Abstract of Doctoral Dissertation

Degree requested: Doctor of Science Applicant's name: Garas Kevin Lariosa

Title of Doctoral Dissertation

Influence of East Asian Monsoon and El Niño Southern Oscillation (ENSO) to Holocene Hydroclimate deduced from Northwest Pacific corals
(完新世のサンゴ骨格記録を用いた東アジアモンスーンが ENSO に与える影響の解明)

Proxy-based climate archives are important evidence of past climate and environmental changes beyond historical and instrumental records. However, the diverging results of climate reconstructions resulted in difficult conundrums of the complex Holocene climate. The inconsistencies are caused by the 1) highly varied regional hydroclimate response to ocean-climate systems; 2) issues on varying temporal resolutions, and 3) varying environmental and climatic signals of geological materials. This dissertation will focus on the interaction of East Asian monsoon (EAM) and El Niño Southern Oscillation (ENSO) in modulating the interannual and seasonal sea surface temperature (SST), sea surface salinity (SSS), and rainfall variabilities in the subtropical and tropical Northwest Pacific during the Holocene. Investigating how the interannual ENSO affects the monsoon is vital in seasonal rainfall prediction. Due to the complex teleconnections of equatorial Pacific SST anomalies (SSTA) and the East-Southeast Asian climate, few paleoclimate records were able to explain the mechanism of EAM-ENSO interaction in the Holocene.

The strategy of this research is to explore the potential of corals from Kikai Island, Japan and NW Luzon Island, Philippines in reconstructing the unique response of subtropical and tropical NW Pacific to EAM and ENSO. There are 40 *Porites* colonies collected from the two study areas. A series of screening of fossil corals was done using thin section analysis, X-ray Diffraction (XRD), and Scanning Electron microscopy (SEM). Fossil corals with excellent preservation were dated using Accelerator Mass Spectrometer to measure the radiocarbon age dates. Corals were cut into 5-mm slab, cleaned, and prepared for X-radiography, microsampling, and geochemical analysis. Coral growth parameters such as linear extension rate, skeletal density, and calcification rate were calculated from the X-ray photographs of corals. Sr/Ca ratio was measured with an Inductively Coupled Plasma-Atomic Emission Spectrometry (iCAP 6300 ICP Spectrometer). Similar coral powder samples were analyzed using Isotope Ratio Mass Spectrometer (MAT Finnigan 253) with automated carbonate device Kiel IV for oxygen isotope analysis.

Results of thin section analysis, XRD, and SEM have shown that 6 fossil Porites have excellent to good fossil preservation. These samples $\leq$1% calcite content based on phase mineral estimates from Reference Intensity Ratio (RIR) Method. Corals with excellent preservation are devoid of dissolution, fine- to medium-sized acicular aragonite and rhombohedral calcite overgrowths. Well-preserved fossil corals from Kikai Island yielded radiocarbon age dates of 3235±20 (KIKJ-20160907-II) and 5712±24 (KIST-20160518-I) years BP. Well-preserved fossil corals from NW Luzon Island yielded radiocarbon age dates of 6285±79 (CuPf-180218-1), 6144±77 (CuPf-180218-4), 4336±21 (DMT-2), and 4200±20 (DMT-1) years BP. To investigate the effect of growth rate to coral geochemistry, the annual linear extension rates of modern corals from Kikai and NW Luzon islands were plotted against the annual Sr/Ca and $\delta^{18}O_{coral}$ for each coral colony. The absence of strong linear correlation between these variables suggests that growth has minimal effect to the variation of these two climate proxies.

The ordinary least square (OLS) bivariate regression analysis was performed to demonstrate the dependence of coral Sr/Ca, $\delta^{18}O_{coral}$, and $\delta^{18}O_{sw}$ to SST, SSS, and rainfall. The monthly-resolved Sr/Ca of modern corals from Kikai Island and NW Luzon Island are negatively correlated to the AVHRR SST from 1989-2015 (slope: -0.0643 mmol/mol°C^{-1}) and OISST from 2011-2017 (slope: -0.0057 mmol/mol°C^{-1}) respectively. The monthly-resolved $\delta^{18}O_{coral}$ datasets were regressed to SODAv3.3.1 SSS and have shown statistically significant positive linear correlation for both Kikai Island coral ($r=0.71$; $p<0.000$; $n = 310$) and NW Luzon Island coral ($r=0.50$; $p<0.000$; $n = 48$). The 5-point running average of $\delta^{18}O_{sw}$ and monthly in-situ rainfall data of Kikai Island from 2007-2015 were regressed and have shown statistically significant negative linear correlation ($r=0.55$; $p<0.000$; $n = 93$). The monthly-

resolved $\delta^{18}O_{sw}$ from NW Luzon Island coral and SODAv3.3.1 SSS from 2011-2017 have statistically significant positive linear correlation ($r=0.50$; $p<0.000$; $n = 48$). The modern coral Sr/Ca calibration slopes were used to invert the fossil coral Sr/Ca to SST records. The bivariate regression of $\delta^{18}O_{coral}$ and $\delta^{18}O_{sw}$ to SSS and rainfall were used to interpret the hydroclimatic signals in fossil coral geochemical records. The mean seasonal climatological trends of all modern and fossil corals colonies revealed the seasonality of SST, SSS, and rainfall. The changes of coral-based SST, SSS, and rainfall records in different time-windows of mid- to late Holocene were possibly driven by the changes in the monsoon intensity.

The summer, winter, and annual mean Sr/Ca-SST and $\delta^{18}O_{coral}$ records from fossil *Porites* in subtropical and tropical NW Pacific were compiled to investigate seasonal SST and SSS change in mid-Holocene towards late Holocene. The lower SSS and higher rainfall in subtropical NW Pacific were coeval to the higher SSS and lower rainfall in tropical NW Pacific from 7.0 ka to 5.0 ka. In this time-window, both the subtropical and tropical SSTA records are consistent that the period was not significantly different and warmer (+0-2°C) at times than the present-day. The SSS trend of subtropical NW Pacific shifted positively after 4.9 ka while the SSS trend in tropical NW Pacific shifted negatively around 4.3 to 4.2 ka. After 5.0 ka, the summer SSTA both show cooling trend in subtropical (-1.8°C) and tropical (-0.9°C) NW Pacific. The coral evidence supports the widely reported EASM intensification (8.2 ka to 4.7 ka) and weakening (4.7 ka to 3.0 ka) based on the stacked marine and terrestrial sediment records from NW Pacific. Moreover, the coral-derived SST and SSS datasets agree that the mean position of intertropical convergence zone (ITCZ) migrated southwards from mid-Holocene towards late Holocene. The northward ITCZ migration and intensification of EASM resulted in the enhancement of summer rainfall in the subtropics while the rainfall in tropical NW Pacific was reduced in mid-Holocene. The southward migration of the ITCZ and weakening of the EASM resulted in the aridification of East Asia and reduced rainfall/higher SSS of subtropical NW Pacific. The southerly position of the ITCZ brought more rainfall in tropical NW Pacific.

The interaction of ENSO to the prevailing climate systems such as monsoon and ITCZ is poorly understood due to lack of high temporal resolution climate archives. The interannual variability of coral-derived $\delta^{18}O_{sw}$ was isolated using the 2-8-year bandpass filtering. The El Niño years are defined by the occurrence of positive SSTA in NINO3.4 and positive $\delta^{18}O_{sw}$ values which reflects higher SSS and lower rainfall in NW Pacific. The La Niña years are defined by the occurrence of negative SSTA in NINO3.4 and negative $\delta^{18}O_{sw}$ values which reflects lower SSS and higher rainfall in NW Pacific. The $\delta^{18}O_{sw}$ threshold values for different ENSO intensity were determined using the statistically significant positive correlation ($r=0.75$; $r2=0.56$; $p<0.000$) of 2-8-year bandpass filtered $\delta^{18}O_{sw}$ data and the ERSST v4 NINO 3.4 SSTA from 1982 to 2012. The 1-year periodicity was systematically removed from the monthly-resolved $\delta^{18}O_{sw}$ time series. Then, spectral analysis using REDFIT method was performed to show the "red-noise" spectrum of modern and fossil coral $\delta^{18}O_{sw}$ with 90%, 95%, and 99% statistical significance. These data analyses revealed 4.2 ka and 4.3 ka corals from NW Luzon Island recorded frequent strong to very strong El Niño. The mean seasonal climatology of $\delta^{18}O_{sw}$ of these corals show an increase in SSS during El Niño years relative to neutral years. The 6.1 ka coral recorded frequent moderate El Niño events. The frequency and magnitude of the El Niño events recorded in 3.2 ka, 4.9 ka, and 5.7 ka corals from Kikai Island were weaker than the present-day.

This dissertation proposes a new way to investigate ENSO impacts to rainfall and SSS changes in NW Pacific and to establish the teleconnections of NINO3.4 SSTA and NW Pacific hydroclimate. The new coral data from NW Pacific agree to the mid-Holocene reduction of ENSO variabilities as suggested by paleo-ENSO analysis from Western, Central and Eastern Pacific corals. However, the intensity and frequency of El Niño were varied in mid-Holocene. In mid-Holocene, a weak El Niño condition was coeval with strong West Pacific Subtropical High (WPSH). The ocean-climate condition changed from mid-Holocene towards its termination around 4.2 ka when the stronger El Niño prevailed suppressing the WPSH. The established positive ocean-climate feedback mechanism of EAM-ENSO in mid-Holocene will constraint the parameters of climate models on how ENSO and monsoon rainfall will react in the next few decades under different warming (RCP 2.6, 4.5, 6.0, and 8.5) scenarios.