p = 0.01$) compared to those of winter and annual SSTs ($r > 0.70$, $p << 0.0001$), raising concerns on the reliability of the SST reconstructions during this season (Table D3.1 and Fig. D3.1). Previous studies in slow growing corals have demonstrated that summer Sr/Ca variability compared to winter is impacted by

growth effects (e.g. Goodkin et al., 2007; Goodkin et al., 2005), resulting in dampened slopes and ineffective calibrations during this season. No previous studies have found this effect in faster growing *Porites* corals. However, previous studies have shown that relatively higher summer SST variability compared to gridded SST challenges a robust summer SST reconstruction (e.g. Ramos et al., 2017 and See Chapter 3). While Houbihu summer Sr/Ca do not correspond to varying extension rates (Fig. D3.2), SST variability during this season is small (i.e. 1.6°C) (Table D3.1 and Fig. D3.1), potentially preventing us from constraining the reconstruction errors enough to interpret interannual trends. Due to these reasons, we further investigate the SST variability in Houbihu during the winter season only. Annual SSTs are effectively an average of the summer and winter SST variabilities, hence focusing on the winter season eliminates the impacts of the poorly constrained summer variability.

The winter Sr/Ca-SST varies 3.6°C over the calibration period, approximately 0.9°C greater than that of the IGOSS SST (i.e. 2.7°C, Fig. 4.2c), implying an overestimation in winter SST variability back in time. One possible source of the observed discrepancy may be due to ENSO-related changes in extension rates that may potentially lead to periods of no aragonite accretion. The years contributing to systematically higher Sr/Ca estimates coincide with some of the strongest El Niño events known to inhibit coral growth or cause die-offs due to bleaching (e.g. Suzuki et al., 2003). However, our *Porites* core extends at a consistent rate, 12 mm yr⁻¹ (± 0.95 , 1 σ), over the calibration period. In addition, the winter Sr/Ca values do not correlate with annual extension rate ($r < 0.02$, $p >$

0.05, Fig. D3.2), indicating that the high Sr/Ca-SST variability is not caused by growth effects.

The spatial coverage of the gridded SST likely explains the observed difference in SST variability. The gridded SST averages multiple measurements over a $\sim 110 \text{ km}^2$ area, where subtle SST changes (e.g. tidally-induced upwelling in Nanwan Bay) may not be fully represented. Despite the increased Sr/Ca variability likely reflecting real local SST changes, the interannual trends between coral Sr/Ca-SST and IGOSS SST show similar patterns of variability, giving indication that relative variability compared to the present should be consistent.

4.3.1.3 Interannual winter SST reconstruction

Interannual winter Sr/Ca values extending back to 1788 were converted to SST using Eqn. 4.1. The winter Sr/Ca-SST reconstruction exhibits interannual to multidecadal-scale variability within a 4.8°C SST range (21.7°C to 26.5°C , Fig. 4.3a). The lowest SSTs were observed during the late 19th century, when the winter minimum reached 21.7°C in 1874. This period between the late 18th century and 20th century, which shows cooling of about $\sim 0.4^\circ\text{C}$ below the mean, coincides with the end of the LIA. During this period, episodes of distinct warming of similar magnitude were also observed in the mid-1840s and at the turn of the 20th century, about $\sim 1.5^\circ\text{C}$ above the mean of the whole record. The warmest SSTs were recorded in the most recent years, reaching a winter SST maximum of 26.5°C in 1982. The winter SST record exhibits a significant

warming trend of about $0.016^{\circ}\text{C yr}^{-1}$ or $\sim 1.0^{\circ}\text{C}$ over the last 6 decades beginning 1950 ($r_{\text{winter}} = 0.40$, $p = 0.002$).

Figure 4.3. Comparison of our SST reconstruction with other multiproxy surface temperature reconstructions in the region since the late 18th century. (a) Houbihu winter SST record (blue). Thinner line represents the interannual record whereas the thicker line represents the 11-year running mean. (b) Asia (brown, Shi et al.,

2015) and Northern Hemisphere (green, D'Arrigo et al., 2006) 100-year smoothed and interannual surface temperature reconstructions, respectively, primarily based on tree-ring chronologies. Temperature records from ice cores and other historical documents are additionally included in Shi et al., 2015. Dashed brown line representing a grid point closest to Taiwan was extracted for a similar-scale comparison. (c) Western Pacific SST reconstruction based on coral Sr/Ca and $\delta^{18}\text{O}$ records (Tierney et al., 2015). The above regional surface temperature reconstructions show anomalies with respect to the most recent 30 to 40 years of each record. Radiative forcing data include (d) interannual (thin red line) and 11-year running mean (thick red line) record of solar irradiance (Lean, 2000), (e) reconstructed volcanic forcing (black line, inverted axis) (Crowley, 2000) and (f) well-mixed greenhouse gases (GHGs, olive line, Schmidt et al., 2002).

4.3.1.4 Influences on the observed winter SST variability

The Houbihu winter SST record broadly reflects trends from a long-term multi-proxy surface temperature reconstruction in Asia (Shi et al., 2014, Fig. 4.3b), from a coral-based western Pacific SST reconstruction (Tierney et al., 2015, Fig. 4.3c) and from a tree-ring-based northern hemisphere surface temperature reconstruction (D'Arrigo et al., 2006, Fig. 4.3b). This suggests that subtropical western Pacific climate is largely controlled by global forcing factors such as solar (i.e. Lean, 2000) and volcanic radiative forcings (i.e. Crowley, 2000, Fig. 4.3d and 4.3e). The 11-yr smoothed winter SST is significantly correlated with solar irradiance ($r_{\text{winter}} = 0.61$, $p < 0.0001$, $n = 203$). Spectral coherence between these records reveal a significant in-phase correlation at multidecadal to centennial frequencies (i.e. 26 to 208 years cycle⁻¹, Fig. 4.4b.1), similarly captured by regional-scale surface temperature reconstructions from both land and ocean. A lagged relationship at higher frequencies (i.e. 2 to 3 years cycle⁻¹) is also observed between winter SST and solar irradiance (Fig. 4.4b.1),

likely explained by the ocean's higher heat capacity and processes such as ocean mixing, delaying the oceanic response to atmospheric forcing (e.g. Goodkin et al., 2008; Long et al., 2014).

The Dalton Minimum, a period of lower solar flux at the beginning of the 19th century, coincides with a period of high volcanic activity (Fig. 4.3a and 4.3e), which is known to induce atmospheric cooling for up to ~4 years (e.g. ~1.5°C cooling after Mt. Pinatubo eruption, Robock & Mao, 1995; Wigley, 2005). Therefore, solar and volcanic forcing both played a significant role in LIA cooling (Bradley & Jones, 1993; Crowley, 2000), reflected in hemispheric-scale records and in our winter SST reconstruction (Fig. 4.3). Following the Dalton Minimum, the increase in solar flux likely contributed to an increase in winter SST in the mid-1840s (Fig. 4.3a and 4.3d), evident in other local and regional records (e.g. Shi et al., 2014, Fig. 4.3b). Between 1850 and 1900, the gradual decrease in solar flux and volcanic activity (Fig. 4.3d and 4.3e) do not explain the observed fluctuation in the winter SST at Houbihu (Fig. 4.3a). During this time, the Houbihu coral record disagrees with other surface temperature records, indicating that the SST variation during this period may be more locally influenced. At the turn of the 20th century, the effect of the gradual increase in solar flux (Fig. 4.3d) is likely masked by the relatively high volcanic activity during this period. The expected SST rise at our site is not evident (Fig. 4.3a) whereas some regions in Asia experienced declining temperature (e.g. Shi et al., 2014, Fig. 4.3b). Between 1950 and 2000, solar irradiance plateaued but recorded its highest values over the last 2 centuries (Fig. 4.3d). During this

period, the winter SST at our site shows an overall increasing trend (Fig. 4.3a) likely tied to anthropogenic warming (Fig. 4.3f). A record of well-mixed greenhouse gas-radiative forcing (Schmidt et al., 2012) show that its magnitude increased twice as much in the recent 50 years relative to its initial rise in ~1840. However, this warming trend is punctuated with periods of lower SSTs, potentially forced by high volcanic activity occurring during or before these pronounced SST dips (Fig. 4.3a and 4.3e).

Spectral analysis on the 225-year winter SST record also reveals significant variance between multidecadal frequencies of 52 and 70 years cycle⁻¹ and at interannual frequencies between 2 and 5 years cycle⁻¹ (Fig. 4.4a), suggesting that our SST record is sensitive to interannual and decadal scale variability influencing the subtropical western Pacific. Spectral coherence between our winter SST record and ENSO (Emile-Geay et al., 2013), which has power at several frequencies between 2.4 and 5 years cycle⁻¹ (Fig. 4.4c), reveals significant correlation at multidecadal frequencies > 26 years cycle⁻¹, and between 2 and 3 years cycle⁻¹ (Fig. 4.4c.1). Comparing our record to the EAWM (D'Arrigo et al., 2005) and the PDO (<http://research.jisao.washington.edu/pdo/PDO.latest>), we found no significant coherence at expected frequencies between our record and these indices, (i.e. no coherence at interannual and multidecadal periods, respectively, Fig. D3.3), indicating that their impacts are limited or masked by other atmospheric and oceanic forcing.

Figure 4.4. Spectral analysis of (a) detrended (i.e. linear trend is removed) Houbihu winter SST anomalies, (b) solar irradiance and (c) ENSO index. Significance level greater than 90% (red lines) are labelled. Spectral coherence and phase analyses were also performed between our winter record and (b.1) solar irradiance and (c.1) ENSO.

To further investigate the variability between ENSO and Houbihu winter SST, we filtered both records using a central frequency of 0.4087 ± 0.0817 cycles year⁻¹, isolating 2- to 3-year periods (biennial, average of 2.1 years cycle⁻¹). The maximum correlation between records is found when the winter SST record is moved forward in time by a year ($r = 0.34$, $p < 0.0001$, $n = 207$, Fig. 4.5a). This offset relationship may be due to age-model uncertainties, where an extra 1 year is artificially added when merging the overlapping sampling tracks. The low but significant overall correlation of the bandpass filtered records is potentially due to the varying phase relationship within the 2 to 3-year band (Fig. 4.4c.1). Between 1868 and 1949, ENSO and winter SST are significantly correlated showing the expected phase relationship (Fig. 4.5b). Beyond this period, between 1823 and 1867, and 1950 towards the present, coinciding with the end of the LIA and the onset of the recent warming trend in Houbihu, respectively, both records are weakly correlated (Fig. 4.5b).

Results of the 50-year running variance applied on the bandpass filtered records exhibit a covarying relationship between ENSO and Houbihu winter SST (Fig. 4.5c). Both records exhibit reduced variance at biennial frequencies at the end of the LIA and towards the end of the 20th century, although not of comparable magnitudes. An increased variance, on the other hand, is observed around the turn of the 20th century. The above results suggest that the reduced variance at the end of the LIA and during the recent warming may explain the weak correlation between ENSO and winter SST at Houbihu (Fig. 4.5).

Figure 4.5. (a) Bandpass (2 to 3-year cycle⁻¹) filtered winter SST (blue) and ENSO (black) timeseries. A 1-year offset is observed between the filtered records possibly due to age-model uncertainties. The winter SST record is then moved forward in time by a year (b) 50-year running correlation reveals significant relationship between 1860 and 1950. Horizontal red line represents 95% significance level. (c) 50-year running variance of winter SST (blue) and ENSO (black) records reveal changes in decadal behavior.

4.3.2 $\delta^{18}\text{O}$ -SSS

4.3.2.1 *Monthly calibration*

Monthly coral carbonate $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_c$) is positively correlated with SODA SSS ($r = 0.64$, $p = 0$, $n = 348$, Fig. D3.4) and negatively correlated with IGOSS SST ($r = -0.81$, $p = 0$, $n = 377$, Fig. D3.4). The paired $\delta^{18}\text{O}_c$ and Sr/Ca records are

also strongly correlated ($r = 0.83$, $p = 0$, $n = 377$, Fig. D3.4) as both proxies are dependent on SST. The SST dependence of monthly $\delta^{18}\text{O}_c$ in Houbihu is $-0.19\text{‰ }^{\circ}\text{C}^{-1}$, similar to a previous offshore *Porites* $\delta^{18}\text{O}_c$ – SST calibration southeast of Nanwan Bay (i.e. $-0.18\text{‰ }^{\circ}\text{C}^{-1}$, Li et al., 2017). These records exhibit higher SST sensitivity than those collected from the water intake pond (i.e. $-0.14\text{‰ }^{\circ}\text{C}^{-1}$, Chiang et al., 2010), likely a result of the environmental differences between the collection sites. Nonetheless, the above slopes are typical of known *Porites* $\delta^{18}\text{O}_c$ – SST sensitivity (i.e. -0.15 to $-0.22\text{‰ }^{\circ}\text{C}^{-1}$, Corrège, 2006; Gagan et al., 2000; Lough, 2004). The strong $\delta^{18}\text{O}_c$ relationship to instrumental and Sr/Ca-derived SST records may indicate that seasonal $\delta^{18}\text{O}_c$ in Houbihu is primarily influenced by SST variations. However, due to the strong correlation between monthly instrumental SST and SSS records ($r = -0.75$, $p = 0$, $n = 348$), the interannual $\delta^{18}\text{O}_c$ signal may be attenuated as SST and SSS impact $\delta^{18}\text{O}_c$ in opposite directions. Therefore, we further evaluate the $\delta^{18}\text{O}$ sensitivity at interannual timescales.

4.3.2.2 Inter-annual calibrations

Similar to our Sr/Ca data, we derived 4-month dry (winter-DJFM) and wet (summer-JJAS) season $\delta^{18}\text{O}_c$ records and compared these with instrumental data over the calibration period. Because we are interested in regional scale salinity changes, we first present the dry season $\delta^{18}\text{O}_c$ – SSS calibration and reconstruction in this chapter. The wet season $\delta^{18}\text{O}_c$ calibration results reflecting local rainfall patterns are described in Appendix E.

At interannual and 3-yr binned timescales, dry season $\delta^{18}\text{O}_c$ is significantly correlated to IGOSS SST and its Sr/Ca pair (See Appendix D3.2). This suggests that the $\delta^{18}\text{O}$ of the seawater ($\delta^{18}\text{O}_{\text{sw}}$) may be isolated by removing the significant $\delta^{18}\text{O}_{\text{SST}}$ component from the total $\delta^{18}\text{O}_c$ values. While the resultant $\delta^{18}\text{O}_{\text{sw}}$ is significantly correlated with SODA SSS (See Appendix D3.2), the reconstructed $\delta^{18}\text{O}_{\text{sw}}$ -SSS exhibits variability that is 1.5 times larger than that of the instrumental SSS (Fig. D3.5), indicating that the reconstruction error is less constrained and may generate unrealistic SSS estimates back in time. Because SSS dominates the dry season $\delta^{18}\text{O}_c$ rather than SST (See Appendix D3.2), which is supported by the higher correlation strength between $\delta^{18}\text{O}_c$ and SSS compared to those of SST and Sr/Ca (See Appendix D3.2), directly regressing $\delta^{18}\text{O}_c$ to SSS may be a more reasonable approach. Doing so yields (Fig. 4.6):

$$\delta^{18}\text{O}_{c_3\text{yr_dry}} = -34.746 (\pm 6.586) + 0.876 (\pm 0.191) \times \text{SODA SSS}_{3\text{yr_dry}} (\text{psu})$$

$$r = 0.85, p = 0.002, n = 10, \text{RMSR} = 0.07 \text{ psu} \quad (4.2)$$

where the RMSR is equivalent to 18% of the mean dry SSS range (i.e. 0.40 psu). Regressing $\delta^{18}\text{O}_c$ to SODA SSS reduced the reconstruction error by half (See Appendix D3.2, Fig. D3.5), generating more reliable SSS estimates. Local rainfall during this season does not exert influence on the $\delta^{18}\text{O}_c$ -SSS variability ($r = 0.25, p > 0.05, n = 10$), indicating that regional scale atmospheric or oceanographic processes impact surface salinity variability during the dry season.

Figure 4.6. (a) Dry season $\delta^{18}\text{O}_c$ and SODA SSS are strongly correlated. (b) Reconstructed SSS shows good agreement with instrumental SSS data. Shading represent RMSR = 0.07 psu.

While we have effectively constrained potential errors in deriving $\delta^{18}\text{O}_{\text{sw}}$ and increased the signal-to-noise ratio by consistently using a 3-yr binned calibration, discrepancies in the absolute values between the instrumental and reconstructed SSS data can still be expected. Nevertheless, the overall interannual means and trends between records are similar, giving indication that relative variability should be captured consistently across time.

4.3.2.3 Inter-annual dry season SSS reconstruction

To fully assess the climatic drivers of the dry season surface salinity variability, we extended the dry season $\delta^{18}\text{O}_c$ -SSS records back to 1788 at 3-yr binned timescales (Fig. 4.7a). The extended dry season $\delta^{18}\text{O}_c$ -SSS record exhibits interannual to multidecadal scale variability stippled with several rapid salinity shifts over a 2-century period (Fig. 4.7a). From 1826 to 1835, salinity rapidly

rose by 0.79 psu, reaching a record maximum of 35.27 psu. Following this period, salinity steeply decreased to 34.48 in 1844. Prior to the sharp increase in the early 1860s, salinity reached one of its minimum values in 1856 (i.e. ~34.34 psu). These abrupt salinity shifts in a period showing higher salinity values relative to the present, maximum of ~0.62 psu relative to the mean, coincide with the end of the LIA. Salinity gradually decreased to one of its lowest values of 34.34 psu in 1940, indicating a freshening trend around the turn of the 20th century (i.e. 0.006 psu yr⁻¹ or 0.48 psu over ~8 decades (1862 to 1940); $r = -0.78$, $p < 0.0001$). After which, salinity began to rapidly shift by ~0.6 psu to more saline values in 1964. From this period towards 2012, a steeper freshening trend relative to the previous period is observed (i.e. 0.015 psu yr⁻¹ or 0.70 psu over the past ~5 decades (1964 to 2012); $r = -0.83$, $p < 0.0001$).

4.3.2.4 Influences on the observed dry season SSS variability

We compared our dry season SSS record with an index of the EAWM (i.e. D'Arrigo et al., 2005), to examine its influence on the salinity variability in Houbihu and the surrounding region. The dry season SSS record is significantly correlated with the EAWM ($r = -0.33$, $p = 0.02$, $n = 48$, Fig. 4.7b), such that stronger (positive) EAWM corresponds to low salinity, indicating wetter/fresher conditions and vice versa. The freshening trend observed between 1862 to 1940 corresponds to the strengthening of the EAWM during this period. Conversely, the shift towards more saline values around the 1930s lasting until the next three decades corresponds to weaker EAWM conditions. Stronger than normal EAWM

generally leads to active convection over the tropical western Pacific, the Maritime Continent and the SCS region and reduced precipitation in Eastern China (D'Arrigo et al., 2005; Wang & Chen, 2014). Because records of local rainfall during the dry season do not correspond to SSS variability during this season, the influence of the EAWM may lie in the advection of these surface waters across the Luzon Strait, where the western Pacific and SCS waters effectively interact.

The dry season SSS record is also significantly correlated with the winter PDO index ($r = -0.49$, $p = 0.002$, $n = 38$, Fig. 4.7c), where warm (cold) PDO phases correspond to low (high) SSS estimates. This correlation is opposite of the surface salinity-PDO relationship brought about by its link with ENSO and rainfall (e.g. Delcroix et al., 2007), suggesting that similar to the EAWM, the PDO impacts Houbihu salinity through water advection.

The water exchange across the Luzon Strait is dominated by the Kuroshio Intrusion delivering warmer and more saline western Pacific waters into the SCS (Nan et al., 2015). Both the PDO and the EAWM are known to enhance intrusion into the SCS. Warm (positive) PDO phases are associated with slower Kuroshio transport and increased intrusion across the strait (Wu, 2013), advecting Pacific waters across this region. A stronger winter monsoon, on the other hand, is related to maximum intrusions across the strait (Hsin et al., 2012), where the northeast winds drive Ekman transport westwards and into the SCS. If surface salinity in Houbihu is a signal of water mass advection, SSS variability of the surrounding

waters (i.e. the western Pacific and SCS) in response to the PDO- and EAWM-related drivers should be reflected in our site.

We compared our Houbihu dry season SSS reconstruction with our coral-derived SSS record in Palau, located at the southern end of the Luzon Strait (Ramos et al., 2017, see also Chapter 3) and to an instrumental SSS record (Fig. 4.7a) extracted at a grid point in the northern SCS (i.e. 17.8°N, 115.8°E). Between 1880 and the mid-1940s, Palau and Houbihu SSS show similar values (i.e. small SSS difference) compared to the lower salinity values in the northern SCS (Fig. 4.7a and 4.7d). However, all sites exhibit a significant freshening trend during this period (i.e. 0.24 psu, 0.34 psu, and 0.15 psu over ~7 decades for Houbihu, Palau and northern SCS, respectively; $r > 0.40$, $p < 0.05$). The freshening trend during this period may be attributed to the strengthening of the EAWM, lowering salinity in the western Pacific and the SCS regions through intensified atmospheric convection. This time period coincides with an overall warm PDO phase, which increases the Kuroshio Intrusion (e.g. Wu, 2013) facilitating mixing across the Luzon Strait. Around the early 1950s to 1960s, the observed small salinity difference between the northern SCS and Houbihu is likely due to the weakening of the EAWM (Fig. 4.7a and 4.7b), reducing precipitation in the SCS region (e.g. (Wang & Chen, 2014)). Palau, on the other hand, exhibits higher sensitivity to ENSO-related salinity changes when La Niña conditions predominates during this period (Ramos et al., 2017, Fig. 4.7a). Weaker EAWM and La Niña conditions, in addition to the predominantly cold PDO phase during this period, are unviable for intrusion and advection of Pacific

waters into the strait (e.g. (Hsin et al., 2012; Qu et al., 2004; Wu, 2013). Hence, without the input of “new” Pacific waters, mixing between the northern SCS and Houbihu is a more viable explanation for the similarity in SSS between these sites (Fig. 4.7a). Around the mid 1970s, the salinity difference between Houbihu and Palaui decreased with similar values (i.e. within error) compared with the northern SCS surface salinity (Fig. 4.7a and 4.7d). This period coincides with stronger EAWM conditions and the predominance of warm PDO phases, indicating that the salinity of the surrounding waters and advection/mixing of these waters across the Luzon Strait is largely driven by these processes, respectively.

Spectral analysis further provides evidence on the PDO’s role in modifying salinity variability across the Luzon Strait at multidecadal timescales. Spectral coherence between reconstructed SSS records across the Luzon Strait (i.e. Houbihu minus Palaui) and winter PDO, which have spectral power at ~ 55 years cycle⁻¹, reveals significant correlation at frequencies > 0.026 cycles year⁻¹ (> 38 years cycle⁻¹, Fig. 4.8a and 4.8b). Both records were filtered using a central frequency of 0.018 ± 0.0045 cycles year⁻¹ to isolate ~ 55 -yr periods to observe variability. The low pass filtered records show a strong negative relationship with the PDO leading by 3 years ($r = -0.91$, Fig. 4.8c) and annually (i.e. with a 3-year lag applied on the PDO time-series, $r = -0.99$), indicating a strong PDO-related impact on the Luzon Strait surface salinity variability at multidecadal timescales.

Figure 4.7. (a) 3-year binned dry season SSS reconstruction (light brown) and 30-yr (10-point) moving average (dark brown) compared with coral reconstructed dry season SSS in Palau (red, Ramos et al., 2017 and see Chapter 3) and instrumental dry season SSS in northern SCS (green). Shading indicates RMSR = 0.07 psu. EAWM (black, b) and winter PDO (blue, c). Thicker lines are 30-yr moving averages. Note that the axes were inverted to facilitate comparison between overall trends. (d) Dry season SSS difference between Houbiu and Palau (brown) corresponds with the phase of the PDO (blue). Hollow circles indicate times when the SSS values are statistically equivalent. Significant difference was calculated by propagating the reconstruction errors between the SSS records.

Figure 4.8. (a) Spectral analysis of detrended Houbihu-Palau SSS difference (brown) and PDO (blue) records. Significance level greater than 90% (solid red line for the SSS difference, dashed red line for PDO) are labelled. (b) Spectral coherence with phase analysis between records reveal significant coherence at period >38 years. Red lines indicate 90% significance level while gray dashed line represent confidence intervals. (c) Low pass (55-yr) filtered SSS difference (brown) and PDO (blue) records with a 3-yr PDO lead.

4.4 Discussion

Houbihu winter SST and dry season SSS reconstructions since the late 18th century reveal relatively cooler and drier (i.e. higher salinity) conditions at the end of the LIA compared to the recent century. Houbihu winter SST exhibits 0.5°C to 0.9°C SST cooling at the end of the LIA (1850 CE, *sensu stricto*) relative to the 20th century and the most recent ~30 years, respectively. This estimate is comparable to various LIA cooling estimates from the northern SCS (e.g. 1.1°C

to 1.5°C; Chen et al., 2018; Deng et al., 2017; Yan et al., 2015); the tropical western Pacific (e.g. 0.5°C to 1.5°C; Newton et al., 2006; Oppo et al., 2009); subtropical western Pacific (e.g. 0.4°C; Wu et al., 2012) and the south Pacific (e.g. 1.4°C; Corrège et al., 2001) during the peak LIA period (~1700 CE), consistent with those from the tropical and subtropical Atlantic records (i.e. 1°C to 2°C; Goodkin et al., 2008; Watanabe et al., 2001). SST cooling during the LIA is currently considered a synchronous global event (e.g. Hendy et al., 2002; Rosenthal et al., 2013) linked to minimum solar irradiance and high volcanic activity during this period (Bradley & Jones, 1993; Crowley, 2000). Particularly in the western Pacific, LIA cooling is associated with the contraction of the warm pool during this period (Chen et al., 2018). The observed reduced winter SST variance at biennial frequencies concurrent with weak correlation between ENSO and our SST record in Houbihu at the end of the LIA (Fig. 4.5) may provide evidence of a restricted warm pool during this period.

Dry season surface salinity in Houbihu, on the other hand, is higher by 0.26 psu and 0.38 psu at the end of the LIA (1788 to 1850 CE) relative to the 20th century and the most recent ~30 years, respectively. This period is past the peak period of the LIA (i.e. 1700 CE) when most marine-based records in the northern SCS and the western Pacific exhibit fresher surface waters and/or wetter conditions relative to the late 20th century (e.g. 1 to 1.5 psu Deng et al., 2017; Newton et al., 2006; Oppo et al., 2009). Wetter climate during the LIA is attributed to the strengthening of the Walker Circulation (e.g. Yan et al., 2011) and weakening of the East Asian Summer Monsoon (EASM) (e.g. Deng et al.,

2017; Zeng et al., 2012) affecting the hydrological climate over the northern SCS. Additionally, the southward migration of the Intertropical Convergence Zone (e.g. Newton et al., 2006; Oppo et al., 2009; Sachs et al., 2009) and/or contraction of the East Asia-Australia monsoon region due to reduced solar irradiance (e.g. Griffiths et al., 2016; Yan et al., 2015) resulted in increased precipitation and hence, lower surface salinity in the tropical Western Pacific during the peak LIA period. In contrast, land-derived (i.e. lake sediments, speleothems) proxy reconstructions in mid-to high-latitude China reveal drought conditions during the LIA due to the weakening of EASM and/or strengthening of the EAWM, significantly reducing precipitation in the region (e.g. Liu et al., 2011; Qiao et al., 2011; Tan et al., 2010; Yan et al., 2015).

We infer the higher surface salinity or drier conditions in Houbihu relative to the late 20th-early 21st century to represent a transitional period when the tropical western Pacific hydrological climate began to recover from wetter conditions during the peak LIA period. Marine-based records from this region (e.g. Newton et al., 2006; Oppo et al., 2009) exhibit a shift towards a more saline surface salinity/drier condition from ~1700 towards the end of the LIA (i.e. 1850) relative to the late 20th century record (e.g. Deng et al., 2017). This shift to drier conditions likely implies a change to stronger EASM, a weaker EAWM and/or a weaker Pacific Walker Circulation relative to the peak LIA period. Comparing this trend to the modern impact of the EAWM on our Houbihu dry season SSS record and the surrounding seas, higher surface salinities possibly from the northern SCS is consistent with a weaker-EAWM-monsoon scenario at the end

of the LIA. However, marine-based records extending beyond the LIA are rare to absent along the path of Kuroshio current and intrusion, therefore more records are needed to verify the impact of the EAWM during this period. Similarly, due to the scarcity of marine-based records of the PDO extending beyond the LIA, the PDO's behavior during this period remains uncertain. Using the strong relationship between the modern PDO record and the salinity difference across the Luzon Strait, it may be inferred that a cold PDO regime predominated at the end of the LIA, leading to less intrusions during this period and hence mixing between northern SCS and Houbihu surface waters is more viable. An independent reconstruction of the Kuroshio Current from a sediment record downstream of the Kuroshio path corroborates this assumption (i.e. Zhang et al., 2019), where the enhanced Kuroshio current during the LIA interval is likely to reduce intrusion across the Luzon Strait.

In the late 20th to early 21st century, Houbihu Sr/Ca-SST and $\delta^{18}\text{O}_\text{c}$ -SSS reconstructions reveal significant warming and freshening trends, similarly observed in the tropical western Pacific region, though relative magnitudes are expected to vary. Overlapping the onset of the subtropical warming trend in Houbihu (i.e. 0.16°C per decade since 1950), coral-derived western Pacific SST reconstructions (i.e. Tierney et al., 2015) and a 1° square resolution instrumental winter SST near our site (i.e. Rayner et al., 2003) show an SST rise of 0.032°C per decade and 0.22°C per decade, respectively. Our estimate is comparable to that of the instrumental SST data (i.e. Rayner et al., 2003) near our site in contrast to the ensemble of reconstructions over the western Pacific (i.e. Tierney et al.,

2015) due to the latter's greater spatial coverage and the concentration of proxy reconstructions in the tropical region compared to the subtropics. Differences in magnitude aside, the onset of SST rise in our site is consistent with the onset of regional warming, likely tied to anthropogenic forcing. The freshening trend in Houbihu (i.e. 0.15 psu per decade), on the other hand, which commenced in the mid-1960s, is in the upper range of the observed freshening in the tropical western Pacific over the same time period (e.g. 0.06 psu per decade, Cravatte et al., 2009); 0.03 to 1 psu per decade, Delcroix et al., 2007). Lower salinity towards the present is related to the strengthened hydrological patterns since the start of the 20th century (Cobb et al., 2003; Nurhati et al., 2009) with strong links to the concurrent warming trend during this century (Cravatte et al., 2009; Nurhati et al., 2009).

4.5 Conclusions

Robust winter Sr/Ca-SST and dry season $\delta^{18}\text{O}_c$ -SSS calibrations in Houbihu allow for reconstructing subtropical climate variability over the past ~2 centuries. Multidecadal winter SST trends broadly agrees with various surface temperature reconstructions in the region, indicating the dominant control of solar and volcanic radiative forcing factors in the subtropical western Pacific climate variability. These global forcings potentially obscure the influence of the PDO and the EAWM on the winter SST record at interannual to decadal timescales. In contrast, biennial-scale changes evident in the winter SST record are likely driven by ENSO. Surface salinity, on the other hand, reflects an

advection signal linked to the EAWM and PDO variations. A strong EAWM leads to freshening in the SCS and western Pacific regions, which water is especially advected across the Luzon Strait during warm PDO phases. Comparing our salinity record with another site across the Luzon Strait (i.e. Palau) provides evidence of the PDO-related changes in salinity associated with the strength of the Kuroshio Intrusion.

Reconstructed winter SST and dry season SSS records also document $<1^{\circ}\text{C}$ cooler and <0.5 psu drier conditions (higher salinity), respectively, at the end of the LIA (1850 CE) relative to the late 1900s. These estimates are consistent with other multiproxy records in the region, pointing to changes in the size of the warm pool and strength of the monsoon as probable mechanisms. In contrast, significant warming of $\sim 0.16^{\circ}\text{C}$ per decade and freshening of ~ 0.15 psu per decade are observed in Houbihu in the late 20th to early 21st century. These trends are in line with other regional records highlighting the impact of anthropogenic forcing in recent climate change.

4.6 References

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Chapter 5

Interannual coral $\Delta^{14}\text{C}$ records of surface water exchange across the Luzon Strait

Ramos, R. D., N. F. Goodkin, E. R. M. Druffel, T. Y. Fan, F. P. Siringan (2019). Interannual coral $\Delta^{14}\text{C}$ records of surface water exchange across the Luzon Strait. *Journal of Geophysical Research: Oceans*, 124. <http://doi.org/10.1029/2018JC014735>.

Abstract

The Luzon Strait (LS) hosts the largest transport of water between the Western Pacific Ocean (WPO) and the South China Sea (SCS). The transport through the strait, dominated by the westward propagation of the Kuroshio Intrusion (KI), influences the climate and circulation of the SCS. While numerical models have investigated the interannual variability of the transport and subsequent water exchange across the LS, a lack of long-term on-site records prevents a general consensus on the transport rates, variability and drivers. Corals offer high-resolution, continuous histories of radiocarbon ($\Delta^{14}\text{C}$) content of the seawater dissolved inorganic carbon, allowing us to track changes in ocean transport and circulation through time. Seasonal and annual $\Delta^{14}\text{C}$ samples from Houbihu, Taiwan and Palaui, Philippines, located on either side of the strait, are

compared to the WPO and SCS $\Delta^{14}\text{C}$ records to examine the spatial and temporal $\Delta^{14}\text{C}$ variability in the region. We calculated the mean transport across the strait using a 5-box mixing model and identified its potential drivers. The mean amount of water exchanged across the strait from 1970 to 1999 was 2.2 Sv, ranging from -13.4 to 16 Sv, where a positive (negative) value indicates net flow into (out of) the SCS. A weaker East Asian Winter Monsoon (EAWM) increases the contribution of the SCS outflow on the KI-dominated LS, while the El Niño Southern Oscillation (ENSO) primarily drives the intrusion into the SCS. These results provide support to the dominant control of ENSO on the long-term ocean circulation variability in this region.

5.1 Introduction

The Luzon Strait (LS), ~350 km wide with a sill depth of ~2500 m, is the widest and deepest channel surrounding the South China Sea (SCS), and thus provides the largest exchange between the Western Pacific Ocean (WPO) and the SCS (Fig. 5.1) (Chen et al., 2015; Jia & Chassignet, 2011; Liang et al., 2008; Metzger & Hurlburt, 2001; Nan et al., 2015; Peñaflor et al., 2007). The northward flowing Kuroshio Current (KC) periodically intrudes through the strait into the SCS as the Kuroshio Intrusion (KI), significantly contributing to mean Luzon Strait Transport (LST) (Caruso et al., 2006; Centurioni et al., 2004; Hu et al., 2000; Jia & Liu, 2004; Nan et al., 2015; Wyrski, 1961). The KI delivers warmer and more saline waters from the WPO into the SCS, regulating heat, moisture and water exchange along its path (Caruso et al., 2006; Chen et al., 2001; Hu et

al., 2015; Nan et al., 2015; Qiu & Lukas, 1996). SCS outflow crosses the LS towards the WPO at lower rate, causing water and nutrient exchange along the strait (Chern & Wang, 1998; Du et al., 2013; Hsin et al., 2012; Qu et al., 2004; Xue et al., 2004).

Intermittent measurements and multi-year hydrographic observations of the water exchange across the strait reveal a spatially variable structure of the LST. The mean transport across the strait has a sandwich-like vertical structure, such that the upper (i.e. < 500 m) and deep (i.e. 1500 m) layers flow into the SCS and the middle layer (i.e. 500 to 1500 m) flows out to the WPO (Nan et al., 2015; Qu et al., 2006; Qu et al., 2000; Shaw & Chao, 1994; Tian et al., 2006). In the upper layers (i.e. 0 to 300 m), eastward and westward currents are also observed to alternate spatially. Inflow to the SCS is commonly observed across 19.5°N to 21°N (Chen et al., 2011; Hsin et al., 2012; Liang et al., 2008; Xue et al., 2004) and the direction typically reverses north of 21°N (Chen et al., 2011; Hsin et al., 2012; Liang et al., 2008; Nan et al., 2015; Xue et al., 2004). The net flow into the SCS varies between 3 to 6.5 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) annually (Nan et al., 2015). The LST also shows strong monsoon-driven seasonal variation, where maximum intrusions (minimal outflows) of 2.75 to 13.7 Sv (0.2 to 2.75 Sv) occur during winter (summer) when the northeast (southwest) monsoon predominates (Centurioni et al., 2004; Chen et al., 2011; Hsin et al., 2012; Metzger & Hurlburt, 1996; Nan et al., 2015; Qu et al., 2004; Qu et al., 2000; Tian et al., 2006; Wyrtki, 1961; Yang et al., 2010; Yaremchuk & Qu, 2004). Numerical models are able to reproduce similar spatial and temporal variability

but further magnify quantitative inconsistencies in the observed mean transport. Model-derived LST estimates (e.g. Hsin et al., 2012; Nan et al., 2015) indicate a mean westward transport of 0.6 to 10.2 Sv while seasonal transports vary from 3.1 to 12.2 Sv and 0.7 to 8.2 Sv for winters and summers, respectively. The large range of these estimates primarily result due to the differences in the methodology and model assumptions (Hsin et al., 2012; Nan et al., 2015).

Compared to seasonal variability, the interannual LST variation and its controlling mechanisms are less understood due to scarcity of continuous direct observations (Nan et al., 2015; Wu, 2013). Numerical models show that the El Niño Southern Oscillation (ENSO) exerts influence on the interannual variability of the LST by means of shifting the position of the North Equatorial Current (NEC) bifurcation latitude (e.g. Qu et al., 2004). The position of the bifurcation latitude determines the volume of the Kuroshio relative to the southward flowing Mindanao Current (MC) and the subsequent intrusion into the SCS. During El Niño years, anomalous southerly winds east of the Philippines push the bifurcation latitude northward reducing the Kuroshio transport east of Luzon (Kim et al., 2004; Qiu & Chen, 2010; Qiu & Lukas, 1996; Wang & Hu, 2006) and increasing the KI into the SCS potentially a result of inertial effects (Gordon et al., 2014; Qu et al., 2004; Yaremchuk & Qu, 2004). The situation then reverses for La Niña periods. However, recent studies show that the interannual variability of the NEC bifurcation and consequently, the mean flow across the strait is strongly linked to the Pacific Decadal Oscillation (PDO) and not ENSO (e.g. Nan et al., 2016; Wu, 2013; Wu et al., 2016). With the more frequent PDO shifts in

the recent years, ENSO is hypothesized to exert less impact on the NEC bifurcation latitude migration and mean LST, especially after 1995 when the PDO became predominantly negative (Wu, 2013). Similar to the ENSO-related wind forcing, anomalous winds during warm (cold) PDO phase induces northward (southward) shift of the NEC bifurcation, which enhances (reduces) the KI (Wu, 2013; Wu et al., 2016). The weakening trend of the KI, -0.12 Sv yr^{-1} from 1993 to 2012, estimated from satellite data and hydrographic observations across the strait, is likewise attributed to the changes in PDO phase (Nan et al., 2016). Due to the predominantly cold (negative) PDO regime since the early 1990s, the position of the NEC bifurcation latitude is southward, lessening the penetration of the KI into the SCS (Nan et al., 2016; Wu, 2013). Another study highlights the role of long-term changes in pressure gradient on the reduction of KI across the strait in the recent decades (e.g. Nan et al., 2013). Whether the intrusion is linked with the ENSO or PDO and driven by the local and large-scale wind forcing or pressure difference across the strait still remains a subject of disagreement (Nan et al., 2015).

Paleoreconstructions based on both marine sediments and coral proxies provide insights into the long-term change of Kuroshio transport. Changes in planktonic foraminiferal assemblages and stable isotope geochemistry reveal fluctuations in Kuroshio flow patterns and intensities along the east coast of Japan since the Late Quaternary to the Holocene (e.g. Jian et al., 2000; Ujiie & Ujiie, 1999). Similarly, coral $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ from east of Japan and south of Taiwan record Kuroshio variability in the last 50 to ~150 years (e.g. Li et al.,

2017; Yamazaki et al., 2016). Paleoreconstruction of the KI strength, on the other hand, is limited to the Holocene (e.g. Liu et al., 2013), where ENSO-related mechanisms remained unclear. While direct measurements, satellite data, numerical models and proxy reconstructions have advanced our present-day knowledge of current movements and transport variability in recent decades, there is still a need for multidecadal, high-resolution on-site LST records to better understand its interannual variation.

This study presents annually resolved histories of mean transport variability across the LS based on coral radiocarbon ($\Delta^{14}\text{C}$) records. In this approach, we aim to investigate how the surface transport across the LS has changed in the past 68 years. Moreover, we aim to provide insights on the possible mechanisms that drive its variability. This information is critical to understanding the causes and impacts of long-term ocean circulation variability in this region.

5.1.1 Radiocarbon as a tracer of ocean circulation

Radiocarbon (^{14}C) is naturally produced in the upper atmosphere through the collision of cosmic ray neutrons and ^{14}N (Anderson et al., 1947; Broecker, 2014). The resultant ^{14}C rapidly oxidizes to $^{14}\text{CO}_2$ gas and is distributed in the Earth's carbon reservoirs. In the surface ocean, atmospheric ^{14}C is admitted into seawater and becomes part of the dissolved inorganic carbon (DIC) pool with a $\Delta^{14}\text{C}_{\text{DIC}_{\text{sw}}}$ that is lower than that in the atmosphere. Relative to the surface, deeper waters have lower $\Delta^{14}\text{C}$ values because of isolation from the atmosphere and

subsequent radioactive decay. Consequently, upwelling or vertical mixing introduces older and deeper water to the surface resulting in an overall lowering of $\Delta^{14}\text{C}_{\text{DICsw}}$ values. During the late 1950s and early 1960s, thermonuclear bomb testing increased the difference between the surface and deep ocean $\Delta^{14}\text{C}$ values, making ^{14}C a more sensitive tracer of ocean circulation and mixing (Broecker, 2014; Grottoli & Eakin, 2007).

Corals utilize calcium and DIC in seawater for the production of aragonite (CaCO_3), hence changes in the $\Delta^{14}\text{C}_{\text{DICsw}}$ through time are stored in the CaCO_3 skeleton of the corals (Druffel, 1997a; Grottoli & Eakin, 2007). Relative to other coral proxy records, $\Delta^{14}\text{C}_{\text{coral}}$ is not affected by biological process, thus they provide a conservative tracer of ocean circulation (Dunbar & Cole, 1999). Coral $\Delta^{14}\text{C}$ records of various temporal resolution and length are available in the WPO, SCS and Indonesia regions (Fig. 5.1). These records provide histories of basin-scale changes in ocean circulation since the beginning of the 20th century. In conjunction with our coral $\Delta^{14}\text{C}$ records, we take advantage of this extensive spatial and temporal information to examine the interaction between the WPO and the SCS through the LS.

5.2 Coral sampling and analytical methods

5.2.1 Coral sites and sampling

In May 2013 and May 2012, vertical cores of *Porites* sp. were drilled underwater in Houbihu, Nanwan Bay, Taiwan (21.9°N, 120.7 °E) and offshore Palaui Island, Philippines (18.5°N, 122.2°E) at 4 to 6 m depths, respectively (Fig.

5.1). The ~3 m and 2 m long cores from Houbihu and Palaui, respectively, were cut, slabbed and X-radiographed to reveal annual density banding. Select years between 1942-2010 identified using annual density bands and high-resolution Sr/Ca time-series (e.g. Ramos et al., 2017) were subsampled using a tungsten carbide drill burr attached in a Dremel® tool. Select years from 1952 to 2010 were additionally scored parallel to the growth bands at sub-annual resolution (~4 to 6 samples per year, width of 2 to 3 mm) to further examine the seasonal $\Delta^{14}\text{C}$ variability at each site. Age errors are estimated to be roughly 1 to 2 months based on comparing the seasonal $\Delta^{14}\text{C}$ record and seasonally averaged Sr/Ca data.

Figure 5.1. Mean absolute dynamic topography (ADT, 1993-2017) over the Western Pacific region derived from the Archiving, Validation, and Interpolation

of Satellite Oceanographic data (AVISO, <http://www.aviso.altimetry.fr/duacs/>). Gray box marks the Luzon Strait (LS). Black solid and dotted lines delineate the general ocean circulation pattern over the WPO (Hu et al., 2015; Qiu & Lukas, 1996), the SCS (dotted lines are during winter, solid lines are during summer, (Wang & Li, 2009), and the ITF (Gordon et al., 2012). Colored symbols indicate the location of coral $\Delta^{14}\text{C}$ records used in this study: blue circle – Houbihu, Taiwan and red circle – Palau, Philippines (this study); gray diamond – Guam, USA (Andrews et al., 2016); light green diamond – Palau (Glynn et al., 2013); yellow diamond – Ishigaki Island, Japan (Hirabayashi, et al., 2017a); orange triangle – Langkai, Indonesia (Fallon & Guilderson, 2008); light blue triangle – Lombok Strait, Indonesia (Guilderson et al., 2009); green square – Currima, Philippines (Hirabayashi et al., 2017b); pink square – Hon Tre, Vietnam (Bolton et al., 2016); and brown square – Con Dao, Vietnam (Mitsuguchi et al., 2007). The red line across the strait at 120.8°E running from 18°N to 22°N define the transect where surface zonal currents and sea surface heights (SSH) from the Simple Ocean Data Assimilation dataset (SODA v.2.2.4, http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4) are derived (shown in Figs. 5.3 and 5.4c, respectively). (NEC – North Equatorial Current; NECC – North Equatorial Counter Current; KC – Kuroshio Current; KI – Kuroshio Intrusion; MC – Mindanao Current).

5.2.2 $\Delta^{14}\text{C}$ measurements

Seven to 8 mg aragonite powder samples were acidified with 85% phosphoric acid to produce CO_2 gas. The resultant CO_2 gas was subsequently purified and converted to graphite on Fe powder using the Zn-reduction method (Xu et al., 2007). The graphite was then analyzed for ^{14}C using an accelerator mass spectrometer (AMS) at the Keck Carbon Cycle AMS laboratory using standard techniques (Southon et al., 2004). Backgrounds were subtracted using measurements of ^{14}C -free, spar calcite. The ^{14}C measurements are reported as Δ values that are corrected for known age to 1950 (Stuiver & Polach, 1977). Analytical precision is $\pm 1.5\%$ based on long-term analyses of a modern coral standard (CSTD) and duplicate measurements of samples.

5.3 Results

5.3.1 Luzon Strait $\Delta^{14}\text{C}$ record

Seventy-nine annual and 228 seasonal $\Delta^{14}\text{C}$ samples from the Houbihu and Palaui coral cores were analyzed covering the last 68 years (Fig. 5.2a and See Appendix B). From the pre-bomb period of 1942 to 1953, Houbihu coral $\Delta^{14}\text{C}$ values ranged from -68.0‰ to -60.9‰, and were lower than those from Palaui, which ranged from -60.6‰ to -56.2‰. Early bomb-produced ^{14}C spikes are recorded in both corals in 1955, increasing by 45.0‰ and 69.4‰ from the Houbihu and Palaui pre-bomb values, respectively. Both $\Delta^{14}\text{C}$ values decreased slightly in 1956 to 1957 and began to increase rapidly following the input of more bomb ^{14}C . Bomb tests during this period obscured seasonality in both $\Delta^{14}\text{C}$ records.

The highest $\Delta^{14}\text{C}$ values were recorded in the early 1970s, approximately 10 years after the atmospheric bomb peak (Nydal, 2000), reaching a maximum of 149.7‰ in Houbihu and 165.2‰ in Palaui. Subsequently, the bomb curves decreased at a rate of about $\sim 3\text{‰ yr}^{-1}$. The seasonality in the records became more distinct during this period, where Palaui shows greater variability than Houbihu especially in the early 1970s (*F*-test, 2-tailed, $p = 0.0008$, Fig. 5.2a). Compared to the mean surface zonal current direction across the strait derived from Simple Ocean Data Assimilation dataset (SODA v.2.2.4, Carton & Giese, 2008, see details in Fig. 5.1), Houbihu seasonal $\Delta^{14}\text{C}$ maxima (minima) coincided with westward (eastward) current flows (Fig. 5.3). The short and discontinuous seasonal $\Delta^{14}\text{C}$ records prevents us from statistically quantifying this relationship

at this site. However, considering that the surface flow across the Luzon Strait is far more complex than presented here, the observed general agreement between records provides indication that zonal flow influences Houbihu $\Delta^{14}\text{C}$ seasonality. In contrast, the timing of the Palaui seasonal $\Delta^{14}\text{C}$ maxima and minima was more variable with respect to the mean flow direction (Fig. 5.3). In addition, the Palaui $\Delta^{14}\text{C}$ record was on average $\sim 4\text{‰}$ higher than the Houbihu record which is greater than the propagated analytical error of 2.1‰ (Fig. 5.2a) suggesting that Palaui and Houbihu are influenced by different water masses and/or surface processes.

5.3.2 Regional $\Delta^{14}\text{C}$ variability

Compared with the WPO and SCS annual records (Fig. 5.1), Houbihu pre-bomb $\Delta^{14}\text{C}$ values are lower than most other records in the region (i.e. $-64.6 \pm 2.5\text{‰}$, $n = 8$, 1σ , Fig. 5.2b). In contrast, Palaui pre-bomb $\Delta^{14}\text{C}$ ($-58.4 \pm 1.6\text{‰}$, $n = 12$, 1σ) is regionally comparable to Hon Tre, Vietnam ($-57.1 \pm 3.7\text{‰}$, $n_{\text{from}_1942} = 10$, 1σ , Bolton et al., 2016), Ishigaki, Japan ($-57.9 \pm 7.6\text{‰}$, $n = 18$, 1σ , Hirabayashi et al., 2017a), Guam ($-54.0 \pm 5.4\text{‰}$, $n = 18$, 1σ , Andrews et al., 2016) and Palau ($-54.9 \pm 2.4\text{‰}$, $n = 9$, 1σ , Glynn et al., 2013) (Fig. 5.2b). Con Dao, Vietnam ($-47.9 \pm 3.3\text{‰}$, $n = 6$, 1σ , Mitsuguchi et al., 2007) on the SCS shelf has the highest $\Delta^{14}\text{C}$ values during this period (Fig. 5.2b).

Figure 5.2. (a) Annual (open circles) and seasonal (solid lines) coral $\Delta^{14}\text{C}$ from Houbiu (blue) and Palau (red) from 1942 to 2011. (b) Annual $\Delta^{14}\text{C}$ records from this study compared to WPO, SCS and ITF records. Inset (b.1) shows the early bomb records from these sites. Black triangles indicate the timing of the bomb-testing operations in the Pacific (Andrews et al., 2016).

Figure 5.3. Houbihu (blue) and Palaui (red) seasonal $\Delta^{14}\text{C}$ record compared with surface zonal currents averaged along 120.8°N (see Fig. 5.1). Dashed lines (shaded areas) represent the northeast (southwest) monsoon season where the general current direction is westward (eastward). In general, Houbihu $\Delta^{14}\text{C}$ seasonal maxima (minima) coincides during the northeast (southwest) monsoon seasons. Palaui $\Delta^{14}\text{C}$ maxima and minima, on the other hand, show variable timing with respect to the mean flow direction.

Initial $\Delta^{14}\text{C}$ bomb spikes in 1954 and 1955 are not evident in the SCS records but are distinct in the WPO, Indonesian Throughflow (ITF) records (i.e. Langkai (Fallon and Guilderson, 2008) and Lombok (Guilderson et al., 2009), Indonesia, Fig. 5.2b.1), and our sites, indicating the role of the location and distance between sites in the delivery of bomb-contaminated waters and its preservation in the coral skeletons. The early $\Delta^{14}\text{C}$ spikes were attributed to the early thermonuclear tests conducted in Bikini and Enewatak Atolls in the Pacific in 1954. Guam, nearest to the atolls, shows the earliest $\Delta^{14}\text{C}$ increase (i.e. ~ 3 months after the initial test) and the most pronounced spike (i.e. $\sim 710\text{‰}$ in the seasonal record, not shown, Andrews et al., 2016). Guam also shows distinct bomb-related peaks in 1957 and 1959, similarly captured by the high-resolution $\Delta^{14}\text{C}$ record in Ishigaki, but with a year lagged (Andrews et al., 2016; Hirabayashi et al., 2017a). Palau, nearest to Guam, records an early $\Delta^{14}\text{C}$ rise in 1954 but sustained a lower bomb peak that lasted until late 1956 (Glynn et al., 2013). Houbihu $\Delta^{14}\text{C}$ shows an earlier rise and broader bomb peak than that of Palau, but both records reached peak values in mid-1955, a year after the initial bomb detonations. Langkai and Lombok $\Delta^{14}\text{C}$ records show the same initial rise in mid-1955 (Fallon & Guilderson, 2008; Guilderson et al., 2009), within the same time period as our sites (± 1 to 2 months), which may highlight the similar transport times between the bomb-contaminated water – the Pacific western boundary currents (WBC) (i.e. NEC, KC and Mindanao Current – MC) and the ITF and between the Pacific WBC and the KI. Moreover, the smaller $\Delta^{14}\text{C}$ peaks and the

absence of other bomb-related peaks in the late 1950s in the ITF and our records suggest other water mass exchanges along these passageways.

In the 1960s, Houbihu $\Delta^{14}\text{C}$ along with other SCS records rose earlier than those of Palaui and the WPO (Fig. 5.2b). In the following decade, all records reached the post-bomb $\Delta^{14}\text{C}$ peak showing variable amplitude and timing of the peak. WPO records reached the post-bomb peak in 1972. Ishigaki records the highest $\Delta^{14}\text{C}$ peak (i.e. 163.1‰), while Guam and Palau recorded 150‰ and 137.8‰, respectively. The SCS records, on the other hand, peaked in 1973 and recorded higher post-bomb values than the WPO. Con Dao and Currimao, Philippines, (Hirabayashi et al., 2017b) recorded the highest values at 173.8‰ and 165.8‰, respectively, while Hon Tre recorded 155.3‰. Palaui (151.2‰) and Houbihu (147.2 ‰) $\Delta^{14}\text{C}$ values are comparable to Guam.

In the post-bomb period after the 1970s (Fig. 5.2b), when lateral advection and vertical mixing mainly controls the surface ocean $\Delta^{14}\text{C}$ variability, Palaui shows more variability compared to Guam that, except for the post bomb peak and early 1980s, exhibits a 16-year plateau that lasted until 1986 (Andrews et al., 2016). Houbihu $\Delta^{14}\text{C}$ values are close to Palaui in the early 1970s and subsequently fluctuated between those of Currimao and Guam in the mid 1980s. Ishigaki and Con Dao $\Delta^{14}\text{C}$ values remained higher than the other records. Con Dao and Hon Tre values approach the WPO records in the mid-1980s. The $\Delta^{14}\text{C}$ differences between sites and its potential drivers will be further investigated in the following section.

5.4 Discussion

Compared with Houbihu, higher $\Delta^{14}\text{C}$ values in Palaui may reflect the constant influence of water masses with a greater exposure to the atmosphere. Gyre and gyre-fed western boundary currents, like the Kuroshio that passes east of Luzon, have generally long residence times at the surface (Grottoli & Eakin, 2007; Mahadevan, 2001). This enables air-sea CO_2 exchange to increase $\Delta^{14}\text{C}$, as long as $\Delta^{14}\text{C}$ in the air remains higher than that in the surface water. The lower $\Delta^{14}\text{C}$ values in Houbihu, on the other hand, suggest regular renewal of surface waters from those at depth that contain lower $\Delta^{14}\text{C}$ values. Tidally induced upwelling from the depths of 100 to 200 m offshore occurs in Houbihu on a daily basis (Lee et al., 1999; Lee et al., 1997), likely causing the dilution of surface $\Delta^{14}\text{C}$ with lower $\Delta^{14}\text{C}$ values and the observed dampening in $\Delta^{14}\text{C}$ seasonality at this site. However, since the LS is a site of water mass exchange between the SCS and the WPO, the $\Delta^{14}\text{C}$ values at our sites must be additionally affected by the $\Delta^{14}\text{C}$ variability between these basins.

The occurrence of early-bomb peaks in both Houbihu and Palaui $\Delta^{14}\text{C}$ records indicates influence of the western Pacific circulation across the LS. Relative to air-sea CO_2 exchange which typically takes a decade (Nydal, 2000), the quick $\Delta^{14}\text{C}$ rise in Houbihu and Palaui recorded one year after the initial bomb detonations is likely due to a nuclear fallout signal distributed by the advection of tropical Pacific currents (i.e. NEC and KC) originating at the testing sites at Bikini and Enewetak atolls (Andrews et al., 2016; Glynn et al., 2013; Hirabayashi et al., 2017a). This current system delivers bomb-contaminated NEC waters

through Guam, with a current speed of ~ 0.1 to 0.2 m s^{-1} , until it bifurcates to the northward flowing KC and the southward flowing MC whose speeds are roughly 5 to 10 times faster (Andrews et al., 2016; Lien et al., 2014; Qu et al., 1998) (Fig. 5.1). The difference in the transport velocities between the NEC and its branches (i.e. KC and MC) explains the one-year lag time between the initial detonations and the early bomb peaks in the coral records (Hirabayashi et al., 2017a).

In the Pacific, the interannual variability of the location and speed of the western boundary currents are strongly influenced by ENSO (Kim et al., 2004; Qiu & Chen, 2010). To further investigate this control on the $\Delta^{14}\text{C}$ variability at our sites during the post bomb period (i.e. after 1970), we compared our results with Guam $\Delta^{14}\text{C}$ since the Kuroshio waters reaching our sites originate from the NEC that flow by Guam. Compared to other WPO sites, Palau, located south of the NEC (i.e. in the North Equatorial Counter Current, NECC) experiences vertical mixing induced by the MC-NECC interaction (Glynn et al., 2013). Offshore Ishigaki is influenced by eddy activities dominating the downstream end of the Kuroshio (Hirabayashi et al., 2017a), far beyond the Luzon Strait. We found that the interannual $\Delta^{14}\text{C}$ difference between Palaui and Guam is statistically correlated with the meridional shift of the NEC bifurcation latitude (NBL hereafter; e.g. Qiu & Chen, 2010) with a one-year lag ($r = 0.65$, $p = 0.001$, $n = 21$, Fig. 5.4a) from 1980 to 2000. Positive (negative) Palaui-Guam $\Delta^{14}\text{C}$ difference corresponds to the northerly (southerly) position of the NBL. Wind-induced NBL migration and the offshore Kuroshio transport velocities are well correlated with ENSO (e.g. Niño 3.4 - Qiu & Chen, 2010, Fig. 5.3a); and the

Southern Oscillation Index (SOI - Kim et al., 2004). During El Niño years, the northward NBL position causes less NEC water to flow northward to the KC relative to the southward flow east of Mindanao (Kim et al., 2004; Qiu & Chen, 2010; Qiu & Lukas, 1996). Due to the dampened winds, the NEC and Kuroshio velocities are slower, and transports are at their minimum during El Niño (Kim et al., 2004; Qiu & Chen, 2010; Qiu & Lukas, 1996). This leads to a positive Palau-Guam $\Delta^{14}\text{C}$ difference (i.e. Palau $\geq$ Guam) where the slow-moving currents induce more surface $\Delta^{14}\text{C}_{\text{DICsw}}$ entrainment. Conversely, La Niña years are associated with the southward NBL migration, faster and greater NEC and Kuroshio transports leading to less surface water entrainment and therefore, higher $\Delta^{14}\text{C}$ values in Guam than Palau. The observed NBL anomaly leading the Palau-Guam $\Delta^{14}\text{C}$ difference by a year may be explained by the difference in transport velocities between the NEC and Kuroshio as previously discussed above.

Prior to 1980, the positive Palau-Guam $\Delta^{14}\text{C}$ difference during 1970-71, 1975-76 and 1979, is opposite of what the above mechanism predicts. This period coincides with the broad $\Delta^{14}\text{C}$ plateau recorded in Guam (Andrews et al., 2016). The cause of the small $\Delta^{14}\text{C}$ variability after the bomb peak in Guam is not well understood (Andrews et al., 2016). However, the higher $\Delta^{14}\text{C}$ values in Palau and other sites at the downstream end of KC (i.e. Houbihu and Ishigaki) and the SCS compared to Guam may indicate a forcing not related to the position of the NEC latitude and/or ENSO. We further investigate by similarly taking the $\Delta^{14}\text{C}$ difference between Ishigaki and Guam. The variability in Ishigaki-Guam $\Delta^{14}\text{C}$

difference is likewise controlled by the bifurcation latitude after 1980 and not before this period ($r = 0.54$, $p = 0.02$, $n = 18$). We hypothesize that the post-bomb peak in 1973 has obscured the NBL-related surface water entrainment, where the higher and spatially variable $\Delta^{14}\text{C}$ distribution at these sites during this period precedes the mean circulation patterns. Other possible mechanisms include the influence of local oceanographic processes such as occurrence of mesoscale eddies and upwelling (e.g. Ishigaki, Hirabayashi et al., 2017b). In contrast with the Palaui-Guam $\Delta^{14}\text{C}$ difference, Houbihu-Guam $\Delta^{14}\text{C}$ is not correlated with the NBL migration ($r = 0.22$, $p = 0.24$, $n = 31$, not shown), likely due to its inward location within the strait where offshore Kuroshio influence is driven by the KI.

Figure 5.4. $\Delta^{14}\text{C}$ difference between (a) Palaui and Guam compared with the NEC bifurcation latitude (Qiu & Chen, 2010) and the Niño 3.4 index; (b) Houbihu and Currimao compared with the EAWMI index (D'Arrigo et al., 2005); and (c) Houbihu and Palaui compared with the Niño 3.4 index (gray bars, reversed axis) and SODA-derived sea surface height anomalies (green-SSHa). Hollow dots indicate that the $\Delta^{14}\text{C}$ difference between records is zero (i.e. the $\Delta^{14}\text{C}$ values being compared are statistically equivalent).

Between the winter and summer monsoon systems, the East Asian Winter Monsoon (EAWM) has a greater impact on the westward flow across the strait and circulation within the SCS (Hsin et al., 2012). To examine the monsoonal control on the circulation and $\Delta^{14}\text{C}$ variability between our sites and the SCS records, we similarly calculated the interannual $\Delta^{14}\text{C}$ differences between Houbihu $\Delta^{14}\text{C}$ and Con Dao, Hon Tre and Currimao. Con Dao sits on a continental shelf in shallow waters and is mainly impacted by atmospheric $\Delta^{14}\text{C}$ processes (Mitsuguchi et al., 2007). In contrast, Hon Tre and Currimao are monsoon driven sites with seasonal upwelling and advection impacting $\Delta^{14}\text{C}$. Southeast monsoon winds blow parallel to the Vietnam coast at Hon Tre driving summer upwelling at this site (Bolton et al., 2016). $\Delta^{14}\text{C}$ in Currimao shows significant correspondence with the strength of the winter monsoon winds (Hirabayashi et al, 2017b), which drives upwelling and $\Delta^{14}\text{C}$ variability along the northwest coast of Luzon (Shaw et al., 1996). Due to these site attributes, only the $\Delta^{14}\text{C}$ difference between Houbihu and Currimao shows a significant relationship with the EAWM winds (e.g. D'Arrigo et al., 2005) with a one-year lag ($r = 0.46$, $p = 0.02$, $n = 25$, Fig. 5.4b). Because of westward intrusions across the strait and upwelling offshore of Currimao during stronger (positive) EAWM periods, the $\Delta^{14}\text{C}$ difference between Houbihu and Currimao is positive (i.e. Houbihu > Currimao). Conversely, the SCS outflow is more evident during weak EAWM periods, leading to a negative Houbihu-Currimao $\Delta^{14}\text{C}$ difference (i.e. Houbihu < Currimao). The slower currents within the strait and in the northern

SCS region (i.e. maximum of 0.35 m s^{-1} ; Hu et al., 2000; Nan et al., 2015) compared with the surrounding waters may explain the one-year delay.

Across the strait, the interannual $\Delta^{14}\text{C}$ difference between Houbihu and Palaui is significantly correlated with ENSO (e.g. Niño 3.4) with a one-year lag ($r = -0.46$, $p = 0.003$, $n = 41$, Fig. 5.4c). The negative correlation indicates that large (small) $\Delta^{14}\text{C}$ differences (i.e. greater/lesser than $\sim 4\text{‰}$) coincide with El Niño (La Niña) years. The influence of ENSO to the $\Delta^{14}\text{C}$ difference between our sites arise due to the meridional pressure difference across the strait. SODA-derived SSH anomalies, an indicator of pressure difference (See details in Fig. 5.1 and Appendix D, Fig. D4.2), show a significant negative correlation with ENSO from 1970 to 2010 ($r = -0.48$, $p = 0.007$, $n = 31$, Fig. 5.4c). The negative relationship indicates that El Niño (La Niña) years coincide with lower (higher) SSH anomalies. Since the mean SSH in the western Pacific is higher than that of the SCS (Fig. 5.1), a higher SSH across our sites must be due to the piling-up of water across the strait. During La Niña, the enhanced trade winds push more water towards the western Pacific, leading to higher SSHs in this region, indicating presence of the KI along the strait (Nan et al., 2013; 2015), and thus, smaller $\Delta^{14}\text{C}$ differences between our Houbihu and Palaui sites. Conversely, due to the relaxed trade winds during El Niño, the Western Pacific warm pool spreads towards the east, flattening the SSH in this region and increasing the $\Delta^{14}\text{C}$ difference between our sites. Other satellite altimetry studies along the strait have shown that SSH anomalies in conjunction with density stratification data are indicative of the presence or absence of the KI along the strait (e.g. DeCarlo et

al., 2015). However, whether the KI penetrates into the SCS based on the above $\Delta^{14}\text{C}$ differences remains ambiguous.

Overall, basin-specific processes controlling the $\Delta^{14}\text{C}$ variability of the Luzon Strait sites are evident from quantifying the $\Delta^{14}\text{C}$ difference between our sites and other $\Delta^{14}\text{C}$ records in the region. Palaui $\Delta^{14}\text{C}$, relative to that of Guam, documents the impact of the ENSO-modulated NBL migration in the Pacific on the Kuroshio transport east of Luzon. During El Niño, the Kuroshio influence at Palaui is enhanced. Houbihu $\Delta^{14}\text{C}$, relative to that of Currimaao, records evidence of the EAWM-driven water mass exchange along the strait and in the northern SCS. A weaker EAWM relatively increases the SCS outflow contribution across the strait. In between our sites, La Niña-related high-pressure gradient across the strait may indicate the occurrence of KI but whether it reaches the SCS remains to be further investigated.

5.4.1 Box model calculation

To integrate the above observations and fully assess the drivers of water transport across the strait, we employed a five-box model based on previous models developed for the North Atlantic and Indian Oceans (Druffel, 1989, 1997b; Goodkin et al., 2012; Grumet et al., 2004). Figure 5.5 shows the schematic of the box model, which includes the atmosphere (*A*), surface boxes of the LS, KI which implicitly includes the influence of the KC, and SCS outflow (*LS*, *KI*, *SO*) and the subsurface box of the thermocline (*D*). The inputs and data sources for each box are summarized in Table D4.1 in Appendix D.

Figure 5.5. Schematic of the box model used to estimate the lateral advection between the SCS and the Pacific. The $\Delta^{14}\text{C}$ of the surface box of the Luzon Strait (LS) is affected by the inputs from the atmosphere (A), the subsurface (D) and the lateral contributions from the SCS outflow (SO) and the Kuroshio Intrusion (KI).

With equal amounts lost in the LS box to conserve mass, the rate of change in the surface LS $\Delta^{14}\text{C}$, $\frac{dLS}{dt}$, is affected by air-sea gas exchange A , vertical contribution from D and lateral advection with inputs from both the SO and the KI , such that:

$$\frac{dLS}{dt} = k_{-1} \left(\frac{A}{0.983} - LS \right) + k_D (D - LS) + k_{SO} (SO - LS) + k_{KI} (KI - LS) \quad (5.1)$$

where 0.983 is the isotopic fractionation factor describing the influx of CO_2 from the atmosphere to the sea surface (Broecker & Peng, 1982). Box A is represented by the annual $\Delta^{14}\text{C}$ values of tree ring and atmospheric CO_2 $\Delta^{14}\text{C}$ data. The pre-bomb (1942 to 1953) values are from Stuiver & Quay, 1981 and the post-bomb

(1970 to 2012) values are from Hua et al., 2013. The surface boxes of *LS* and *KI* are represented by the $\Delta^{14}\text{C}$ values of corals from our study sites, Houbihu and Palaui, respectively. The values for the surface box, *SO*, are averaged $\Delta^{14}\text{C}$ records from Hon Tre (Bolton et al., 2016), Con Dao (Mitsuguchi et al., 2007) and Currimao (Hirabayashi et al., 2017b), duly representing the SCS $\Delta^{14}\text{C}$ variability in the model. Unlike the other boxes, the subsurface data for *D* is temporally and spatially sparse with no direct measurements across the strait. Box *D* is assumed to have pre-bomb values (e.g. Ostlund & Stuiver, 1980; Stuiver et al., 1981) between depths of 50 and 200 m, well within the mean penetration depth of bomb ^{14}C (e.g. Peng et al., 1998). The pre-bomb $\Delta^{14}\text{C}$ depth profiles cover a wide area in the North Pacific, between 10°N to 50°N , and are estimated from surveys conducted by the Geochemical Ocean Section (GEOSECS) Program in 1973. The post-bomb values for *D*, on the other hand, are derived from the subsequent international surveys of the World Ocean Circulation Experiment (WOCE) in 1993 and the Climate and Ocean – Variability, Predictability and Change (CLIVAR) in 2004 and 2006, which are verified and synthesized by the Global Ocean Data Analysis Project (GLODAP, <https://cdiac3.ornl.gov/waves/glodapv2/>, Lauvset et al., 2016; Olsen et al., 2016). These surveys include transects covering the Northern Pacific gyre but only the westernmost transects (i.e. 15°N to 35°N and 125°N to 145°N) along the path of the Kuroshio are selected (Fig. D4.1 in Appendix D). The data in between the available years were then linearly interpolated to construct an annual record of $\Delta^{14}\text{C}$ for *D*. This data assumption is supported by the advection of subsurface

(i.e. 100 to 200m) tropical waters from the Pacific into the SCS via the Luzon Strait evidenced in the Hon Tre coral Pb/Ca signals (e.g. Chen et al., 2016). The terms k_{-I} , k_{SO} , k_{KI} and k_D , are the exchange rates between the boxes estimated with respect to the volume of the surface and subsurface boxes. The volume of the LS and D boxes is calculated using lengths delineating KI extension, from 123°E inward to 118°E; widths based on the locations of our coral sites, 18°N to 22°N, and depths where both vertical and lateral exchanges occur, ~200 m (Hu et al., 2000; Nan et al., 2015; Shen et al., 2005).

The rate of $^{14}\text{CO}_2$ input from the air to the sea surface, k_{-I} , is expressed as:

$$k_{-1} = \frac{V_p \times CO_2 \times 365 \text{ days yr}^{-1}}{Z \times \Sigma CO_2} \text{ yr}^{-1} \quad (5.2),$$

where V_p (m day^{-1}) is the gas exchange piston velocity, a function of wind speed ($WS = 6.4 \text{ m s}^{-1}$ from NCEP-NCAR Reanalysis, (Kalnay et al., 1996)) and equivalent to $V_p = WS * 0.9995 - 3.47$ (Druffel, 1997b; Goodkin et al., 2012; Grumet et al., 2004); $CO_{2(aq)}$ is the dissolved CO_2 fixed to a value of 0.019 mol m^{-3} (Druffel, 1997b; Goodkin et al., 2012; Grumet et al., 2004); Z is the mixed layer depth fixed to a value of 50 m based on the OGCM for Earth Simulator dataset (OFES, Masumoto et al., 2004) and NOAA World Ocean Database (Levitus, 1982; Monterey & Levitus, 1997); and ΣCO_2 is the total CO_2 dissolved in the surface waters equivalent to 2.06 mol m^{-3} (Broecker & Peng, 1982; Levitus, 1982). Thus, k_{-I} is equal to 0.20 yr^{-1} .

The exchange rate from the subsurface, k_D , is approximated from the upwelling index reported off southwest Taiwan. The mean upwelling rate is $78.2 \text{ m}^3 \text{ s}^{-1} 100^{-1} \text{ m}$ of coastline (i.e. total coastline is $\sim 1700 \text{ km}$; Ndah et al., 2017). With respect to the volume of the subsurface box (i.e. $3.13 \times 10^{13} \text{ m}^3$), the ventilation rate, k_D , is equivalent to 1.2 yr^{-1} or, in terms of the mean amount of water exchanged, about $\sim 1.3 \text{ Sv}$.

To approximate the lateral exchange rates from *SO* and *KI* boxes, we assumed that k_{SO} and k_{KI} are fractions of the total lateral input, k_{Lat} , such that 25% and 75% of k_{SO} and k_{KI} constitutes k_{Lat} , respectively based on Nan et al., 2015 (Table D4.2 in Appendix D). Here, the direction of k_{Lat} represents the mean flow along the strait, which is from the WPO into the SCS. The lateral terms in Eqn. 5.1 were then expressed in terms of k_{Lat} :

$$\frac{dLS}{dt} = k_{-1} \left(\frac{A}{0.983} - LS \right) + k_D (D - LS) + k_{Lat} [0.25 (SO - LS) + 0.75 (KI - LS)] \quad (5.3).$$

Assuming steady state conditions,

$$k_{Lat} = \frac{-\left[k_{-1} \left(\frac{A}{0.983} - LS \right)\right] - [k_D (D - LS)]}{[0.25 (SO - LS) + 0.75 (KI - LS)]} \quad (5.4),$$

where the average Fraction Modern (FM, Stuiver & Polach, 1977) values for 1942 to 1953 are $A = 0.9770$ (-23.0‰); $LS = 0.9366$ (-63.4‰); $KI = 0.9411$ (-58.9‰); $SO = 0.9456$ (-54.4‰); and $D = 0.9250$ (-75.0‰). In the pre-bomb

steady-state conditions, we find that k_{Lat} is equal to 0.37 yr^{-1} , where k_{KI} and k_{SO} are 0.28 yr^{-1} and 0.09 yr^{-1} , respectively. With respect to the volume of the *LS*, the amount of water exchanged, k_{KI} and k_{SO} are correspondingly equal to 0.11 Sv and 0.04 Sv . Among the calculated exchange rates during the pre-bomb period, k_D is the highest, highlighting the importance of subsurface ventilation in the $\Delta^{14}\text{C}$ content of the strait.

We applied this model to the post-bomb period after 1970 using constant values for k_{-I} and k_D , and solving for k_{Lat} . We excluded the year 1979 because the values for surface boxes *SO*, *LS* and *KI* are equivalent (Table D4.1), resulting in a lateral mass value close to zero and hence, an anomalous estimate of the lateral flux. The mean amount of water exchange from 1970 to 1999 across the strait is $2.2 \pm 5.2 \text{ Sv}$ (1σ , $n = 28$), Sv , ranging from -13.4 to 16 Sv , where a negative value is net flow out of the *SCS* and a positive flow is into the *SCS* (Fig. 5.6). These values are within the magnitude of the mean flow measurements across the strait commonly conducted in shorter time periods (e.g. Nan et al., 2015) but are likely to be overestimated due to limitations of the model. While k_D is likely to vary with time, we do not have measurements to inform us of changes to the rate. As the largest flux into the strait, small variability of k_D will have minimal impact on the model. In addition, $D \Delta^{14}\text{C}$ values are the least constrained through time adding additional uncertainty.

Figure 5.6. Calculated lateral advection, k_{Lat} (black line with filled circles), compared to the Niño 3.4 (gray bars) and EAWM indices (gray line). Positive (negative) values indicate El Niño (La Niña) and strong (weak) EAWM conditions.

The net lateral exchange rate, k_{Lat} , is significantly correlated with ENSO ($r = 0.42$, $p = 0.03$, $n = 29$, Fig. 5.6), indicating its influence in driving the transport variability across the strait. Higher (lower) k_{Lat} generally coincides with El Niño (La Niña) periods, highlighting ENSO's role in the meridional shifts of the NEC bifurcation latitude and subsequent transport across the LS. During El Niño, the northward position of the NEC bifurcation latitude leads to weaker Kuroshio and stronger intrusion across the strait (Fig. 5.7). The reverse is expected during La Niña conditions. However, in 1971-72, 1974, 1977, 1984-85, 1988 and 1996, the k_{Lat} values are on the opposite direction of what the above ENSO relationship predicts. The El Niño years of 1972 and 1977 show a lower k_{Lat} value while the La Niña years of 1971, 1984-85, 1988 and 1996 show higher

k_{Lat} values. The observed k_{Lat} anomalies at beginning of the record may be impacted by the post-bomb peak $\Delta^{14}\text{C}$ distribution that is not advection-related as previously discussed.

Because the EAWM is shown to exert influence on the westward transport across the strait, we also compared these anomalous years with the EAWM index and found that the weaker (stronger) monsoon strength in 1972 (1984-85, 1988 and 1996) may explain the above discrepancies. Weaker EAWM during an El Niño event may indicate the relative dominance of k_{SO} to k_{KI} in 1972. A stronger EAWM during a La Niña event, on the other hand, may enhance overall k_{Lat} across the strait. However, the negative relationship between ENSO and EAWM is not consistent for each ENSO period such that not all weak (strong) EAWM coincides with El Niño (La Niña) years (e.g. D'Arrigo et al., 2005). The PDO may impact the ENSO-EAWM relationship (e.g. Wang et al., 2008; Kim et al., 2014) and hence, the lateral transport across the strait (e.g. Wu, 2003; Wu et al., 2006). However, we do not find a significant relationship between ENSO and the EAWM at different PDO phases and between k_{Lat} and PDO ($p > 0.10$). Due to the length of the record, the interdecadal modulation of the PDO may not be apparent. Nevertheless, the time-varying response of the EAWM to ENSO, regardless of the PDO phase, gives indication of the secondary control of the reversing monsoons over the lateral advection across the strait.

Figure 5.7. Schematic of the general circulation pattern east of Luzon and across the Luzon Strait during El Niño (solid lines) and La Niña (dashed lines) years. The thickness of the lines and arrows indicate the relative amount of transport.

5.5 Summary and conclusions

Interannual histories of the mean transport across the Luzon Strait based on coral-derived $\Delta^{14}\text{C}$ records show that Houbihu (Taiwan) $\Delta^{14}\text{C}$ is lower compared to Palaui (Philippines). Both Houbihu and Palaui $\Delta^{14}\text{C}$ records show early bomb-produced spikes as a result of a nuclear fallout signal carried by the tropical Pacific western boundary currents. The early $\Delta^{14}\text{C}$ spikes at our sites and the WPO records indicate that circulation in the Pacific has direct influence on the strait but does not reach the SCS sites. During the post-bomb period, Palaui $\Delta^{14}\text{C}$ relative to that of Guam, generally shows entrainment of surface waters

modified by the ENSO-driven shifts of the NEC bifurcation latitude. This highlights the continued influence of the Pacific circulation patterns on the Palau $\Delta^{14}\text{C}$ record. This signal is absent in the Houbihu $\Delta^{14}\text{C}$ record, but when compared to that of Currimao (west side of Luzon), the $\Delta^{14}\text{C}$ difference between these sites shows a significant relationship with the EAWM, the main driver of the SCS general circulation and alternating flow patterns across the strait. While the ENSO-driven pressure difference between our sites offers support on the occurrence of KI across the strait, whether KI reaches the SCS remains unclear. In conjunction with other $\Delta^{14}\text{C}$ records in the region, we were able to calculate the changes in the lateral transport across the strait. The mean amount of water exchanged across the strait from after the post-bomb peak is 2.2 Sv, ranging from -13.4 to 16 Sv, where a positive (negative) value indicates net flow into (out of) the SCS. By shifting the position of the NEC bifurcation latitude, ENSO plays a critical role on the interannual variability of water mass exchange across the Luzon Strait and circulation and water mass renewal in the SCS.

5.6 References

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Chapter 6

Conclusions

This thesis utilized proxy records of Sr/Ca, $\delta^{18}\text{O}$ and $\Delta^{14}\text{C}$ generated from Luzon Strait corals to investigate climatic and oceanographic variability across the strait. High-resolution 132- and 230-year paired SST and SSS reconstructions from Palaui and Houbihu, respectively, and a ~ 68 -yr $\Delta^{14}\text{C}$ record from each site reveal site-specific drivers of observed variability.

Robust calibrations of Sr/Ca-SST allow for reconstructing tropical to subtropical SST variability over the past ~ 2 centuries. Palaui *Diploastrea* and *Porites* winter SST records both exhibit decadal variability strongly correlated to the PDO. The longer Houbihu winter SST record, on the other hand, exhibits hemispheric-scale SST patterns driven by global forcing factors. The additional ~ 100 years in Houbihu relative to the Palaui record indicate cooler SST conditions at the end of the Little Ice Age (LIA) relative to the most recent 30 years. Both records exhibit a significant SST rise commencing around the mid-20th century likely tied to anthropogenic warming.

In both sites, $\delta^{18}\text{O}_c$ is strongly correlated to SSS variability. The Palaui wet- and dry-season SSS record exhibit local and ENSO-related changes in hydrological processes. The seasonal SSS difference, however, reveals the additional influence of the PDO in enhancing the advection of Pacific waters at

this site. The Houbihu dry-season SSS record, on the other hand, reflects EAWM-related changes in hydrological processes, likely modifying the surface salinity of its source waters. Comparing the SSS record between the Luzon Strait sites, the dominant influence of the PDO in the Kuroshio-related transport across the strait is evident at decadal timescales. Using the strong modern relationships between the SSS record at this site and the EAWM and the PDO, the intrusion across the Luzon Strait is hypothesized to be reduced at the end of the LIA.

A more direct approach of tracing water mass circulation, coral $\Delta^{14}\text{C}$ similarly revealed basin-specific processes controlling the $\Delta^{14}\text{C}$ variability across the strait. Palau $\Delta^{14}\text{C}$ relative to Pacific $\Delta^{14}\text{C}$ values is sensitive to the ENSO-forced migration of the North Equatorial Current (NEC) bifurcation latitude. In contrast, Houbihu $\Delta^{14}\text{C}$ relative to SCS $\Delta^{14}\text{C}$ values reflects EAWM-mediated transport across the Luzon Strait and circulation of the SCS. Using a simple 5-box mixing model, the interannual $\Delta^{14}\text{C}$ difference between our sites and the surrounding seas reveals the dominant influence of ENSO in driving the Kuroshio intrusion into the SCS at interannual timescales.

The results generated in this thesis highlight the importance of independently investigating the processes related to the EAWM, ENSO and PDO variability at each site, in order to better understand their interaction which controls the Kuroshio-dominated water exchange across the Luzon Strait. Therefore, continuing to capitalize on more marine-based paleo-reconstructions at key western Pacific and SCS sites could lead to more detailed spatio-temporal characterization of the Kuroshio intrusion and water exchange across the Luzon

Strait and a better understanding of its contribution to larger-scale climatic and oceanographic variability.

Appendix A

Coral X-radiographs

A1. Palaui *Porites lobata* and *Diploastrea heliopora* core

Cont'd.

Figure A1.1. X-ray positive of Palaui *Porites* (first 6 images) and *Diploastrea* (last image) slabs.

A2. Houbihu *Porites* core

1cm
■

Cont'd.

Cont'd.

Figure A2.1. X-ray positive of Houbihu *Porites* slabs.

Appendix B

Geochemical Data

B1. Palaui Sr/Ca, $\delta^{18}\text{O}$ and $\Delta^{14}\text{C}$

Table B1.1. Palaui *Porites* and *Diploastrea* Sr/Ca and stable isotope data

Date	<i>Porites</i> Sr/Ca	<i>Porites</i> $\delta^{18}\text{O}$	<i>Porites</i> $\delta^{13}\text{C}$	<i>Diplo</i> Sr/Ca	<i>Diplo</i> $\delta^{18}\text{O}$
1880.04	8.9575				
1880.13	8.9354				
1880.21	8.9133				
1880.29	8.8912				
1880.38	8.7993				
1880.46	8.7901				
1880.54	8.8492				
1880.63	8.8583				
1880.71	8.8268				
1880.79	8.7871				
1880.88	8.8729				

1880.96	8.9196
1881.04	8.9583
1881.13	8.9654
1881.21	8.9278
1881.29	8.8773
1881.38	8.8355
1881.46	8.8212
1881.54	8.8220
1881.63	8.8699
1881.71	8.8823
1881.79	8.8908
1881.88	8.9396
1881.96	9.0037
1882.04	9.0392
1882.13	9.0351
1882.21	8.9818
1882.29	8.8961
1882.38	8.8536
1882.46	8.8307
1882.54	8.8176
1882.63	8.8425
1882.71	8.8742
1882.79	8.9059

1882.88	8.9403
1882.96	9.0015
1883.04	9.0814
1883.13	9.0822
1883.21	9.0365
1883.29	8.9629
1883.38	8.9128
1883.46	8.9085
1883.54	8.9133
1883.63	8.9364
1883.71	8.9316
1883.79	8.9461
1883.88	8.9643
1883.96	9.0080
1884.04	9.0138
1884.13	9.0102
1884.21	8.9688
1884.29	8.8878
1884.38	8.8207
1884.46	8.8320
1884.54	8.8096
1884.63	8.8255
1884.71	8.8550

1884.79	8.8408
1884.88	8.9259
1884.96	9.0049
1885.04	9.0840
1885.13	9.0773
1885.21	9.0267
1885.29	8.9121
1885.38	8.7973
1885.46	8.7753
1885.54	8.7768
1885.63	8.7793
1885.71	8.7972
1885.79	8.8199
1885.88	8.9143
1885.96	8.9668
1886.04	9.0193
1886.13	9.0257
1886.21	9.0042
1886.29	8.8631
1886.38	8.7942
1886.46	8.7658
1886.54	8.7534
1886.63	8.7731

1886.71	8.7928
1886.79	8.8533
1886.88	8.9233
1886.96	8.9581
1887.04	8.9994
1887.13	8.9992
1887.21	8.9457
1887.29	8.8591
1887.38	8.8068
1887.46	8.7677
1887.54	8.7648
1887.63	8.7723
1887.71	8.7745
1887.79	8.7927
1887.88	8.8641
1887.96	8.9430
1888.04	8.9591
1888.13	8.9609
1888.21	8.9268
1888.29	8.8398
1888.38	8.7931
1888.46	8.7796
1888.54	8.7781

1888.63	8.7823
1888.71	8.7898
1888.79	8.8327
1888.88	8.8965
1888.96	8.9248
1889.04	8.9364
1889.13	8.9408
1889.21	8.9038
1889.29	8.8388
1889.38	8.7896
1889.46	8.7150
1889.54	8.7246
1889.63	8.7257
1889.71	8.7194
1889.79	8.7445
1889.88	8.9194
1889.96	8.9375
1890.04	8.9230
1890.13	8.9527
1890.21	8.9075
1890.29	8.8262
1890.38	8.7135
1890.46	8.7120

1890.54	8.7431
1890.63	8.7681
1890.71	8.7160
1890.79	8.7568
1890.88	8.8706
1890.96	8.9196
1891.04	8.9403
1891.13	8.9316
1891.21	8.8847
1891.29	8.8091
1891.38	8.7633
1891.46	8.7443
1891.54	8.6935
1891.63	8.6914
1891.71	8.7319
1891.79	8.7471
1891.88	8.8419
1891.96	8.9078
1892.04	8.9088
1892.13	8.9201
1892.21	8.9122
1892.29	8.8351
1892.38	8.7675

1892.46	8.7144		
1892.54	8.7086		
1892.63	8.7666		
1892.71	8.7678		
1892.79	8.7241		
1892.88	8.8467		
1892.96	9.0149		
1893.04	8.9882		
1893.13	8.9722		
1893.21	8.9666		
1893.29	8.8281		
1893.38	8.7870		
1893.46	8.7545		
1893.54	8.7295		
1893.63	8.8077		
1893.71	8.7749		
1893.79	8.8233		
1893.88	8.8636		
1893.96	8.9142		
1894.04	8.9536	-3.8087	-1.2025
1894.13	8.9469	-4.0715	-1.0308
1894.21	8.9139	-4.3343	-0.8592
1894.29	8.8431	-4.5842	0.9137

1894.38	8.7751	-4.7405	0.4628
1894.46	8.7832	-4.8781	-0.1845
1894.54	8.7650	-4.9849	-0.4890
1894.63	8.7966	-5.0021	-0.6196
1894.71	8.7625	-5.1722	-1.2133
1894.79	8.7778	-4.7815	-1.4210
1894.88	8.8725	-4.3569	-1.3703
1894.96	8.9354	-4.3357	-2.2341
1895.04	9.0050	-4.3091	-2.3518
1895.13	9.0293	-4.3056	-1.2528
1895.21	8.9829	-4.1927	0.5750
1895.29	8.8782	-5.2058	-0.3765
1895.38	8.7877	-5.3084	-0.3873
1895.46	8.7740	-5.2739	-0.6004
1895.54	8.7729	-5.1997	-0.8440
1895.63	8.7904	-5.0216	-1.0901
1895.71	8.7828	-4.8476	-1.2261
1895.79	8.8549	-4.7177	-1.7800
1895.88	8.8802	-4.5715	-1.8537
1895.96	9.0118	-4.3744	-1.4803
1896.04	8.9888	-4.2032	0.0623
1896.13	9.0143	-4.1262	0.7661
1896.21	8.9467	-4.1173	1.5243

1896.29	8.8416	-4.1373	1.7064
1896.38	8.7648	-4.7125	0.8031
1896.46	8.7437	-4.9701	0.0632
1896.54	8.7274	-5.0865	-0.1348
1896.63	8.7301	-4.9714	-0.2170
1896.71	8.7416	-4.8660	-0.4444
1896.79	8.7916	-4.8453	-0.4619
1896.88	8.8732	-4.7333	-0.9647
1896.96	8.9740	-4.3131	-1.0529
1897.04	9.0324	-4.3216	-0.9955
1897.13	9.0298	-4.2890	-0.4779
1897.21	8.9879	-4.3846	-0.1377
1897.29	8.9013	-4.5459	0.2173
1897.38	8.8537	-4.5163	1.0155
1897.46	8.8284	-4.8349	-0.1453
1897.54	8.8186	-5.2462	-1.1910
1897.63	8.8598	-5.1458	-1.1902
1897.71	8.8279	-4.6280	-0.8535
1897.79	8.8362	-4.4597	-1.0181
1897.88	8.9307	-4.4540	-1.2707
1897.96	8.9897	-4.4323	-2.0252
1898.04	9.0338	-4.3617	-1.6970
1898.13	9.0376	-4.3891	-1.2117

1898.21	9.0013	-4.4654	-1.0294
1898.29	8.8696	-4.7297	0.2586
1898.38	8.8528	-4.9557	-0.5976
1898.46	8.8170	-5.4115	-1.0179
1898.54	8.8071	-5.4640	-0.9828
1898.63	8.8069	-5.4290	-1.6079
1898.71	8.8412	-5.2408	-2.2091
1898.79	8.8431	-4.9100	-1.9837
1898.88	8.9339	-4.7772	-1.9103
1898.96	9.0462	-4.6200	-1.8600
1899.04	9.0489	-4.3569	-1.4595
1899.13	9.0489	-4.5131	-1.2140
1899.21	9.0445	-4.7049	-0.8000
1899.29	8.8816	-4.8975	-0.3440
1899.38	8.8173	-5.1567	-1.1739
1899.46	8.8423	-4.9839	-0.8331
1899.54	8.8991	-5.0988	-1.1891
1899.63	8.8362	-4.7779	-0.2029
1899.71	8.8305	-5.2390	-2.3171
1899.79	8.9081	-4.9228	-2.5385
1899.88	8.9213	-4.8937	-3.8179
1899.96	8.9725	-4.8146	-3.9313
1900.04	9.0278	-4.6375	-2.2601

1900.13	9.0279	-4.5516	-1.4656
1900.21	8.9551	-4.7835	-0.6921
1900.29	8.8695	-4.9943	0.1231
1900.38	8.8467	-5.0204	-0.4451
1900.46	8.8265	-5.3490	-0.8359
1900.54	8.8255	-5.0341	-0.5917
1900.63	8.8133	-4.9551	-1.0146
1900.71	8.8291	-4.9445	-1.1184
1900.79	8.8532	-4.9502	-1.2096
1900.88	8.9423	-5.0847	-1.2012
1900.96	8.9476	-4.7608	-1.3187
1901.04	8.9746	-4.4093	-1.6560
1901.13	9.0040	-4.2991	-0.4808
1901.21	8.9504	-4.6232	-0.4976
1901.29	8.8811	-4.5878	-0.5207
1901.38	8.8352	-4.7613	0.6050
1901.46	8.8009	-5.0756	0.0774
1901.54	8.8317	-5.2992	-0.5555
1901.63	8.8078	-5.3948	-1.3291
1901.71	8.8036	-5.3406	-0.5888
1901.79	8.8426	-4.9677	-0.4099
1901.88	8.9484	-4.7643	-1.8424
1901.96	9.0003	-4.7575	-2.0472

1902.04	9.0626	-4.7700	-1.8612
1902.13	8.9638	-4.6268	-1.6342
1902.21	8.9673	-4.3252	-0.1103
1902.29	8.8830	-4.6729	-0.0614
1902.38	8.7958	-4.9345	-0.0640
1902.46	8.8262	-4.8961	-0.5421
1902.54	8.8163	-5.1004	-0.3712
1902.63	8.8518	-5.0219	-0.1071
1902.71	8.8197	-5.0115	0.1638
1902.79	8.8219	-5.1148	-0.3523
1902.88	8.9330	-4.8489	-1.5934
1902.96	8.9748	-4.6435	-2.1978
1903.04	8.9681	-4.3422	-1.5196
1903.13	8.9964	-4.3569	-0.2062
1903.21	8.9818	-4.4220	0.0191
1903.29	8.8879	-4.6079	1.1033
1903.38	8.7829	-4.6846	0.6459
1903.46	8.8326	-4.8946	0.0118
1903.54	8.8518	-5.1388	-0.7271
1903.63	8.8562	-5.2053	-0.6386
1903.71	8.8640	-5.2739	-0.3620
1903.79	8.8329	-5.0858	-0.8016
1903.88	8.9446	-4.6891	-2.1504

1903.96	8.9617	-4.5033	-1.5588
1904.04	9.0286	-4.1872	-1.8667
1904.13	9.0609	-4.3091	-1.4310
1904.21	9.0043	-4.5461	-0.7542
1904.29	8.8991	-4.4987	-0.4544
1904.38	8.9017	-4.6383	-0.0829
1904.46	8.8459	-4.8887	0.1628
1904.54	8.7928	-4.8495	0.0980
1904.63	8.8418	-5.1286	-0.5425
1904.71	8.8419	-5.2178	-0.6548
1904.79	8.8529	-5.1286	-0.9302
1904.88	8.9066	-4.8201	-0.7127
1904.96	8.9788	-4.5312	-1.0417
1905.04	8.9533	-4.4076	-0.8215
1905.13	8.9703	-4.3847	-0.3399
1905.21	8.9439	-4.4915	-0.0201
1905.29	8.8682	-4.4987	0.1515
1905.38	8.8252	-4.5569	0.3450
1905.46	8.8203	-4.8334	0.2723
1905.54	8.7598	-4.8016	0.4450
1905.63	8.8711	-4.6274	0.3437
1905.71	8.8231	-4.7759	0.2296
1905.79	8.8397	-4.7477	-0.4261

1905.88	8.9478	-4.3368	-0.9069
1905.96	9.0201	-4.2547	-1.0894
1906.04	9.0505	-3.5361	-1.2051
1906.13	9.0369	-4.3595	-1.3028
1906.21	8.9840	-4.5626	-0.3789
1906.29	8.9275	-4.6331	0.0853
1906.38	8.8540	-5.0457	-0.9997
1906.46	8.8843	-5.0836	-0.7337
1906.54	8.8232	-4.9379	-0.3926
1906.63	8.8449	-4.1298	0.1211
1906.71	8.8297	-4.6853	-0.2239
1906.79	8.8704	-4.4143	-1.0414
1906.88	8.9266	-4.2810	-1.1740
1906.96	8.9758	-4.4140	-1.2715
1907.04	9.0175	-4.2539	-1.2970
1907.13	9.0109	-4.5725	-0.8374
1907.21	8.9654	-4.4425	-0.0378
1907.29	8.8976	-4.6808	0.2814
1907.38	8.8260	-4.9057	-0.1384
1907.46	8.7892	-4.8767	-0.0788
1907.54	8.8044	-4.9345	0.4029
1907.63	8.8230	-5.0573	-0.0614
1907.71	8.8005	-5.1301	-0.2991

1907.79	8.8631	-5.2337	-0.9512
1907.88	8.8647	-4.8811	-1.3481
1907.96	8.9797	-4.4048	-0.9899
1908.04	8.9816	-4.6980	-1.1422
1908.13	9.0093	-4.5924	-0.1617
1908.21	8.9620	-4.7476	-0.3753
1908.29	8.8518	-5.0105	-0.0485
1908.38	8.8000	-5.0634	-0.0393
1908.46	8.8256	-4.9716	-0.2281
1908.54	8.7677	-4.9718	-0.3111
1908.63	8.7877	-5.0510	-0.3716
1908.71	8.7655	-4.8824	-0.6718
1908.79	8.8545	-4.9681	-2.0858
1908.88	8.9149	-4.7683	-2.2307
1908.96	8.9818	-4.3717	-1.2056
1909.04	8.9963	-4.4727	-0.7011
1909.13	8.9855	-4.4432	-1.4972
1909.21	8.9613	-4.5301	-0.3794
1909.29	8.8337	-4.8371	0.2049
1909.38	8.7669	-4.9299	0.2362
1909.46	8.7296	-4.9814	0.4465
1909.54	8.7193	-4.9364	0.1114
1909.63	8.7660	-5.0796	0.0638

1909.71	8.8046	-4.9907	-0.2969
1909.79	8.8278	-4.9371	-0.7199
1909.88	8.9545	-4.8595	-1.9505
1909.96	8.9486	-4.4804	-0.9711
1910.04	9.0054	-4.2145	-0.6250
1910.13	9.0011	-4.2879	-0.6433
1910.21	8.9682	-4.3714	-0.4575
1910.29	8.8996	-4.4905	0.2298
1910.38	8.8315	-4.8040	-0.1503
1910.46	8.8190	-4.7239	-0.3014
1910.54	8.7587	-4.4790	-0.3542
1910.63	8.7598	-5.1066	-1.4022
1910.71	8.8060	-5.0326	-0.8304
1910.79	8.7930	-4.8376	-1.6649
1910.88	8.9041	-4.7894	-3.0068
1910.96	8.9381	-4.6978	-2.8137
1911.04	8.9484	-4.6301	-2.9304
1911.13	8.9985	-4.7571	-2.7989
1911.21	8.9651	-4.5869	-2.5807
1911.29	8.8261	-4.7351	0.5922
1911.38	8.7603	-5.0024	-0.5403
1911.46	8.7635	-5.0749	-0.4471
1911.54	8.6992	-5.1953	-0.6714

1911.63	8.7179	-5.3016	-1.5407
1911.71	8.7582	-5.1516	-2.3465
1911.79	8.8196	-5.1837	-2.8444
1911.88	8.9062	-4.9982	-3.7338
1911.96	8.9378	-4.8821	-3.0403
1912.04	8.9575	-4.8109	-1.7964
1912.13	8.9429	-4.7405	-1.2073
1912.21	8.9039	-4.5670	-0.9109
1912.29	8.9000	-4.5556	0.7504
1912.38	8.7924	-4.7617	1.5673
1912.46	8.7999	-5.1707	-0.2859
1912.54	8.7208	-5.1885	-0.0766
1912.63	8.7583	-5.1007	-0.7168
1912.71	8.7933	-5.1635	-0.9892
1912.79	8.8254	-4.9917	-1.1285
1912.88	8.8716	-5.0313	-1.1221
1912.96	8.9848	-4.8109	-2.1474
1913.04	8.9912	-4.4693	-1.4883
1913.13	9.0080	-4.5754	-0.6741
1913.21	8.9689	-4.6575	-0.7858
1913.29	8.8990	-4.4033	0.6865
1913.38	8.8135	-4.8401	0.9099
1913.46	8.7764	-4.8996	1.0008

1913.54	8.7378	-5.0657	0.6941
1913.63	8.7640	-5.1783	-0.3238
1913.71	8.7644	-5.1893	-0.9536
1913.79	8.7855	-5.2252	-1.2878
1913.88	8.8709	-4.7014	-2.0452
1913.96	8.9131	-4.6414	-1.6151
1914.04	8.9425	-4.7544	-1.6651
1914.13	8.9514	-4.6007	-1.3172
1914.21	8.9244	-4.6257	-1.3816
1914.29	8.8611	-4.7184	-0.5852
1914.38	8.7750	-4.7528	0.3855
1914.46	8.7695	-5.0136	-0.2447
1914.54	8.6928	-5.0882	-0.3221
1914.63	8.7071	-5.3224	-0.8764
1914.71	8.7282	-5.5687	-1.4665
1914.79	8.8170	-5.4290	-1.4600
1914.88	8.8795	-4.5420	-1.9214
1914.96	8.9757	-4.3697	-1.5980
1915.04	8.9849	-4.3200	-1.1731
1915.13	8.9772	-4.4886	-0.9719
1915.21	8.9226	-4.4371	-0.3776
1915.29	8.9278	-4.4731	-0.0564
1915.38	8.7692	-4.5048	0.3945

1915.46	8.7175	-5.0637	-0.1577
1915.54	8.6960	-5.1055	-0.4054
1915.63	8.7183	-5.1562	-0.5693
1915.71	8.7406	-5.2070	-0.7333
1915.79	8.7930	-5.0522	-0.8480
1915.88	8.8726	-4.6477	-1.1811
1915.96	8.9199	-4.5860	-1.6637
1916.04	8.9444	-4.4842	-1.0770
1916.13	8.9540	-4.4035	-0.5508
1916.21	8.9298	-4.4717	-0.2906
1916.29	8.8395	-4.4678	0.1434
1916.38	8.8051	-4.6120	0.8919
1916.46	8.7752	-4.6475	1.0436
1916.54	8.7669	-4.6518	0.8587
1916.63	8.7833	-4.7027	0.5174
1916.71	8.7852	-5.0683	-0.5703
1916.79	8.7787	-5.2108	-1.3435
1916.88	8.8875	-4.8445	-1.2779
1916.96	8.9351	-4.5745	-1.7877
1917.04	8.9454	-4.4408	-1.7084
1917.13	8.9590	-4.4162	-0.7356
1917.21	8.8988	-4.3951	-0.4858
1917.29	8.9056	-4.5035	-0.3725

1917.38	8.7968	-4.7122	-0.0087
1917.46	8.7714	-4.9958	-0.7725
1917.54	8.7584	-5.1220	-0.9769
1917.63	8.7648	-5.0129	-1.0353
1917.71	8.7856	-4.8767	-1.0381
1917.79	8.8300	-4.6093	-0.9949
1917.88	8.8614	-4.4327	-1.6971
1917.96	8.9524	-4.4228	-1.6778
1918.04	8.9524	-4.6255	-2.3437
1918.13	8.9489	-4.6591	-1.6709
1918.21	8.9149	-4.6148	-1.0099
1918.29	8.8495	-4.5305	-0.5035
1918.38	8.7893	-4.7556	-0.1816
1918.46	8.7374	-4.7465	-0.3202
1918.54	8.7167	-4.9282	-0.7078
1918.63	8.7641	-4.9945	-1.4373
1918.71	8.8013	-4.9123	-1.3307
1918.79	8.7856	-4.8577	-1.4085
1918.88	8.8791	-4.9254	-2.4544
1918.96	8.9600	-4.7386	-3.2156
1919.04	8.9706	-4.7283	-2.7248
1919.13	8.9781	-4.5055	-1.4959
1919.21	8.9396	-4.5570	-1.3978

1919.29	8.8978	-4.4969	-1.0530
1919.38	8.8065	-4.6630	0.9703
1919.46	8.7768	-4.8651	0.6259
1919.54	8.7620	-5.0658	-0.3096
1919.63	8.7685	-5.2047	-1.4080
1919.71	8.8195	-5.2380	-2.9255
1919.79	8.8445	-4.9881	-2.5535
1919.88	8.9022	-4.6446	-2.8715
1919.96	8.9834	-4.5626	-2.4251
1920.04	9.0089	-4.6177	-2.0637
1920.13	8.9960	-4.6626	-2.0896
1920.21	8.9460	-4.7987	-0.9931
1920.29	8.8953	-4.7133	-0.5802
1920.38	8.8412	-4.9716	0.2090
1920.46	8.8152	-5.0551	-0.3040
1920.54	8.7810	-5.4264	-1.6973
1920.63	8.7988	-5.1901	-1.4683
1920.71	8.8192	-4.9718	-1.2793
1920.79	8.8641	-4.9370	-1.5082
1920.88	8.9093	-4.8197	-1.8327
1920.96	8.9928	-4.5828	-2.2203
1921.04	9.0561	-4.4470	-2.2004
1921.13	9.0384	-4.5429	-1.2769

1921.21	8.9859	-4.4615	-0.3675
1921.29	8.9242	-4.5328	0.1341
1921.38	8.8364	-4.7192	0.1209
1921.46	8.7792	-4.8836	-0.2493
1921.54	8.7745	-4.9997	-1.0943
1921.63	8.7912	-5.2169	-1.0602
1921.71	8.8157	-5.3308	-2.0717
1921.79	8.8332	-5.2497	-2.3244
1921.88	8.9136	-4.7262	-2.0665
1921.96	8.9482	-4.6399	-2.3567
1922.04	8.9743	-4.5706	-2.4576
1922.13	8.9681	-4.6258	-2.8524
1922.21	8.9860	-4.6445	-1.7455
1922.29	8.8963	-4.5967	-0.1556
1922.38	8.8243	-4.5997	0.1171
1922.46	8.8067	-4.9659	0.1699
1922.54	8.7678	-5.1514	0.0575
1922.63	8.8097	-5.1921	-1.3013
1922.71	8.8313	-5.0130	-0.6118
1922.79	8.8409	-4.9077	-1.8555
1922.88	8.9091	-4.8143	-1.8816
1922.96	9.0038	-4.7900	-2.9834
1923.04	9.1110	-4.6883	-2.9370

1923.13	9.0374	-4.5246	-2.7371
1923.21	9.0572	-4.6840	-2.4266
1923.29	8.9564	-4.6203	-1.7368
1923.38	8.8921	-4.7201	-0.4155
1923.46	8.8245	-4.9435	-0.2700
1923.54	8.8096	-5.2478	-0.7752
1923.63	8.7986	-5.2325	-1.2818
1923.71	8.8427	-5.2126	-1.2021
1923.79	8.8472	-5.0582	-1.3310
1923.88	8.9436	-4.9215	-1.6041
1923.96	8.9876	-4.8618	-1.7651
1924.04	9.0322	-4.7791	-1.9612
1924.13	9.0361	-4.7237	-2.0580
1924.21	8.9961	-4.6801	-2.2171
1924.29	8.9251	-4.7341	-0.5954
1924.38	8.8624	-4.8845	0.4973
1924.46	8.8257	-4.9712	0.3521
1924.54	8.8051	-5.1258	0.0075
1924.63	8.8126	-5.1237	-0.1938
1924.71	8.8386	-5.1116	-0.7667
1924.79	8.8478	-5.0809	-0.8534
1924.88	8.9481	-4.6806	-0.8786
1924.96	9.0264	-4.5210	-0.9610

1925.04	9.0258	-4.5177	-0.9563
1925.13	9.0308	-4.5249	-0.9788
1925.21	9.0278	-4.6322	-0.9190
1925.29	8.9397	-4.7394	-0.8592
1925.38	8.7366	-4.6950	-0.2969
1925.46	8.8517	-4.9707	0.4088
1925.54	8.6642	-5.2475	-0.9202
1925.63	8.7890	-5.3104	-0.9671
1925.71	8.7501	-5.2214	-1.4662
1925.79	8.8143	-4.9279	-1.2435
1925.88	8.8982	-4.8075	-2.7676
1925.96	9.0360	-4.7415	-2.7131
1926.04	9.0665	-4.6396	-1.9892
1926.13	9.0771	-4.6785	-1.1489
1926.21	8.9981	-4.6302	-0.6668
1926.29	8.9784	-4.4933	-0.3601
1926.38	8.8493	-5.2712	-1.2184
1926.46	8.8298	-5.2457	-1.0166
1926.54	8.7929	-5.3817	-0.8134
1926.63	8.7906	-5.2849	-1.3488
1926.71	8.8164	-5.1004	-1.4333
1926.79	8.8636	-4.8770	-1.1975
1926.88	8.9289	-4.7367	-1.7209

1926.96	9.0037	-4.5076	-1.3367
1927.04	9.0237	-4.4931	-1.2721
1927.13	9.0103	-4.5465	-1.3135
1927.21	8.9868	-4.6319	-1.3675
1927.29	8.9033	-4.5530	0.5586
1927.38	8.8450	-5.0902	-0.1530
1927.46	8.8612	-5.0579	-0.2751
1927.54	8.8373	-4.8903	-0.3667
1927.63	8.8360	-4.9934	-0.3176
1927.71	8.8149	-5.0853	-0.2748
1927.79	8.8167	-4.9815	-0.5865
1927.88	8.9164	-4.8778	-0.8983
1927.96	8.9915	-4.8326	-1.8584
1928.04	9.0068	-4.6358	-1.9995
1928.13	9.0305	-4.5928	-1.4732
1928.21	8.9610	-4.4955	-1.4054
1928.29	8.9181	-4.7195	-1.6170
1928.38	8.9341	-4.7906	-0.7939
1928.46	8.8520	-5.0986	-0.2024
1928.54	8.8414	-5.4108	-1.1581
1928.63	8.8338	-5.3064	-0.3966
1928.71	8.8749	-5.1853	-0.4183
1928.79	8.8493	-5.1911	-0.6977

1928.88	8.9800	-4.6953	-1.4223
1928.96	8.9903	-4.4410	-2.1637
1929.04	9.0701	-4.4651	-2.5542
1929.13	9.0427	-4.2761	-2.0575
1929.21	8.9822	-4.4725	-1.1861
1929.29	8.9182	-4.3039	-0.0753
1929.38	8.8638	-4.4636	0.1038
1929.46	8.8389	-4.9388	-0.6402
1929.54	8.8261	-4.7835	-0.1748
1929.63	8.8724	-4.7671	-0.5658
1929.71	8.8408	-5.0024	-0.8721
1929.79	8.8338	-5.1371	-1.3341
1929.88	8.9045	-4.7604	-1.8752
1929.96	8.9722	-4.8179	-1.8507
1930.04	8.9751	-4.6697	-1.7516
1930.13	8.9653	-4.4439	-1.9102
1930.21	8.9654	-4.5198	-1.0186
1930.29	8.8517	-4.5395	0.4269
1930.38	8.7686	-5.0225	0.2812
1930.46	8.8260	-4.9413	-0.2433
1930.54	8.7737	-5.1784	-0.7790
1930.63	8.7899	-5.1312	-0.7788
1930.71	8.8060	-5.0840	-0.7786

1930.79	8.8341	-4.9951	-0.7782
1930.88	8.9427	-4.3743	-1.4602
1930.96	8.9644	-4.4838	-1.4363
1931.04	8.9743	-4.4445	-1.7136
1931.13	8.9760	-4.2727	-0.2753
1931.21	8.9540	-4.3071	-0.1138
1931.29	8.8991	-4.4965	0.2468
1931.38	8.8409	-4.4370	0.5482
1931.46	8.8042	-5.0784	-0.1464
1931.54	8.8292	-4.8495	-0.3331
1931.63	8.8946	-4.9397	-0.4032
1931.71	8.8430	-5.0639	-0.6795
1931.79	8.8885	-5.0517	-1.5029
1931.88	9.0209	-3.9508	-1.8374
1931.96	9.0759	-3.9687	-1.7431
1932.04	9.0819	-4.0872	-1.1480
1932.13	9.0977	-4.1411	-0.9319
1932.21	9.0220	-4.2509	-0.7204
1932.29	8.9119	-4.4890	-0.7863
1932.38	8.8389	-4.6726	0.3083
1932.46	8.8342	-4.8323	0.5660
1932.54	8.7330	-5.2710	-0.7237
1932.63	8.8045	-5.1850	-0.5565

1932.71	8.7954	-5.1006	-0.3923
1932.79	8.8155	-5.0377	-0.4312
1932.88	8.9047	-4.9871	-0.9731
1932.96	8.9520	-4.6726	-1.3303
1933.04	8.9662	-4.5922	-1.5881
1933.13	9.0107	-4.4873	-1.4650
1933.21	8.9749	-4.5808	-1.4772
1933.29	8.8854	-4.5925	0.3665
1933.38	8.8132	-4.9691	0.0230
1933.46	8.7735	-5.0369	-0.1437
1933.54	8.7694	-4.9671	-0.0972
1933.63	8.8155	-4.9633	-0.3284
1933.71	8.8238	-4.9501	-0.5364
1933.79	8.8603	-4.9891	-0.4642
1933.88	8.9639	-4.9794	-1.3644
1933.96	9.0438	-4.4829	-1.6034
1934.04	9.0660	-4.2971	-2.0202
1934.13	9.0470	-4.2299	-1.9993
1934.21	8.9778	-4.0342	-0.5840
1934.29	8.9454	-4.3993	-0.2433
1934.38	8.8436	-4.7051	0.2271
1934.46	8.9146	-4.8956	-0.7634
1934.54	8.8192	-4.5617	-0.5758

1934.63	8.8765	-5.0000	-1.2501
1934.71	8.8665	-4.9922	-1.7956
1934.79	8.8870	-4.9211	-2.4025
1934.88	8.9666	-4.9390	-3.0551
1934.96	9.0549	-4.2768	-2.2916
1935.04	9.0631	-4.0541	-1.8318
1935.13	9.0565	-3.9921	-1.2170
1935.21	9.0507	-4.1972	-0.7625
1935.29	8.9333	-4.7341	-1.1838
1935.38	8.8534	-4.9752	-1.3945
1935.46	8.7991	-5.2110	-1.4621
1935.54	8.8112	-5.2636	-2.0205
1935.63	8.8039	-5.0813	-1.9556
1935.71	8.9258	-4.9913	-2.3347
1935.79	8.8360	-4.9288	-2.7505
1935.88	9.0186	-4.6175	-2.1134
1935.96	9.0244	-4.4709	-1.9960
1936.04	9.0682	-4.5454	-1.7822
1936.13	9.0374	-4.6294	-2.3125
1936.21	8.9952	-4.6730	-0.6026
1936.29	8.8950	-4.7381	0.1707
1936.38	8.7839	-5.1490	0.0815
1936.46	8.8054	-5.1821	-0.7078

1936.54	8.7747	-5.1702	-0.6347
1936.63	8.7877	-5.5333	-1.3828
1936.71	8.8083	-5.2687	-1.5377
1936.79	8.8311	-5.1419	-1.9359
1936.88	9.0546	-4.8631	-2.7627
1936.96	9.0048	-4.8581	-2.8329
1937.04	9.0474	-4.7612	-3.3597
1937.13	9.0961	-4.6889	-1.6467
1937.21	9.0497	-4.7061	-3.0368
1937.29	8.9319	-4.8253	-0.7507
1937.38	8.8932	-5.0120	-0.2059
1937.46	8.8514	-5.1791	-1.0510
1937.54	8.8048	-5.0548	-0.4304
1937.63	8.8624	-5.3269	-0.8874
1937.71	8.8223	-5.6136	-1.8505
1937.79	8.7969	-5.5376	-2.0250
1937.88	8.9300	-5.1717	-2.4122
1937.96	9.0319	-4.8408	-1.5788
1938.04	9.0513	-4.7791	-1.6746
1938.13	9.0716	-4.6502	-1.9492
1938.21	9.0249	-4.6023	-1.8832
1938.29	8.9403	-4.7113	-0.2124
1938.38	8.8243	-4.9223	0.0679

1938.46	8.8051	-4.8402	-0.1971
1938.54	8.7696	-5.0334	-0.5607
1938.63	8.7806	-5.1022	-0.4525
1938.71	8.8603	-4.7391	-0.4593
1938.79	8.8492	-4.5165	-0.7667
1938.88	9.0929	-4.4924	-2.4510
1938.96	9.0715	-4.4877	-2.3235
1939.04	9.1269	-4.4598	-2.0961
1939.13	9.1175	-4.3880	-1.9003
1939.21	9.0139	-4.2932	-0.4940
1939.29	8.9175	-4.3673	0.2423
1939.38	8.7903	-4.9812	-0.7581
1939.46	8.8412	-5.1262	-0.8658
1939.54	8.8205	-5.1885	-1.4191
1939.63	8.8418	-5.4873	-2.4637
1939.71	8.7647	-5.2080	-2.0633
1939.79	8.7947	-4.9518	-2.0320
1939.88	8.9132	-4.7423	-2.8324
1939.96	8.9411	-4.8119	-3.2686
1940.04	9.0071	-4.7956	-2.8432
1940.13	8.9522	-4.7031	-2.9230
1940.21	8.9369	-4.7242	-2.2168
1940.29	8.9031	-4.5300	0.4276

1940.38	8.8075	-4.7689	1.0465
1940.46	8.7470	-5.0898	0.3840
1940.54	8.7516	-5.2838	0.1721
1940.63	8.7826	-5.5769	-0.8366
1940.71	8.8014	-5.5009	-1.4595
1940.79	8.8645	-5.3503	-1.6433
1940.88	8.9216	-4.8728	-2.2373
1940.96	8.9462	-4.9905	-2.7411
1941.04	9.0193	-4.9201	-2.6466
1941.13	8.9725	-4.6696	-1.5212
1941.21	8.9977	-4.6756	-1.1373
1941.29	8.8899	-4.4801	-0.2379
1941.38	8.8284	-4.6257	0.2433
1941.46	8.7559	-5.2698	-0.6606
1941.54	8.7312	-5.4212	-1.5902
1941.63	8.7732	-5.3985	-1.7676
1941.71	8.7532	-5.2196	-1.6948
1941.79	8.8119	-5.2060	-2.2610
1941.88	8.8463	-5.0484	-2.2839
1941.96	8.9877	-4.6912	-3.1491
1942.04	9.0365	-4.4832	-2.5012
1942.13	9.0331	-4.4964	-1.8269
1942.21	8.9778	-4.4945	-1.5476

1942.29	8.9292	-4.6702	-0.9185
1942.38	8.7541	-5.1499	-0.8927
1942.46	8.7009	-5.2664	-0.7488
1942.54	8.7019	-5.3780	-1.3531
1942.63	8.7932	-5.3948	-1.7433
1942.71	8.7735	-5.2295	-1.3506
1942.79	8.7806	-5.1074	-1.4703
1942.88	8.9105	-4.7321	-1.9133
1942.96	8.9511	-4.5028	-1.5626
1943.04	8.9731	-4.4807	-1.1640
1943.13	8.9435	-4.5673	-1.6784
1943.21	8.9419	-4.7114	-1.7432
1943.29	8.8703	-4.6972	-1.3813
1943.38	8.7834	-4.9416	-1.1869
1943.46	8.7467	-5.0834	-0.6495
1943.54	8.7328	-5.2694	-0.4822
1943.63	8.7588	-5.1754	-1.1225
1943.71	8.7636	-5.3272	-1.3354
1943.79	8.7239	-5.1497	-1.2853
1943.88	8.8401	-4.8996	-1.3683
1943.96	8.9199	-4.6236	-2.0249
1944.04	8.9506	-4.5782	-1.8274
1944.13	8.9385	-4.5442	-1.3708

1944.21	8.9224	-4.5878	-1.0268
1944.29	8.8832	-4.6368	-0.8532
1944.38	8.7723	-4.8570	-0.4933
1944.46	8.7601	-4.8715	-0.6373
1944.54	8.7467	-4.8826	0.6793
1944.63	8.8432	-5.4059	-0.9977
1944.71	8.8463	-5.2812	-0.8003
1944.79	8.8632	-5.1241	-1.2590
1944.88	8.8924	-4.9195	-1.8756
1944.96	8.9864	-4.7312	-1.3494
1945.04	8.9968	-4.6638	-1.8316
1945.13	8.9906	-4.5641	-1.3914
1945.21	8.9552	-4.4804	-0.2923
1945.29	8.9031	-4.5133	0.7850
1945.38	8.7818	-5.1948	-0.0131
1945.46	8.7413	-5.2827	-0.1166
1945.54	8.7386	-5.3588	-0.2800
1945.63	8.7396	-5.2530	-0.5162
1945.71	8.7640	-5.1137	-0.5576
1945.79	8.8283	-4.9172	-0.2668
1945.88	8.9584	-4.8658	-2.5697
1945.96	8.9615	-4.6930	-1.9734
1946.04	9.0033	-4.5575	-1.0899

1946.13	9.0115	-4.4742	-0.5983
1946.21	8.9314	-4.5713	-0.2820
1946.29	8.8762	-4.5635	0.2016
1946.38	8.7577	-4.8589	0.8782
1946.46	8.7302	-5.1679	-0.1648
1946.54	8.7285	-5.2078	0.1761
1946.63	8.7361	-5.1024	0.2614
1946.71	8.7432	-5.2699	-0.8149
1946.79	8.7967	-5.1768	-1.5314
1946.88	8.8404	-4.6185	-1.5691
1946.96	8.9390	-4.5434	-1.5859
1947.04	8.9667	-4.6080	-1.4929
1947.13	8.9724	-4.6565	-1.4012
1947.21	8.9217	-4.6636	-1.3126
1947.29	8.8862	-4.7624	-1.0598
1947.38	8.7801	-5.0195	0.5452
1947.46	8.7415	-4.9081	0.5193
1947.54	8.7192	-4.9420	0.4404
1947.63	8.8041	-5.3463	-1.4660
1947.71	8.8058	-5.2101	-1.2384
1947.79	8.8508	-4.9767	-1.6855
1947.88	8.9126	-4.8978	-1.5461
1947.96	8.9751	-4.6150	-2.2842

1948.04	9.0272	-4.5243	-2.6191
1948.13	9.0048	-4.5489	-2.3607
1948.21	8.9466	-4.8085	-1.1826
1948.29	8.9178	-4.4351	-0.0936
1948.38	8.7662	-4.9297	0.5911
1948.46	8.7901	-5.3549	-0.8915
1948.54	8.7940	-5.5326	-1.2832
1948.63	8.7897	-5.2881	-1.0057
1948.71	8.7853	-5.1546	-1.1656
1948.79	8.8289	-5.1277	-1.3397
1948.88	8.9067	-4.9121	-1.9748
1948.96	8.9741	-4.6715	-1.8003
1949.04	8.9721	-4.7636	-2.2787
1949.13	9.0144	-4.5847	-1.7592
1949.21	8.9722	-4.5959	-1.6020
1949.29	8.9208	-4.6461	-0.5652
1949.38	8.7626	-5.0660	0.1004
1949.46	8.8358	-5.3132	-1.0793
1949.54	8.8264	-5.4107	-1.0504
1949.63	8.8038	-5.1226	-0.9952
1949.71	8.8118	-5.2219	-0.7764
1949.79	8.8569	-5.2366	-1.6158
1949.88	8.8788	-4.8631	-1.4213

1949.96	8.9736	-4.5948	-2.1176
1950.04	9.0187	-4.4467	-2.2760
1950.13	9.0223	-4.4023	-1.3388
1950.21	8.9827	-4.4981	-0.7236
1950.29	8.9010	-4.5248	0.3744
1950.38	8.7912	-5.1778	-0.0754
1950.46	8.7812	-5.1579	-0.7426
1950.54	8.7472	-5.1419	-1.0252
1950.63	8.7912	-5.3436	-1.5163
1950.71	8.7994	-5.2556	-1.3370
1950.79	8.8474	-5.0713	-1.2929
1950.88	8.9230	-4.7884	-2.0780
1950.96	8.9996	-4.7051	-2.2246
1951.04	9.0885	-4.6167	-2.4918
1951.13	9.0748	-4.5378	-2.2271
1951.21	9.0274	-4.5989	-2.0135
1951.29	8.9384	-4.4498	-0.3856
1951.38	8.8034	-4.8998	-0.2599
1951.46	8.8025	-5.2185	-0.4175
1951.54	8.8094	-5.0394	-0.4579
1951.63	8.8098	-5.0423	-0.3973
1951.71	8.7840	-5.2260	-0.8914
1951.79	8.8159	-5.1570	-0.5919

1951.88	8.9312	-4.9753	-1.7258
1951.96	8.9609	-4.6650	-1.8198
1952.04	8.9920	-4.5982	-1.9682
1952.13	8.9769	-4.6585	-1.6984
1952.21	8.9734	-4.5894	-0.9810
1952.29	8.8889	-4.6464	0.1070
1952.38	8.7883	-4.7818	0.3643
1952.46	8.7453	-4.9292	0.4091
1952.54	8.7390	-5.1065	0.1335
1952.63	8.7974	-5.2217	-0.9057
1952.71	8.8058	-5.1606	-0.9411
1952.79	8.8633	-5.1500	-1.8400
1952.88	8.9033	-4.6932	-1.6571
1952.96	9.0051	-4.5897	-2.0289
1953.04	9.0184	-4.4257	-1.8427
1953.13	9.0278	-4.4897	-1.3318
1953.21	8.9909	-4.4479	-1.1083
1953.29	8.9022	-4.8320	-0.1722
1953.38	8.8047	-5.0739	-0.3425
1953.46	8.8191	-4.9966	-0.3085
1953.54	8.7745	-5.0044	-0.1448
1953.63	8.7798	-5.0478	-0.2634
1953.71	8.7851	-5.0912	-0.3820

1953.79	8.8304	-4.9168	-0.9578	
1953.88	8.9505	-4.3349	-2.3889	
1953.96	9.0526	-4.4901	-2.7461	
1954.04	9.0269	-4.3954	-2.7446	9.1631
1954.13	8.9118	-4.8284	-2.7431	9.2073
1954.21	8.8069	-5.0497	-1.1232	9.1292
1954.29	8.7894	-4.9542	-0.3127	9.0952
1954.38	8.7505	-5.1397	-0.1159	9.0072
1954.46	8.7419	-4.9828	-0.1243	8.9901
1954.54	8.7409	-4.9418	-0.5718	9.0381
1954.63	8.8267	-4.8923	-0.3709	9.0091
1954.71	8.8190	-4.7218	-0.7501	9.0125
1954.79	8.8975	-4.4881	-1.0911	9.0571
1954.88	8.9575	-4.4553	-3.1609	9.0978
1954.96	8.9831	-4.5712	-3.3500	9.1385
1955.04	8.9432	-4.6152	-2.9834	9.1681
1955.13	8.9003	-4.7621	-2.7811	9.1355
1955.21	8.7821	-5.3435	-1.8469	9.1028
1955.29	8.7801	-5.3918	0.6714	9.0702
1955.38	8.7589	-5.1572	0.7004	9.0376
1955.46	8.7546	-4.9774	0.7111	9.0017
1955.54	8.7416	-4.7077	0.6634	9.0617
1955.63	8.7703	-4.8339	0.6157	9.0866

1955.71	8.7998	-4.4483	0.5680	9.0220
1955.79	8.9826	-4.4327	-2.3373	9.0760
1955.88	9.0485	-4.2458	-2.7322	9.1473
1955.96	9.0060	-4.2891	-2.5368	9.1984
1956.04	8.9733	-4.2491	-1.8968	9.2351
1956.13	8.9389	-4.4595	-1.3289	9.2014
1956.21	8.8621	-4.9923	-0.6699	9.1678
1956.29	8.7758	-5.0571	0.6926	9.1341
1956.38	8.8337	-5.2583	0.3487	9.1288
1956.46	8.7273	-4.9895	-0.0048	9.1442
1956.54	8.7461	-4.8748	-0.5598	9.1160
1956.63	8.7342	-4.6946	-1.4043	9.0786
1956.71	8.8565	-4.5802	-1.6191	9.0796
1956.79	8.9427	-4.5451	-1.4362	9.0886
1956.88	8.9400	-4.3372	-2.9450	9.1204
1956.96	9.0144	-4.3154	-2.5251	9.1522
1957.04	8.9729	-4.4349	-2.1094	9.1840
1957.13	8.9201	-4.5483	-1.8928	9.1870
1957.21	8.8491	-4.6519	-0.1086	9.1531
1957.29	8.8078	-4.6836	0.5315	9.0326
1957.38	8.8229	-4.8791	0.2935	9.0065
1957.46	8.7756	-5.0097	-0.5788	8.9684
1957.54	8.8042	-5.0998	-0.9528	8.9571

1957.63	8.7459	-5.1888	-1.2038	8.9829
1957.71	8.8371	-4.5292	-1.2989	9.0088
1957.79	8.9507	-4.6982	-1.4869	9.0346
1957.88	9.0338	-4.5110	-2.6946	9.0521
1957.96	9.0011	-4.2842	-2.9492	9.0673
1958.04	9.0267	-4.1891	-2.9922	9.0826
1958.13	8.9133	-4.8530	-2.8925	9.0918
1958.21	8.8076	-5.0023	-1.4947	9.0722
1958.29	8.8195	-5.1758	0.1359	9.0418
1958.38	8.7791	-5.2519	-0.4693	8.9623
1958.46	8.7778	-5.1731	-0.5946	9.0655
1958.54	8.7075	-5.0877	-0.8702	9.1345
1958.63	8.7724	-4.7911	-1.1452	9.1376
1958.71	8.9105	-4.5973	-1.2652	9.0560
1958.79	8.9714	-4.6721	-1.2366	9.0502
1958.88	9.0430	-4.5932	-2.7082	9.1144
1958.96	8.9629	-4.6689	-2.5707	9.1506
1959.04	8.9780	-4.9340	-2.4117	9.1868
1959.13	8.9201	-5.0155	-1.7010	9.1703
1959.21	8.8155	-5.0944	-0.6635	9.1489
1959.29	8.7954	-5.0389	-0.1907	9.0998
1959.38	8.7825	-4.9949	0.0208	9.0546
1959.46	8.8006	-5.0004	0.0996	9.0898

1959.54	8.8118	-4.9765	0.1013	9.1150
1959.63	8.7756	-4.7502	-0.1905	9.1292
1959.71	8.9034	-4.4703	-0.4823	9.1155
1959.79	9.0288	-4.5166	-1.6826	9.1018
1959.88	9.1257	-4.7217	-1.3978	9.1808
1959.96	9.0197	-4.8049	-1.9033	9.1558
1960.04	8.9775	-4.9331	-1.8539	9.1982
1960.13	8.8712	-4.9541	-1.3066	9.2406
1960.21	8.8096	-5.0822	-0.2111	9.1053
1960.29	8.7953	-5.0870	0.1979	9.0094
1960.38	8.7811	-5.0918	-0.1201	8.9765
1960.46	8.7684	-5.0953	-0.3702	8.9447
1960.54	8.7809	-5.0783	-0.6011	8.8897
1960.63	8.8036	-5.1948	-0.7775	8.9228
1960.71	8.8604	-4.5477	-0.8973	8.9575
1960.79	8.9240	-4.5245	-0.2477	9.0877
1960.88	8.9596	-4.3980	-1.0642	9.0801
1960.96	8.9897	-4.4863	-0.8472	9.1079
1961.04	8.9745	-4.8194	-0.8939	9.1357
1961.13	8.8843	-4.9154	-1.1147	9.1635
1961.21	8.8920	-5.0413	-0.2560	9.1323
1961.29	8.8146	-5.0242	-0.0097	9.0545
1961.38	8.8544	-5.0913	-0.2778	8.9767

1961.46	8.7635	-5.6864	-0.1891	8.8857	
1961.54	8.7829	-5.5413	-0.6752	8.9023	
1961.63	8.7913	-5.1612	-0.8042	8.9422	
1961.71	8.9402	-4.5239	-1.1744	8.9924	
1961.79	8.9914	-4.5606	-1.1612	9.0425	
1961.88	9.0353	-4.5622	-1.0788	9.0927	
1961.96	9.0255	-4.4910	-0.6281	9.1311	
1962.04	8.9388	-4.9463	-0.5332	9.1278	-4.1339
1962.13	8.8792	-5.1408	-0.5254	9.1315	-3.5466
1962.21	8.8421	-5.0332	-0.3956	9.1296	-3.1090
1962.29	8.8199	-5.0437	0.6854	9.0901	-3.6884
1962.38	8.7977	-5.0541	0.5862	8.9521	-4.3106
1962.46	8.7755	-5.0646	0.4382	8.9497	-4.4161
1962.54	8.7924	-5.1742	0.0554	8.9484	-4.4736
1962.63	8.8304	-5.2126	-0.5402	8.9532	-4.2110
1962.71	8.8632	-4.7099	-1.6435	8.9581	-3.9485
1962.79	8.9572	-4.4395	-1.9421	9.0578	-3.6219
1962.88	9.0379	-4.5552	-1.6758	9.1101	-3.5864
1962.96	8.9756	-4.7980	-1.1449	9.1395	-3.7969
1963.04	8.9243	-4.9781	-1.0590	9.1676	-4.0353
1963.13	8.8741	-5.0944	-1.1933	9.1957	-4.4372
1963.21	8.8377	-5.1212	-1.4350	9.1750	-4.6088
1963.29	8.8012	-5.1479	-1.8718	9.1526	-4.7726

1963.38	8.8936	-5.1986	0.5865	9.1480	-5.0995
1963.46	8.8181	-5.1849	0.3540	9.1450	-5.2399
1963.54	8.7848	-4.8598	0.1215	9.1419	-4.6704
1963.63	8.8120	-4.8290	-0.1109	9.1433	-4.1110
1963.71	8.8684	-4.7475	0.1784	9.1474	-3.5597
1963.79	9.0025	-4.6804	-0.1953	9.0943	-3.9546
1963.88	8.9584	-4.6720	-0.6686	9.1239	-4.1711
1963.96	9.0646	-4.6036	-1.1285	9.1478	-4.2866
1964.04	8.9669	-4.6652	-0.8969	9.1702	-4.4041
1964.13	8.8767	-4.5280	-0.4841	9.1858	-4.4092
1964.21	8.8542	-4.8140	0.1863	9.1708	-4.0121
1964.29	8.8285	-4.9870	0.3501	9.0887	-4.3014
1964.38	8.8189	-5.1214	0.4745	9.0357	-4.4801
1964.46	8.7746	-4.7327	-0.9863	9.0236	-4.5447
1964.54	8.7797	-4.7723	-1.0670	9.0428	-4.5662
1964.63	8.8254	-4.7689	-1.3276	9.0621	-4.5877
1964.71	8.9250	-4.3484	-1.6482	9.0814	-4.6092
1964.79	9.0253	-4.5423	-1.1654	9.1007	-4.6307
1964.88	9.0713	-4.4635	-1.3894	9.1200	-4.6503
1964.96	8.9949	-4.4565	-1.1513	9.1815	-3.9156
1965.04	8.9493	-4.4904	-1.2210	9.2911	-2.9239
1965.13	8.8390	-4.9992	-1.2987	9.2417	-2.7463
1965.21	8.8250	-5.1847	-0.8696	9.2008	-2.8836

1965.29	8.8107	-5.2328	0.2626	9.1100	-2.9396
1965.38	8.8171	-5.2498	-0.6214	9.0193	-2.9957
1965.46	8.8024	-5.1706	-0.4329	8.9931	-3.0361
1965.54	8.7847	-5.0653	-0.1227	9.0064	-3.0670
1965.63	8.8114	-4.9669	-0.5725	9.0196	-3.0979
1965.71	8.8555	-4.8686	-1.1499	9.0329	-3.1289
1965.79	8.9890	-4.4201	-1.5155	9.0462	-3.1598
1965.88	9.0822	-4.3338	-1.4755	9.1047	-3.9202
1965.96	9.0327	-4.4704	-2.1889	9.1244	-4.4497
1966.04	8.9835	-4.6101	-2.0113	9.1709	-4.4524
1966.13	8.8844	-4.9289	-0.9283	9.2105	-4.5207
1966.21	8.7956	-5.2984	0.0779	9.1178	-3.1280
1966.29	8.7791	-5.3046	0.2306	9.0044	-4.4962
1966.38	8.7733	-5.3122	-0.0146	8.9796	-4.1813
1966.46	8.7433	-5.1564	-0.0283	8.9548	-3.8663
1966.54	8.7477	-5.0640	-0.0937	8.9300	-3.5514
1966.63	8.7689	-4.9508	-0.3913	8.9070	-3.2197
1966.71	8.8433	-4.6906	-0.7877	8.9812	-2.6707
1966.79	8.9067	-4.4428	-1.0440	9.0057	-3.0235
1966.88	8.9839	-4.3376	-1.4435	9.0302	-3.3764
1966.96	9.0561	-4.2506	-2.0567	9.0546	-3.7292
1967.04	9.0349	-4.3095	-1.2798	9.0791	-4.0821
1967.13	8.9842	-4.5277	-0.4458	9.0901	-4.2788

1967.21	8.8411	-4.8808	-0.8659	9.0802	-4.2347
1967.29	8.7960	-5.0143	0.3117	9.0493	-4.2078
1967.38	8.7771	-5.0575	-0.4990	8.9532	-4.2394
1967.46	8.7511	-5.0083	-0.9554	8.9879	-4.3348
1967.54	8.7637	-5.0078	-0.7573	8.9916	-3.9044
1967.63	8.7924	-5.0275	-0.6896	8.9885	-3.3588
1967.71	8.9317	-4.5453	-0.6982	9.0006	-3.1602
1967.79	8.9575	-4.5499	-0.7068	9.0298	-3.3456
1967.88	8.9773	-4.5627	-1.7367	9.0597	-3.5185
1967.96	8.9578	-4.5511	-1.4252	9.0970	-3.5796
1968.04	8.9381	-4.5393	-1.2943	9.1343	-3.6408
1968.13	8.9383	-4.8882	-1.1629	9.1675	-3.7154
1968.21	8.8550	-5.1802	-1.1408	9.1436	-3.9761
1968.29	8.8177	-5.1943	-0.4990	9.1223	-4.1464
1968.38	8.7803	-5.2083	-0.2260	9.1138	-3.8589
1968.46	8.7690	-5.2961	-0.3145	9.1054	-3.7106
1968.54	8.8102	-5.4954	-0.4479	9.0970	-4.1572
1968.63	8.7684	-5.1793	-0.6889	9.0867	-4.4755
1968.71	8.8242	-4.9162	-0.7399	9.0698	-4.3236
1968.79	8.9768	-4.6256	-0.8077	9.0693	-4.1690
1968.88	8.9982	-4.5676	-1.7971	9.1204	-4.0061
1968.96	9.0021	-4.6356	-1.0268	9.1715	-3.8432
1969.04	8.9466	-5.1411	-0.7967	9.1719	-3.9442

1969.13	8.8602	-5.2241	-0.0338	9.1671	-4.1209
1969.21	8.8746	-5.3883	1.1161	9.1034	-4.1637
1969.29	8.8585	-5.2571	1.1698	9.0397	-4.2065
1969.38	8.8409	-5.0650	0.6389	8.9977	-4.3416
1969.46	8.8456	-5.0049	0.1973	8.9760	-4.5632
1969.54	8.8308	-5.0071	-0.4938	8.9542	-4.7849
1969.63	8.8399	-4.9579	-1.0896	8.9605	-4.4693
1969.71	8.8552	-4.6734	-1.2967	8.9692	-4.4972
1969.79	8.9334	-4.5673	-1.4538	8.9778	-4.9997
1969.88	9.0385	-4.4595	-1.8119	9.1390	-3.6180
1969.96	9.0251	-4.6732	-2.2504	9.1685	-3.5555
1970.04	8.9687	-4.8799	-2.3642	9.1981	-3.4931
1970.13	8.8857	-4.8645	-2.4710	9.2221	-3.4203
1970.21	8.8570	-5.1533	-0.4215	9.1307	-4.0214
1970.29	8.8702	-5.1253	0.5402	9.0911	-4.1666
1970.38	8.8450	-5.0124	0.1806	9.0516	-4.3118
1970.46	8.8681	-5.0357	-0.4279	9.0120	-4.4570
1970.54	8.8750	-5.0887	-0.7386	9.0534	-4.6428
1970.63	8.8242	-5.1529	-0.9680	9.1039	-4.8331
1970.71	8.9026	-4.6300	-0.9685	9.1371	-4.9279
1970.79	9.0347	-4.3555	-1.0413	9.1068	-4.6716
1970.88	9.0844	-4.3061	-1.1704	9.0765	-4.4153
1970.96	9.1275	-4.2171	-0.9799	9.1096	-3.6775

1971.04	8.9725	-4.4821	-1.8119	9.2188	-3.7936
1971.13	8.8889	-5.3926	-1.4937	9.3205	-3.2844
1971.21	8.8822	-5.3322	-1.3398	9.2201	-3.8626
1971.29	8.8331	-5.4267	-0.8180	9.1498	-4.3133
1971.38	8.8226	-5.2827	-0.1733	9.0111	-4.1707
1971.46	8.8171	-5.1890	0.1265	8.9976	-3.8344
1971.54	8.8129	-5.1997	-0.0119	8.9896	-3.6685
1971.63	8.8210	-4.5863	-0.8700	9.0010	-4.1321
1971.71	8.8963	-4.5479	-1.1181	8.9593	-3.6535
1971.79	8.9668	-4.4973	-1.3199	9.0259	-3.6043
1971.88	9.0448	-4.3824	-1.7437	9.1100	-3.6241
1971.96	9.0075	-4.4106	-2.8643	9.1940	-3.5478
1972.04	8.9367	-4.5604	-2.0690	9.2699	-3.4781
1972.13	8.8729	-4.9044	-1.4342	9.2214	-3.5649
1972.21	8.8145	-5.0409	-0.7889	9.1730	-3.6516
1972.29	8.8294	-4.9942	-0.2014	9.0904	-3.7631
1972.38	8.7971	-5.5626	-0.2022	8.9698	-4.1610
1972.46	8.8083	-5.3294	-0.1599	8.9204	-4.5452
1972.54	8.8196	-5.0962	-0.9303	8.9329	-4.4396
1972.63	8.8309	-4.8631	-1.4870	8.9656	-4.4193
1972.71	8.9721	-4.5768	-1.9767	8.9984	-4.3989
1972.79	8.9945	-4.5617	-2.0294	9.0311	-4.3786
1972.88	9.0080	-4.5533	-2.0821	9.0639	-4.3583

1972.96	9.0085	-4.5659	-2.5734	9.0649	-4.1762
1973.04	8.9823	-4.6217	-2.2849	9.1554	-3.5751
1973.13	8.9349	-4.8652	-2.1640	9.2108	-3.4432
1973.21	8.8616	-5.0291	-0.6985	9.1075	-4.3556
1973.29	8.8103	-5.0675	-0.3749	9.0368	-3.8333
1973.38	8.8237	-5.1735	-0.9236	9.0109	-4.0822
1973.46	8.7857	-5.0227	-1.5300	8.9851	-4.3311
1973.54	8.7345	-4.8067	-1.8163	9.0220	-4.4180
1973.63	8.7463	-4.6781	-1.8683	9.0538	-4.5267
1973.71	8.8986	-4.5015	-1.9204	9.0204	-4.9010
1973.79	8.9541	-4.3257	-1.9725	9.0163	-4.9604
1973.88	9.0591	-4.2984	-2.0387	9.0785	-4.0685
1973.96	9.0349	-4.2525	-1.9785	9.1871	-3.4170
1974.04	8.9937	-4.2412	-2.0208	9.3297	-3.8394
1974.13	8.9438	-4.4279	-1.8218	9.2689	-4.0035
1974.21	8.8613	-4.4715	-1.3406	9.1811	-4.0917
1974.29	8.8720	-4.4511	-0.2576	9.0933	-4.1798
1974.38	8.8681	-4.8932	-0.6921	9.0055	-4.2680
1974.46	8.9127	-5.2200	-1.5274	8.9555	-4.3097
1974.54	8.7559	-4.8535	-1.6831	8.9934	-4.2434
1974.63	8.7846	-5.1147	-1.6031	9.0565	-4.3575
1974.71	8.8508	-4.8934	-1.4542	9.0210	-4.7727
1974.79	8.9975	-4.5104	-1.6550	9.0273	-4.9278

1974.88	9.0248	-4.4421	-1.6283	9.0917	-4.4731
1974.96	9.0169	-4.7495	-2.8436	9.1817	-3.6923
1975.04	8.9555	-4.8342	-1.0815	9.1964	-4.0332
1975.13	8.8833	-5.1185	-1.5308	9.1699	-4.0100
1975.21	8.8244	-5.0671	-1.1703	9.1206	-3.9670
1975.29	8.8298	-5.3035	-0.5975	9.0472	-4.0709
1975.38	8.7841	-5.2116	-0.8325	9.0011	-4.0187
1975.46	8.7299	-5.1057	-0.6692	8.9620	-4.1608
1975.54	8.7396	-5.0565	-0.9971	8.9293	-4.5717
1975.63	8.7719	-5.0273	-0.9883	8.9566	-5.1041
1975.71	8.8794	-4.8493	-0.9574	8.9729	-4.8273
1975.79	8.9478	-4.5034	-0.9264	8.9950	-4.1619
1975.88	9.0773	-4.2717	-1.6521	9.0882	-4.1992
1975.96	9.0520	-4.5365	-2.2076	9.1054	-4.1982
1976.04	8.9639	-4.5904	-3.0679	9.1229	-3.9886
1976.13	8.8863	-4.3007	-2.8185	9.1336	-4.2462
1976.21	8.8778	-5.0886	-1.3111	9.1114	-3.9938
1976.29	8.8379	-4.4974	0.3003	9.0898	-4.2601
1976.38	8.8225	-4.4421	0.1580	8.9760	-4.6557
1976.46	8.8072	-4.3867	-0.4132	8.8926	-4.6121
1976.54	8.8408	-4.7905	-0.3858	8.8889	-4.5253
1976.63	8.8080	-4.0343	-0.2716	8.8912	-4.4779
1976.71	8.8802	-4.3849	-0.3082	8.9400	-4.7404

1976.79	8.9467	-4.3753	-0.3801	8.9888	-4.7790
1976.88	9.0016	-4.1224	-2.5449	9.0677	-4.7827
1976.96	9.0345	-4.6247	-2.3538	9.1232	-4.5879
1977.04	8.9873	-4.5793	-1.6472	9.1151	-4.1158
1977.13	8.9373	-4.5089	-2.3252	9.1851	-4.0813
1977.21	8.8055	-4.7497	-1.3383	9.1291	-4.1303
1977.29	8.8050	-4.8296	-0.2183	9.0730	-4.1793
1977.38	8.7672	-4.8347	0.2016	9.0170	-4.2284
1977.46	8.7721	-4.8248	-0.6161	8.9694	-4.8139
1977.54	8.7767	-4.8511	-1.1737	8.9957	-4.4897
1977.63	8.7831	-4.7788	-0.7764	9.0221	-4.1655
1977.71	8.8701	-4.7431	-0.8780	9.0214	-4.1831
1977.79	9.0033	-4.3238	-1.4016	9.0170	-4.2455
1977.88	9.0468	-4.2349	-1.7914	9.0722	-4.2899
1977.96	9.0211	-4.3002	-1.5712	9.1510	-4.3272
1978.04	8.9837	-4.6614	-0.5758	9.2297	-4.3644
1978.13	8.9022	-4.7333	-1.2640	9.2918	-3.8530
1978.21	8.8837	-4.5440	-0.6872	9.1168	-3.7249
1978.29	8.8157	-4.6204	-0.5324	9.0855	-4.0045
1978.38	8.8085	-4.6480	-0.9933	9.0751	-4.2257
1978.46	8.7862	-4.6274	-0.9989	9.0683	-4.4468
1978.54	8.7521	-4.5685	-0.9036	9.0630	-4.6590
1978.63	8.8235	-4.8717	-0.9230	9.0728	-4.7759

1978.71	8.8512	-4.7048	-1.1541	9.0826	-4.8928
1978.79	9.0061	-4.5329	-1.7696	9.0965	-4.7518
1978.88	9.0516	-4.6232	-2.1343	9.1122	-4.5967
1978.96	9.0542	-4.5771	-2.4590	9.2058	-4.3290
1979.04	9.0220	-4.6350	-2.7587	9.2033	-3.9886
1979.13	8.9896	-4.6925	-1.4048	9.1884	-3.8038
1979.21	8.8025	-4.6924	-0.1580	9.1290	-4.2131
1979.29	8.8179	-5.1415	0.1919	9.0561	-4.3707
1979.38	8.7887	-5.4104	-0.1195	9.0124	-4.3936
1979.46	8.7381	-5.3626	-0.3240	8.9905	-4.5240
1979.54	8.7523	-5.1391	-0.7889	8.9687	-4.6544
1979.63	8.7733	-5.0526	-0.5666	8.9861	-4.5514
1979.71	8.9501	-4.5040	-0.9015	9.0063	-4.4313
1979.79	8.9563	-4.4845	-1.6501	9.0403	-4.3643
1979.88	8.9728	-4.4859	-1.8511	9.1185	-4.3928
1979.96	8.9829	-4.5117	-1.6475	9.1602	-4.4231
1980.04	8.9811	-4.5297	-1.4718	9.1821	-4.3172
1980.13	8.9575	-4.5499	-1.3793	9.2013	-4.1994
1980.21	8.9127	-4.7596	-1.1634	9.1295	-3.9930
1980.29	8.7278	-4.8182	-0.0701	9.0492	-4.1013
1980.38	8.7419	-4.7916	-0.1767	8.9665	-4.4495
1980.46	8.7560	-4.7651	0.0829	8.9478	-4.7307
1980.54	8.7701	-4.7386	-0.4239	8.9584	-4.7089

1980.63	8.8149	-4.6689	-0.9010	8.9691	-4.6854
1980.71	8.8694	-4.5859	-1.3553	8.9799	-4.6619
1980.79	8.9185	-4.5269	-1.7078	8.9906	-4.6384
1980.88	9.0129	-4.6556	-2.0262	9.0674	-3.7983
1980.96	9.0325	-4.6559	-1.9224	9.1240	-3.7946
1981.04	8.9847	-4.7132	-1.7413	9.1863	-3.8147
1981.13	8.9488	-4.6802	-1.2377	9.1637	-3.8716
1981.21	8.8476	-4.9441	-1.0220	9.1412	-3.9285
1981.29	8.7998	-5.1982	-0.8243	9.0836	-4.0891
1981.38	8.7622	-4.7658	-0.3270	8.9918	-4.4370
1981.46	8.7609	-4.8397	-0.5767	8.9650	-4.6485
1981.54	8.7424	-4.8964	-0.9189	8.9379	-4.6978
1981.63	8.7702	-4.9925	-1.1441	8.9543	-4.7079
1981.71	8.8215	-4.8666	-0.3301	8.9974	-4.7223
1981.79	8.9155	-4.4543	-1.4931	9.0406	-4.7367
1981.88	9.0699	-4.5239	-1.9686	9.0837	-4.7511
1981.96	9.0420	-5.3075	-1.5470	9.2151	-3.9015
1982.04	9.0140	-4.3650	-0.8935	9.0360	-4.1937
1982.13	8.9857	-4.4024	-0.8908	9.2159	-3.9041
1982.21	8.9574	-4.4397	-0.8881	9.1600	-4.2133
1982.29	8.8849	-4.5956	-0.7831	9.1042	-4.5225
1982.38	8.7559	-4.7466	0.3511	9.0484	-4.8318
1982.46	8.7172	-5.0232	-0.1525	8.9750	-4.8097

1982.54	8.7608	-5.2686	-1.2452	8.9801	-4.4537
1982.63	8.7687	-5.1070	-0.9108	8.9989	-4.5505
1982.71	8.8211	-4.7459	-1.1625	9.0176	-4.6473
1982.79	8.8990	-4.7882	-2.9039	9.0363	-4.7441
1982.88	8.8496	-4.4735	-2.5710	9.1033	-4.4299
1982.96	8.9460	-4.3353	-1.5332	9.1057	-4.3453
1983.04	9.0603	-4.1912	-0.0203	9.2020	-4.1399
1983.13	9.0030	-4.3767	-0.2594	9.0789	-4.8689
1983.21	8.9185	-4.5712	-0.6743	9.0966	-4.7114
1983.29	8.8989	-4.4837	-0.3516	9.0082	-4.2522
1983.38	8.8069	-4.6992	-0.6628	8.9706	-4.2645
1983.46	8.8139	-4.7188	0.0119	8.9495	-4.3392
1983.54	8.7474	-4.9135	-0.8067	8.9636	-4.5481
1983.63	8.7871	-4.9135	-0.9242	8.9777	-4.7570
1983.71	8.7984	-4.9151	-0.9291	8.9589	-4.7023
1983.79	8.8484	-4.8734	-0.8884	8.9797	-4.6049
1983.88	8.9221	-4.8256	-2.1533	9.0871	-4.4349
1983.96	9.0871	-4.4427	-2.2447	9.1945	-4.2649
1984.04	9.0502	-4.3889	-2.7585	9.1934	-4.2353
1984.13	9.0465	-4.3751	-2.1874	9.1684	-4.2365
1984.21	9.0086	-4.5592	-1.6692	9.1435	-4.2376
1984.29	8.9075	-4.5381	-0.6211	9.1335	-4.6243
1984.38	8.8892	-4.6883	-0.4457	8.9692	-4.7147

1984.46	8.7887	-4.9345	-0.2925	8.8250	-5.0571
1984.54	8.8297	-5.1422	-0.4030	8.8569	-4.8011
1984.63	8.7827	-5.0928	-0.0231	8.9586	-4.4285
1984.71	8.7626	-5.2070	-0.7936	9.0120	-4.6964
1984.79	8.8360	-5.2103	-1.1819	8.9685	-4.6965
1984.88	8.9110	-4.9006	-1.4027	9.0558	-4.6338
1984.96	8.9872	-4.9873	-2.5873	9.1431	-4.5710
1985.04	9.0430	-4.6132	-1.7806	9.2210	-4.5025
1985.13	8.9504	-4.4950	-1.1094	9.1022	-4.3125
1985.21	8.9356	-4.6379	-1.1116	9.0650	-4.8358
1985.29	8.9050	-4.6857	-0.2465	9.0242	-4.8562
1985.38	8.8274	-4.8059	-0.4868	8.9833	-4.8765
1985.46	8.8390	-5.0734	-0.7780	9.0073	-4.8885
1985.54	8.8084	-4.8956	0.1132	9.0142	-4.9309
1985.63	8.8062	-5.0506	-0.5520	8.9026	-5.0924
1985.71	8.8447	-5.0298	-0.7676	8.9087	-5.0111
1985.79	8.8628	-4.8540	-1.4730	9.0361	-4.6796
1985.88	8.9309	-4.8804	-2.0503	9.0690	-4.7906
1985.96	9.0022	-4.8333	-2.7120	9.2068	-4.3549
1986.04	9.1601	-4.4036	-3.0895	9.3667	-4.3640
1986.13	9.0875	-4.2925	-1.8152	9.3078	-4.3694
1986.21	9.0229	-4.5163	-1.2181	9.2469	-4.3746
1986.29	8.9698	-4.7070	-0.7084	9.1860	-4.3799

1986.38	8.8573	-4.6728	-0.0619	8.9860	-4.9871
1986.46	8.8600	-5.1235	-1.1240	8.9526	-4.9986
1986.54	8.8972	-5.1284	-1.1893	8.9192	-5.0101
1986.63	8.8261	-5.2333	-0.8960	8.8858	-5.0215
1986.71	8.8184	-5.2785	-1.1794	8.9381	-5.0146
1986.79	8.8567	-5.3411	-1.6003	9.0178	-5.0018
1986.88	8.9194	-4.8953	-2.1366	9.0975	-4.9890
1986.96	9.0056	-4.6222	-2.6802	9.1178	-4.6400
1987.04	9.0376	-4.5516	-2.3206	9.2813	-4.9734
1987.13	9.0655	-4.4507	-1.4789	9.2966	-4.9507
1987.21	8.9528	-4.5038	-0.9287	9.2257	-4.5223
1987.29	8.8527	-4.4659	-0.7325	9.0991	-4.5884
1987.38	8.8064	-4.6397	-0.6070	9.0807	-4.9539
1987.46	8.7788	-4.9377	-0.8305	9.0399	-4.8891
1987.54	8.7935	-4.8979	-0.7791	8.9992	-4.8243
1987.63	8.7899	-4.9357	-0.9053	8.9880	-4.7489
1987.71	8.7998	-4.9999	-1.3543	9.0224	-4.6574
1987.79	8.8053	-4.8869	-1.0883	9.0568	-4.5660
1987.88	8.8892	-4.9584	-1.9817	9.0912	-4.4745
1987.96	9.0034	-4.8415	-2.4925	9.1255	-4.3830
1988.04	9.0489	-4.6063	-2.7867	9.1691	-4.2066
1988.13	8.9310	-4.7260	-1.5507	9.1247	-4.2842
1988.21	8.9328	-4.7343	-1.0105	9.0314	-4.6597

1988.29	8.8126	-4.8246	-0.6264	8.9369	-4.9590
1988.38	8.7787	-5.1710	-1.1221	8.8551	-5.0601
1988.46	8.7687	-5.1581	-0.7999	8.9607	-4.9762
1988.54	8.7835	-5.0867	-0.4981	8.9842	-4.9971
1988.63	8.7455	-5.1103	-0.4724	8.9278	-5.1192
1988.71	8.7822	-5.0260	-0.3780	8.9027	-5.1748
1988.79	8.8028	-4.9683	-0.1628	8.9641	-5.0466
1988.88	8.9082	-4.9623	-1.9906	9.1031	-4.6654
1988.96	9.0003	-4.6921	-2.5625	9.1122	-4.7645
1989.04	9.0525	-4.6296	-2.5707	9.1212	-4.8636
1989.13	9.0659	-4.5847	-2.5004	9.1302	-4.9627
1989.21	9.0040	-4.4884	-1.9217	9.1005	-5.1068
1989.29	8.9141	-4.6108	-0.8886	9.0454	-5.2805
1989.38	8.8186	-4.7975	-0.6542	8.9803	-5.4287
1989.46	8.7746	-5.0769	-0.7606	8.8923	-4.9208
1989.54	8.8106	-5.1709	-1.2941	8.8774	-4.8428
1989.63	8.7911	-5.2974	-1.0849	8.9191	-4.7924
1989.71	8.7623	-5.5251	-2.0808	8.9609	-4.7420
1989.79	8.8107	-5.3883	-1.9074	9.0026	-4.6916
1989.88	8.9034	-4.7450	-1.4472	9.0372	-4.3086
1989.96	8.9660	-4.5922	-2.0412	9.0824	-4.2338
1990.04	9.0097	-4.3409	-1.7921	9.1192	-4.1825
1990.13	8.9898	-4.3423	-1.4804	9.1033	-4.2767

1990.21	8.9699	-4.3436	-1.1687	9.0874	-4.3709
1990.29	8.9449	-4.3341	-1.0268	8.9870	-4.9710
1990.38	8.7366	-5.3200	-1.1415	8.9349	-4.9553
1990.46	8.7593	-5.2772	-1.2341	8.9071	-4.9651
1990.54	8.7496	-5.1812	-1.5416	8.9179	-5.1503
1990.63	8.7397	-5.2633	-1.5549	8.9508	-5.0835
1990.71	8.7489	-4.9982	-2.2803	9.0094	-4.5602
1990.79	8.8541	-4.8788	-2.4510	9.0555	-4.4404
1990.88	8.9093	-4.7033	-2.4053	9.0321	-4.4518
1990.96	8.9237	-4.3668	-1.2479	9.1075	-4.2001
1991.04	8.9164	-4.3868	-1.1835	9.0959	-4.1933
1991.13	8.9077	-4.4198	-1.1780	9.0711	-4.2227
1991.21	8.8991	-4.4527	-1.1725	9.0463	-4.2521
1991.29	8.8873	-4.4912	-1.1680	9.0214	-4.2816
1991.38	8.8294	-4.6151	-1.1715	8.9368	-5.0928
1991.46	8.7511	-4.8231	-0.9180	8.8859	-5.1230
1991.54	8.7451	-4.9209	-1.2133	8.8534	-5.1392
1991.63	8.7257	-5.3816	-1.4182	8.8926	-5.1009
1991.71	8.7851	-5.2443	-1.6307	8.9453	-4.9920
1991.79	8.8467	-4.6104	-1.3725	9.0294	-4.7179
1991.88	8.9044	-4.5096	-1.9301	9.0885	-4.5558
1991.96	8.9253	-4.5149	-2.0755	9.1293	-4.4753
1992.04	8.9462	-4.5202	-2.2209	9.1649	-4.3931

1992.13	8.9322	-4.2105	-1.2957	9.1344	-4.2903
1992.21	8.9343	-4.4510	-1.6872	9.1039	-4.1875
1992.29	8.8760	-4.5257	-1.4009	9.0000	-4.7727
1992.38	8.8399	-4.7041	-1.2472	8.8886	-5.2754
1992.46	8.8227	-4.9051	-0.9469	8.8907	-5.2787
1992.54	8.7680	-4.9084	-0.7172	8.8863	-5.2706
1992.63	8.7354	-5.1589	-1.5733	8.8715	-5.2523
1992.71	8.7561	-5.3348	-2.0846	8.8919	-5.0964
1992.79	8.8568	-5.0758	-2.3979	9.0297	-4.3800
1992.88	8.9459	-4.5708	-2.8621	9.0704	-4.2893
1992.96	8.9623	-4.6150	-2.7645	9.1111	-4.1985
1993.04	8.9638	-4.5979	-2.5656	9.1518	-4.1078
1993.13	8.9638	-4.5806	-2.3580	9.1925	-4.0171
1993.21	8.9377	-4.5606	-2.0091	9.1343	-4.3398
1993.29	8.9102	-4.5367	-1.5419	9.0700	-4.6881
1993.38	8.8157	-4.5532	-1.3929	8.9900	-4.8986
1993.46	8.7600	-4.6695	-0.9155	8.9538	-5.0424
1993.54	8.7718	-4.8505	-0.5613	8.9285	-5.0902
1993.63	8.7840	-4.9548	-0.9463	8.9230	-4.0133
1993.71	8.7794	-5.1693	-2.3718	8.9649	-4.0361
1993.79	8.8515	-5.2676	-3.0696	9.0068	-4.0590
1993.88	8.9074	-4.9075	-3.7821	9.0487	-4.0818
1993.96	8.9966	-4.8357	-3.8877	9.0906	-4.1046

1994.04	9.0172	-4.8186	-3.7337	9.1284	-4.1339
1994.13	9.0059	-4.8269	-3.4585	9.1125	-4.2473
1994.21	8.9621	-4.7656	-3.2868	9.0969	-4.4109
1994.29	8.8523	-4.7834	-1.0050	8.9972	-4.6112
1994.38	8.7389	-4.8784	-0.6782	8.9509	-4.8328
1994.46	8.7764	-4.8265	-1.2867	8.9835	-4.7142
1994.54	8.7725	-5.1983	-2.0670	9.0272	-4.6261
1994.63	8.7831	-5.2631	-1.8265	9.0025	-4.6734
1994.71	8.7696	-5.3794	-2.1632	8.9865	-4.6629
1994.79	8.8494	-4.8980	-2.2452	9.0626	-4.1612
1994.88	8.9713	-4.5964	-3.0211	9.0746	-4.1908
1994.96	9.0490	-4.5177	-2.9861	9.0866	-4.2204
1995.04	9.1000	-4.4625	-2.9383	9.0986	-4.2500
1995.13	9.1042	-4.4227	-2.9929	9.1107	-4.2796
1995.21	9.0803	-4.4750	-2.6950	9.0816	-4.4843
1995.29	8.8999	-4.6477	-1.4759	9.0410	-4.7381
1995.38	8.8081	-4.9286	-1.1185	8.9778	-5.3583
1995.46	8.7928	-5.0074	-1.2353	8.9353	-5.4042
1995.54	8.7592	-4.9799	-1.6139	8.9442	-5.3015
1995.63	8.7687	-4.9762	-1.7669	8.9604	-5.1777
1995.71	8.7821	-4.9916	-1.9174	8.9767	-5.0539
1995.79	8.8018	-5.0380	-2.0640	8.9929	-4.9301
1995.88	8.9137	-5.1159	-3.5288	9.0134	-4.7953

1995.96	8.9856	-4.6966	-3.7286	9.1489	-4.5557
1996.04	9.0199	-4.6003	-2.8263	9.1701	-3.9310
1996.13	9.0296	-4.5759	-2.6833	9.2117	-3.8077
1996.21	8.9931	-4.6400	-2.3201	9.1625	-4.1087
1996.29	8.9281	-4.7700	-1.9103	9.1132	-4.4097
1996.38	8.8800	-4.8620	-1.6421	9.0554	-4.7650
1996.46	8.7851	-4.9123	-0.8846	8.9690	-5.0096
1996.54	8.7519	-4.9995	-1.1485	8.9314	-4.9574
1996.63	8.8152	-5.3606	-1.8837	8.9342	-4.8991
1996.71	8.7722	-5.0094	-1.0803	8.9515	-4.8722
1996.79	8.7840	-5.1314	-1.8036	8.9688	-4.8452
1996.88	8.8498	-5.0699	-2.9369	8.9862	-4.8183
1996.96	8.9839	-4.7620	-3.6727	9.1120	-4.6003
1997.04	9.1078	-4.7100	-3.9131	9.1719	-4.4284
1997.13	9.1151	-4.6845	-3.9276	9.1722	-4.3177
1997.21	9.1036	-4.6408	-2.6831	9.1725	-4.2070
1997.29	8.9025	-4.6597	-1.2803	9.0442	-4.3124
1997.38	8.7639	-5.0505	-0.8806	9.0346	-4.7982
1997.46	8.7553	-5.1329	-1.6358	8.9324	-5.1738
1997.54	8.7165	-5.1616	-1.7429	8.9240	-5.2726
1997.63	8.7202	-4.9714	-1.1778	8.9731	-5.2013
1997.71	8.7344	-4.9278	-1.9255	8.9499	-5.1158
1997.79	8.7723	-4.9710	-2.4880	8.9863	-4.8754

1997.88	8.8190	-4.7024	-2.2258	8.9940	-4.4829
1997.96	8.9501	-4.6088	-3.1057	9.0577	-4.3279
1998.04	8.9686	-4.6696	-2.6056	9.1161	-4.1866
1998.13	8.9387	-4.5920	-2.9364	9.0974	-4.2439
1998.21	8.8834	-4.6154	-2.0963	9.0787	-4.3013
1998.29	8.8142	-4.5426	-1.8212	8.9471	-4.6723
1998.38	8.8003	-4.9740	-1.2391	8.9157	-4.8363
1998.46	8.7074	-4.9792	-1.0345	8.8843	-5.0002
1998.54	8.6863	-4.9233	-1.1536	8.8530	-5.1641
1998.63	8.6748	-4.8577	-1.1592	8.8590	-5.2702
1998.71	8.6825	-4.8240	-1.0369	8.8830	-5.3482
1998.79	8.7151	-4.9390	-1.4691	8.8948	-5.3642
1998.88	8.8473	-5.1162	-3.1939	9.0199	-5.3722
1998.96	8.8434	-4.9417	-3.3736	9.0087	-4.5276
1999.04	8.8641	-4.8185	-2.9585	9.1122	-4.3296
1999.13	8.8895	-4.7576	-2.4776	9.1382	-4.2281
1999.21	8.8820	-4.7154	-1.8953	9.0938	-4.3233
1999.29	8.8442	-4.8636	-1.5608	9.0334	-4.4261
1999.38	8.7708	-4.8801	-0.8433	8.9158	-4.5467
1999.46	8.7634	-5.1143	-0.9487	8.8849	-4.6357
1999.54	8.7504	-5.3430	-1.0010	8.8793	-4.7053
1999.63	8.7591	-5.1934	-0.5890	8.8964	-4.7412
1999.71	8.7573	-5.2822	-1.4139	8.9136	-4.7771

1999.79	8.7951	-5.3277	-2.1280	8.9307	-4.8130
1999.88	8.9127	-5.4672	-2.0650	9.0207	-4.8398
1999.96	8.8934	-5.6776	-3.2026	9.0597	-4.6566
2000.04	9.0127	-5.1148	-3.3799	9.1049	-4.6441
2000.13	9.0298	-4.9851	-4.5485	9.1479	-4.6318
2000.21	8.9904	-4.9992	-4.2488	9.0819	-4.6274
2000.29	8.8718	-4.7707	-2.7511	9.0484	-4.7605
2000.38	8.8212	-4.8181	-2.1183	9.0049	-4.9724
2000.46	8.8034	-4.9104	-1.6278	8.9864	-5.1307
2000.54	8.7944	-5.1656	-1.5513	8.9800	-5.1904
2000.63	8.7738	-5.3022	-1.5513	8.9742	-5.2342
2000.71	8.7620	-5.1691	-1.4616	8.9942	-5.2157
2000.79	8.7923	-5.3124	-1.9348	9.0169	-5.1907
2000.88	8.8674	-5.4061	-2.8924	9.0409	-5.0856
2000.96	8.9290	-5.1101	-4.0807	9.1111	-4.7668
2001.04	8.9908	-4.8238	-3.6694	9.1531	-4.5614
2001.13	9.1372	-5.0199	-2.5999	9.1916	-4.3635
2001.21	8.8742	-4.8218	-0.5561	9.1013	-4.4427
2001.29	8.7837	-4.8923	-0.1915	9.0348	-4.4702
2001.38	8.7704	-5.1155	-0.6011	8.9683	-4.4977
2001.46	8.7635	-5.2038	-0.5702	8.9646	-4.5644
2001.54	8.8753	-5.4994	-2.3147	9.0108	-4.6612
2001.63	8.7594	-5.5595	-2.3223	8.9554	-4.6779

2001.71	8.7854	-5.7632	-2.9177	8.9627	-4.5388
2001.79	8.7975	-5.6823	-2.7768	8.9790	-4.3774
2001.88	8.8465	-4.9879	-2.7840	8.9999	-4.7166
2001.96	8.9352	-4.5300	-3.1555	9.0456	-4.8029
2002.04	8.9849	-4.5535	-3.1384	9.0513	-4.7459
2002.13	9.0315	-4.5783	-3.1014	9.0570	-4.6889
2002.21	8.9838	-4.6351	-2.3597	9.0159	-4.5398
2002.29	8.8878	-4.6830	-1.5519	8.9524	-5.0299
2002.38	8.7859	-4.8659	-0.4943	8.9312	-5.1866
2002.46	8.7436	-4.9880	-0.4350	8.9100	-5.3433
2002.54	8.7243	-5.1995	-1.2601	8.9030	-5.4042
2002.63	8.7242	-5.3963	-1.2651	8.9161	-5.3292
2002.71	8.7212	-5.3190	-1.2107	8.9291	-5.2543
2002.79	8.7157	-5.2545	-2.4377	8.9422	-5.1793
2002.88	8.8191	-5.0464	-3.3307	8.9892	-5.0668
2002.96	8.9244	-4.7669	-3.4092	9.0853	-4.9000
2003.04	9.0045	-4.5889	-3.6855	9.1440	-4.2787
2003.13	9.0172	-4.6560	-3.2723	9.2017	-4.1930
2003.21	8.9598	-4.6999	-2.1327	9.1606	-4.2090
2003.29	8.9146	-4.7949	-1.6854	9.1028	-4.2250
2003.38	8.8247	-4.5889	-0.3501	9.0112	-4.2410
2003.46	8.8565	-4.7199	0.1939	8.9715	-4.4977
2003.54	8.7207	-5.0185	-0.9953	8.9400	-4.9184

2003.63	8.7516	-5.2454	-1.7364	8.9708	-4.8677
2003.71	8.7596	-5.2923	-2.0635	9.0030	-4.8071
2003.79	8.7807	-5.1986	-1.9680	9.0352	-4.7466
2003.88	8.8765	-4.9228	-2.9172	9.0674	-4.6860
2003.96	8.9567	-4.7366	-3.1772	9.1221	-4.4743
2004.04	8.9848	-4.6539	-2.8995	9.1864	-4.2957
2004.13	8.9650	-4.7126	-2.7553	9.2062	-4.3027
2004.21	8.9436	-4.6468	-2.4074	9.1576	-4.4991
2004.29	8.8896	-4.7116	-1.5879	9.0555	-4.3818
2004.38	8.7346	-4.8687	-1.2642	9.0198	-4.3881
2004.46	8.7558	-5.1383	-1.2284	9.0049	-4.4329
2004.54	8.7482	-5.1505	-1.3902	8.9900	-4.4777
2004.63	8.7305	-5.3199	-1.8549	8.9876	-4.7111
2004.71	8.8473	-4.9352	-2.3576	8.9908	-5.0294
2004.79	8.8590	-4.8551	-3.2307	9.0576	-5.0106
2004.88	8.9769	-4.6972	-3.7255	9.1927	-4.6805
2004.96	9.0907	-4.6105	-2.8120	9.2681	-4.5283
2005.04	9.0139	-4.5811	-2.5045	9.2884	-4.2243
2005.13	9.0072	-4.5664	-2.1784	9.2581	-4.0269
2005.21	9.0075	-4.6625	-1.5693	9.1197	-4.3660
2005.29	8.8762	-4.8100	-1.2042	9.0398	-4.5092
2005.38	8.7982	-4.9075	-1.0264	9.0026	-4.4595
2005.46	8.7328	-5.0773	-0.7169	8.9836	-4.4368

2005.54	8.7092	-5.1298	-0.6473	8.9687	-4.4299
2005.63	8.7090	-5.1162	-0.7130	8.9797	-4.4259
2005.71	8.7089	-5.1026	-0.7787	8.9954	-4.4224
2005.79	8.7590	-5.1495	-0.9740	9.0112	-4.4188
2005.88	8.8351	-5.4665	-2.5119	9.0451	-4.3859
2005.96	9.0728	-4.8610	-2.1678	9.1852	-4.1084
2006.04	9.0438	-4.9191	-2.2232	9.1750	-4.0010
2006.13	9.0437	-4.9150	-1.1257	9.1859	-4.0363
2006.21	8.9141	-4.8341	0.1272	9.0896	-4.1851
2006.29	8.8311	-5.0125	-0.4263	9.0445	-4.2864
2006.38	8.7870	-5.1151	-0.7834	9.0283	-4.7199
2006.46	8.7621	-5.1729	-0.9844	9.0079	-5.2689
2006.54	8.8171	-5.3611	-1.6391	9.0381	-5.0546
2006.63	8.7871	-5.3698	-1.2437	9.0775	-4.6990
2006.71	8.7359	-5.3258	-1.9178	9.0267	-4.6328
2006.79	8.8087	-5.2605	-2.3042	9.0480	-4.5894
2006.88	8.8385	-5.1939	-2.6304	9.0814	-4.5499
2006.96	8.9162	-4.9970	-4.1878	9.1148	-4.5104
2007.04	9.0478	-4.8592	-3.7089	9.1481	-4.4709
2007.13	9.0743	-4.8344	-3.5798	9.2097	-4.4059
2007.21	8.9100	-4.5784	-0.2879	9.1235	-4.3490
2007.29	8.8065	-4.5978	0.4353	9.0107	-4.2555
2007.38	8.7668	-4.6879	0.3186	8.9782	-4.5706

2007.46	8.7593	-4.8259	-0.1692	8.9619	-4.9682
2007.54	8.7629	-5.5783	-2.0533	8.9690	-5.0251
2007.63	8.7667	-5.5782	-2.5958	8.9831	-5.0613
2007.71	8.7825	-5.4794	-2.7729	8.9922	-5.3391
2007.79	8.8160	-5.2956	-2.2635	9.0546	-4.1753
2007.88	8.9231	-4.9302	-2.7717	9.1239	-4.1579
2007.96	8.9874	-4.8938	-3.2745	9.1537	-4.0407
2008.04	9.0598	-4.9864	-3.6855	9.1834	-3.9235
2008.13	9.1137	-4.9840	-3.3806	9.1695	-3.9559
2008.21	9.0019	-5.0004	-1.0418	9.1247	-4.0935
2008.29	8.8648	-4.9148	0.0739	9.0435	-4.5505
2008.38	8.7862	-5.0542	-0.1978	8.9928	-4.7025
2008.46	8.7833	-5.2672	-0.7163	8.9683	-4.7644
2008.54	8.8205	-5.5737	-1.4897	8.9672	-4.7462
2008.63	8.8484	-5.7098	-1.7715	8.9652	-4.7260
2008.71	8.8242	-5.5326	-1.1140	8.9551	-4.6862
2008.79	8.7842	-5.4625	-2.0095	8.8845	-5.2669
2008.88	8.8878	-5.3582	-2.0589	8.9704	-5.0860
2008.96	8.9441	-5.1839	-4.3984	9.0760	-4.6184
2009.04	8.9806	-4.7266	-3.3931	9.2789	-4.0250
2009.13	8.9561	-4.7247	-3.1100	9.2346	-3.8450
2009.21	8.9266	-5.0661	-2.3993	9.1186	-5.0764
2009.29	8.8526	-5.0770	-1.7546	9.0728	-5.0087

2009.38	8.7854	-5.3725	-0.4330	9.0624	-4.7033
2009.46	8.7263	-5.3128	-0.5564	9.0519	-4.3980
2009.54	8.7320	-5.5656	-1.2594	9.0507	-4.2985
2009.63	8.7359	-5.6654	-2.3829	9.0672	-4.5897
2009.71	8.6922	-5.7182	-3.7861	9.0836	-4.8809
2009.79	8.8343	-5.1072	-3.1996	9.1000	-5.1722
2009.88	8.8732	-5.0060	-3.6880	9.1026	-3.5883
2009.96	8.9533	-4.8746	-3.7335	9.1449	-3.9662
2010.04	9.0208	-4.9282	-3.7099	9.1872	-4.3441
2010.13	8.9993	-4.7935	-3.2365	9.1476	-3.9847
2010.21	8.9201	-4.8767	-2.6287	9.1385	-4.4247
2010.29	8.8607	-4.8153	-2.2338	9.0276	-4.5578
2010.38	8.7094	-4.9368	-0.4187	8.9538	-4.0094
2010.46	8.6494	-5.0782	-0.6338	8.9333	-4.5190
2010.54	8.6446	-5.2134	-0.8394	8.9157	-5.0854
2010.63	8.7454	-5.1161	-1.1047	8.9305	-5.2847
2010.71	8.7837	-5.1229	-1.6865	8.9571	-5.3501
2010.79	8.7250	-5.1399	-2.9446	8.9837	-5.4156
2010.88	8.8623	-5.3202	-3.4580	9.0103	-5.4810
2010.96	8.9143	-5.1245	-3.3515	9.1015	-4.8566
2011.04	8.9518	-4.9925	-3.8078	9.1985	-4.4856
2011.13	8.9702	-4.8928	-4.1519	9.2121	-4.4749
2011.21	8.9666	-4.9026	-4.0575	9.1993	-4.5782

2011.29	8.9283	-4.9136	-3.5544	9.1392	-4.6657
2011.38	8.7843	-5.3589	-1.0488	9.0517	-4.9599
2011.46	8.7435	-5.4418	-1.0328	9.0209	-4.9782
2011.54	8.7418	-5.3586	-0.9725	8.9901	-4.9965
2011.63	8.7428	-5.3341	-1.0363	8.9594	-5.0147
2011.71	8.7967	-5.4405	-1.9902	8.9682	-4.9320
2011.79	8.7947	-5.3558	-2.4094	8.9802	-4.8411
2011.88	8.9103	-5.2825	-4.2165	9.0622	-4.9279
2011.96	8.9296	-5.0606	-2.8384	9.1523	-4.5172
2012.04	8.9210	-4.9801	-2.5040	9.1406	-4.4204
2012.13	8.9021	-5.0507	-2.3229	9.1014	-4.4348
2012.21	8.8832	-5.1213	-2.1418	9.0384	-4.4470
2012.29	8.8398	-4.9728	-1.9437	8.9616	-5.3828
2012.38	8.7847	-5.1519	-0.5509	9.0572	-5.0203

Table B1.2. Palaui $\Delta^{14}\text{C}$ data

Year	$\Delta^{14}\text{C}$, ‰	$\pm 1\sigma$, ‰
1945	-60.50	1.62
1946		
1947		
1948	-60.64	1.72
1949		

1950	-56.24	1.72
1951		
1952.666667	-56.35	1.28
1952.833333	-59.59	1.37
1953	-56.70	1.28
1953.142857	-58.55	1.33
1953.285714	-59.27	1.33
1953.428571	-57.75	1.33
1953.571429	-58.72	1.33
1953.714286	-59.79	1.39
1953.857143	-57.06	1.42
1954	-60.93	1.42
1954.125	-57.96	1.34
1954.25	-62.54	1.33
1954.375	-57.58	1.34
1954.5	-57.36	1.72
1954.625	-55.90	1.34
1954.75	-58.25	1.34
1954.875	-56.95	1.34
1955	-57.55	1.34
1955.2	-53.91	1.30
1955.4	-41.23	1.32
1955.6	11.00	1.39

1955.8	1.96	1.43
1956	-12.76	1.63
1956.166667	-14.28	1.36
1957	-34.38	1.38
1957.166667	-37.03	1.33
1957.333333	-35.86	1.33
1957.5	-35.18	1.33
1957.666667	-33.46	1.33
1957.833333	-33.42	1.33
1958		
1959		
1960	-12.56	1.83
1960.166667	-10.86	1.42
1960.333333	-12.67	1.42
1960.5	-18.29	1.89
1960.666667	-11.31	1.60
1960.833333	-11.34	1.50
1961		
1962		
1963	3.03	2.63
1963.166667	7.94	2.67
1963.333333	17.17	3.09
1963.5	26.98	3.06

1963.666667	28.08	2.66
1963.833333	31.31	2.86
1964		
1965		
1966		
1967		
1968		
1969		
1970	123.03	2.51
1971	138.38	3.16
1971.166667	138.62	3.00
1971.333333	140.29	2.99
1971.5	129.92	3.51
1971.666667	128.99	2.98
1971.833333	129.02	3.15
1972	153.21	2.48
1972.166667	155.30	1.80
1972.333333	152.03	2.51
1972.5	146.53	2.39
1972.666667	130.70	2.26
1972.833333	134.56	2.64
1973	158.02	1.52
1973.166667	157.16	2.92

1973.333333	165.22	2.16
1973.5	148.98	2.36
1973.666667	139.38	2.43
1973.833333	138.50	2.46
1974	139.73	2.55
1975	156.34	3.69
1975.166667	152.53	2.00
1975.333333	147.10	1.75
1975.5	141.31	1.60
1975.666667	147.83	1.69
1975.833333	147.69	1.77
1976	145.11	2.52
1977	141.11	2.52
1978	144.98	2.56
1979	147.21	2.49
1980	138.57	2.47
1981	138.65	2.54
1981.166667	140.09	1.61
1981.333333	137.82	2.11
1981.5	136.18	2.83
1981.666667	138.42	1.88
1981.833333	142.07	2.28
1982	144.97	1.68

1982.166667	142.35	2.10
1982.333333	139.32	2.83
1982.5	136.23	1.80
1982.666667	119.69	4.55
1982.833333	130.42	2.50
1983	138.20	1.60
1983.166667	133.08	1.79
1983.333333	134.93	2.82
1983.5	133.12	1.90
1983.666667	128.11	2.67
1983.833333	131.95	2.02
1984	139.70	2.05
1984.166667	118.99	2.41
1984.333333	131.33	2.01
1984.5	135.47	2.20
1984.666667	123.48	1.63
1984.833333	129.36	2.55
1985	129.82	1.79
1986	128.83	1.71
1987	126.17	1.70
1988	120.29	3.10
1989	116.22	2.93
1990	113.17	2.92

1991	111.21	2.92
1992	108.63	2.91
1993	109.30	2.91
1994	99.80	3.44
1995	97.36	2.87
1996	93.24	2.86
1997	95.75	1.63
1997.2	95.97	1.63
1997.4	89.63	1.61
1997.6	90.03	1.61
1997.8	93.42	1.61
1998	89.84	1.61
1998.142857	91.39	1.61
1998.285714	87.59	1.60
1998.428571	90.36	1.80
1998.571429	86.81	1.60
1998.714286	86.41	1.85
1998.857143	86.49	1.60
1999	88.31	2.80
2000	80.63	2.78
2001	81.42	2.78
2002	79.84	2.79
2003	74.29	2.70

2004	73.55	2.82
2005	66.17	2.82
2006	63.62	2.78
2007	60.05	2.77
2008	56.99	2.95
2009	57.88	1.69
2009.2	55.08	1.61
2009.4	54.94	1.60
2009.6	55.85	1.61
2009.8	52.21	1.59
2010	55.36	1.60
2010.142857	54.58	1.60
2010.285714	54.70	1.60
2010.428571	52.24	1.84
2010.571429	52.46	1.59
2010.714286	50.28	1.59
2010.857143	50.04	1.69
2011	48.92	2.80

B2. Houbihu Sr/Ca, $\delta^{18}\text{O}$ and $\Delta^{14}\text{C}$

Table B2.1. Houbihu Sr/Ca and stable isotope data

Date	Sr/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
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1788.04	9.0893
1788.13	9.1360
1788.21	9.0974
1788.29	8.9738
1788.38	8.8807
1788.46	8.8079
1788.54	8.7748
1788.63	8.8273
1788.71	8.8490
1788.79	8.8266
1788.88	8.9983
1788.96	9.0752
1789.04	9.1234
1789.13	9.0895
1789.21	9.0718
1789.29	8.9583
1789.38	8.8614
1789.46	8.8480
1789.54	8.8086
1789.63	8.8366
1789.71	8.7964
1789.79	8.8138
1789.88	8.9582

1789.96	9.0578
1790.04	9.1467
1790.13	9.0954
1790.21	9.0371
1790.29	8.9721
1790.38	8.8617
1790.46	8.8136
1790.54	8.7904
1790.63	8.7864
1790.71	8.7928
1790.79	8.8289
1790.88	8.9624
1790.96	9.0451
1791.04	9.0599
1791.13	9.0620
1791.21	9.0438
1791.29	8.9582
1791.38	8.8233
1791.46	8.8022
1791.54	8.7050
1791.63	8.7660
1791.71	8.7676
1791.79	8.8520

1791.88	8.9702
1791.96	9.0858
1792.04	9.1559
1792.13	9.1049
1792.21	9.0640
1792.29	8.9710
1792.38	8.7883
1792.46	8.7406
1792.54	8.7744
1792.63	8.7880
1792.71	8.7909
1792.79	8.9135
1792.88	8.8776
1792.96	9.0477
1793.04	9.1668
1793.13	9.1645
1793.21	9.1007
1793.29	8.9879
1793.38	8.8513
1793.46	8.7749
1793.54	8.7165
1793.63	8.7408
1793.71	8.7727

1793.79	8.8356
1793.88	8.9376
1793.96	9.0532
1794.04	9.0846
1794.13	9.0687
1794.21	9.0411
1794.29	8.9838
1794.38	8.7761
1794.46	8.7569
1794.54	8.7085
1794.63	8.7744
1794.71	8.7739
1794.79	8.8765
1794.88	8.9724
1794.96	9.0572
1795.04	9.1423
1795.13	9.1325
1795.21	9.1202
1795.29	8.9553
1795.38	8.8819
1795.46	8.8544
1795.54	8.7792
1795.63	8.8796

1795.71	8.8737
1795.79	8.9251
1795.88	9.0152
1795.96	9.1596
1796.04	9.1952
1796.13	9.1708
1796.21	9.1172
1796.29	8.9980
1796.38	8.8651
1796.46	8.8710
1796.54	8.8007
1796.63	8.8083
1796.71	8.8179
1796.79	8.8607
1796.88	8.9526
1796.96	9.0436
1797.04	9.0579
1797.13	9.0435
1797.21	9.0291
1797.29	8.9771
1797.38	8.8480
1797.46	8.7883
1797.54	8.7938

1797.63	8.7670
1797.71	8.7359
1797.79	8.8061
1797.88	8.9970
1797.96	9.0461
1798.04	9.0572
1798.13	9.0473
1798.21	9.0175
1798.29	8.9540
1798.38	8.7878
1798.46	8.7154
1798.54	8.7640
1798.63	8.8006
1798.71	8.7751
1798.79	8.8094
1798.88	8.9892
1798.96	9.0039
1799.04	9.0561
1799.13	9.0468
1799.21	9.0081
1799.29	8.9490
1799.38	8.8337
1799.46	8.8126

1799.54	8.7736
1799.63	8.7292
1799.71	8.8375
1799.79	8.8634
1799.88	9.0169
1799.96	9.0989
1800.04	9.1579
1800.13	9.1558
1800.21	9.1089
1800.29	9.0430
1800.38	8.8212
1800.46	8.8070
1800.54	8.8027
1800.63	8.7665
1800.71	8.8216
1800.79	8.8384
1800.88	8.9510
1800.96	9.0485
1801.04	9.1597
1801.13	9.1496
1801.21	9.0972
1801.29	8.9365
1801.38	8.8121

1801.46	8.8332
1801.54	8.7924
1801.63	8.8192
1801.71	8.8097
1801.79	8.8329
1801.88	8.9522
1801.96	8.9975
1802.04	9.0115
1802.13	9.0095
1802.21	8.9765
1802.29	8.9350
1802.38	8.7905
1802.46	8.7796
1802.54	8.7615
1802.63	8.7782
1802.71	8.8240
1802.79	8.8552
1802.88	8.9478
1802.96	9.0938
1803.04	9.1529
1803.13	9.1241
1803.21	9.0953
1803.29	8.9257

1803.38	8.8624
1803.46	8.8083
1803.54	8.7445
1803.63	8.7463
1803.71	8.8270
1803.79	8.8638
1803.88	9.0180
1803.96	9.1277
1804.04	9.1706
1804.13	9.1433
1804.21	9.1159
1804.29	8.9996
1804.38	8.8714
1804.46	8.7298
1804.54	8.7720
1804.63	8.8197
1804.71	8.8264
1804.79	8.8159
1804.88	8.9675
1804.96	9.0507
1805.04	9.1320
1805.13	9.1348
1805.21	9.0906

1805.29	9.0177
1805.38	8.8472
1805.46	8.7598
1805.54	8.7880
1805.63	8.7615
1805.71	8.7944
1805.79	8.8508
1805.88	8.9447
1805.96	9.0714
1806.04	9.1709
1806.13	9.1457
1806.21	9.0782
1806.29	8.9643
1806.38	8.8338
1806.46	8.7746
1806.54	8.7505
1806.63	8.7757
1806.71	8.8387
1806.79	8.8586
1806.88	8.9871
1806.96	9.0761
1807.04	9.1543
1807.13	9.1329

1807.21	9.0915
1807.29	8.9882
1807.38	8.8108
1807.46	8.7789
1807.54	8.7629
1807.63	8.7980
1807.71	8.7919
1807.79	8.8392
1807.88	8.9642
1807.96	9.1176
1808.04	9.1142
1808.13	9.1040
1808.21	9.0938
1808.29	9.0652
1808.38	8.8208
1808.46	8.7932
1808.54	8.7933
1808.63	8.7932
1808.71	8.8144
1808.79	8.8562
1808.88	8.9919
1808.96	9.0479
1809.04	9.0773

1809.13	9.0806
1809.21	9.0693
1809.29	8.9342
1809.38	8.8449
1809.46	8.8028
1809.54	8.8514
1809.63	8.8340
1809.71	8.8339
1809.79	8.8988
1809.88	8.9980
1809.96	9.0513
1810.04	9.0448
1810.13	9.0465
1810.21	9.0188
1810.29	8.9910
1810.38	8.8015
1810.46	8.7917
1810.54	8.7764
1810.63	8.7700
1810.71	8.8092
1810.79	8.8615
1810.88	8.9686
1810.96	9.0654

1811.04	9.0763
1811.13	9.0644
1811.21	9.0523
1811.29	8.9755
1811.38	8.8690
1811.46	8.8212
1811.54	8.8255
1811.63	8.8050
1811.71	8.8429
1811.79	8.8664
1811.88	8.9787
1811.96	9.1174
1812.04	9.2449
1812.13	9.2132
1812.21	9.1078
1812.29	8.8357
1812.38	8.8389
1812.46	8.7721
1812.54	8.7684
1812.63	8.7732
1812.71	8.7823
1812.79	8.8863
1812.88	8.9704

1812.96	9.0677
1813.04	9.1318
1813.13	9.0984
1813.21	9.0709
1813.29	8.9768
1813.38	8.8747
1813.46	8.7529
1813.54	8.7535
1813.63	8.7769
1813.71	8.7575
1813.79	8.8066
1813.88	8.9949
1813.96	9.0371
1814.04	9.0583
1814.13	9.0485
1814.21	9.0209
1814.29	8.9782
1814.38	8.8266
1814.46	8.7503
1814.54	8.7867
1814.63	8.8234
1814.71	8.8137
1814.79	8.8587

1814.88	8.9759
1814.96	9.0871
1815.04	9.1135
1815.13	9.1102
1815.21	9.0793
1815.29	8.9902
1815.38	8.8883
1815.46	8.7912
1815.54	8.7591
1815.63	8.7720
1815.71	8.8270
1815.79	8.8666
1815.88	8.9787
1815.96	9.1270
1816.04	9.1686
1816.13	9.1226
1816.21	9.0674
1816.29	8.9978
1816.38	8.8774
1816.46	8.8820
1816.54	8.7966
1816.63	8.8046
1816.71	8.8252

1816.79	8.8876
1816.88	8.9996
1816.96	9.1071
1817.04	9.1699
1817.13	9.1433
1817.21	9.0836
1817.29	9.0244
1817.38	8.8644
1817.46	8.8247
1817.54	8.8171
1817.63	8.8296
1817.71	8.8323
1817.79	8.8971
1817.88	9.0194
1817.96	9.1147
1818.04	9.1446
1818.13	9.1192
1818.21	9.0894
1818.29	9.0290
1818.38	8.8684
1818.46	8.8023
1818.54	8.7948
1818.63	8.7821

1818.71	8.7757
1818.79	8.7860
1818.88	8.9626
1818.96	9.0473
1819.04	9.1248
1819.13	9.0846
1819.21	9.0574
1819.29	8.9795
1819.38	8.8562
1819.46	8.8335
1819.54	8.7808
1819.63	8.7662
1819.71	8.7806
1819.79	8.8324
1819.88	8.9723
1819.96	9.1313
1820.04	9.1827
1820.13	9.1670
1820.21	9.1451
1820.29	8.9504
1820.38	8.8774
1820.46	8.8887
1820.54	8.8588

1820.63	8.8600
1820.71	8.8649
1820.79	8.8524
1820.88	8.9420
1820.96	9.0486
1821.04	9.0861
1821.13	9.0604
1821.21	9.0346
1821.29	9.0031
1821.38	8.8330
1821.46	8.8224
1821.54	8.8222
1821.63	8.8224
1821.71	8.8482
1821.79	8.8588
1821.88	8.9636
1821.96	9.1148
1822.04	9.1619
1822.13	9.1345
1822.21	9.1029
1822.29	9.0067
1822.38	8.8374
1822.46	8.8332

1822.54	8.8560
1822.63	8.8294
1822.71	8.8713
1822.79	8.8571
1822.88	9.0183
1822.96	9.1788
1823.04	9.2309
1823.13	9.1851
1823.21	9.1292
1823.29	9.0285
1823.38	8.9174
1823.46	8.9319
1823.54	8.8462
1823.63	8.8956
1823.71	8.8820
1823.79	8.8952
1823.88	8.9851
1823.96	9.0683
1824.04	9.1299
1824.13	9.1221
1824.21	9.0925
1824.29	9.0461
1824.38	8.8520

1824.46	8.8175
1824.54	8.7819
1824.63	8.7630
1824.71	8.7803
1824.79	8.8598
1824.88	8.9550
1824.96	9.0418
1825.04	9.1117
1825.13	9.0903
1825.21	9.0617
1825.29	9.0151
1825.38	8.8588
1825.46	8.7975
1825.54	8.7387
1825.63	8.7572
1825.71	8.7783
1825.79	8.8973
1825.88	9.0446
1825.96	9.0985
1826.04	9.0805
1826.13	9.0533
1826.21	9.0351
1826.29	8.9384

1826.38	8.7990
1826.46	8.7001
1826.54	8.7297
1826.63	8.7693
1826.71	8.7592
1826.79	8.8119
1826.88	8.9081
1826.96	9.0036
1827.04	9.0724
1827.13	9.0362
1827.21	9.0784
1827.29	8.9464
1827.38	8.8121
1827.46	8.7199
1827.54	8.7015
1827.63	8.7757
1827.71	8.7730
1827.79	8.8100
1827.88	8.9941
1827.96	9.0410
1828.04	9.0559
1828.13	9.0482
1828.21	9.0160

1828.29	8.9173
1828.38	8.7971
1828.46	8.7287
1828.54	8.6773
1828.63	8.7034
1828.71	8.7341
1828.79	8.8042
1828.88	8.9750
1828.96	9.0328
1829.04	9.1010
1829.13	9.1104
1829.21	9.0547
1829.29	8.9063
1829.38	8.8201
1829.46	8.7468
1829.54	8.7367
1829.63	8.7388
1829.71	8.7757
1829.79	8.8477
1829.88	8.9247
1829.96	9.0568
1830.04	9.1236
1830.13	9.1019

1830.21	9.0585
1830.29	8.9183
1830.38	8.8228
1830.46	8.7686
1830.54	8.7570
1830.63	8.7908
1830.71	8.8139
1830.79	8.8663
1830.88	8.9709
1830.96	9.1260
1831.04	9.1788
1831.13	9.1509
1831.21	9.1080
1831.29	8.9184
1831.38	8.8906
1831.46	8.8375
1831.54	8.7999
1831.63	8.8110
1831.71	8.8287
1831.79	8.8517
1831.88	8.9154
1831.96	8.9893
1832.04	9.0193

1832.13	9.0012
1832.21	8.9755
1832.29	8.9292
1832.38	8.8707
1832.46	8.8365
1832.54	8.7984
1832.63	8.8081
1832.71	8.8260
1832.79	8.8426
1832.88	8.9559
1832.96	8.9950
1833.04	9.0703
1833.13	9.0298
1833.21	9.0076
1833.29	8.9432
1833.38	8.8210
1833.46	8.7775
1833.54	8.7241
1833.63	8.7703
1833.71	8.8060
1833.79	8.8370
1833.88	8.9667
1833.96	9.0302

1834.04	9.1498
1834.13	9.1351
1834.21	9.0934
1834.29	8.9840
1834.38	8.8052
1834.46	8.8128
1834.54	8.7907
1834.63	8.7760
1834.71	8.7840
1834.79	8.8374
1834.88	8.9616
1834.96	8.9923
1835.04	9.1213
1835.13	9.0567
1835.21	9.0464
1835.29	8.9373
1835.38	8.8347
1835.46	8.7545
1835.54	8.7403
1835.63	8.7697
1835.71	8.8229
1835.79	8.8581
1835.88	9.0046

1835.96	9.0996
1836.04	9.1582
1836.13	9.1171
1836.21	9.0546
1836.29	8.9451
1836.38	8.8880
1836.46	8.8482
1836.54	8.8108
1836.63	8.8032
1836.71	8.7906
1836.79	8.8580
1836.88	8.9723
1836.96	9.0760
1837.04	9.1573
1837.13	9.1228
1837.21	9.0790
1837.29	8.8727
1837.38	8.7860
1837.46	8.7249
1837.54	8.7706
1837.63	8.7519
1837.71	8.8088
1837.79	8.8349

1837.88	8.9798
1837.96	9.0653
1838.04	9.1706
1838.13	9.1450
1838.21	9.0893
1838.29	9.0059
1838.38	8.7897
1838.46	8.7569
1838.54	8.7220
1838.63	8.6970
1838.71	8.7053
1838.79	8.7748
1838.88	8.9061
1838.96	9.0307
1839.04	9.0798
1839.13	9.0672
1839.21	9.0596
1839.29	8.9203
1839.38	8.7762
1839.46	8.7217
1839.54	8.7470
1839.63	8.7556
1839.71	8.7063

1839.79	8.8006
1839.88	8.9016
1839.96	8.9472
1840.04	9.0384
1840.13	9.0157
1840.21	8.9883
1840.29	8.9122
1840.38	8.8094
1840.46	8.7788
1840.54	8.8067
1840.63	8.7665
1840.71	8.7766
1840.79	8.8167
1840.88	8.9047
1840.96	8.9944
1841.04	8.9845
1841.13	8.9850
1841.21	8.9599
1841.29	8.9864
1841.38	8.8044
1841.46	8.8026
1841.54	8.7870
1841.63	8.6933

1841.71	8.7578
1841.79	8.8458
1841.88	8.9657
1841.96	9.0281
1842.04	9.0750
1842.13	9.0471
1842.21	9.0225
1842.29	8.9305
1842.38	8.8231
1842.46	8.7539
1842.54	8.7365
1842.63	8.8015
1842.71	8.7761
1842.79	8.8764
1842.88	8.9859
1842.96	8.9890
1843.04	9.0420
1843.13	9.0120
1843.21	8.9943
1843.29	8.9059
1843.38	8.7770
1843.46	8.7781
1843.54	8.7365

1843.63	8.7663
1843.71	8.7833
1843.79	8.7937
1843.88	8.8717
1843.96	8.9127
1844.04	8.9582
1844.13	8.9559
1844.21	8.9284
1844.29	8.8916
1844.38	8.7650
1844.46	8.7421
1844.54	8.6969
1844.63	8.6657
1844.71	8.7135
1844.79	8.7923
1844.88	8.9280
1844.96	8.9915
1845.04	9.0297
1845.13	9.0025
1845.21	8.9753
1845.29	8.9589
1845.38	8.8423
1845.46	8.7585

1845.54	8.7287
1845.63	8.7367
1845.71	8.7614
1845.79	8.8458
1845.88	8.9740
1845.96	9.0350
1846.04	9.0490
1846.13	9.0346
1846.21	9.0083
1846.29	8.9364
1846.38	8.8639
1846.46	8.8162
1846.54	8.8107
1846.63	8.7984
1846.71	8.8083
1846.79	8.8319
1846.88	8.9580
1846.96	9.0557
1847.04	9.0999
1847.13	9.0501
1847.21	9.0437
1847.29	8.9501
1847.38	8.7940

1847.46	8.7237
1847.54	8.7608
1847.63	8.8119
1847.71	8.7891
1847.79	8.8389
1847.88	8.9672
1847.96	9.0279
1848.04	9.1079
1848.13	9.0741
1848.21	9.0255
1848.29	8.9180
1848.38	8.8132
1848.46	8.7666
1848.54	8.7586
1848.63	8.7962
1848.71	8.7994
1848.79	8.8387
1848.88	8.9371
1848.96	9.0164
1849.04	9.0881
1849.13	9.0852
1849.21	9.0640
1849.29	9.0305

1849.38	8.8176
1849.46	8.7724
1849.54	8.7412
1849.63	8.7645
1849.71	8.7894
1849.79	8.8239
1849.88	8.9920
1849.96	9.0818
1850.04	9.1046
1850.13	9.1013
1850.21	9.0753
1850.29	9.0220
1850.38	8.8578
1850.46	8.7804
1850.54	8.7042
1850.63	8.7377
1850.71	8.7824
1850.79	8.8943
1850.88	8.9725
1850.96	9.0264
1851.04	9.1226
1851.13	9.0963
1851.21	9.0296

1851.29	8.9317
1851.38	8.8674
1851.46	8.7479
1851.54	8.7312
1851.63	8.8417
1851.71	8.8113
1851.79	8.8103
1851.88	8.9330
1851.96	8.9820
1852.04	9.0544
1852.13	9.0211
1852.21	9.0311
1852.29	8.9784
1852.38	8.7836
1852.46	8.7536
1852.54	8.7870
1852.63	8.7801
1852.71	8.7781
1852.79	8.8323
1852.88	8.9277
1852.96	9.1116
1853.04	9.1319
1853.13	9.1261

1853.21	9.0848
1853.29	9.0148
1853.38	8.7847
1853.46	8.7394
1853.54	8.7980
1853.63	8.8126
1853.71	8.8063
1853.79	8.8524
1853.88	8.9873
1853.96	9.1182
1854.04	9.1547
1854.13	9.1214
1854.21	9.0828
1854.29	8.9420
1854.38	8.8219
1854.46	8.7889
1854.54	8.8781
1854.63	8.8675
1854.71	8.8773
1854.79	8.8595
1854.88	8.9521
1854.96	9.0645
1855.04	9.0922

1855.13	9.0585
1855.21	9.0774
1855.29	8.9527
1855.38	8.9603
1855.46	8.8643
1855.54	8.8472
1855.63	8.8671
1855.71	8.8401
1855.79	8.8569
1855.88	8.9176
1855.96	9.0333
1856.04	9.1249
1856.13	9.0804
1856.21	9.0401
1856.29	8.9232
1856.38	8.7884
1856.46	8.6901
1856.54	8.7110
1856.63	8.7839
1856.71	8.7997
1856.79	8.8056
1856.88	8.9287
1856.96	9.0652

1857.04	9.1036
1857.13	9.0843
1857.21	9.0436
1857.29	8.9012
1857.38	8.8198
1857.46	8.8029
1857.54	8.8472
1857.63	8.8387
1857.71	8.8372
1857.79	8.8795
1857.88	9.0154
1857.96	9.0186
1858.04	9.0623
1858.13	9.0217
1858.21	9.0322
1858.29	8.9699
1858.38	8.8258
1858.46	8.7354
1858.54	8.8200
1858.63	8.7949
1858.71	8.7698
1858.79	8.8379
1858.88	8.9531

1858.96	9.0219
1859.04	9.0853
1859.13	9.0563
1859.21	9.0357
1859.29	8.9341
1859.38	8.7893
1859.46	8.7718
1859.54	8.7055
1859.63	8.7499
1859.71	8.8198
1859.79	8.8181
1859.88	8.9096
1859.96	9.0920
1860.04	9.1784
1860.13	9.1615
1860.21	9.1121
1860.29	8.9401
1860.38	8.8617
1860.46	8.8259
1860.54	8.8438
1860.63	8.8729
1860.71	8.8261
1860.79	8.8615

1860.88	9.0367
1860.96	9.1502
1861.04	9.1742
1861.13	9.1170
1861.21	9.0843
1861.29	9.0205
1861.38	8.8731
1861.46	8.8346
1861.54	8.8130
1861.63	8.8737
1861.71	8.9118
1861.79	8.9264
1861.88	9.0633
1861.96	9.1421
1862.04	9.2477
1862.13	9.2312
1862.21	9.1614
1862.29	9.0387
1862.38	8.8983
1862.46	8.8822
1862.54	8.9134
1862.63	8.9122
1862.71	8.8943

1862.79	8.9308
1862.88	9.0317
1862.96	9.1020
1863.04	9.1263
1863.13	9.1197
1863.21	9.1193
1863.29	9.0518
1863.38	8.9261
1863.46	8.8935
1863.54	8.8779
1863.63	8.8844
1863.71	8.8992
1863.79	8.9282
1863.88	8.9908
1863.96	9.0884
1864.04	9.1447
1864.13	9.1055
1864.21	9.0516
1864.29	8.9227
1864.38	8.7837
1864.46	8.7249
1864.54	8.7249
1864.63	8.7443

1864.71	8.7342
1864.79	8.7787
1864.88	8.9429
1864.96	9.0899
1865.04	9.1266
1865.13	9.0995
1865.21	9.1102
1865.29	9.0111
1865.38	8.7622
1865.46	8.7078
1865.54	8.6998
1865.63	8.7607
1865.71	8.8314
1865.79	8.8514
1865.88	9.0071
1865.96	9.0746
1866.04	9.1140
1866.13	9.1094
1866.21	9.0749
1866.29	9.0072
1866.38	8.9111
1866.46	8.8072
1866.54	8.8506

1866.63	8.8130
1866.71	8.7960
1866.79	8.8276
1866.88	8.9442
1866.96	9.0577
1867.04	9.1208
1867.13	9.0885
1867.21	9.0532
1867.29	8.9437
1867.38	8.7637
1867.46	8.6064
1867.54	8.6830
1867.63	8.7040
1867.71	8.7303
1867.79	8.8030
1867.88	8.9509
1867.96	9.0411
1868.04	9.1150
1868.13	9.1012
1868.21	9.0549
1868.29	8.8950
1868.38	8.7671
1868.46	8.7101

1868.54	8.6905
1868.63	8.7534
1868.71	8.8017
1868.79	8.8279
1868.88	8.9944
1868.96	9.0620
1869.04	9.1043
1869.13	9.0659
1869.21	9.0587
1869.29	8.9785
1869.38	8.8869
1869.46	8.8651
1869.54	8.8781
1869.63	8.8006
1869.71	8.8033
1869.79	8.8363
1869.88	8.8921
1869.96	9.1293
1870.04	9.2309
1870.13	9.2013
1870.21	9.1725
1870.29	9.0028
1870.38	8.8163

1870.46	8.8184
1870.54	8.7726
1870.63	8.7177
1870.71	8.7552
1870.79	8.8383
1870.88	8.9510
1870.96	9.1526
1871.04	9.1515
1871.13	9.1388
1871.21	9.0668
1871.29	9.0046
1871.38	8.8743
1871.46	8.8328
1871.54	8.8192
1871.63	8.7870
1871.71	8.8052
1871.79	8.8502
1871.88	8.9734
1871.96	9.0767
1872.04	9.0913
1872.13	9.0874
1872.21	9.0367
1872.29	8.9375

1872.38	8.7730
1872.46	8.7799
1872.54	8.7641
1872.63	8.8014
1872.71	8.8435
1872.79	8.8903
1872.88	8.9462
1872.96	9.1050
1873.04	9.1144
1873.13	9.0766
1873.21	9.0196
1873.29	8.9822
1873.38	8.7670
1873.46	8.7163
1873.54	8.7624
1873.63	8.7704
1873.71	8.7511
1873.79	8.8730
1873.88	8.9666
1873.96	9.1864
1874.04	9.2979
1874.13	9.2492
1874.21	9.1325

1874.29	9.0257
1874.38	8.9540
1874.46	8.9155
1874.54	8.8890
1874.63	8.9214
1874.71	8.8450
1874.79	8.8985
1874.88	9.0687
1874.96	9.1713
1875.04	9.2108
1875.13	9.1942
1875.21	9.1618
1875.29	9.0339
1875.38	8.9451
1875.46	8.8932
1875.54	8.8832
1875.63	8.9065
1875.71	8.9352
1875.79	8.9593
1875.88	9.0485
1875.96	9.0941
1876.04	9.1924
1876.13	9.1636

1876.21	9.1150
1876.29	9.0476
1876.38	8.8736
1876.46	8.8568
1876.54	8.8331
1876.63	8.7490
1876.71	8.8125
1876.79	8.8740
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1876.96	9.0466
1877.04	9.1338
1877.13	9.1066
1877.21	9.0794
1877.29	9.0482
1877.38	8.8609
1877.46	8.8564
1877.54	8.8589
1877.63	8.8458
1877.71	8.8098
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1877.88	8.8812
1877.96	8.9321
1878.04	9.0516

1878.13	9.0721
1878.21	9.0661
1878.29	8.9724
1878.38	8.9509
1878.46	8.9102
1878.54	8.8463
1878.63	8.8415
1878.71	8.8687
1878.79	8.9551
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1878.96	9.1962
1879.04	9.2651
1879.13	9.2264
1879.21	9.1096
1879.29	8.9868
1879.38	8.9098
1879.46	8.9052
1879.54	8.8905
1879.63	8.8729
1879.71	8.8402
1879.79	8.8950
1879.88	9.0084
1879.96	9.1264

1880.04	9.2530
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1880.21	9.1038
1880.29	9.0721
1880.38	8.8331
1880.46	8.8145
1880.54	8.7715
1880.63	8.7711
1880.71	8.7875
1880.79	8.8621
1880.88	8.9456
1880.96	9.0725
1881.04	9.1732
1881.13	9.1433
1881.21	9.0537
1881.29	8.9089
1881.38	8.8235
1881.46	8.9069
1881.54	8.6987
1881.63	8.7528
1881.71	8.8062
1881.79	8.8525
1881.88	9.0120

1881.96	9.1132
1882.04	9.1674
1882.13	9.1322
1882.21	9.0796
1882.29	8.9820
1882.38	8.8371
1882.46	8.7786
1882.54	8.7450
1882.63	8.7621
1882.71	8.7925
1882.79	8.8590
1882.88	8.9936
1882.96	9.0637
1883.04	9.1505
1883.13	9.1227
1883.21	9.0877
1883.29	9.0106
1883.38	8.8675
1883.46	8.8399
1883.54	8.7856
1883.63	8.8520
1883.71	8.8723
1883.79	8.8922

1883.88	9.0120
1883.96	9.0910
1884.04	9.1910
1884.13	9.1495
1884.21	9.1079
1884.29	9.0736
1884.38	8.8283
1884.46	8.8548
1884.54	8.7451
1884.63	8.8325
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1884.79	8.8544
1884.88	9.0027
1884.96	9.0769
1885.04	9.1535
1885.13	9.1084
1885.21	9.0222
1885.29	8.9361
1885.38	8.8357
1885.46	8.6969
1885.54	8.7386
1885.63	8.7205
1885.71	8.7106

1885.79	8.7913
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1885.96	9.0560
1886.04	9.0728
1886.13	9.0710
1886.21	9.0403
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1886.38	8.7828
1886.46	8.7950
1886.54	8.7556
1886.63	8.7541
1886.71	8.7848
1886.79	8.8093
1886.88	8.9716
1886.96	9.0581
1887.04	9.0796
1887.13	9.0643
1887.21	9.0685
1887.29	8.9331
1887.38	8.7685
1887.46	8.7825
1887.54	8.7899
1887.63	8.7815

1887.71	8.7900
1887.79	8.8603
1887.88	8.9627
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1888.04	9.0288
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1888.38	8.8527
1888.46	8.7369
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1888.63	8.7368
1888.71	8.7494
1888.79	8.8362
1888.88	8.9950
1888.96	9.0976
1889.04	9.1612
1889.13	9.1581
1889.21	9.1136
1889.29	8.9797
1889.38	8.8843
1889.46	8.8392
1889.54	8.7592

1889.63	8.7544
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1889.96	9.0601
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1890.54	8.8115
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1890.88	8.9973
1890.96	9.1128
1891.04	9.1680
1891.13	9.1621
1891.21	9.1220
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1891.46	8.8648

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1892.79	8.8859
1892.88	8.9929
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1893.04	9.1448
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1893.21	9.0693
1893.29	9.0128
1893.38	8.8328

1893.46	8.7729
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1895.04	9.1576
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1897.46	8.7812
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1905.88	8.8924		
1905.96	8.9451		
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1906.13	9.0633	-4.6653	-1.7319
1906.21	9.0278	-4.6930	-1.6577
1906.29	8.9429	-4.9305	-1.0966
1906.38	8.7845	-5.4000	-1.7886
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1906.54	8.7088	-5.5880	-2.1824
1906.63	8.7176	-5.5932	-2.0660
1906.71	8.7308	-5.5864	-2.3434
1906.79	8.7778	-5.4176	-2.4586

1906.88	8.9585	-4.8289	-2.4842
1906.96	9.0042	-4.8487	-2.5123
1907.04	9.0381	-4.5848	-1.9139
1907.13	9.0290	-4.3702	-1.6454
1907.21	9.0180	-4.7284	-1.5785
1907.29	8.9187	-4.6369	-1.1848
1907.38	8.7810	-5.3364	-1.5631
1907.46	8.7105	-5.6672	-2.0287
1907.54	8.7388	-5.7562	-1.9548
1907.63	8.7298	-5.8642	-1.8814
1907.71	8.7333	-5.7217	-2.0084
1907.79	8.7932	-5.5891	-2.7392
1907.88	8.9629	-4.9595	-2.5196
1907.96	8.9619	-4.8394	-1.8868
1908.04	9.0090	-4.8448	-1.3875
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1908.29	8.9215	-4.9596	-0.9616
1908.38	8.7966	-5.6737	-0.9627
1908.46	8.7238	-5.3257	-0.8937
1908.54	8.7140	-5.8470	-2.0913
1908.63	8.6832	-5.7125	-2.2650
1908.71	8.7682	-5.5665	-2.6706

1908.79	8.8474	-5.1987	-2.5075
1908.88	8.9545	-4.7613	-2.4737
1908.96	9.0875	-4.6700	-2.4411
1909.04	9.1415	-4.1311	-1.9167
1909.13	9.1170	-4.0272	-1.5732
1909.21	9.0844	-4.0341	-1.2876
1909.29	8.9448	-4.9359	-1.0810
1909.38	8.8355	-5.2269	-0.9630
1909.46	8.7466	-5.5621	-1.2036
1909.54	8.7003	-5.7810	-2.0335
1909.63	8.7936	-5.6352	-2.2518
1909.71	8.7647	-5.6348	-2.5168
1909.79	8.8641	-5.3052	-2.6304
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1909.96	9.1089	-4.3778	-2.8233
1910.04	9.1630	-4.2217	-2.7390
1910.13	9.1660	-4.2275	-2.4861
1910.21	9.1450	-4.3249	-2.1987
1910.29	9.0180	-4.9145	-1.6537
1910.38	8.8610	-5.1611	-1.1143
1910.46	8.8311	-5.3208	-1.7643
1910.54	8.8375	-5.2857	-2.3756
1910.63	8.8709	-5.2571	-2.2954

1910.71	8.8900	-5.2218	-2.0452
1910.79	8.9134	-5.1273	-1.6863
1910.88	8.9633	-5.0764	-1.2758
1910.96	9.0605	-4.4791	-2.5056
1911.04	9.1115	-4.2989	-2.1246
1911.13	9.0924	-4.2990	-1.7871
1911.21	9.0239	-4.4033	-1.0467
1911.29	8.9876	-4.3286	-1.3581
1911.38	8.7986	-5.0196	-1.3401
1911.46	8.7411	-5.3410	-2.0190
1911.54	8.7319	-5.5726	-1.8111
1911.63	8.7441	-5.4015	-2.1262
1911.71	8.7876	-5.1501	-2.6847
1911.79	8.8179	-5.2468	-2.6823
1911.88	8.9885	-4.9336	-3.8654
1911.96	9.0560	-4.5577	-3.1596
1912.04	9.0876	-4.5230	-2.6290
1912.13	9.0766	-4.5907	-2.8612
1912.21	9.0554	-4.5804	-2.3931
1912.29	8.9305	-4.9306	-1.9405
1912.38	8.8076	-5.1421	-1.7214
1912.46	8.7793	-5.3541	-1.6236
1912.54	8.7638	-5.6501	-1.9827

1912.63	8.7692	-5.6563	-2.2066
1912.71	8.7648	-5.6596	-2.1705
1912.79	8.7955	-5.4578	-2.2051
1912.88	8.9579	-4.8211	-3.1798
1912.96	9.0210	-4.6709	-3.3609
1913.04	9.0740	-4.3144	-2.9576
1913.13	9.0789	-4.5390	-2.6375
1913.21	9.0483	-4.6055	-2.1003
1913.29	8.9552	-4.6951	-1.3939
1913.38	8.8528	-4.9244	-0.7895
1913.46	8.8550	-5.0749	-1.0444
1913.54	8.8334	-5.2404	-1.8081
1913.63	8.8467	-5.3747	-2.4089
1913.71	8.8471	-5.2256	-2.3813
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1913.88	8.9287	-4.5959	-2.5017
1913.96	8.9803	-4.6908	-2.4223
1914.04	9.0079	-4.7478	-2.4415
1914.13	8.9843	-4.7492	-2.4135
1914.21	8.9607	-4.7506	-2.3856
1914.29	8.9278	-4.8489	-2.2033
1914.38	8.8153	-5.0830	-2.4741
1914.46	8.7432	-5.3706	-1.5125

1914.54	8.6460	-5.7368	-1.9960
1914.63	8.6698	-5.7400	-2.0538
1914.71	8.7119	-5.6929	-2.6479
1914.79	8.8842	-5.1692	-3.3541
1914.88	8.9865	-4.8356	-3.5519
1914.96	9.0584	-4.6585	-3.4601
1915.04	9.1079	-4.5660	-3.3029
1915.13	9.0992	-4.4268	-3.0110
1915.21	9.1192	-4.8074	-2.9411
1915.29	8.9671	-4.9999	-1.8660
1915.38	8.8414	-5.0940	-1.2110
1915.46	8.7714	-5.4969	-0.9989
1915.54	8.7275	-5.6751	-1.3326
1915.63	8.7732	-5.4058	-2.8664
1915.71	8.7915	-5.6027	-2.7317
1915.79	8.8214	-5.5648	-2.4680
1915.88	8.9693	-4.9758	-3.6722
1915.96	9.0431	-4.8423	-2.9417
1916.04	9.1188	-4.5419	-2.0545
1916.13	9.0765	-4.5802	-1.9170
1916.21	9.0259	-4.6186	-1.7795
1916.29	8.9347	-4.9934	-1.8543
1916.38	8.7623	-5.6285	-2.1744

1916.46	8.7981	-5.6263	-1.8009
1916.54	8.8550	-5.4602	-1.3646
1916.63	8.8139	-5.5168	-2.2434
1916.71	8.7628	-5.5707	-2.0932
1916.79	8.8383	-4.8968	-2.2327
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1916.96	9.1014	-4.5870	-2.6714
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1917.38	8.8720	-5.1388	-1.4354
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1917.54	8.7827	-5.3684	-1.4091
1917.63	8.8380	-5.5042	-1.9249
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1917.79	8.8397	-5.5239	-1.9221
1917.88	8.9802	-4.8638	-2.5020
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1918.04	9.0448	-4.6068	-2.3254
1918.13	9.0319	-4.7594	-2.4852
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1918.38	8.8303	-5.0048	-1.4100
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1918.79	8.8621	-5.2728	-2.3273
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1919.04	9.2185	-4.1445	-2.3450
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1919.21	9.0888	-4.4586	-1.8070
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1919.46	8.8291	-5.4563	-2.1194
1919.54	8.7876	-5.5630	-2.0373
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1920.46	8.8043	-5.6084	-1.6999
1920.54	8.7757	-5.8389	-1.7881
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1922.46	8.8523	-5.3939	-1.0937
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1922.63	8.8452	-5.3588	-1.5130
1922.71	8.8339	-5.3624	-1.6732
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1923.46	8.7573	-5.6978	-2.2057
1923.54	8.8101	-5.7750	-2.1021
1923.63	8.7835	-5.7250	-1.8812
1923.71	8.7657	-5.6135	-2.4339
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1923.96	9.1152	-4.6645	-2.6281
1924.04	9.1882	-4.4044	-2.2668

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1924.21	9.1277	-4.5064	-1.6320
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1924.38	8.8049	-5.4057	-1.8474
1924.46	8.8139	-5.6679	-1.7499
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1925.88	8.9626	-4.8886	-2.2602
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1926.04	9.1493	-4.3079	-2.2006
1926.13	9.1290	-4.3972	-2.1402
1926.21	9.0906	-4.4829	-1.6826
1926.29	9.0021	-4.6849	-1.5647
1926.38	8.8529	-5.0379	-0.8777
1926.46	8.7596	-5.3135	-1.0468
1926.54	8.7022	-5.6569	-1.7023
1926.63	8.7189	-5.6561	-2.0634
1926.71	8.7649	-5.4378	-1.9673
1926.79	8.8562	-5.2985	-1.7859
1926.88	8.9426	-5.0481	-2.1484
1926.96	9.0252	-4.7517	-1.8444
1927.04	9.0781	-4.8756	-1.6475
1927.13	9.0497	-4.8896	-1.6561
1927.21	9.0213	-4.9036	-1.6647
1927.29	8.9670	-5.0138	-1.4881
1927.38	8.7989	-5.6947	-1.4894
1927.46	8.7648	-5.8777	-1.8849
1927.54	8.7362	-5.9527	-2.5073
1927.63	8.7644	-5.8834	-2.2549
1927.71	8.7790	-5.6870	-1.6424
1927.79	8.8193	-5.5938	-1.6841
1927.88	8.9281	-4.9375	-3.0586

1927.96	8.9742	-4.8967	-2.7254
1928.04	8.9964	-4.7956	-2.2977
1928.13	8.9927	-4.8958	-2.1083
1928.21	8.9814	-4.9351	-2.2619
1928.29	8.9377	-4.9805	-1.7286
1928.38	8.8198	-5.4804	-1.8648
1928.46	8.7560	-5.7716	-1.9097
1928.54	8.7694	-5.7080	-2.4637
1928.63	8.7693	-5.8241	-2.1926
1928.71	8.7525	-5.6583	-2.1360
1928.79	8.8127	-5.1535	-2.3488
1928.88	8.9244	-4.9128	-2.6825
1928.96	9.0288	-4.7598	-2.3823
1929.04	9.0641	-4.5903	-1.9310
1929.13	9.0485	-4.5098	-1.7108
1929.21	9.0286	-4.5675	-1.6496
1929.29	8.9503	-4.8948	-1.5385
1929.38	8.8688	-5.3286	-1.5576
1929.46	8.8293	-5.3692	-1.5604
1929.54	8.8504	-5.5959	-1.7672
1929.63	8.8071	-5.7783	-1.7140
1929.71	8.7531	-5.8275	-1.5681
1929.79	8.7994	-5.4488	-1.9629

1929.88	8.9498	-5.0926	-2.5846
1929.96	9.0532	-4.9840	-1.8739
1930.04	9.0563	-4.8188	-1.7587
1930.13	9.0430	-4.8324	-1.5505
1930.21	9.0153	-4.8599	-1.3604
1930.29	8.9139	-5.2187	-0.9077
1930.38	8.7924	-5.6516	-1.4976
1930.46	8.8261	-5.6143	-1.4903
1930.54	8.7974	-5.6432	-1.2498
1930.63	8.7525	-5.5580	-1.8631
1930.71	8.7786	-5.5032	-2.0575
1930.79	8.8183	-5.4238	-2.2374
1930.88	8.9085	-5.0951	-2.6911
1930.96	8.9897	-4.8664	-2.7907
1931.04	9.0635	-4.6880	-2.2463
1931.13	9.0218	-4.7012	-1.7509
1931.21	8.9996	-4.8201	-1.3395
1931.29	8.9056	-5.1044	-1.7317
1931.38	8.8221	-5.4178	-1.3510
1931.46	8.7752	-5.6905	-1.1018
1931.54	8.7016	-5.7852	-2.4604
1931.63	8.7484	-5.6302	-2.7604
1931.71	8.7544	-5.6476	-2.6427

1931.79	8.8695	-5.3251	-2.5194
1931.88	9.0001	-4.8628	-3.1575
1931.96	9.1453	-4.5674	-2.5091
1932.04	9.1807	-4.3769	-2.1571
1932.13	9.1524	-4.3825	-1.8616
1932.21	9.1031	-4.5262	-1.7090
1932.29	9.0063	-4.5513	-1.2398
1932.38	8.8135	-5.0531	-1.1199
1932.46	8.7704	-5.3394	-2.0054
1932.54	8.8137	-5.7575	-1.9521
1932.63	8.7814	-5.5417	-2.1128
1932.71	8.8090	-5.5655	-2.8805
1932.79	8.8990	-5.4570	-3.1087
1932.88	8.9802	-5.1350	-3.0438
1932.96	9.0899	-4.8270	-3.0005
1933.04	9.1284	-4.4306	-2.9535
1933.13	9.1228	-4.6310	-2.7411
1933.21	9.0725	-4.6977	-2.1427
1933.29	8.9819	-4.8897	-1.7168
1933.38	8.8427	-5.3024	-1.3669
1933.46	8.7856	-5.5283	-2.2816
1933.54	8.7885	-5.6860	-1.0042
1933.63	8.7806	-5.7341	-1.0768

1933.71	8.7499	-5.7857	-2.0119
1933.79	8.7755	-5.6513	-2.7757
1933.88	9.0419	-4.9012	-2.5278
1933.96	9.0684	-4.7269	-1.9475
1934.04	9.1785	-4.6541	-1.8434
1934.13	9.1161	-4.6500	-1.8558
1934.21	9.0537	-4.6458	-1.8681
1934.29	8.9311	-5.1316	-1.6444
1934.38	8.8353	-5.2519	-1.7069
1934.46	8.8095	-5.4075	-1.8516
1934.54	8.8010	-5.6007	-1.7521
1934.63	8.7942	-5.7413	-1.5260
1934.71	8.8234	-5.6199	-1.8534
1934.79	8.8411	-5.5006	-2.5300
1934.88	8.9389	-5.1673	-2.8415
1934.96	9.0725	-4.5429	-3.0246
1935.04	9.1264	-4.3865	-2.0812
1935.13	9.1034	-4.3244	-1.8222
1935.21	9.0712	-4.7578	-1.7187
1935.29	9.0013	-4.6004	-1.8664
1935.38	8.8410	-5.1773	-1.7246
1935.46	8.8117	-5.3797	-2.1125
1935.54	8.8570	-5.7557	-2.0891

1935.63	8.8608	-5.6546	-2.0963
1935.71	8.8124	-5.7117	-2.0920
1935.79	8.8729	-5.4086	-1.8526
1935.88	8.9506	-4.7229	-2.3508
1935.96	9.0502	-4.5082	-2.4022
1936.04	9.0697	-4.6095	-2.4361
1936.13	9.0661	-4.6422	-2.1270
1936.21	9.0755	-4.6952	-1.4021
1936.29	8.9965	-4.9506	-1.0261
1936.38	8.7935	-5.4904	-0.8156
1936.46	8.7616	-5.6372	-1.2864
1936.54	8.7918	-5.5353	-1.4179
1936.63	8.8106	-5.5891	-1.3014
1936.71	8.8142	-5.4006	-1.8147
1936.79	8.8485	-5.2094	-1.6091
1936.88	8.9489	-4.8878	-1.5490
1936.96	9.0155	-4.6737	-1.5939
1937.04	9.0420	-4.5968	-1.7788
1937.13	9.0327	-4.5819	-1.6880
1937.21	9.0345	-4.6663	-1.0407
1937.29	8.9834	-4.8982	-0.6719
1937.38	8.8384	-5.3275	-0.9037
1937.46	8.7668	-5.6175	-1.5833

1937.54	8.7678	-5.6448	-1.8367
1937.63	8.7394	-5.7996	-1.7269
1937.71	8.7531	-5.8158	-2.1756
1937.79	8.8658	-5.3426	-2.0421
1937.88	8.9787	-5.0402	-2.1791
1937.96	9.0392	-4.9558	-2.0356
1938.04	9.0844	-4.7494	-1.4759
1938.13	9.0558	-4.7511	-1.4130
1938.21	9.0215	-4.7723	-1.3968
1938.29	8.9659	-4.9343	-1.1645
1938.38	8.7793	-5.4360	-1.0661
1938.46	8.7099	-5.6886	-1.5953
1938.54	8.7445	-6.0024	-2.2514
1938.63	8.6828	-5.9891	-2.8586
1938.71	8.7159	-5.8272	-2.3673
1938.79	8.8193	-5.5583	-2.4444
1938.88	8.9622	-5.4084	-2.5605
1938.96	9.0923	-4.9265	-2.3071
1939.04	9.1400	-4.4822	-2.0547
1939.13	9.1061	-4.5101	-1.8142
1939.21	9.0722	-4.5380	-1.5737
1939.29	8.9835	-5.1313	-1.9586
1939.38	8.8508	-5.5608	-2.2317

1939.46	8.8135	-5.8406	-2.5529
1939.54	8.7737	-5.7937	-1.9196
1939.63	8.7817	-5.8355	-1.7949
1939.71	8.8646	-5.4856	-2.3994
1939.79	8.8873	-5.2766	-2.5435
1939.88	9.0081	-5.1500	-2.6469
1939.96	9.0900	-4.6248	-2.6969
1940.04	9.1820	-4.1257	-1.7553
1940.13	9.1717	-4.1741	-1.4788
1940.21	9.1167	-4.3695	-1.4713
1940.29	9.0149	-4.8291	-1.6327
1940.38	8.8705	-5.2222	-1.3666
1940.46	8.8565	-5.3534	-1.8054
1940.54	8.8237	-5.5206	-2.0855
1940.63	8.8035	-5.6471	-1.9014
1940.71	8.8339	-5.4563	-2.2796
1940.79	8.8756	-5.0232	-2.2231
1940.88	8.9807	-4.9160	-2.3367
1940.96	9.0950	-5.0569	-2.2949
1941.04	9.2094	-5.1978	-2.2531
1941.13	9.1221	-5.1664	-1.9262
1941.21	9.0341	-5.1344	-1.5984
1941.29	8.9683	-4.8959	-1.3473

1941.38	8.8032	-5.5868	-1.9782
1941.46	8.7305	-5.6972	-1.7514
1941.54	8.7037	-5.8095	-1.9208
1941.63	8.7223	-5.9005	-2.5188
1941.71	8.8150	-5.5203	-1.1623
1941.79	8.8156	-5.3408	-1.6465
1941.88	8.9307	-5.0480	-2.0639
1941.96	8.9758	-4.8939	-1.9349
1942.04	9.0061	-4.6751	-1.2048
1942.13	8.9805	-4.7467	-1.0790
1942.21	8.9548	-4.8184	-0.9533
1942.29	8.8987	-4.8686	-1.0712
1942.38	8.7774	-5.2346	-0.6430
1942.46	8.7758	-5.5827	-1.5897
1942.54	8.7856	-5.5497	-1.8396
1942.63	8.7478	-5.6994	-1.6338
1942.71	8.7246	-5.8510	-2.3681
1942.79	8.8020	-5.4632	-2.2527
1942.88	8.9538	-4.9533	-2.6357
1942.96	9.0042	-4.8124	-2.3225
1943.04	9.0136	-4.6982	-1.6909
1943.13	9.0122	-4.7955	-1.4492
1943.21	8.9893	-4.8566	-1.4506

1943.29	8.9544	-4.8955	-1.4672
1943.38	8.8498	-4.9245	-1.3589
1943.46	8.8291	-5.3287	-2.3164
1943.54	8.7906	-5.7221	-2.2466
1943.63	8.7431	-5.9356	-1.9117
1943.71	8.7728	-5.6737	-2.0975
1943.79	8.8469	-5.2376	-2.3216
1943.88	8.9833	-4.6123	-2.2043
1943.96	9.0954	-4.4755	-1.7183
1944.04	9.1087	-4.2523	-1.4951
1944.13	9.0572	-4.4776	-1.7045
1944.21	9.0056	-4.7030	-1.9139
1944.29	8.9783	-4.6946	-1.8270
1944.38	8.8269	-5.3623	-1.3590
1944.46	8.7353	-5.8432	-2.7116
1944.54	8.7374	-5.8939	-2.7275
1944.63	8.7508	-5.8744	-1.9945
1944.71	8.7426	-5.7919	-2.4508
1944.79	8.8287	-5.6540	-2.6163
1944.88	8.9557	-5.0443	-2.3779
1944.96	9.0022	-4.4644	-2.3885
1945.04	9.0598	-4.6013	-2.3035
1945.13	9.0577	-4.6426	-2.1742

1945.21	9.0417	-4.7070	-2.0620
1945.29	8.9765	-4.9606	-1.4538
1945.38	8.8500	-5.1532	-0.8945
1945.46	8.7840	-5.5353	-1.0617
1945.54	8.7565	-5.8269	-2.0291
1945.63	8.7473	-5.9008	-2.3946
1945.71	8.7473	-5.8642	-2.3698
1945.79	8.8944	-4.8406	-3.1717
1945.88	8.9507	-4.8598	-1.8741
1945.96	9.0884	-4.8209	-1.7793
1946.04	9.0557	-4.6229	-1.5624
1946.13	9.0348	-5.0039	-2.4099
1946.21	9.0120	-5.0204	-2.2697
1946.29	8.9741	-5.1738	-1.6595
1946.38	8.8601	-5.2831	-1.7176
1946.46	8.7963	-5.1258	-1.9500
1946.54	8.7384	-5.2197	-1.9905
1946.63	8.7782	-5.5443	-1.9052
1946.71	8.8332	-5.1524	-2.4328
1946.79	8.8764	-5.2815	-2.6595
1946.88	8.9831	-5.0704	-2.3588
1946.96	9.0332	-4.5987	-2.7019
1947.04	9.0731	-4.4929	-2.3303

1947.13	9.0516	-4.5214	-2.2337
1947.21	9.0292	-4.5521	-2.1427
1947.29	9.0068	-4.5828	-2.0518
1947.38	8.8763	-5.2646	-2.5262
1947.46	8.8539	-5.5940	-2.1771
1947.54	8.7576	-5.7999	-2.7953
1947.63	8.7803	-5.9539	-2.7353
1947.71	8.8412	-5.5912	-2.4101
1947.79	8.8931	-5.3542	-2.7145
1947.88	8.9655	-4.8534	-2.2182
1947.96	9.0939	-4.4784	-2.5418
1948.04	9.1350	-4.4266	-2.1393
1948.13	9.0978	-4.4988	-1.4869
1948.21	9.0430	-4.5359	-0.6904
1948.29	8.9911	-4.9254	-0.8608
1948.38	8.8723	-5.4784	-1.5722
1948.46	8.8365	-5.4841	-1.7616
1948.54	8.8007	-5.4897	-1.9510
1948.63	8.8049	-5.4852	-2.5746
1948.71	8.8361	-5.5104	-2.2060
1948.79	8.8703	-5.2857	-2.8160
1948.88	8.9778	-4.6795	-3.0042
1948.96	9.0970	-4.3443	-2.8986

1949.04	9.1622	-4.3004	-2.4873
1949.13	9.0980	-4.4242	-1.9759
1949.21	9.0864	-4.7219	-1.6938
1949.29	8.9556	-4.9973	-1.5129
1949.38	8.8579	-5.2750	-1.5111
1949.46	8.7958	-5.4264	-1.8489
1949.54	8.7447	-5.5217	-1.9875
1949.63	8.7641	-5.6050	-2.0039
1949.71	8.8096	-5.4679	-2.1385
1949.79	8.8670	-4.8517	-2.9144
1949.88	8.9341	-4.7313	-2.7833
1949.96	9.0012	-4.6110	-2.6523
1950.04	9.0519	-4.3407	-2.2136
1950.13	9.0272	-4.5952	-1.9994
1950.21	9.0185	-4.7280	-1.7290
1950.29	8.9131	-4.8592	-0.9824
1950.38	8.8186	-5.3116	-1.7729
1950.46	8.7490	-5.5038	-2.2319
1950.54	8.7255	-5.7900	-3.8601
1950.63	8.7261	-5.8418	-3.2054
1950.71	8.7236	-5.6603	-2.4884
1950.79	8.7927	-5.8180	-3.0106
1950.88	8.8916	-5.4633	-2.8157

1950.96	9.0188	-4.5988	-2.5811
1951.04	9.1089	-3.6232	-2.3050
1951.13	9.0725	-3.9236	-2.1600
1951.21	9.0537	-4.2374	-1.9321
1951.29	8.9228	-4.2098	-1.7079
1951.38	8.8427	-5.2625	-2.6564
1951.46	8.7954	-5.3422	-2.3026
1951.54	8.7857	-5.4245	-1.7890
1951.63	8.8035	-5.2145	-1.8081
1951.71	8.8335	-5.1117	-1.9103
1951.79	8.8769	-4.9613	-2.0906
1951.88	8.9774	-4.5821	-2.5449
1951.96	9.0624	-4.0568	-2.8688
1952.04	9.1159	-3.9609	-2.6277
1952.13	9.0956	-4.3029	-2.2745
1952.21	9.0720	-4.6869	-2.1265
1952.29	8.9811	-4.7697	-2.1865
1952.38	8.8678	-5.0137	-2.0581
1952.46	8.8115	-5.4900	-2.2269
1952.54	8.7263	-5.7306	-3.0827
1952.63	8.8030	-5.6460	-2.9760
1952.71	8.7973	-5.4972	-2.2450
1952.79	8.8185	-5.5340	-1.9388

1952.88	8.9401	-4.9205	-3.0014
1952.96	9.0581	-4.7727	-3.4475
1953.04	9.1236	-4.5005	-3.0428
1953.13	9.1108	-4.3599	-2.5382
1953.21	9.0623	-4.3508	-1.7501
1953.29	8.9636	-4.7320	-2.1124
1953.38	8.8795	-5.2618	-2.6414
1953.46	8.7776	-5.4457	-2.5970
1953.54	8.7592	-5.6006	-1.4369
1953.63	8.7989	-5.6127	-2.0758
1953.71	8.8065	-5.5053	-2.3534
1953.79	8.8625	-5.4761	-2.3240
1953.88	8.9473	-4.9820	-3.1694
1953.96	9.0758	-4.3715	-2.8949
1954.04	9.1108	-4.4154	-2.4131
1954.13	9.0652	-4.5197	-2.2760
1954.21	9.0179	-4.6195	-2.1454
1954.29	8.9740	-4.7129	-1.9809
1954.38	8.8683	-4.9259	-1.4177
1954.46	8.7556	-5.5380	-2.5971
1954.54	8.7676	-5.6394	-2.3260
1954.63	8.7813	-5.3874	-2.6237
1954.71	8.7820	-5.3387	-2.8480

1954.79	8.8328	-5.1142	-3.4747
1954.88	8.9929	-4.7615	-3.3602
1954.96	9.0128	-4.5775	-3.3451
1955.04	9.0820	-4.2621	-2.7013
1955.13	9.0620	-4.2398	-2.4560
1955.21	9.0380	-4.2278	-2.3039
1955.29	8.9704	-4.8267	-2.3420
1955.38	8.8583	-4.9806	-2.4386
1955.46	8.7674	-5.3964	-2.0560
1955.54	8.7456	-5.5013	-1.9314
1955.63	8.7774	-5.5207	-2.3922
1955.71	8.8312	-5.4937	-2.4383
1955.79	8.8634	-5.4366	-2.5751
1955.88	8.9421	-5.3484	-2.2241
1955.96	9.0254	-4.6534	-3.2168
1956.04	9.1119	-3.7257	-2.2306
1956.13	9.0971	-3.7805	-2.2469
1956.21	9.0456	-3.9900	-2.1519
1956.29	8.9678	-4.5783	-1.8030
1956.38	8.8216	-5.0735	-1.8760
1956.46	8.7882	-5.3471	-1.8459
1956.54	8.7868	-5.0401	-2.3444
1956.63	8.8136	-5.1201	-2.2826

1956.71	8.8505	-4.6894	-2.1040
1956.79	8.8572	-4.9329	-2.0186
1956.88	8.9008	-4.5267	-2.4055
1956.96	8.9663	-4.4889	-2.3542
1957.04	8.9915	-4.5385	-2.3058
1957.13	8.9612	-4.4303	-1.9970
1957.21	8.9607	-4.6631	-1.2870
1957.29	8.8684	-4.7664	-0.8183
1957.38	8.7876	-5.3502	-1.6448
1957.46	8.7833	-5.3850	-1.5786
1957.54	8.7615	-5.3699	-1.8904
1957.63	8.7571	-5.4345	-2.6247
1957.71	8.7901	-5.2325	-2.4851
1957.79	8.8395	-5.0960	-2.1728
1957.88	8.9122	-4.9566	-2.0216
1957.96	8.9735	-4.7253	-1.9583
1958.04	8.9869	-4.6772	-2.4333
1958.13	8.9700	-4.1303	-1.8589
1958.21	8.9845	-3.8750	-1.4401
1958.29	8.9205	-3.8756	-1.9884
1958.38	8.8426	-5.0958	-1.8332
1958.46	8.7885	-4.3894	-2.2027
1958.54	8.7836	-4.2618	-2.0975

1958.63	8.7999	-4.2360	-2.1524
1958.71	8.8302	-4.0684	-2.4126
1958.79	8.8840	-4.0928	-2.3821
1958.88	8.9634	-4.2451	-2.2698
1958.96	9.0409	-4.4209	-2.1970
1959.04	9.0883	-4.3442	-2.1228
1959.13	9.0787	-4.3972	-1.8645
1959.21	9.0416	-4.4704	-1.5342
1959.29	8.9103	-4.1079	-0.7621
1959.38	8.8472	-5.1035	-1.2804
1959.46	8.8065	-5.4408	-1.7870
1959.54	8.7945	-5.5282	-1.9612
1959.63	8.8263	-5.3135	-1.7020
1959.71	8.8191	-5.1591	-1.5779
1959.79	8.8438	-5.0399	-1.7592
1959.88	8.9646	-4.6636	-2.1149
1959.96	9.0726	-4.5119	-2.2065
1960.04	9.1074	-4.5796	-2.4637
1960.13	9.0773	-4.3088	-1.5249
1960.21	9.0470	-4.5942	-1.3795
1960.29	8.9795	-4.5461	-1.0609
1960.38	8.8627	-5.0357	-1.4049
1960.46	8.8312	-5.0202	-1.5581

1960.54	8.7806	-5.4563	-1.5666
1960.63	8.8015	-5.3268	-1.3579
1960.71	8.8155	-4.7649	-1.5277
1960.79	8.8651	-4.5814	-2.2606
1960.88	8.9590	-4.5235	-2.0005
1960.96	9.0064	-4.5208	-1.7741
1961.04	9.0235	-4.5229	-1.5963
1961.13	9.0226	-4.5248	-1.4325
1961.21	9.0018	-4.5566	-1.3722
1961.29	8.9315	-4.6190	-1.2575
1961.38	8.7337	-5.1677	-1.2555
1961.46	8.7077	-5.5554	-2.1314
1961.54	8.7386	-5.4372	-1.8699
1961.63	8.7741	-5.3030	-1.4807
1961.71	8.8108	-5.2979	-1.3234
1961.79	8.8720	-5.1046	-1.8881
1961.88	8.9489	-4.6552	-2.3037
1961.96	9.0533	-4.5705	-2.2001
1962.04	9.1496	-4.0552	-1.9412
1962.13	9.0730	-4.6135	-2.9771
1962.21	9.0623	-4.6578	-1.7175
1962.29	9.0109	-4.3507	-1.6248
1962.38	8.8755	-5.1774	-1.7064

1962.46	8.8280	-5.0061	-2.2830
1962.54	8.8354	-5.0773	-2.1760
1962.63	8.7649	-5.1709	-1.9743
1962.71	8.7889	-5.0933	-2.3907
1962.79	8.8284	-5.0051	-2.8637
1962.88	8.9472	-4.8640	-2.7455
1962.96	9.0078	-4.6765	-2.5292
1963.04	9.0515	-4.3961	-2.2057
1963.13	9.0339	-3.9814	-2.2074
1963.21	9.0076	-3.5514	-2.2567
1963.29	8.9807	-4.5344	-1.9938
1963.38	8.8264	-5.0726	-2.3368
1963.46	8.7347	-5.2719	-2.1794
1963.54	8.6843	-5.4709	-2.0201
1963.63	8.7698	-5.1038	-1.6620
1963.71	8.8192	-5.1332	-2.7142
1963.79	8.8819	-5.0421	-2.2993
1963.88	8.9677	-4.8236	-2.3110
1963.96	9.0549	-4.4648	-2.1975
1964.04	9.1051	-3.9110	-2.0348
1964.13	9.1001	-3.9134	-1.8582
1964.21	9.0832	-4.5245	-1.5266
1964.29	8.9720	-4.8085	-1.5148

1964.38	8.8768	-4.5963	-1.2515
1964.46	8.8491	-5.1212	-1.1872
1964.54	8.8144	-5.1967	-1.2736
1964.63	8.7723	-5.3869	-1.5011
1964.71	8.7861	-5.0741	-2.2332
1964.79	8.8517	-4.8131	-2.6441
1964.88	8.9311	-4.4633	-2.5488
1964.96	8.9697	-4.0669	-2.4377
1965.04	8.9803	-4.2141	-2.4898
1965.13	8.9820	-4.3792	-2.4581
1965.21	8.9756	-4.4531	-2.2619
1965.29	8.9313	-4.7476	-1.7568
1965.38	8.8601	-4.9832	-2.1879
1965.46	8.8506	-4.9584	-2.3820
1965.54	8.8562	-5.0518	-1.9791
1965.63	8.8377	-4.4482	-1.8474
1965.71	8.8842	-4.8405	-2.4418
1965.79	8.9055	-4.8559	-2.7155
1965.88	9.0178	-4.4021	-2.8789
1965.96	9.1004	-4.2354	-2.9461
1966.04	9.1791	-3.9187	-2.1689
1966.13	9.1594	-4.2586	-1.7298
1966.21	9.0407	-4.3566	-1.5019

1966.29	8.9596	-4.7130	-1.2518
1966.38	8.8659	-5.0816	-1.5824
1966.46	8.8432	-4.8649	-0.9359
1966.54	8.7880	-5.0634	-1.4461
1966.63	8.7619	-5.0218	-2.0391
1966.71	8.8360	-4.8126	-2.2884
1966.79	8.9131	-4.6148	-2.6833
1966.88	8.9811	-4.4508	-2.8484
1966.96	9.1060	-4.4543	-2.7306
1967.04	9.1859	-3.7609	-2.6188
1967.13	9.1282	-4.0957	-2.9713
1967.21	9.1021	-4.3651	-1.9446
1967.29	8.9611	-4.2554	-2.2213
1967.38	8.8941	-5.0477	-1.8346
1967.46	8.8349	-5.3616	-1.8054
1967.54	8.8205	-5.5140	-2.0630
1967.63	8.7759	-5.4147	-2.3438
1967.71	8.8306	-5.5527	-2.4804
1967.79	8.8400	-5.4196	-2.6642
1967.88	8.9227	-5.2201	-2.3968
1967.96	9.0511	-4.6679	-2.5172
1968.04	9.1186	-4.4702	-2.1299
1968.13	9.1088	-4.4892	-1.8908

1968.21	9.0889	-4.4348	-1.6859
1968.29	9.0553	-4.5177	-1.4903
1968.38	8.8634	-4.3127	-1.6940
1968.46	8.7845	-5.3271	-2.2168
1968.54	8.7807	-4.9203	-2.1195
1968.63	8.8188	-5.1315	-2.6667
1968.71	8.7891	-5.3912	-2.0874
1968.79	8.8586	-4.9215	-2.3346
1968.88	8.9646	-4.5605	-2.4412
1968.96	9.0567	-4.3000	-2.2089
1969.04	9.1000	-4.1113	-2.0145
1969.13	9.0926	-3.9220	-1.9249
1969.21	9.0558	-3.6396	-1.7885
1969.29	8.9692	-4.3259	-1.8550
1969.38	8.8602	-4.7891	-2.1192
1969.46	8.7984	-5.1072	-2.6283
1969.54	8.8078	-5.1908	-2.0503
1969.63	8.7789	-5.0472	-2.3907
1969.71	8.8146	-5.5751	-2.4245
1969.79	8.8388	-4.8193	-2.5833
1969.88	8.9655	-4.5674	-2.4187
1969.96	9.0284	-4.1615	-2.1461
1970.04	9.0583	-4.3237	-1.9525

1970.13	9.0459	-4.3367	-2.3999
1970.21	9.0443	-4.4393	-2.4971
1970.29	8.9469	-4.5429	-2.2056
1970.38	8.8425	-5.0451	-1.8586
1970.46	8.8289	-5.0796	-2.0370
1970.54	8.8021	-5.1472	-2.0338
1970.63	8.7667	-5.2369	-1.9096
1970.71	8.7603	-5.2469	-1.8882
1970.79	8.8586	-4.9707	-2.2354
1970.88	8.9678	-4.8026	-1.9551
1970.96	9.0620	-4.7051	-2.5162
1971.04	9.0790	-4.7431	-2.4263
1971.13	9.0638	-4.6059	-2.2253
1971.21	9.0486	-4.4687	-2.0243
1971.29	8.9881	-4.3928	-1.8914
1971.38	8.8523	-5.1529	-2.0885
1971.46	8.8567	-5.3126	-1.8440
1971.54	8.8189	-5.4013	-2.0374
1971.63	8.8126	-5.4178	-1.7134
1971.71	8.8320	-5.2186	-1.9164
1971.79	8.8560	-5.1173	-2.5198
1971.88	8.9628	-4.7255	-2.4101
1971.96	9.0389	-4.4480	-1.9598

1972.04	9.0541	-4.3899	-2.1587
1972.13	9.0438	-4.2467	-2.1302
1972.21	9.0238	-4.0915	-2.0191
1972.29	8.9299	-4.4753	-1.7835
1972.38	8.8048	-4.5053	-2.2431
1972.46	8.7862	-4.8478	-2.0149
1972.54	8.8145	-4.9468	-2.8826
1972.63	8.7459	-5.4561	-2.3646
1972.71	8.7545	-5.6653	-2.2009
1972.79	8.8611	-5.2914	-2.9628
1972.88	8.9686	-4.9159	-3.0321
1972.96	9.0155	-4.6884	-3.6330
1973.04	9.0714	-4.4335	-3.4650
1973.13	9.0686	-4.1342	-3.1940
1973.21	9.0318	-4.4015	-3.5089
1973.29	8.9508	-4.7063	-2.6621
1973.38	8.8292	-4.8214	-2.4996
1973.46	8.8102	-5.1193	-2.9325
1973.54	8.7890	-5.3201	-2.9369
1973.63	8.7888	-5.5704	-2.9011
1973.71	8.8235	-5.7157	-3.3197
1973.79	8.8670	-5.4770	-3.4648
1973.88	8.9398	-5.2129	-4.7147

1973.96	9.0327	-4.9148	-4.7515
1974.04	9.0712	-3.1838	-3.9925
1974.13	9.0162	-4.1715	-3.6176
1974.21	9.0211	-3.9798	-3.3193
1974.29	8.9014	-4.2569	-2.3583
1974.38	8.7904	-4.7913	-1.9130
1974.46	8.7828	-4.8243	-1.6944
1974.54	8.7854	-5.1277	-2.2279
1974.63	8.7831	-5.5038	-3.2712
1974.71	8.7644	-5.6133	-3.2364
1974.79	8.8441	-4.9728	-4.2146
1974.88	8.9775	-4.5184	-3.7526
1974.96	9.0331	-4.3764	-3.7162
1975.04	9.0686	-4.1868	-3.9044
1975.13	9.0262	-4.4413	-3.4159
1975.21	9.0260	-4.6471	-3.3391
1975.29	8.8868	-4.7765	-2.8938
1975.38	8.7767	-5.0648	-2.8038
1975.46	8.7448	-5.0185	-2.2626
1975.54	8.7506	-4.7642	-2.7615
1975.63	8.7479	-5.4662	-3.1573
1975.71	8.7755	-5.3227	-3.0820
1975.79	8.8334	-4.8744	-3.1574

1975.88	8.9445	-4.5316	-3.6498
1975.96	8.9817	-4.1732	-3.5149
1976.04	9.0139	-4.2719	-3.1043
1976.13	9.0011	-4.6690	-2.7525
1976.21	8.9796	-4.6973	-2.4531
1976.29	8.9300	-4.5547	-1.4871
1976.38	8.7830	-5.2173	-3.3604
1976.46	8.7461	-5.3064	-3.3897
1976.54	8.7551	-5.2043	-3.3934
1976.63	8.7628	-5.4578	-3.3452
1976.71	8.7711	-5.4591	-3.0793
1976.79	8.8599	-4.9214	-3.4891
1976.88	8.9203	-4.8828	-3.1383
1976.96	8.9658	-4.7900	-2.9242
1977.04	9.0214	-4.5549	-2.6260
1977.13	8.9670	-4.6697	-2.1486
1977.21	8.9778	-4.6385	-2.7086
1977.29	8.8874	-5.0899	-2.6959
1977.38	8.7751	-5.0258	-2.7711
1977.46	8.6755	-5.4185	-2.8727
1977.54	8.7017	-5.5449	-3.9274
1977.63	8.7235	-5.5905	-3.5717
1977.71	8.7403	-5.2031	-3.3134

1977.79	8.8291	-5.5621	-4.3420
1977.88	8.9371	-4.9539	-2.9276
1977.96	8.9611	-4.4988	-3.6647
1978.04	9.0160	-4.3347	-2.7542
1978.13	8.9950	-4.5747	-2.8406
1978.21	8.9757	-4.6508	-2.9333
1978.29	8.9098	-4.8256	-3.0118
1978.38	8.8293	-5.3194	-3.0236
1978.46	8.7642	-5.4303	-2.8017
1978.54	8.7445	-5.5927	-3.0596
1978.63	8.7743	-5.6089	-3.1273
1978.71	8.7562	-5.3316	-3.3581
1978.79	8.8408	-4.8937	-3.2217
1978.88	8.9739	-4.5861	-3.1464
1978.96	9.0605	-4.7853	-3.1755
1979.04	9.1442	-4.1771	-3.2407
1979.13	9.1341	-4.0636	-3.2140
1979.21	9.0769	-4.1658	-3.0840
1979.29	9.0144	-4.5611	-2.8659
1979.38	8.8053	-5.1003	-2.3051
1979.46	8.8132	-5.2253	-2.1156
1979.54	8.8244	-5.2266	-2.0684
1979.63	8.7828	-5.2450	-2.0891

1979.71	8.7508	-5.2078	-2.3940
1979.79	8.8036	-4.9612	-3.1566
1979.88	8.9372	-4.8765	-3.5157
1979.96	8.9958	-4.6910	-2.9145
1980.04	9.0646	-4.4455	-2.7068
1980.13	9.0553	-4.4096	-2.4806
1980.21	9.0170	-4.5184	-2.1033
1980.29	8.9514	-4.4693	-2.3103
1980.38	8.8549	-4.7739	-2.5088
1980.46	8.8734	-4.5631	-2.6445
1980.54	8.8334	-5.0301	-2.4089
1980.63	8.8076	-4.9751	-2.3466
1980.71	8.7977	-4.7276	-2.5446
1980.79	8.8197	-4.9933	-3.1752
1980.88	8.9569	-4.4635	-3.7835
1980.96	9.0463	-4.4199	-3.0863
1981.04	9.0711	-4.2090	-2.6145
1981.13	9.0472	-4.2837	-2.4531
1981.21	9.0193	-4.3962	-2.3109
1981.29	8.9897	-4.6170	-2.2513
1981.38	8.8745	-4.7193	-1.8457
1981.46	8.8310	-4.8741	-2.6089
1981.54	8.8100	-5.0753	-3.1394

1981.63	8.7975	-5.2686	-3.1209
1981.71	8.7891	-4.9148	-3.4769
1981.79	8.8257	-4.5031	-3.3769
1981.88	8.8941	-4.6273	-4.3335
1981.96	8.9048	-4.5096	-2.6959
1982.04	8.9254	-4.9513	-2.2823
1982.13	8.9126	-4.9577	-1.7463
1982.21	8.8959	-4.9421	-1.6961
1982.29	8.8754	-4.9046	-2.1256
1982.38	8.8374	-5.2213	-1.7738
1982.46	8.7813	-5.2270	-2.0914
1982.54	8.7556	-5.2777	-2.5585
1982.63	8.7722	-4.9973	-2.6197
1982.71	8.7877	-5.3197	-2.3455
1982.79	8.8873	-4.6625	-2.7630
1982.88	8.8977	-4.5747	-2.7346
1982.96	8.9958	-4.3438	-2.3153
1983.04	9.0510	-4.3909	-2.2994
1983.13	9.0420	-4.4458	-2.2809
1983.21	9.0283	-4.5013	-2.2621
1983.29	8.9471	-4.7646	-2.2928
1983.38	8.8200	-5.2902	-2.9917
1983.46	8.7915	-5.2036	-2.8261

1983.54	8.7655	-5.1312	-2.6596
1983.63	8.7849	-4.7305	-2.3640
1983.71	8.7886	-4.8032	-3.3719
1983.79	8.8281	-4.4046	-3.3855
1983.88	8.9286	-4.2109	-2.9227
1983.96	9.0552	-4.1553	-2.5791
1984.04	9.1419	-4.4534	-2.2510
1984.13	9.0780	-4.6822	-2.3981
1984.21	9.0295	-4.6880	-2.5526
1984.29	8.9932	-5.0560	-2.4602
1984.38	8.8270	-5.4866	-3.9593
1984.46	8.8049	-5.4893	-3.9172
1984.54	8.7417	-5.2681	-3.6401
1984.63	8.7448	-5.1953	-3.6263
1984.71	8.7816	-5.2036	-3.7493
1984.79	8.8184	-5.2120	-3.8722
1984.88	8.9225	-4.6662	-3.2180
1984.96	9.0072	-4.4236	-3.1250
1985.04	9.0769	-4.3952	-3.2210
1985.13	9.0576	-4.4112	-2.6518
1985.21	8.9889	-4.9707	-2.8254
1985.29	8.8660	-5.1073	-3.0991
1985.38	8.8267	-5.4206	-3.6703

1985.46	8.7698	-5.6538	-2.8905
1985.54	8.7254	-5.5433	-3.0268
1985.63	8.7336	-5.7147	-3.3201
1985.71	8.7726	-5.6178	-3.6218
1985.79	8.8081	-5.5227	-3.6871
1985.88	8.9194	-5.1291	-3.2961
1985.96	9.1073	-4.1783	-2.8660
1986.04	9.1708	-4.0221	-2.4970
1986.13	9.1607	-4.1644	-2.3553
1986.21	9.1175	-4.2443	-2.2756
1986.29	8.9386	-4.8020	-2.0956
1986.38	8.8580	-5.0341	-2.3841
1986.46	8.8357	-5.1812	-2.7754
1986.54	8.7800	-5.5324	-3.1181
1986.63	8.7755	-5.7999	-2.5888
1986.71	8.7944	-5.4535	-3.1028
1986.79	8.9111	-5.1777	-3.1579
1986.88	8.9824	-4.9157	-3.0614
1986.96	9.0085	-5.1979	-2.1553
1987.04	9.0279	-4.9544	-2.4338
1987.13	9.0470	-4.6855	-2.7697
1987.21	9.0246	-4.8342	-2.2740
1987.29	8.9079	-4.9291	-2.4699

1987.38	8.9042	-5.0837	-2.4233
1987.46	8.7547	-5.4415	-2.4526
1987.54	8.7266	-5.6279	-3.0956
1987.63	8.7358	-5.7197	-3.5197
1987.71	8.7412	-5.8062	-4.2584
1987.79	8.8107	-5.5630	-4.3558
1987.88	8.9246	-5.2242	-4.2009
1987.96	9.0333	-4.4521	-3.0212
1988.04	9.0864	-4.5286	-3.6451
1988.13	9.0469	-4.7214	-3.1996
1988.21	8.9736	-4.9468	-2.7852
1988.29	8.9093	-5.1104	-2.6345
1988.38	8.8018	-5.3534	-2.8586
1988.46	8.7649	-5.4043	-2.6172
1988.54	8.7481	-5.5730	-3.0116
1988.63	8.7663	-5.5252	-3.5667
1988.71	8.7635	-5.6558	-3.5545
1988.79	8.8078	-5.2884	-3.6796
1988.88	8.9152	-5.0696	-3.0355
1988.96	9.0174	-4.4117	-3.6450
1989.04	9.1060	-4.2057	-3.0664
1989.13	9.0832	-4.2960	-3.0823
1989.21	9.0543	-4.4067	-3.1100

1989.29	8.9417	-4.6309	-3.3191
1989.38	8.8446	-5.1632	-3.2956
1989.46	8.8058	-5.4284	-2.8744
1989.54	8.7693	-5.4426	-2.9497
1989.63	8.7994	-5.4722	-2.5454
1989.71	8.8216	-5.2122	-2.9576
1989.79	8.8465	-5.0798	-3.3160
1989.88	8.9663	-4.6206	-3.6653
1989.96	9.0524	-4.5757	-3.4680
1990.04	9.0887	-4.5084	-3.0443
1990.13	9.1727	-4.6193	-2.9167
1990.21	9.0381	-4.6575	-2.7040
1990.29	8.9659	-4.9976	-2.5172
1990.38	8.7948	-5.4474	-2.6227
1990.46	8.7503	-5.2809	-2.6738
1990.54	8.7456	-5.4924	-3.1001
1990.63	8.7594	-5.6846	-3.4113
1990.71	8.7948	-5.4677	-3.4772
1990.79	8.8476	-5.4279	-3.7583
1990.88	8.9129	-5.0807	-3.8747
1990.96	9.0509	-4.5308	-3.1402
1991.04	9.0555	-4.4653	-2.7256
1991.13	9.0453	-4.5257	-2.3690

1991.21	9.0354	-4.5669	-2.1275
1991.29	8.9711	-4.6591	-1.6182
1991.38	8.8394	-4.9311	-2.0962
1991.46	8.8396	-5.3148	-2.2710
1991.54	8.7641	-5.4326	-2.4872
1991.63	8.7869	-5.3984	-2.6575
1991.71	8.8175	-5.2941	-2.5371
1991.79	8.8911	-4.8744	-2.6929
1991.88	9.0331	-4.4970	-2.9759
1991.96	9.0330	-4.5223	-2.9808
1992.04	9.0348	-4.5178	-2.7584
1992.13	9.0627	-4.4199	-2.3074
1992.21	9.0386	-4.6777	-2.8470
1992.29	8.9614	-4.8863	-2.8222
1992.38	8.7965	-5.2734	-3.0886
1992.46	8.7470	-5.6563	-2.9964
1992.54	8.7032	-5.6632	-2.9781
1992.63	8.6903	-5.4961	-2.6538
1992.71	8.7813	-5.4463	-2.7516
1992.79	8.8281	-5.2509	-2.8373
1992.88	8.9591	-4.7755	-3.2886
1992.96	8.9798	-4.7513	-3.0973
1993.04	9.0005	-4.7272	-2.9060

1993.13	9.0140	-4.7179	-2.7336
1993.21	8.9990	-4.7895	-2.5992
1993.29	8.9305	-5.1082	-2.3510
1993.38	8.8150	-5.4055	-3.0092
1993.46	8.7716	-5.6598	-2.8780
1993.54	8.6932	-5.6855	-3.7548
1993.63	8.7270	-5.4900	-3.4715
1993.71	8.7591	-5.4180	-3.2749
1993.79	8.8347	-5.3445	-3.9555
1993.88	8.9635	-4.5655	-3.6997
1993.96	9.1117	-4.3141	-3.0040
1994.04	9.0984	-4.4524	-2.7616
1994.13	9.0366	-4.8305	-2.8891
1994.21	8.9505	-4.9555	-2.8698
1994.29	8.8670	-5.2203	-3.2546
1994.38	8.7889	-5.4913	-3.4419
1994.46	8.7525	-5.4494	-3.3158
1994.54	8.7234	-5.4280	-3.1873
1994.63	8.7800	-5.5360	-3.2271
1994.71	8.7921	-5.2167	-2.5519
1994.79	8.8157	-5.3051	-4.3357
1994.88	8.9353	-5.0871	-3.5997
1994.96	8.9955	-4.4560	-3.8757

1995.04	9.0111	-4.4950	-3.3319
1995.13	9.0643	-4.7549	-3.2772
1995.21	9.0244	-4.8335	-3.6716
1995.29	8.9033	-5.5386	-3.6184
1995.38	8.8108	-5.5133	-3.5951
1995.46	8.7774	-5.5672	-2.9174
1995.54	8.7460	-5.7501	-2.7593
1995.63	8.7590	-5.6722	-3.5418
1995.71	8.7763	-5.6114	-3.5369
1995.79	8.8163	-5.6213	-4.6360
1995.88	8.8819	-4.7624	-3.4630
1995.96	9.0216	-4.0930	-3.9504
1996.04	9.0770	-4.2751	-3.8456
1996.13	9.1020	-4.6009	-4.1328
1996.21	9.0654	-4.5320	-3.6507
1996.29	8.9822	-4.8356	-2.5451
1996.38	8.8242	-5.1978	-2.9085
1996.46	8.7651	-5.7097	-3.3135
1996.54	8.7628	-5.2782	-3.6383
1996.63	8.7552	-5.4342	-4.1083
1996.71	8.7643	-5.2561	-4.2466
1996.79	8.8090	-5.1818	-4.3166
1996.88	8.9117	-4.5772	-4.2962

1996.96	8.9154	-4.6718	-4.3940
1997.04	8.9479	-4.5702	-4.5540
1997.13	8.9764	-4.4225	-4.7888
1997.21	8.9476	-4.5519	-3.6695
1997.29	8.8710	-5.0400	-2.6896
1997.38	8.7951	-5.1381	-2.7239
1997.46	8.8199	-5.4637	-4.0689
1997.54	8.7284	-5.7091	-4.1447
1997.63	8.7194	-5.5246	-4.4531
1997.71	8.7511	-5.3711	-4.7676
1997.79	8.7829	-5.2175	-5.0822
1997.88	8.8472	-4.9947	-4.9484
1997.96	8.9440	-4.7028	-4.3679
1998.04	9.0120	-4.7270	-3.1349
1998.13	8.9607	-4.8773	-2.8178
1998.21	8.9524	-5.1323	-2.7161
1998.29	8.8604	-5.2025	-2.6224
1998.38	8.7694	-5.4431	-3.2663
1998.46	8.7441	-5.7349	-3.8505
1998.54	8.7181	-5.9595	-3.9476
1998.63	8.7177	-5.9201	-4.0733
1998.71	8.7341	-5.7319	-4.1648
1998.79	8.7709	-5.5435	-3.8463

1998.88	8.8504	-5.0620	-3.3613
1998.96	8.9465	-4.4285	-3.6734
1999.04	9.0521	-4.5340	-3.0333
1999.13	8.9900	-4.7433	-2.6204
1999.21	8.9554	-4.8035	-2.3344
1999.29	8.9207	-5.0960	-2.5965
1999.38	8.8398	-5.2378	-2.6584
1999.46	8.7581	-5.9653	-2.7406
1999.54	8.7395	-6.0160	-2.8214
1999.63	8.7651	-5.5092	-2.9597
1999.71	8.7641	-5.5313	-2.3169
1999.79	8.7909	-5.4458	-2.3296
1999.88	8.8395	-5.2411	-3.1808
1999.96	8.9721	-4.7713	-3.1191
2000.04	9.0196	-4.4134	-3.9375
2000.13	9.0385	-4.8660	-3.9746
2000.21	8.9656	-5.0153	-3.8638
2000.29	8.9177	-4.9646	-3.6951
2000.38	8.8280	-5.1393	-3.4947
2000.46	8.7130	-5.0769	-3.5762
2000.54	8.7391	-5.8675	-3.4752
2000.63	8.7364	-5.8488	-2.8827
2000.71	8.7425	-5.6151	-3.6517

2000.79	8.7822	-5.1149	-3.6437
2000.88	8.8633	-4.9282	-4.0321
2000.96	8.9803	-4.7362	-3.6445
2001.04	8.9932	-4.7146	-2.8058
2001.13	8.9635	-4.8735	-2.9195
2001.21	8.9542	-5.0609	-3.4541
2001.29	8.8070	-5.0166	-3.0846
2001.38	8.7216	-5.2242	-3.8008
2001.46	8.6715	-5.4299	-2.7311
2001.54	8.6822	-5.3160	-3.7092
2001.63	8.6697	-5.2318	-3.5656
2001.71	8.7028	-5.0679	-3.9202
2001.79	8.7640	-5.1647	-3.9173
2001.88	8.8821	-4.6431	-3.5567
2001.96	9.0007	-4.0537	-3.6827
2002.04	9.0056	-4.5995	-3.3885
2002.13	9.0253	-4.4541	-3.3775
2002.21	8.9841	-4.5406	-2.9614
2002.29	8.8402	-4.7783	-2.9861
2002.38	8.7616	-4.7603	-2.7586
2002.46	8.7217	-4.9127	-2.8372
2002.54	8.6784	-5.0949	-2.9777
2002.63	8.7236	-5.4702	-3.5264

2002.71	8.7434	-4.8771	-3.3671
2002.79	8.7653	-4.9675	-3.4181
2002.88	8.8517	-4.9843	-3.6149
2002.96	8.9263	-4.8290	-3.6096
2003.04	8.9852	-4.4811	-3.4608
2003.13	8.9508	-4.6767	-2.6901
2003.21	8.9398	-4.6821	-2.7312
2003.29	8.9045	-4.7420	-2.7409
2003.38	8.8067	-4.6863	-2.2403
2003.46	8.7909	-5.3595	-2.4103
2003.54	8.6984	-5.5013	-3.1931
2003.63	8.7062	-5.4217	-3.4272
2003.71	8.7830	-5.2569	-3.5688
2003.79	8.8348	-5.0070	-3.6980
2003.88	8.8744	-4.8744	-3.7411
2003.96	9.0234	-4.5683	-3.7817
2004.04	9.1079	-4.4128	-3.9409
2004.13	9.1335	-4.4554	-3.5183
2004.21	9.0372	-4.4080	-2.9572
2004.29	8.8632	-4.7730	-2.1320
2004.38	8.7352	-5.4971	-2.8818
2004.46	8.7752	-5.2124	-2.6146
2004.54	8.7743	-5.5643	-3.2542

2004.63	8.7238	-5.3141	-3.1865
2004.71	8.7681	-4.9659	-3.1430
2004.79	8.8727	-4.9494	-3.3781
2004.88	8.9356	-4.0226	-3.2750
2004.96	9.0327	-4.2294	-3.9092
2005.04	9.1445	-4.2492	-3.1116
2005.13	9.1013	-4.2155	-3.1283
2005.21	9.0129	-4.7594	-2.8494
2005.29	8.8831	-4.8127	-2.8156
2005.38	8.8022	-5.0552	-3.2902
2005.46	8.7964	-5.3090	-3.2237
2005.54	8.7783	-5.3795	-3.1164
2005.63	8.7998	-5.4009	-2.6971
2005.71	8.7755	-5.4200	-3.1668
2005.79	8.8151	-5.3970	-3.0406
2005.88	8.8715	-5.1138	-3.4970
2005.96	8.9900	-4.3500	-3.6890
2006.04	9.0456	-4.6885	-3.1623
2006.13	9.0000	-5.0278	-2.8340
2006.21	8.9152	-4.7067	-2.3420
2006.29	8.8810	-4.7399	-2.6188
2006.38	8.7688	-5.1908	-2.9427
2006.46	8.6848	-5.4475	-3.3748

2006.54	8.6450	-5.3904	-3.4042
2006.63	8.6795	-5.3181	-3.4316
2006.71	8.7144	-5.2185	-3.4064
2006.79	8.8002	-5.2324	-3.5060
2006.88	8.8693	-4.7668	-3.8031
2006.96	8.9806	-4.5992	-4.2424
2007.04	8.9787	-4.5568	-2.6748
2007.13	8.9627	-4.6771	-2.8671
2007.21	8.9626	-5.5117	-4.3221
2007.29	8.9161	-5.1961	-3.2371
2007.38	8.8241	-5.0148	-2.6811
2007.46	8.7152	-5.2779	-3.2785
2007.54	8.6391	-5.6103	-3.0661
2007.63	8.6693	-5.4350	-2.9606
2007.71	8.7530	-5.2991	-3.5860
2007.79	8.8009	-5.2201	-3.6519
2007.88	8.8633	-5.1367	-3.5818
2007.96	9.0057	-5.0143	-3.4790
2008.04	8.9713	-4.7658	-3.4731
2008.13	9.0144	-5.0848	-2.8280
2008.21	8.9547	-5.3511	-2.3729
2008.29	8.8296	-5.3620	-2.6464
2008.38	8.7950	-5.7093	-2.9076

2008.46	8.7346	-5.8784	-2.8970
2008.54	8.7523	-5.8609	-3.1441
2008.63	8.7806	-5.8002	-3.4543
2008.71	8.7789	-5.7524	-3.3048
2008.79	8.7737	-5.7061	-3.1032
2008.88	8.8378	-5.2710	-3.3593
2008.96	8.9337	-4.6834	-3.2949
2009.04	9.0072	-4.8306	-3.1529
2009.13	8.9889	-4.7394	-3.3518
2009.21	8.9680	-4.6411	-3.5904
2009.29	8.9084	-4.9736	-3.1711
2009.38	8.7971	-5.4243	-2.8563
2009.46	8.7490	-5.3519	-2.8647
2009.54	8.6878	-5.7517	-2.9402
2009.63	8.6518	-5.7136	-4.5168
2009.71	8.6383	-5.4626	-3.8802
2009.79	8.8492	-4.9989	-3.4108
2009.88	8.9454	-4.8030	-3.7708
2009.96	9.0084	-4.6017	-3.6654
2010.04	9.0172	-4.6185	-2.7492
2010.13	9.0165	-4.8953	-2.9928
2010.21	8.9943	-4.9206	-3.2680
2010.29	8.9368	-4.8885	-3.1183

2010.38	8.7932	-5.2778	-3.7698
2010.46	8.7598	-5.4353	-3.1092
2010.54	8.6593	-5.8060	-3.9061
2010.63	8.6238	-6.0093	-4.6269
2010.71	8.6965	-5.6768	-4.1197
2010.79	8.7546	-5.4654	-4.0255
2010.88	8.8884	-5.1348	-3.5005
2010.96	8.9571	-4.9083	-3.3898
2011.04	9.0148	-4.7206	-3.8592
2011.13	9.0492	-4.6644	-3.7708
2011.21	9.0411	-4.6613	-3.4477
2011.29	9.0119	-4.3952	-3.0479
2011.38	8.8548	-5.2580	-2.9565
2011.46	8.7101	-5.7354	-3.2986
2011.54	8.7271	-5.8960	-3.3819
2011.63	8.6889	-5.7476	-3.9472
2011.71	8.7389	-5.6138	-4.0652
2011.79	8.8171	-5.2959	-3.8118
2011.88	8.8551	-4.6712	-4.3918
2011.96	8.9854	-4.6604	-4.0597
2012.04	9.0657	-4.8378	-3.2766
2012.13	9.0214	-5.2623	-3.4031
2012.21	8.9377	-5.2151	-2.9731

2012.29	8.8684	-5.3206	-2.9629
2012.38	8.6901	-5.6336	-2.8173
2012.46	8.7790	-6.0461	-3.0554
2012.54	8.7148	-5.4543	-3.4853
2012.63	8.7411	-5.4907	-3.4657
2012.71	8.7839	-5.3988	-3.3558
2012.79	8.8814	-5.2022	-3.6149
2012.88	8.8938	-5.1796	-3.1424
2012.96	8.9085	-5.2032	-3.1710
2013.04	8.9151	-5.1814	-3.2023
2013.13	8.9151	-5.1218	-3.2357
2013.21	8.9100	-5.1490	-3.2094
2013.29	8.8852	-5.1906	-3.1706
2013.38	8.8496	-5.2643	-2.6875

Table B2.2 Houbihu dry-season stable isotope data (1788 to 1905).

Date	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
1788	-4.4348	-1.8682
1789	-4.3990	-1.2245
1790	-4.5566	-1.8159
1791	-4.2952	-1.3408

1792	-4.3334	-1.4907
1793	-4.3663	-1.4254
1794	-4.3314	-1.1586
1795	-4.3447	-1.0391
1796	-4.0066	-1.2245
1797	-4.5398	-1.5177
1798	-4.4146	-1.1431
1799	-4.5958	-1.4514
1800	-4.0205	-1.2440
1801	-4.0764	-1.6633
1802	-4.5400	-1.2850
1803	-4.4609	-1.4861
1804	-3.9364	-1.7923
1805	-4.0618	-2.5644
1806	-4.2722	-2.5609
1807	-4.1710	-2.2964
1808	-4.3825	-2.2686
1809	-4.1838	-1.8181
1810	-4.3453	-1.8482
1811	-4.5678	-1.1279
1812	-3.9146	-1.7891
1813	-4.4000	-1.6779
1814	-4.6950	-1.2867

1815	-4.2802	-1.5579
1816	-3.8987	-1.4218
1817	-4.1051	-1.2191
1818	-4.4078	-1.8016
1819	-4.4967	-1.6759
1820	-4.1700	-1.8044
1821	-4.6151	-0.8912
1822	-4.2506	-1.4099
1823	-4.2370	-1.5433
1824	-4.3074	-1.5125
1825	-4.5460	-2.1407
1826	-4.5672	-1.6001
1827	-4.6605	-1.3456
1828	-4.6258	-1.4618
1829	-4.4217	-2.1165
1830	-4.3537	-0.9479
1831	-3.8066	-0.9388
1832	-4.5738	-1.2231
1833	-4.3861	-0.8655
1834	-3.9445	-1.1606
1835	-4.0437	-1.5362
1836	-3.7719	-1.3567
1837	-3.9777	-1.6824

1838	-3.7457	-1.3905
1839	-4.1307	-1.4979
1840	-4.4161	-2.5727
1841	-4.4692	-2.6161
1842	-4.5961	-1.9700
1843	-4.7600	-2.5278
1844	-4.6037	-1.3547
1845	-4.5078	-1.4409
1846	-4.7567	-0.7602
1847	-4.5128	-1.9584
1848	-4.3754	-1.0797
1849	-4.2585	-1.4457
1850	-4.5700	-1.1534
1851	-4.3517	-1.0532
1852	-4.5415	-1.1259
1853	-4.2219	-1.7792
1854	-4.3122	-1.6028
1855	-4.7142	-1.4097
1856	-4.6022	-1.0504
1857	-4.8019	-1.6318
1858	-4.8281	-1.4256
1859	-4.5905	-1.4309
1860	-4.6098	-1.2863

1861	-4.3869	-1.4179
1862	-3.9629	-0.9759
1863	-4.3464	-0.4900
1864		
1865	-4.4480	-1.2613
1866	-4.4698	-0.9000
1867	-4.3063	-1.4748
1868	-4.3779	-1.6027
1869	-4.3713	-1.4571
1870	-4.0173	-1.0159
1871	-4.3411	-1.0620
1872	-4.4391	-1.4348
1873	-4.4194	-2.0505
1874	-4.1091	-1.4263
1875	-4.0987	-1.5964
1876	-4.4061	-1.2086
1877	-4.3614	-1.5716
1878	-4.7057	-1.5506
1879	-4.1344	-2.1124
1880	-4.7057	-1.5506
1881		
1882	-4.3464	-3.0645
1883	-4.3448	-2.3172

1884	-4.2969	-2.5920
1885	-4.5663	-1.6049
1886		
1887	-4.4933	-2.4375
1888	-4.6651	-2.0813
1889	-4.4265	-2.8711
1890	-4.3279	-1.4789
1891	-4.4489	-2.2339
1892		
1893	-4.3577	-2.4965
1894	-4.4686	-2.3679
1895	-4.4028	-1.9370
1896	-4.7076	-2.2280
1897	-4.8580	-2.5639
1898	-4.5792	-2.3453
1899	-4.6510	-3.0125
1900	-4.5206	-1.7811
1901	-4.3732	-1.9030
1902	-4.7616	-1.3564
1903	-4.5133	-1.8894
1904	-4.6429	-2.1611
1905	-4.6023	-1.3131

Table B2.3. Houbihu $\Delta^{14}\text{C}$ data

Year	Houbihu $\Delta^{14}\text{C}$, ‰	$\pm 1\sigma$, ‰
1942	-60.92	1.62
1943		
1944		
1945	-64.85	1.61
1946		
1947		
1948		
1949		
1950	-62.11	1.62
1951		
1952		
1953	-67.89	2.58
1953.2	-65.27	1.43
1953.4	-63.15	1.72
1953.6	-67.99	6.21
1953.8	-64.24	1.77
1954	-68.50	1.64
1954.25	-61.38	1.90

1954.5	-47.43	1.76
1954.75	-34.17	1.31
1955	-32.37	1.31
1955.2	-26.13	1.32
1955.4	-20.71	1.45
1955.6	-19.57	1.33
1955.8	-22.28	1.61
1956	-25.21	1.32
1956.142857	-28.79	1.74
1956.285714	-28.14	1.26
1956.428571	-30.26	1.26
1956.571429	-35.12	1.27
1956.714286	-38.61	1.64
1956.857143	-41.84	1.41
1957	-40.81	1.25
1957.166667	-41.92	1.31
1957.333333	-40.91	1.35
1958		
1958.666667	-35.66	1.35
1958.833333	-32.25	1.55
1959	-29.41	1.81
1959.166667	-24.81	1.38
1959.333333	-23.62	1.57

1959.5	-19.30	1.38
1960		
1961	-12.00	1.46
1961.166667	-7.96	1.40
1961.333333	-9.40	1.60
1961.5	-8.29	1.34
1961.666667	-4.94	1.35
1961.833333	-3.33	1.55
1962		
1963		
1964	57.27	1.90
1964.25	72.06	1.54
1964.5	75.96	1.54
1964.75	80.66	1.69
1965	79.16	1.61
1965.166667	80.64	2.05
1966		
1967		
1968		
1969		
1970	140.42	2.48
1971	144.78	1.71
1971.25	140.64	2.19

1971.5	143.31	1.80
1971.75	138.63	1.64
1972	148.14	1.71
1972.166667	144.64	1.63
1972.333333	146.56	1.63
1972.5	143.78	1.89
1972.666667	139.19	1.63
1972.833333	135.27	1.52
1973	144.68	1.70
1973.2	142.22	1.79
1973.4	136.96	1.69
1973.6	137.80	1.84
1973.8	135.31	1.70
1974	134.91	1.71
1975	147.15	2.44
1975.166667	151.36	1.65
1975.333333	150.19	1.96
1975.5	146.45	2.06
1975.666667	143.27	1.78
1975.833333	145.19	1.68
1976	145.24	2.49
1977	143.71	2.38
1978	132.90	2.54

1979	147.61	2.39
1980	124.28	2.42
1981	139.33	1.89
1981.142857	145.62	2.41
1981.285714	134.57	1.63
1981.428571	132.59	1.62
1981.571429	131.43	1.62
1981.714286	133.93	1.63
1981.857143	136.70	1.71
1982	139.45	1.71
1982.2	138.61	1.97
1982.4	138.33	1.63
1982.6	132.17	1.62
1982.8	133.99	1.63
1983	131.13	1.64
1983.2	127.59	2.31
1983.4	129.37	1.71
1983.6	129.74	1.63
1983.8	122.80	1.62
1984	121.96	1.62
1984.142857	124.21	1.62
1984.285714	122.51	1.69
1984.428571	125.16	2.16

1984.571429	122.71	1.84
1984.714286	125.97	1.99
1984.857143	126.20	1.66
1985	127.69	1.43
1986	125.70	1.64
1987	122.67	1.43
1988	113.09	1.43
1989	115.17	1.41
1990	108.04	1.43
1991	108.58	1.40
1992	103.59	1.41
1993	99.70	1.40
1994	97.75	1.39
1995	92.65	1.39
1996	90.93	1.39
1996.833333	92.11	1.55
1997	94.42	1.63
1997.166667	92.74	1.62
1997.333333	90.64	1.62
1997.5	91.61	1.62
1997.666667	91.10	1.62
1997.833333	85.68	1.61
1998	84.99	1.61

1998.2	86.03	1.61
1998.4	82.87	1.78
1998.6	81.53	1.79
1998.8	83.20	1.61
1999	79.88	1.38
2000	79.25	1.35
2001	76.06	1.35
2002	73.95	1.49
2003	70.95	1.64
2004	64.96	1.34
2005	62.31	1.78
2006	59.17	1.33
2007	56.86	1.66
2008	51.64	1.32
2009	57.18	1.52
2009.166667	53.10	1.51
2009.333333	54.14	1.58
2009.5	48.52	1.71
2009.666667	53.57	1.64
2009.833333	51.48	1.50
2010	50.24	1.50
2010.166667	53.45	1.63
2010.333333	46.50	2.06

2010.5	45.58	1.78
2010.666667	43.39	2.00
2010.833333	48.00	2.01
2011	43.20	1.31
2012	42.99	1.31

Appendix C

Data evaluation

C1. Sr/Ca long-term drift correction

Strontium and calcium are simultaneously measured on an inductively coupled plasma – optical emission spectrometer (ICP-OES). Solution standards (i.e. 0 to 80 ppm) were routinely measured to correct for instrumental drift and matrix effects from varying calcium concentrations (Schrag, 1999). Powder standards (i.e. JCp-1, Okai et al., 2001 and an in-house *Porites* sp. powder) were also analyzed to evaluate measurement precision.

From September 2013 to February 2016, a day-to day offset was observed in the daily averages of JCp-1 and in-house powder standard Sr/Ca relative to their long-term averages (Table C1.1 and Fig. C1.1).

Figure C1.1. (a) Individual JCp-1 measurements (hollow circles) and their daily average (blue circles). (b) Same as (a) but for in-house powder standard. Red lines indicate the long-term average for each powder standard.

Table C1.1. Average JCp-1 and in-house standards before and after offset corrections.

	JCp-1		In-house standard	
	Before Correction	After Correction	Before Correction	After Correction
Average	0.019315	0.019315	0.019311	0.019311
SD	0.000067	0.000050	0.000077	0.000065
RSD %	0.35	0.26	0.40	0.34
N	2125	2125	1219	1219

The offsets were calculated as follows:

$$\text{Sr/Ca offset}_{\text{JCp-1}} = \text{JCp-1}_{\text{daily_avg}} - \text{JCp-1}_{\text{longterm_avg}} \quad (\text{C1.1})$$

$$\text{Sr/Ca offset}_{\text{in-house}} = \text{In-house Std}_{\text{daily_avg}} - \text{In-house Std}_{\text{longterm_avg}} \quad (\text{C1.2})$$

The resultant offset values between JCp-1 and in-house standard reveal a significant relationship with a slope almost equal to 1.0 (i.e. 0.9021, Eqn. C1.3 and Fig. C1.2), indicating that this offset is systematic and can be corrected.

$$\text{Sr/Ca offset}_{\text{in-house}} = 0.9021 * \text{Sr/Ca offset}_{\text{JCp-1}} - 2e^{-7} \quad (\text{C1.3})$$

$$r = 0.74, p < 0.0001, n = 157$$

Figure C1.2. Daily JCp-1 offset values plotted against daily in-house standard offset values.

The Sr/Ca offset correction was done by subtracting the JCp-1 offset values (C1.1) per day from the individual JCp-1 standards, in-house standards and unknown samples run each day during this period. Both the corrected JCp-1

and in-house standard values yielded lower standard deviations (Table C1.1, Fig. C1.3). This correction was applied on the Sr/Ca data reported in Chapter 2.

Figure C1.3. Offset corrected (a) JCp-1 and (b) in-house powder standards. Red lines indicate the long-term average for each standard.

Beyond this period, no significant day-to-day offsets were observed potentially due to the improved method optimization on the ICP-OES and exchange of the type of spray chamber. Figure C1.4 shows the powder standards run each day including their daily averages compiled for continuous monitoring. Repeat measurements of JCp-1 and in-house powder standard analyzed over a period of two years showed good reproducibility, $0.019291 (\pm 0.00004)$ ppm (1σ , RSD = 0.18%, $n = 1074$) and $0.019289 (\pm 0.00005)$ ppm (1σ , RSD = 0.25%, $n = 396$), respectively. Results in Chapters 3 and 4 benefited from this data evaluation.

Figure C1.4. (a) JCp-1 measurements per day (hollow circles) and their daily averages (red circles) over a 2-year period (i.e. 2016 to 2018). (b) Same as (a) but for in-house powder standard. Blue lines indicate long-term average for each powder standard.

C2. Evaluating $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data and small sample size correction

Stable isotopes oxygen and carbon, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, were measured using an isotope ratio mass spectrometer (IRMS). Evaluation of these measurements were based on four carbonate powder standards with the following known values (i.e. relative to Vienna Pee Dee Belemnite): Estremoz ($\delta^{18}\text{O}$: $-5.95 \pm 0.07\text{‰}$ and $\delta^{13}\text{C}$: $1.63 \pm 0.04\text{‰}$), Carrara ($\delta^{18}\text{O}$: $-1.96 \pm 0.07\text{‰}$ and $\delta^{13}\text{C}$: $2.08 \pm 0.07\text{‰}$), TSF ($\delta^{18}\text{O}$: -2.23‰ and $\delta^{13}\text{C}$: 1.95‰) and NBS-19 ($\delta^{18}\text{O}$: $-2.20 \pm 0.05\text{‰}$ and $\delta^{13}\text{C}$: 1.95‰) (Table C2.1). Individual measurements of the above standards are considered valid when standard deviation is < 0.10 , sample/standard voltage is < 0.20 (i.e. balanced) and sample size is > 500 mV. This criterion is likewise applied on the unknown samples.

A separate method was optimized (i.e. reduced reference gas pressure) for analyzing and calibrating small samples with source pressure voltage ~ 800 mV (e.g. Ostermann and Curry, 2000). However, reduced sample voltage may result to analytical instabilities, impacting the isotopic measurements. Small samples were then evaluated against measurements of small powder standards. The above criterion is similarly applied for these samples, particularly excluding samples with < 500 mV for evaluating size effects.

Figure C2.1 shows the small standard samples analyzed between June 2014 and December 2015. Estremoz, Carrara and TSF $\delta^{18}\text{O}$ anomalies show standard deviations of 0.09‰ ($n = 27$), 0.07‰ ($n = 5$), and 0.05‰ ($n = 13$), respectively. Collectively, the standard deviation is equivalent to 0.08‰ . Between 500 and 1500 mV, $\delta^{18}\text{O}$ anomalies show a linear decrease with increasing sample voltage (Fig. C2.1d, upper panel), indicating a significant size effect at this voltage range. A linear regression is obtained:

$$\begin{aligned} \delta^{18}\text{O anomaly} &= -0.0001 (\pm 0.00005) * (\text{sample voltage, mV}) + 0.2 (\pm 0.05) \\ r &= -0.50, p = 0.009, n = 26; \end{aligned} \tag{C2.1}$$

and applied on standard samples between 500 to 1500 mV to correct for size effects ($n = 26$). Predicted $\delta^{18}\text{O}$ anomaly is calculated using Eqn. C2.1 and subsequently added on the $\delta^{18}\text{O}$ values. This size-correction improved the overall standard deviation from 0.08‰ to 0.06‰ (Fig. C2.1).

Estremoz, Carrara and TSF $\delta^{13}\text{C}$ anomalies, on the other hand, do not exhibit size effects but rather a systematic offset towards more positive $\delta^{13}\text{C}$ values. To correct for this offset, a mean offset value of 0.07‰ calculated from the combined $\delta^{13}\text{C}$ data ($1\sigma = 0.03\text{‰}$, Fig. C2.1d, lower panel) is subtracted from all the individual $\delta^{13}\text{C}$ values (Fig. C2.1). Compared with the normal method (i.e. 40 to 90 ug samples) run over the same time period (Fig. C2.2), the above corrections successfully removed size effects and systematic offsets, collectively improving analytical precision (Table C2.1). The above corrections were similarly applied to small $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ samples reported in Chapter 2.

Table C2.1. Summary of isotopic correction results.

Isotopic composition	Powder standard	Known values		Initial analytical precision, ‰ (<i>n</i>)	Analytical precision	
					After data evaluation and size-correction	After offset correction
$\delta^{18}\text{O}$	Estremoz	-5.95 ± 0.07	±	-5.883 ± 0.093 (27)	-5.912 ± 0.056 (27)	
	Carrara	-1.96 ± 0.07	±	-1.817 ± 0.071 (5)	-1.871 ± 0.047 (5)	
	TSF	-2.23		-2.214 ± 0.053 (13)	-2.223 ± 0.049 (13)	
$\delta^{13}\text{C}$	Estremoz	1.63 ± 0.04	±	1.693 ± 0.036 (27)		1.624 ± 0.036 (27)
	Carrara	2.08 ± 0.02	±	2.144 ± 0.020 (5)		2.075 ± 0.020 (5)
	TSF	1.95		2.033 ± 0.015 (13)		1.963 ± 0.015 (13)

Figure C2.1. Upper panel: (a) Estremoz, (b) Carrara, (c) TSF and (d) combined standards $\delta^{18}\text{O}$ anomalies (hollow circles) plotted against sample voltage to evaluate size effects. Colored circles plot all data points after sample correction. Lower panel: same as upper panel but for $\delta^{13}\text{C}$ anomalies.

Figure C2.2. (a) $\delta^{18}\text{O}$ and (b) $\delta^{13}\text{C}$ anomalies of all standards run on small (colored circles) and normal (hollow) methods.

C3. References

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Appendix D

Supplementary Information

D1. Supplementary Information for Chapter 2

This supporting information includes a summary of the inter-annual calibrations and associated reconstruction errors and additional figures that were useful in the direction of data analysis as described in the main text. Additional tables were prepared to make the above data comparisons clearer. Table D1.2 summarizes other available paired *Diploastrea-Porites* proxy calibration studies.

D1.1 Inter-annual calibrations and reconstruction errors

Diploastrea and *Porites* mean annual and winter Sr/Ca are significantly correlated with SST:

$$\begin{aligned} \text{Diploastrea}_{\text{Annual}} \text{ Sr/Ca} &= 10.204 (\pm 0.528) - 0.045 (\pm 0.189) * \text{SST } (^{\circ}\text{C}) \\ r &= 0.38, p = 0.03, n = 31 \end{aligned} \quad (\text{D1.1})$$

$$\begin{aligned} \text{Porites}_{\text{Annual}} \text{ Sr/Ca} &= 10.237 (\pm 0.350) - 0.049 (\pm 0.012) * \text{SST } (^{\circ}\text{C}) \\ r &= 0.59, p = 0.0004, n = 31 \end{aligned} \quad (\text{D1.2})$$

$$\text{Diploastrea}_{\text{Winter}} \text{ Sr/Ca} = 10.091 (\pm 0.443) - 0.036 (\pm 0.017) * \text{SST } (^{\circ}\text{C})$$

$$r = 0.38, p = 0.04, n = 30 \quad (D1.3)$$

$$Porites_{Winter} Sr/Ca = 10.340 (\pm 0.404) - 0.051 (\pm 0.015) * SST (^{\circ}C)$$

$$r = 0.54, p = 0.0023, n = 30 \quad (D1.4)$$

and only *Porites* summer Sr/Ca shows a significant relationship with SST:

$$Porites_{Summer} Sr/Ca = 10.455 (\pm 0.508) - 0.057 (\pm 0.017) * SST (^{\circ}C)$$

$$r = 0.53, p = 0.002, n = 30 \quad (D1.5)$$

We applied these calibration equations (D1.1 to D1.4) to derive annual and winter Sr/Ca-SST relationships. Using the annual calibration equations, the RMSRs are 1.33°C and 1.16°C for winter *Diploastrea* and *Porites*, respectively. Similarly, using the winter calibration equations, RMSRs are 1.26°C and 0.8°C for *Diploastrea* and *Porites*. In all instances, these reconstruction errors are higher than when applying the monthly calibrations (Equations 2.1 and 2.2 in Chapter 2). The equations above have less steep slopes, which may reflect the limited inter-annual SST variability at our site (mean annual SST range ~ 1.3°C). Nonetheless, we are capturing inter-annual variability as shown by the significant relationships above. To best minimize the reconstruction errors, we used the monthly calibrations in reconstructing winter SSTs, which resulted in a higher signal to noise ratio.

Figure D1.1. *Diploastrea* (blue) and *Porites* (red) monthly $\delta^{18}\text{O}_c$ are (a) negatively correlated with SST, (b) positively correlated with SSS (c) and paired Sr/Ca.

Table D1.1. Summary of the regression coefficients between *Diploastrea* and *Porites* $\delta^{18}\text{O}_c$ and instrumental data for the wet and dry seasons over the calibration period. Bold numbers represent significant relationships ($p < 0.05$).

	Wet Season			Dry Season		
	SST	SSS	Sr/Ca	SST	SSS	Sr/Ca
<i>Diploastrea</i> $\delta^{18}\text{O}_c$	-0.24	-0.04	0.46	-0.01	0.15	0.08
<i>Porites</i> $\delta^{18}\text{O}_c$	0.16	-0.60	-0.08	-0.58	0.48	0.13

Figure D1.2. (a.1 to a.3) Wet *Diploastrea* $\delta^{18}\text{O}_c$ is neither correlated to wet SST ($r = 0.24$, $p = 0.20$) nor wet SSS ($r = 0.03$, $p = 0.85$) but is significantly correlated to its Sr/Ca pair ($r = 0.46$, $p = 0.01$). (a.4 to a.6) Dry *Diploastrea* $\delta^{18}\text{O}_c$ is not correlated to SST and SSS, and to its Sr/Ca counterpart ($r < 0.15$, $p > 0.50$). (b.1 to b.3) Wet *Porites* $\delta^{18}\text{O}_c$ is strongly correlated to SSS ($r = 0.60$, $p = 0.0006$) but not with wet SST and its Sr/Ca pair ($p > 0.40$). (b.4 to b.6) Dry *Porites* $\delta^{18}\text{O}_c$ is both significantly correlated with dry SST ($r = -0.58$, $p = 0.0002$) and SSS ($r = 0.48$, $p = 0.01$) but not with its Sr/Ca pair ($p > 0.20$).

Table D1.2. Summary of other paired *Diploastrea-Porites* proxy calibration studies compared with this study.

Proxy	Source	Study Site	Coral species	y-intercept, <i>b</i>	slope, <i>m</i>	SST dataset	<i>r</i> ²	Monthly SST range (°C)
Sr/Ca	Correge al., 2004	Alor, Indonesia/ New Caledonia	<i>Diploastrea helioporea</i> *	10.57	-0.06	IGOSS (~10 km away/ local SST)	not reported	22 to 30
			<i>Porites</i> sp.	10.51	-0.062	IGOSS (~10 km away/ local SST)	not reported	22 to 30
	Bagnato al., 2004	Savusavu Bay, Fiji Islands	<i>Diploastrea helioporea</i> **	10.08	-0.034	CACSST	0.71	25 to 29
			<i>Porites lutea</i>	10.76	-0.054	CACSST	not reported	25 to 29
	This Study	Palaui Island, Philippines	<i>Diploastrea helioporea</i> *	10.66	-0.057	IGOSS (~30 km away)	0.74	24.6 to 30.5
			<i>Porites lobata</i>	10.79	-0.068	IGOSS (~30 km away)	0.84	24.6 to 30.5
$\delta^{18}\text{O}$	Watanabe al., 2003	Alor, Indonesia/ New Caledonia	<i>Diploastrea helioporea</i> *	-0.23	-0.18	<i>In-situ</i> (New Caledonia)	0.88	25 to 29
			<i>Porites</i> sp.	not reported	-0.19	<i>In-situ</i> (New Caledonia)	not reported	25 to 29
	Bagnato al., 2004	Savusavu Bay, Fiji Islands	<i>Diploastrea helioporea</i> *	-0.26	-0.16	CACSST	0.88	25 to 29
			<i>Porites</i> sp.	not reported	-0.18	CACSST		25 to 29
	Damassa al., 2006	Mafia, Tanzania	<i>Diploastrea helioporea</i> *	not reported	-0.22	ERSST	0.26	25 to 29
	Dassie and Linsley, 2015	Kandavu, Fiji Islands	<i>Diploastrea helioporea</i> *	not reported	-0.17	ERSST	0.55	25 to 29
			<i>Porites</i> sp.	not reported	-0.19	ERSST	0.68	25 to 29

This study	Palaui Island, Philippines	<i>Diploastrea helioporea</i> *	-0.183	-0.159	IGOSS (~30 km away)	0.38	24.6 to 30.5
		<i>Porites lobata</i>	-0.907	-0.143	IGOSS (~30 km away)	0.44	24.6 to 30.5

*sampled along the *columella*

**sampled along the *septa*

D2. Supplementary Information for Chapter 3

This supporting information includes additional spectral analysis results between Palaui winter SST and Niño 3.4 (Fig. D2.1) and Palaui summer SST and the PDO, Niño 3.4 and the EAWM (Fig. D2.2).

Figure D2.1. (a) Spectral analysis of Niño 3.4 and (b) coherence with phase analysis between the Niño 3.4 and winter SST records. Red lines indicate 90% significance levels. Gray dashed lines represent confidence intervals.

Figure D2.2. (a) Spectral analysis of detrended summer Sr/Ca-SST records. Significance level greater than 90% (red lines) are labelled. Spectral coherence with phase analysis is performed to account for variances shared between summer SST and the PDO (b), Niño 3.4 (c) and EAWM (d) indices. Red lines indicate 90% significance level while the gray dashed lines represent confidence intervals.

D3. Supplementary Information for Chapter 4

This supporting information includes additional figure results and a summary of the monthly and interannual Sr/Ca-SST calibration equations and an evaluation of $\delta^{18}\text{O}_c$ and $\delta^{18}\text{O}_{sw}$ -SSS calibrations, pertinent to the direction of data analysis for this site.

D3.1. Comparison between monthly and interannual Sr/Ca-SST calibrations.

Table D3.1 and Figure D3.1 summarizes the difference between applying monthly and interannual Sr/Ca-SST calibrations. Due to the limited SST variability at Houbihu, applying the monthly calibration equations at interannual timescales results in more comparable Sr/Ca-SST reconstructions than the statistically significant interannual calibration equations. However, the interannual trends in the summer SST reconstruction are the least constrained as evident in the Fig. D3.1b. Summer SST variability is relatively limited compared to the mean annual and winter variabilities, preventing us to effectively constrain the reconstruction errors enough to infer interannual trends during this season. Because annual SSTs are effectively an average of summer and winter SST changes, we focused on investigating the interannual to multidecadal scale SST variability in Houbihu during the winter season, where errors and interannual trends are better constrained.

Table D3.1. Monthly vs. interannual calibrations. Reconstruction errors (RMSR) are lower using the monthly calibration equation than the individual equations (in parenthesis).

	<i>Monthly Calibration</i>	<i>Interannual Calibrations</i>		
		Annual	Winter, DJFM	Summer, JJAS
slope, m	-0.064 (± 0.001)	-0.054 (± 0.009)	-0.058 (± 0.011)	-0.049 (± 0.016)
intercept, b	10.604 (± 0.029)	10.334 (± 0.246)	10.466 (± 0.265)	10.181 (± 0.478)
r	-0.95	-0.74	-0.71	-0.49
p	$<< 0.0001$	$<< 0.0001$	$<< 0.0001$	0.005
RMSR	0.59°C	0.33°C (0.38°C)	0.54°C (0.58°C)	0.48°C (0.61°C)
SST range	7.47°C	1.83°C	2.66°C	1.62°C

Figure D3.1. Interannual Sr/Ca-SST calibrations. (a.1) Scatterplot between mean annual Sr/Ca and IGOSS SST over the calibration period, 1981-2013. (a.2) IGOSS SST (dashed line) compared with reconstructed SST using monthly (darker shade) and interannual (lighter shade) calibration equations (Table D3.1). (a.3) Lower residuals (darker shade) result from using the monthly calibration equation. b.1 to b.3 and c.1 to c.3 follow the same descriptions as above but for interannual summer (orange) and winter (blue) calibrations, respectively.

Figure D3.2. Scatterplot comparing mean annual (black), summer (orange) and winter (blue) Sr/Ca values and annual extension rate.

Figure D3.3. (a). Spectral analysis of detrended winter PDO (gray dashed line) and the EAWM (black solid line) covering the same time period. Significant frequencies above the 90% confidence level (red lines) are labelled. Spectral coherence between Houbihu winter SST and these climate indices do not exhibit significant correlation (b and c).

Figure D3.4. Scatter plots comparing (a) $\delta^{18}\text{O}$ and SST, (b) $\delta^{18}\text{O}$ and SSS and (c) $\delta^{18}\text{O}$ and Sr/Ca.

D3.2. Evaluating dry season $\delta^{18}\text{O}_c$ and $\delta^{18}\text{O}_{sw}$ – SSS calibrations

At interannual (Eqns. D3.1 and D3.2) and 3-yr binned timescales (Eqns. D3.1 and D3.4), dry season $\delta^{18}\text{O}_c$ is significantly correlated with IGOSS SST and its Sr/Ca pair, suggesting that $\delta^{18}\text{O}_{sw}$ may be isolated from the dry season $\delta^{18}\text{O}_c$:

$$\delta^{18}\text{O}_{c_dry} = 0.593 (\pm 1.453) - 0.211 (\pm 0.058) \times \text{IGOSS SST}(\text{°C})$$

$$r = -0.56, p = 0.001, n = 31, \text{RMSR} = 0.87\text{°C}; \text{range} = 2.66\text{°C} \quad (\text{D3.1})$$

$$\delta^{18}\text{O}_{c_dry} = -34.951 (\pm 5.331) + 3.36 (\pm 0.591) \times \text{Sr/Ca} (\text{mmol mol}^{-1})$$

$$r = 0.73, p < 0.0001, n = 31, \text{RMSR} = 0.05 \text{ mmol mol}^{-1}; \text{range} = 0.23 \text{ mmol mol}^{-1};$$

$$(\text{D3.2})$$

$$\delta^{18}\text{O}_{c_3yr_dry} = -0.421 (\pm 1.459) - 0.169 (\pm 0.059) \times \text{IGOSS SST}(\text{°C})$$

$$r = -0.71, p = 0.02, n = 10, \text{RMSR} = 0.49\text{°C}; \text{range} = 1.51\text{°C} \quad (\text{D3.3})$$

$$\delta^{18}\text{O}_{\text{c}_{3\text{yr}_{\text{dry}}}} = -30.575 (\pm 6.419) + 2.877 (\pm 0.711) \times \text{Sr/Ca (mmol mol}^{-1}\text{)}$$

$$r = 0.82, p = 0.004, n = 10, \text{RMSR} = 0.02 \text{ mmol mol}^{-1}; \text{range} = 0.10 \text{ mmol mol}^{-1}$$

(D3.4)

We first infer the dry season $\delta^{18}\text{O}_{\text{SST}}$ component by using the regression between $\delta^{18}\text{O}_{\text{c}}$ and its Sr/Ca pair at 3-year binned timescales (Eqn. D3.4). We then calculate $\delta^{18}\text{O}_{\text{sw}}$ by inverting Eqn. D3.4 and subtracting the Sr/Ca-predicted $\delta^{18}\text{O}$ (i.e. $\delta^{18}\text{O}_{\text{SST}}$) values from $\delta^{18}\text{O}_{\text{c}}$. The resultant $\delta^{18}\text{O}_{\text{sw}}$ is then regressed to dry season SODA SSS, yielding a significant relationship at 3-year binned timescale:

$$\delta^{18}\text{O}_{\text{sw}_{3\text{yr}_{\text{dry}}}} = -12.97 (\pm 5.522) + 0.376 (\pm 0.16) \times \text{SODA SSS}_{3\text{yr}_{\text{dry}}} \text{ (psu)}$$

$$r = 0.64, p = 0.04, n = 10, \text{RMSR} = 0.14 \text{ psu}$$

(D3.5)

where RMSR is equivalent to ~35% of the mean dry season SSS range (i.e. 0.40 psu at 3-year binned timescale). However, this variability is 1.5 times larger than the instrumental SSS, which may overestimate SSS reconstructions further back in time.

Dry season $\delta^{18}\text{O}_{\text{c}}$ regressed to instrumental SST and SSS gives a slope of $0.17\text{‰ }^{\circ}\text{C}^{-1}$ and 0.88‰ psu^{-1} , respectively. Using these significant relationships, we calculated the relative contributions of SST and SSS to Houbihu $\delta^{18}\text{O}_{\text{c}}$ during this season. At 3-yr binned timescale, we found that SSS contribution (i.e. 57%)

is larger than that of SST (i.e. 43%), giving indication that directly regressing dry season $\delta^{18}\text{O}_c$ to SSS will result in more reasonable SSS estimates than by removing the less dominant SST component. Directly regressing $\delta^{18}\text{O}_c$ to SODA SSS yields:

$$\delta^{18}\text{O}_{c_{3\text{yr_dry}}} = -34.746 (\pm 6.586) + 0.876 (\pm 0.191) \times \text{SODA SSS}_{3\text{yr_dry}} (\text{psu})$$

$$r = 0.85, p = 0.002, n = 10, \text{RMSR} = 0.07 \text{ psu} \quad (\text{D3.6})$$

Doing so effectively reduced the reconstruction errors into half, resulting in SSS estimates within a more realistic SSS range (Fig. D3.5b). Therefore, we used Eqn. D3.6 in reconstructing dry season SSS further back in time.

Figure D3.5. (a) Scatter plot between $\delta^{18}\text{O}_{\text{sw}}$ (light brown), $\delta^{18}\text{O}_c$ (dark brown) and SODA SSS. (b) Dry season SSS estimates are better constrained using the $\delta^{18}\text{O}_c$ -SSS calibration equation (solid, brown line, Eqn. D3.6) than the $\delta^{18}\text{O}_{\text{sw}}$ -SSS relationship (dashed brown line, Eqn. D3.4). SODA SSS is in gray. Shading indicates $\text{RMSR} = 0.07 \text{ psu}$ (Eqn. D3.6).

D4. Supplementary Information for Chapter 5

This supporting information includes the data sources and inputs for each of the boxes described in Section 5.4.1 of Chapter 5. Atmospheric $\Delta^{14}\text{C}$ values can be found in Table 1 of Stuiver & Quay, 1981 and in the supplementary material of Hua et al., 2013. Coral-derived $\Delta^{14}\text{C}$ data for each of the Western Pacific Ocean (WPO) and South China Sea (SCS) sites are readily available in <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data>. Subsurface $\Delta^{14}\text{C}$ data were extracted from <https://cdiac3.ornl.gov/waves/glodapv2/> (Fig. D4.1). Table D4.1 summarizes the data input for each of the boxes, pertinent to the calculations of k_{Lat} .

The relative percentages of k_{SO} and k_{KI} in the box models are based on data summarized in Table D4.2.

The comparison between satellite-derived and reanalysis data-derived sea surface heights (SSH) is shown in Fig. D4.2.

Table D4.1. Pre-bomb and post-bomb data inputs for each of the boxes in Fig. 5.5 (Chapter 5).

Pre-bomb period (1942 to 1953)		<i>A</i>	<i>SO</i>	<i>KI</i>	<i>LS</i>	<i>D</i>
Source	Stuiver and Quay, 1981; Hua et al., 2013		Averaged $\Delta^{14}\text{C}$ from Con Dao (Mitsuguchi et al., 2007) and Hon Tre, Vietnam (Bolton et al., 2016)	Palau $\Delta^{14}\text{C}$ (This Study)	Houbihu $\Delta^{14}\text{C}$ (This Study)	Ostlund & Stuiver, 1980; Stuiver et al., 1981
Average $\Delta^{14}\text{C}$, ‰		-23.0	-54.4	-58.9	-63.4	-75.0
FM		0.9770	0.9456	0.9411	0.9366	0.9250
Post-bomb period (1970 to 2012)*		<i>A</i>	<i>SO</i>	<i>KI</i>	<i>LS</i>	<i>D</i>
Year	Hua et al., 2013		Averaged $\Delta^{14}\text{C}$ from Con Dao (Mitsuguchi et al., 2007) and Hon Tre, Vietnam (Bolton et al., 2016) and Currimao, Philippines (Hirabayashi et al., 2017)	Palau $\Delta^{14}\text{C}$ (This Study)	Houbihu $\Delta^{14}\text{C}$ (This Study)	GEOSECS (1973); WOCE (1993 to 1995); CLIVAR (2004 and 2006) – derived from GLODAPv2 (Lauvset et al., 2016; Olsen et al., 2016)
1971		1.5259	1.1537	1.1342	1.1434	1.1190
1972		1.4583	1.1553	1.1454	1.1429	1.1223
1973		1.4347	1.1650	1.1512	1.1386	1.1256
1974		1.4105	1.1546	1.1397	1.1471	1.1223
1975		1.3812	1.1608	1.1488	1.1473	1.1190

1976	1.3466	1.1535	1.1454	1.1452	1.1158
1977	1.3302	1.1546	1.1411	1.1437	1.1125
1978	1.3204	1.1544	1.1450	1.1329	1.1092
1979	1.2914	1.1487	1.1472	1.1476	1.1060
1980	1.2652	1.1494	1.1386	1.1243	1.1027
1981	1.2546	1.1468	1.1389	1.1363	1.0994
1982	1.2387	1.1431	1.1355	1.1365	1.0962
1983	1.2264	1.1426	1.1332	1.1267	1.0929
1984	1.2123	1.1377	1.1297	1.1245	1.0896
1985	1.2002	1.1269	1.1298	1.1277	1.0864
1986	1.1897	1.1277	1.1288	1.1257	1.0831
1987	1.1811	1.1214	1.1262	1.1227	1.0798
1988	1.1706	1.1147	1.1203	1.1131	1.0766
1989	1.1621	1.1080	1.1162	1.1152	1.0733
1990	1.1506	1.1111	1.1132	1.1080	1.0701
1991	1.1404	1.1091	1.1112	1.1086	1.0668
1992	1.1342	1.1029	1.1086	1.1036	1.0635
1993	1.1257	1.1002	1.1093	1.0997	1.0603
1994	1.1187	1.0986	1.0998	1.0978	1.0623
1995	1.1134	1.0931	1.0974	1.0927	1.0643
1996	1.1056	1.0938	1.0932	1.0909	1.0664
1997	1.1009	1.0876	1.0930	1.0910	1.0684
1998	1.0972	1.0897	1.0884	1.0837	1.0704
1999	1.0931	1.0860	1.0883	1.0799	1.0725

2000	1.0866	1.0806	1.0793	1.0720
2001	1.0801	1.0814	1.0761	1.0741
2002	1.0745	1.0798	1.0739	1.0762
2003	1.0689	1.0743	1.0710	1.0783
2004	1.0652	1.0735	1.0650	1.0804
2005	1.0592	1.0662	1.0623	
2006	1.0562	1.0636	1.0592	
2007	1.0513	1.0601	1.0569	
2008	1.0478	1.0570	1.0516	
2009	1.0412	1.0552	1.0530	
2010		1.0524	1.0479	
2011		1.0489	1.0432	
2012			1.0430	

**The values are reported as Fraction Modern (FM) values (Stuiver & Polach, 1977).*

Figure D4.1. Station locations for ^{14}C measurements conducted by the Geochemical Ocean Section Program (GEOSECS) in 1973, World Ocean Circulation Experiment (WOCE) in 1993 and Climate and Ocean – Variability, Predictability and Change (CLIVAR) in 2004 and 2006. All data is synthesized in Global Ocean Data Analysis Project for Carbon (GLODAPv2). Base map is similar to Fig. 5.1 of the main text.

Figure D4.2. Comparison between satellite-derived sea surface height anomalies (SSHa) from the Archiving, Validation, and Interpolation of Satellite Oceanographic data (AVISO) and SODA (Simple Ocean Data Assimilation) SSHa reanalysis data. The data between the common years, 1993 to 2010, are significantly correlated ($r = 0.79$, $p = 0.0001$, $n = 18$), allowing us to use the

longer SODA data with certainty. Units are both in m, but differ in magnitude as a function of the reference point used (i.e. AVISO absolute dynamic topography (ADT) is SSH with respect to the geoid while SODA SSH is with respect to mean sea surface).

Table D4.2. Multi-year measurements* and model estimates⁺ of Luzon Strait transport. Studies indicating both minimum and maximum transports were selected to avoid uncertainties that may arise in employing different methodologies.

Source	Minimum transport (Sv)	Maximum transport (Sv)
Qu et al., 2000*	1.2	4.8
Yaremchuk & Qu, 2004*	0.2	5.3
Qu et al., 2004 ⁺	0.9	6.1
Song, 2006 ⁺	8.2	12.2
Zhao & Luo, 2010 ⁺	1	8.1

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Appendix E

Houbihu wet season $\delta^{18}\text{O}_c$ – rainfall calibration and reconstruction

E1. $\delta^{18}\text{O}_c$ – rainfall calibration

In parallel to the dry season Houbihu $\delta^{18}\text{O}_c$ record, we similarly analyzed the wet (summer, JJAS) season $\delta^{18}\text{O}_c$ record over the last century of available high-resolution $\delta^{18}\text{O}_c$ data to evaluate the climatic controls on the summer $\delta^{18}\text{O}_c$ variability. Over the calibration period (i.e. 1982 to 2013), interannual and 3-year binned wet season $\delta^{18}\text{O}_c$ records are not correlated with IGOSS SST, SODA SSS (see Chapter 4 for gridded data sources) and its Sr/Ca pair ($r < 0.15$, $n = 31$, $r_{3\text{-yr_bins}} < 0.3$, $n = 1$; $p > 0.10$). However, significant negative correlations were found between the wet season $\delta^{18}\text{O}_c$ and local rainfall data (i.e. Taiwan Climate Weather Bureau at Heng Chun County) at both interannual (not shown) and 3-yr binned timescales (Fig. E1):

$$\begin{aligned} \delta^{18}\text{O}_{c_wet} &= -5.078 (\pm 0.148) - 0.001 (\pm 3.621^{-4}) \times \\ &\text{rainfall}_{wet} \text{ (mm yr}^{-1}\text{)} \\ r &= -0.46, p = 0.009, n = 31, \text{RMSR} = 178.6 \text{ mm yr}^{-1}; \end{aligned} \tag{E1}$$

$$\delta^{18}\text{O}_{\text{c}_{3\text{yr_wet}}} = -4.581 (\pm 0.327) - 0.002 (\pm 8.147^{-4}) \times \text{rainfall}_{3\text{yr_wet}} (\text{mm yr}^{-1})$$

$$r_{3\text{-yr_wet}} = -0.70, p = 0.03, n = 10, \text{RMSR} = 51.1 \text{ mm yr}^{-1}; \quad (\text{E2})$$

where RMSRs are equivalent to 42% and 32% of the mean interannual and 3-year binned wet season rainfall ranges (i.e. 424.4 mm yr⁻¹ and 157.3 mm yr⁻¹), respectively. Wet season SODA SSS is also significantly correlated with rainfall ($r = -0.37$, $p = 0.05$, $n = 29$, Fig. E1), suggesting that rainfall variability considerably impacts $\delta^{18}\text{O}_{\text{c}}$ and surface salinity locally during this season.

Figure E1. (a) Houbihu wet season $\delta^{18}\text{O}_{\text{c}}$ and rainfall are significantly negatively correlated. (b) Reconstructed rainfall (green line) shows good agreement with instrumental rainfall data (gray line). Shading represents $\text{RMSR} = 51.1 \text{ mm yr}^{-1}$.

E2. $\delta^{18}\text{O}_{\text{c}}$ – rainfall reconstruction

We extended the $\delta^{18}\text{O}_{\text{c}}$ -rainfall record back to the early 1900s to further assess the climatic factors controlling its variability over a longer time period (Fig. E2). Between the early 1900s and 1950s, reconstructed wet season $\delta^{18}\text{O}_{\text{c}}$ -rainfall exhibit above average rainfall conditions, about $\sim 56 \text{ mm yr}^{-1}$ above the

mean value of 390 mm yr⁻¹. Around 1952, rainfall abruptly decreased to 148 mm yr⁻¹, the lowest estimate in record. Following this period until the mid-1980s, the reconstructed rainfall exhibits below average estimates (i.e. ~283 mm yr⁻¹) that gradually increased towards the present with a significant trend of 4.5 mm yr⁻¹ or 241.7 mm over the past half-century ($r = 0.74$, $p < 0.0001$). Compared with both the wet season instrumental SSS and rainfall records, our rainfall estimates during this season remained significantly correlated further back in time ($r_{SODA_SSS} = 0.38$, $p = 0.02$, $n = 36$; $r_{rainfall} = 0.44$, $p = 0.007$, $n = 37$) with all records showing similar decadal trends as previously described. This suggests that surface salinity variability is linked with local hydrological changes during the peak rainfall season.

We compared our wet season rainfall reconstruction with the winter Pacific Decadal Oscillation (PDO) to evaluate its impact on the succeeding summer rainfall. Our coral-derived rainfall record is significantly correlated with the winter PDO leading by 3 to 9 years ($r_{3-yr_lead} = 0.49$, $r_{9-yr_lead} = 0.45$, $r_{9-yr_lead} = 0.64$, $p < 0.01$). The warm (positive) phases of the PDO causes higher rainfall and or runoff, delivering low salinity waters at Houbihu during the wet season. The opposite relationship occurs during cold PDO phases. Similar relationships were observed in monthly coral $\delta^{18}\text{O}$ records from Hainan Island, northern SCS (Deng et al., 2013) and Koshiki Island, Japan over East China Sea (Watanabe et al., 2014). These results indicate that the PDO exerts influence on the rainfall variability and/or runoff regionally.

Figure E2. (a) Reconstructed rainfall record during the wet season extending back to the early 1900s. Shading represents $\text{RMSR} = 51.1 \text{ mm yr}^{-1}$. (b) SODA SSS data (dashed line) and (c) winter PDO index (black line). SODA SSS is inverted to facilitate comparison between overall trends.

Future work will extend the wet season $\delta^{18}\text{O}_c$ record to investigate multidecadal to centennial scale trends in rainfall variability back to the end of the Little Ice Age (LIA), when hydrological processes are significantly different relative to the present. The possible influence of the East Asian Summer Monsoon (EASM) will also be examined.

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