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Hydroclimate variability of central Indo-Pacific region during the Holocene

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Quaternary Science Reviews

Hydroclimate variability of central Indo-Pacific region during the Holocene

--Manuscript Draft--

Manuscript Number:	JQSR-D-20-00385R1
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Corresponding Author:	Sakonvan Chawchai Chulalongkorn University Faculty of Science Bangkok, THAILAND
First Author:	Sakonvan Chawchai
Order of Authors:	Sakonvan Chawchai Liangcheng Tan, Professor Ludvig Löwemark, Professor Hao-Cheng Wang Tsai-Luen Yu Yun-Chuan Chung Horng-Sheng Mii, Professor Guangxin Liu, Dr. Maarten Blaauw, Professor Shou-Yeh Gong, Dr. Barbara Wohlfarth, Professor Chuan-Chou Shen, Professor
Abstract:	<p>Here we present a decadal-resolved hydroclimate record covering the past 11 thousand years based on $\delta^{18}\text{O}$ data of three stalagmites from Klang Cave (TK) on the Thai-Malay Peninsula, southern Thailand. The $\delta^{18}\text{O}$ values indicate wetter conditions/more rainfall during the early Holocene from 11 to 7 thousand years before present (kyr BP). A large increase of 2‰ in $\delta^{18}\text{O}$ is observed from 7.0 to 6.0 kyr BP, indicating a millennial drying period followed by drought conditions between 6.0 and 5.2 kyr BP. After a long hiatus (5.2 – 2.7 kyr BP), $\delta^{18}\text{O}$ data show a millennium-long trend toward dry conditions. An abrupt positive change of 0.8 – 1.0 ‰ in $\delta^{18}\text{O}$ is noticed between 8.29 – 8.17 kyr BP, reflecting the 8.2-ka event, however; the amplitude of the $\delta^{18}\text{O}$ shift is much smaller when compared to 6.0 – 5.2 kyr BP. On orbital time-scales, the TK record agrees with insolation-dominated speleothem records in the Asian-Australian monsoon realm. Noticeable inconsistencies among records in the Southeast Asia region (between 8°N and 4°N – 8°S) have been documented on multi-centennial scales. Lower $\delta^{18}\text{O}$ values are likely associated with the mean position of the Intertropical Convergence Zone (ITCZ). A new reconstruction of Holocene ITCZ shifts index within the central Indo-Pacific region, based on stalagmite $\delta^{18}\text{O}$ records from Klang Cave (8°N) and Liang Luar Cave (8°S), shows that the ITCZ played an important role in hydroclimate variability in the Asian-Australian monsoon regions. The southward shift of the ITCZ in the central Indo-Pacific region, controlled by the interhemispheric extratropical insolation gradient, may strongly correlate with the El Niño-Southern Oscillation (ENSO) activities in the Holocene.</p>
Suggested Reviewers:	<p>Judson W. Partin Professor, University of Texas at Austin jpartin@ig.utexas.edu Experts in Speleothem and climate dynamic in the pacific regions and on a wide range of topics related to paleoclimate change.</p> <p>Yanjun Cai</p>

	<p>Professor, Chinese Academy of Sciences yanjun_cai@ieecas.cn Experts in Speleothem and paleoclimate in Asian Monsoon regions.</p>
	<p>John C. H. Chiang University of California Berkeley jch_chiang@berkeley.edu Experts in climate dynamics of the global atmosphere and its interactions with the ocean and land systems.</p>
	<p>Xianfeng Wang Professor, Nanyang Technological University xianfeng.wang@ntu.edu.sg Experts in Speleothem, isotopes geochemistry and climate dynamics of Southeast Asia</p>
	<p>Ashish Sinha Professor, California State University Dominguez Hills asinha@usc.edu Experts in speleothem isotope geochemistry, past climate dynamics on socially-relevant time scales.</p>
Response to Reviewers:	

Quaternary Science Reviews: manuscript JQSR-D-20-00385

Dear Editor, Dr. Miryam Bar-Matthews,

We would like to express our appreciation to the editor Dr. Miryam Bar-Matthews for handling our manuscript and for the positive comments and for summarizing issues raised by the reviewers. We also thank two anonymous reviewers for their professional and constructive comments and suggestions. We have addressed the Editor's and all reviewers' concerns, rewritten, and made the changes to our manuscript. In the appendix, we list all the reviewers' questions and comments, together with our responses highlighted in blue.

Please find enclosed our revised manuscript. We very much hope that it is acceptable for publication in *Quaternary Science Reviews*. We declare that this manuscript is original, not published, in press, or submitted elsewhere.

Thank you very much again for handling the reviewing process of our manuscript. Should you have any questions, please do not hesitate to contact us.

Your Sincerely,

Sakonvan Chawchai, Chuan-Chou Shen (Corresponding Authors)

Quaternary Science Reviews: manuscript JQSR-D-20-00385

Editor and Reviewer comments:

Response to editor and reviewers's comment in Blue.

Dear Editor, Dr. Miryam Bar-Matthews,

We would like to express our appreciation to the editor Dr. Miryam Bar-Matthews for handling our manuscript and for the positive comments and for summarizing issues raised by the reviewers. We also thank two anonymous reviewers for their professional and constructive comments and suggestions. We have addressed the Editor's and all reviewers' concerns, rewritten, and made the changes to our manuscript. In the appendix, we list all the reviewers' questions and comments, together with our responses highlighted in blue.

Please find enclosed our revised manuscript. We very much hope that it is acceptable for publication in *Quaternary Science Reviews*. We declare that this manuscript is original, not published, in press, or submitted elsewhere.

Thank you very much again for handling the reviewing process of our manuscript. Should you have any questions, please do not hesitate to contact us.

Your Sincerely,

Sakonvan Chawchai, Chuan-Chou Shen (Corresponding Authors)

Editor comments

E1. Chawchai et al. presents a speleothem $\delta^{18}\text{O}$ records spanning most of Holocene from Klang Cave in Thai-Malay Peninsula, southern Thailand, which follow the study by Tan et al. (2019, PNAS). In this study the authors extended the record, for most of the last 11,000 years by using different aragonitic stalagmites which covering the different time periods. The major findings include broad similarity with other speleothem-based monsoon records mostly in East Asia; a millennial drought period in the middle Holocene; identifying the 8.2-ka event in the tropical Indo-Pacific region and reconstructing the ITCZ shift index during the Holocene. The quality of the data is very good, the subject addressed is worthy of investigation, the information presented is new and worthy publication in QSR. The new record is important for understanding the Holocene hydroclimate changes in tropical Indo-Pacific region.

Reply: Thank you for this positive comment.

E2. However, the two reviewers and I found some important problems that need to be addressed before the manuscript can be accepted for publication. I will summarize the most important points:

E3. The manuscript is missing discussion on the petrography of the samples, are there evidence to changes in growth pattern associated with shifts in $\delta^{18}\text{O}$?

Reply: We did XRD analysis to show all three stalagmites, TK7, TK20, and TK40, are aragonite. For TK 7, one dark layer is observed at a depth of 21 mm (Fig. R1). U-Th ages at two depths above and below the layer show that this dark layer is a hiatus. For TK20 and TK40, stalagmites are quite clean and show aragonite texture. We wrote “X-ray diffraction (XRD) analysis at 6 depths (Supplementary Data Fig. 1) show that all stalagmites are composed of pure aragonite without mineral transformation.” (Lines 166-168) and “Two U-Th ages of 2758 ± 20 and 5255 ± 37 yr BP at depths of 18 and 28 mm of stalagmite TK7 indicate that a dark layer at 21 mm is a hiatus (Supplementary Data Fig. 1).” (Lines 213-215)

Fig. R1. The top segment of stalagmite TK7. One discontinuous layer is observed at a depth of 21 mm from top. It is confirmed as a hiatus by using at depths above and below the layer.

E4. Can the author explain the hiatus between 5-3 ka, is it climatic driven or sampling bias?

Reply: We attempted to find any stalagmite samples covering 5-3 ka from all of our collected 46 stalagmites. However, we could not find any stalagmites filling this gap between 5-3 ka. The recent study of Griffiths et al. (2020) shows drought evidence during the mid-Holocene in speleothem from Laos. We cannot fully rule out the possibility that the hiatus is resulting from a prolonged drought. We wrote “A recent study of stalagmite $\delta^{18}\text{O}$ from Laos indicated megadrought in Mainland Southeast Asia between 5 and 3 kyr BP (Griffiths et al., 2020), which could be the possible reason of the observed hiatus at 5.23-2.73 kyr BP in the Klang Cave records (Figs. 2, 4C).” (Lines 339-342)

E5. Although there is a small peak that may be related to the 8.2 ka event, there are other events in the same magnitude that are not discussed. Is indeed the 8.2 event is so significant. The event from ~6.0 to 5.4 ka is be far more prominent. Can the authors explain what drove the 8.2 event in this location?

Reply: We agreed with the editor that compared to the period from ~6.0 to 5.4 ka, the 8.2 ka event in Klang record is less prominent. However, the identification of 8.2 ka event at our location bears its own climate significance. Our Klang Cave record, for the first time to our knowledge, provides strong evidence that the impact of 8.2-ka event can reach the tropical Indo-Pacific.

Regarding what drove the 8.2 ka event in our location, we have invoked the well-accepted mechanism for this teleconnection, i.e., through the weakening of AMOC and consequently the southward shift of the ITCZ (**Lines** 233-240 in the original submission). For clarity, we revised the related discussion to “*It has been attributed to the last outburst flood from glacial Lake Agassiz (Clarke et al., 2004; Lajeunesse and St-Onge, 2008; Teller et al., 2002), which freshened North Atlantic surface waters, reduced the production of North Atlantic Deep Water and weakened the North Atlantic Meridional Overturning Circulation (AMOC). A weakened AMOC hindered the northward transportation of warm surface waters, caused a southward shift of the ITCZ and reduced Asian monsoon (Cheng et al., 2009; Tan et al., 2020), and consequently a reduction of rainfall at our cave site, which led to a positive shift of $\delta^{18}\text{O}$ in our stalagmite record.*” (**Lines** 295-303)

Nevertheless, considering that the foci of the manuscript is to capture the broad picture of Holocene hydroclimate changes, and considering the comments and suggestions from the editor as well as the two reviewers, we lower down the tune regarding the identification of 8.2 ka event, and remove the word “First” in the sentence “First stalagmite record of 8.2-ka event in the tropical Indo-Pacific region” from *Highlights*.

E6. Tan et al. (2019) proposed the ITCZ shift index for the last 2700 years to understand shifts of ITCZ by using normalized speleothem $\delta^{18}\text{O}$ data to overcome the offset between $\delta^{18}\text{O}$ of stalagmites. Can the authors explain why this method can be applied to much longer time scale? There is no overlapping between TK40 and any other stalagmites, thus can the authors explain how reliable the ITCZ index is in the early Holocene. Can the authors be more specific on the position of the ITCZ index?

Reply: In Tan et al. (2009), we used modern (1983-2011 AD) cross-equatorial rainfall gradient between 2 sectors (Fig. S13 of Tan et al., 2009) in northern central Indo-Pacific (NCIP) and southern CIP (SCIP) observations to show the meridional ITCZ shift (Fig. S13 of Tan et al., 2019). Klang and Liang Luar Caves are in the NCIP and SCIP sectors, respectively (Fig. S13 of Tan et al., 2019). The reconstructed ITCZ shift index (ITCZ SI), based on Klang and Liang Luar Cave $\delta^{18}\text{O}$ records, over the past 2 millennia. However, in the early Holocene, sea-level related regional topography are indeed one of the main factors controlling the hydroclimate change during this time period; even though the most important forcing is the insolation (Fig. 7C). We discussed sea-level related Sunda Shelf exposure in the revised manuscript on **Lines** 426-434. We wrote: “*Hydroclimate changes based on $\delta^{18}\text{O}$ record of Klang Cave in the western margin of WPWP are dominantly associated with the ISM (Tan et al., 2019). Substantial early to mid-Holocene decreases in $\delta^{18}\text{O}$ record of Liang Luar Cave are interpreted as an intensification of Australian–Indonesian summer monsoon rainfall in response to deglacial eustatic sea-level rise and flooding of the Sunda Shelf (Griffiths et al., 2009). This new regional ITCZ SI record (Fig. 7A) shows different trends than that of the Cariaco Basin Ti record from 11.0–7.0 kyr BP, especially around 11.0–9.5 kyr BP. This disagreement can likely be attributed to Sunda Shelf exposure due to sea level rise (Griffiths et al., 2009).*”

The Editor was correct. A small gap between TK20 and TK40 $\delta^{18}\text{O}$ records was observed in the original manuscript. In the revised manuscript, we did one additional dating at a depth of 47.6 cm of TK20 and isotopic analyses at a depth interval of 46.4-47.8 cm at the lowermost bottom of TK20 to fill this gap. The uppermost TK40 $\delta^{18}\text{O}$ values of -6.03‰ at 8.840 kyr BP match the lowermost $\delta^{18}\text{O}$ values of TK20 between 8.840-8.878 kyr BP. These agreements show the fidelity of the our reconstructed ITCZ SI record. We wrote “*Systematic offsets between stalagmite $\delta^{18}\text{O}$ records in Klang Cave were reported in Tan et al. (2019). Similar oxygen isotopic discrepancies are not noticeable in this study. $\delta^{18}\text{O}$ variations of TK7 replicate TK20 during 8.35–7.34 kyr BP and show similar pattern with TK133 (published data of Tan et al., 2019) during the 2.65 to 1.67 kyr BP (Fig. 2). The uppermost TK40 $\delta^{18}\text{O}$ values of -6.03‰ at 8.840 kyr BP match the lowermost $\delta^{18}\text{O}$ values of TK20 between 8.840–8.878 kyr BP (Fig. 2; Supplementary Data Table 1). These agreements indicate that TK7, TK20 and TK40 were most likely deposited under isotopic equilibrium and allow presenting the three records combined*”. (Lines 227-235)

E7. The manuscript lacks thorough discussion on the various mechanisms that affect Klang speleothem $\delta^{18}\text{O}$: ITCZ migration, monsoon signal, winter monsoons and tropical cyclones Indian summer monsoon and East Asian Monsoon. All these are mentioned in the text. It is important to add information on present-day local rainfall and cave drip water, and their $\delta^{18}\text{O}$?

Reply: We thank the editor for raising this important point. In this revised manuscript, we added information on present-day local rainfall and cave drip water and $\delta^{18}\text{O}$ in **Section 3.4** Cave drip water and rainwater monitoring; **Result Section 4.2** Cave drip water and rainwater $\delta^{18}\text{O}$; and **Discussion Section 5.1** Climatic significance of $\delta^{18}\text{O}$.

E8. Both reviewers give detailed comments that need to be addressed and if the authors wish to submit a corrected version, they have to explain how they modified the revised version according to the reviewers and the editor comments. The final decision regarding the manuscript will require further review.

Reply: We addressed all issues raised by both reviewers. The detailed point-to-point responses are given below.

Reviewers' Comments:

Reviewer #1: The manuscript by Chawchai et al. presents a speleothem $\delta^{18}\text{O}$ records spanning most of Holocene from Klang Cave in Thai-Malay Peninsula, southern Thailand. The major findings include disclosing a millennial drought period in the middle Holocene; identifying the 8.2-ka event in the tropical Indo-Pacific region and reconstructing the ITCZ shift index during the Holocene. The new record is no doubt important for us to understand the Holocene hydroclimate changes in tropical Indo-Pacific region.

Reply: We thank **Reviewer #1** for encouragement and constructive review.

However, there are several issues in data processing and interpreting need to be revised substantially.

Reply: We would like to thank **Reviewer #1** for the professional and constructive comments and suggestions. In the text below, we list all the reviewer's questions and comments, together with our responses highlighted in blue.

Major comments:

R1.1. Tan et al. (2019) have reported a speleothem $\delta^{18}\text{O}$ records from Klang cave and proposed the ITCZ shift index to understand shifts of ITCZ over the last 2700 years. From the paper by Tan et al., we know that there are substantial offsets of speleothem $\delta^{18}\text{O}$ among different stalagmites from Klang cave. By using normalized speleothem $\delta^{18}\text{O}$ data of single stalagmite to calculate the ITCZ index, these offsets can be ignored. However, by using different stalagmites which covering the different time periods, these offsets might lead to erroneous long-term trend. As seen from figure 4, stalagmite TK7 replicates well with TK20, but the replication between TK133 and TK7 is not so good, and there might be a offset of 0.5‰ between this two stalagmites (please using different colors to denote different stalagmites, the blue curve during the period from 2.5-1.6 kyr BP may mislead the reader that stalagmite TK20 overlapped with stalagmite TK133). Also, as there is no overlapping between TK40 and any other stalagmites, it's hard to evaluate how reliable the ITCZ index is in the early Holocene. Further evidences are necessary to confirm the present assessment.

Reply: (1) Considering the heterogeneous aquifer of different drips with the thickness of the overlying bedrock varying from 10 to 60 m above Klang Cave, the observed offsets could be attributed to different feeding systems for each stalagmite. Mixing of older and younger waters in the epikarst, and percolation along different flow paths can lead to buffering of the $\delta^{18}\text{O}$ signal (Tan et al., 2019). Our observations in the cave show that drip water increases within hours of major rain events. Several intense rain events appear to have left distinct imprints in the cave drip water record with a lag of one week or two weeks. For example, the powerful storms that struck the peninsula around September 12th and November 21th could be recorded as distinct depletions in the cave drip water around September 28th and November 25th, respectively (current manuscript Fig. 3). Therefore, cave drip water $\delta^{18}\text{O}$ values generally reflect seasonal or yearly averages. In addition, similar patterns of $\delta^{18}\text{O}$ variability between TK133 and TK7 support their suitability for tracking the original hydroclimate variability.

(2) The new figure 2 has been changed using different colors according to the comment and suggestion.

(3) **Reviewer #1** pointed out that “as there is no overlapping between TK40 and any other stalagmites, it's hard to evaluate how reliable the ITCZ index is in the early Holocene”. Editor also raised this issue in **E6**. Please refer to our reply in **E6**. “A small gap is between TK20 and TK40 $\delta^{18}\text{O}$ records (in the former manuscript). In the current manuscript, we did

additional dating and isotopes analysis on the bottom of TK20 to fill this gap. The uppermost TK40 $\delta^{18}O$ values of -6.03‰ at 8.840 kyr BP match the lowermost $\delta^{18}O$ values of TK20 between 8.840-8.878 kyr BP. These agreements show the fidelity of our reconstructed ITCZ SI record.”

R1.2. I am confused about the position of the ITCZ at the southeast Asia. In the introduction, it is said that "over the Indian Ocean and adjoining land surfaces, the ITCZ shifts between 20°N in boreal summer and 8°S in boreal winter (Schneider et al., 2014). This shift was recorded over 25°N in the WPWP (e.g. Liu et al., 2015; Wang et al., 2008; Yancheva et al., 2007)." That means the ITCZ could shift to 20°N at least at present time.

Reply: Thank **Reviewer #1** for pointing out this mistake. The text was revised to “*whereas over the Indian Ocean and adjoining land surfaces, the ITCZ shifts between 20°N in boreal summer and 8°S in boreal winter during the observed period (Schneider et al., 2014). However, in paleorecords the ITCZ shifts reached over 25°N in the WPWP (e.g. Liu et al., 2015; Wang et al., 2008; Yancheva et al., 2007).*” (**Lines 97-99**)

At line 271, it is said that "A possible explanation could be a quick southward shift of the ITCZ from 8°N or further north to closer to the equator during this millennium". From figure 7, the ITCZ shift index record indicates that ITCZ was southward shift further during the last 2700 years than during the 6.0-5.2 kyr BP when the author suggest that the ITCZ was closer to the equator. It is to say that the ITCZ should be shift close to the equator at present. So, what position was indicated by the ITCZ index here?

Reply: To clarify this issue, the text was revised as “*In contrast, the stalagmite $\delta^{18}O$ records south of Klang Cave, such as Northern Borneo, Sumatra, Sulawesi, and Flores between 4°N–8°S, generally display opposite oscillations during the same period. Stalagmite $\delta^{18}O$ data set from Flores shows a distinct anti-phase development to Klang $\delta^{18}O$ record between 7.0 and 6.0 kyr BP. The hydroclimate changes recorded in Klang Cave (8°N) and in Secret Cave from Northern Borneo (4°N) show opposite patterns during the early and middle Holocene, but a similar trend during the late Holocene. For the early and middle Holocene, Secret Cave and records from the southern Indo-Pacific region indicate wet conditions, which implies the climatic equator (mean position of the ITCZ) maintained between 4–8 °N. The in-phase variations of the two records during the late Holocene indicate the climatic equator move further south of 4°N due to the declined northern hemisphere summer insolation.*” (**Lines 353-364**)

R1.3. It is interesting that the 8.2 ka event was identified in this tropical Indo-Pacific speleothem record. However, the event from ~6.0 to 5.4 kyr BP is even more prominent than the 8.2-ka event. The authors mentioned that this event indicates a southward shift of ITCZ. But what drove this event, there is no any explanation. I think the explanation for this event is necessary.

Reply: This mid-Holocene event from ~6.0 to 5.4 kyr BP has been discussed in the revised manuscript on **Lines 316-364**. We wrote:

“*The shift of stalagmite $\delta^{18}O$ at ~ 6.00 kyr BP indicates a non-linear response to insolation forcing. To infer spatial patterns of the hydroclimate variability in the central Indo-Pacific region, Figure 4 shows a comparison of Klang Cave data set with speleothem records available in the Asian monsoon region, including (1) Dongge Cave, China (Wang et al., 2005; Dykoski et al., 2005), (2) Mawmluh Cave, India (Berkelhammer et al., 2013; Dutt et al., 2015), (3) Tham Doun Mai Cave, Laos (Griffiths et al., 2020), (4) Secret Cave, Northern Borneo (Carolin et al., 2013; Partin et al., 2007), (5) Tangga Cave, Sumatra (Wurtzel et al., 2018), (6) Gempa*

Bumi Cave, Sulawesi (Krause et al., 2019), and (7) Liang Luar Cave, Flores, Indonesia (Ayliffe et al., 2013; Griffiths et al., 2009) (see locations in Fig. 1).

The records between 25°N and the Indo-Pacific equatorial region indicate strong rainfall and strengthening of the Asian summer monsoon during the early Holocene, which follows the insolation curve for the wettest summer month (Fig. 4). Noticeable inconsistencies between records from 25°N – 8°N and records from 4°N – 8°S are, however; observed for the mid-Holocene. Klang Cave stalagmite $\delta^{18}\text{O}$ values increase rapidly from 7.0 to 6.0 kyr BP, suggesting a shift towards relatively dry conditions in the northern central Indo-Pacific region. A comparable shift in speleothem $\delta^{18}\text{O}$ can be found in Dongge Cave from 7.0 to 6.2 kyr BP (Y. Wang et al., 2005) and from 5.8 to 5.2 kyr BP (Dykoski et al., 2005), and in Mawmluh Cave at 7.0–6.5 kyr BP (Dutt et al., 2015) and 6.0–5.8 kyr BP (Berkelhammer et al., 2013). The sediment sequences of Lake Kumphawapi (17°N; location in Fig. 1) in northeast Thailand also showed multiple hiatuses between 6.5 and 1.4 kyr BP, which are explained by periodic and severe dry time intervals affecting the wetland (Chawchai et al., 2016, 2013; Wohlfarth et al., 2016). A recent study of stalagmite $\delta^{18}\text{O}$ from Laos indicated megadrought in Mainland Southeast Asia between 5 and 3 kyr BP (Griffiths et al., 2020), which could be the possible reason of the observed hiatus at 5.23–2.73 kyr BP in the Klang Cave record (Fig. 2 and 4). Griffith et al (2020) suggested a major decrease of monsoon rainfall in Mainland Southeast Asia during the mid- to late Holocene, coincident with African monsoon failure during the end of the Green Sahara (Pausata et al., 2020; Shanahan et al., 2015; Tierney et al., 2017; Tierney and deMenocal, 2013). The drying of the Sahara reduced vegetation and increased dust loads shifted the Walker circulation eastward and cooled the Indian Ocean. Previous studies also suggested that warm SSTs in the eastern Pacific shifted the Walker circulation cell eastward, cooled and reduced atmospheric convergence in the eastern Indian Ocean (e.g. Abram et al., 2009; Berry and Reeder, 2013; Tian et al., 2017), causing a reduction in rainfall in the ISM regions during the mid-Holocene.

In contrast, the stalagmite $\delta^{18}\text{O}$ records south of Klang Cave, such as Northern Borneo, Sumatra, Sulawesi, and Flores between 4°N – 8°S, generally display opposite oscillations during the same period. Stalagmite $\delta^{18}\text{O}$ data from Flores show a distinct anti-phase development to Klang $\delta^{18}\text{O}$ record between 7.0 and 6.0 kyr BP. The hydroclimate changes recorded in Klang Cave (8°N) and in Secret Cave from Northern Borneo (4°N) show opposite patterns during the early and middle Holocene, but a similar trend during the late Holocene. For the early and middle Holocene, Secret Cave and records from the southern Indo-Pacific region indicated wet conditions, which implies the climatic equator (mean position of the ITCZ) maintained a position between 4–8 °N. The in-phase variations of the two records during the late Holocene indicate the climatic equator move further south of 4°N due to the declined northern hemisphere summer insolation.”

Furthermore, in the ITCZ shift index record, the amplitude of 8.2-ka event is the same as other oscillations, and even smaller than that of some oscillations during the late Holocene. Why the 8.2-ka event was not as prominent as in the $\delta^{18}\text{O}$ record? Is there any other explanation for this?

Reply: Regarding for the small amplitude of 8.2 ka in the derived ITCZ index, we believe that it is largely due to the bias caused by low resolution of the Liang Luar records. The ITCZ index is calculated from the subtraction between Klang Cave record and the Liang Luar record. Unfortunately, the Liang Luar record has lower resolution (~50 yrs/data point) from ~6.2 ka to 8.4 ka, and is particularly “zigzag” around 8.2 ka, largely due to low signal-noise ratio.

While the ITCZ index is admittedly in low resolution around 6.2-8.4 ka, we want to emphasize that the index does capture the broad picture of how ITCZ moves during a major portion of the Holocene on millennial scale.

We added related discussion in **Section 5.2** *“However, the Liang Luar record has a lower resolution (~50 yrs/data point) from 8.4 to ~6.2 kyr BP. The ITCZ SI can only reflect millennial to orbital changes during this time periods.” (Lines 378-381).*

R1.4. In the abstract, it is said that "Noticeable inconsistencies among records in the Southeast Asia region (between 8°N and 4°N-8°S) have been documented on multi-centennial scales, likely resulting from the meridional shift of the intertropical convergence zone (ITCZ)." Why the meridional shift of the ITCZ could induce such inconsistency? Further explanation are necessary. Otherwise, it is a kind of baseless suspicion.

Reply: For two adjacent records, one $\delta^{18}\text{O}$ record shifting positively and another one shifting negatively, it means the ITCZ mean position is moving from the first location to the second. We revised the text as *“Noticeable inconsistencies among records in the Southeast Asia region (between 8°N and 4°N-8°S) have been documented on multi-centennial scales. Lower $\delta^{18}\text{O}$ values are likely associated with the mean position of the intertropical convergence zone (ITCZ).” (Lines 49-52)*

Other minor comments and suggestions

R1.5. Line 38, A large increase of 2‰ in $\delta^{18}\text{O}$ is observed from 7.0 to 6.0 kyr BP, indicating a millennial drought period. Here the drought should be change to 'drying', the time period from 6.0 to 5.2 could be defined as a drought period.

Reply: The text was revised in Abstract according to the comment.

R1.6. Line 104-105, "Paleoclimatic records from the northern and southern regions of Southeast Asia document anti-phased rainfall responses to orbital precessional insolation forcing." Please add the references for this sentence!

Reply: The reference was added.

R1.7. Line 121-122, the new record spans only most of early and middle Holocene and also a very short period in the late Holocene, but not the period from 11.259 to present. The description here should be precise.

Reply: Based on the comment, the text was revised as *“Here, we present a new hydroclimate record of stalagmite $\delta^{18}\text{O}$ from Klang Cave in southern Thailand (8°20'N, 98°44'E; Fig. 1) from 11.23 to 5.23 thousand year (kyr BP, before 1950 AD) combined with the published record from the same cave of Tan et al. (2019) covering the Holocene.”. (Lines 121-123).*

R1.8. Please double check the stalage outputs, it is weird that the age-depth relationship twist in between two well-dated ages in the stalagmites TK40 and TK20.

Reply: We did test run the StalAge outputs several times (Supplementary Data Fig.2A). The twist in age model is a normal feature of StalAge (also confirmed by Prof. Denis Scholz - developer of StalAge model). In addition, we also ran Bacon Age model (Supplementary Data Fig.2B).

“For stalagmite chronology, StalAge (Scholz and Hoffmann, 2011) and Bacon (Blaauw and Christen, 2011) give overlapping output results (Supplementary Data Fig. 2A, B). This consistency shows that the U-Th dated stalagmites ages are not sensitive to the choice of a

specific age-depth model. Herein, we report the ages derived from the Bacon age model."
This text has been added on **Lines 215-219**.

R1.9. In addition, it might be clear and informative to the reader if the author could indicate the dating layer and ages on the pictures of the stalagmite in figure 2.

Reply: The dating layers have been indicated in the current Supplementary Data Figure 1.

R1.10. Line 250, Wang et al., 2005 should be added for the Dongge Cave, China.

Reply: The reference was cited.

R1.11. Line 283-286, the formula [1] here is to normalize the record but not calculate the ITCZ shift index, it should be corrected.

Reply: The text was corrected accordingly.

R1.12. Line 304, "The north to south insolation differences decreased from 30 W/m² at 9.5 kyr BP to 0 W/m² at 6.0 kyr BP." Which month(s) and at what latitudes? Please clarify!

Reply: The text was revised as "*The insolation differences from north (30°N) in June to south (30°S) in December decreased from 30 W/m² at 9.5 kyr BP to 0 W/m² at 6.0 kyr BP.*"

Reviewer #2: Chawchai et al. reported a follow-up study from Klang Cave, southern Thailand, after a recent publication by Tan et al. (2019, PNAS). The authors significantly extended the record, which now covers most of the last 11,000 years. The long record from Klang Cave shares a broad similarity with other speleothem-based monsoon records in East Asia and the western Pacific region. The record also presents its unique features, e.g., a dramatic d18O positive shift at ~6.0 kyr BP, which the authors interpreted as a severe drought event. The authors continued the practice by Tan et al. (2019) and extended the ITCZ shift index. They concluded that the southward movement of the ITCZ since mid-Holocene can be tied to strengthening ENSO. I found the Klang speleothem data is of high quality, particularly in terms of U/Th dates, and ideas presented in the manuscript are also intriguing. I however have a few concerns and hope they can be addressed in the revision.

Reply: We would like to thank **Reviewer #2** for the positive statement and for the comments and suggestions to improve our manuscript.

R2.1. My major concern is that to what degree Klang speleothem d18O can be quantified as a proxy of ITCZ migration. The raining season lasts from May to November in the region. While the rains in May and September are probably driven by the ITCZ, but hardly in other months when the ITCZ is located either far north or south. As the authors acknowledged, winter monsoons and tropical cyclones can also have significant contributions to the annual rainfall in the region. I would expect Chawchai et al. to have thorough discussions here. It seems that monitoring has been done at Klang. Any studies on local rainfall and cave drip water, in particular their d18O?

Reply: We thank this reviewer for raising this important point. In the revised manuscript, we added information on local rainfall and cave drip water, and their $\delta^{18}\text{O}$ in different sections: **Section 3.4** Cave drip water and rain water monitoring; **Result Section 4.2** Cave drip water and rain water $\delta^{18}\text{O}$; **Discussion Section 5.1** Climatic significance of $\delta^{18}\text{O}$.

R2.2. Klang record resembles more closely East Asian monsoon records (e.g., Dongge records) rather than any other records from the tropical Indo-Pacific. This probably suggests that it is more appropriate to consider the record as a monsoon signal instead of ITCZ shift. The authors may argue that monsoon change and the ITCZ migration are in phase. If indeed so, the authors need to carefully elaborate their relationship, instead of arbitrarily lumping them together. Significant differences in fact exist between monsoon and the ITCZ, as the latter is mostly an oceanic feature. For example, figure 6 shows that ITCZ shift index monotonically decreases through the Holocene, also in the last 2,000 year as reported in Tan et al. (2019), but the Asian monsoon in fact becomes strengthened in the past 2,000 years (Cheng et al., 2016, Nature).

Reply: Thank **Reviewer #2** for giving this comment. Klang stalagmite $\delta^{18}\text{O}$ record reflect regional rainfall variation. This cave is located in Asian monsoon realm. It is not surprising that Klang record is similar to stalagmite records from caves located in the same Asian monsoon realm. Klang record itself cannot reveal ITCZ history. Both Klang Cave, located in northern central Indo-Pacific (NCIP), and Liang Luar Cave, located in southern CIP (SCIP), were used to reconstructed ITCZ shift index record.

R2.3. The constructing of the ITCZ shift index is not without question. The early publication by Tan et al. (2019) has done a reasonably good job to argue that ITCZ latitudinal displacement is a dominant control in causing the difference of $\text{d}18\text{O}$ between Klang and Flores speleothems. But can we safely assume this control remains throughout the Holocene?

For example, Sunda Shelf flooding and sea surface temperature change in early-mid Holocene may have different impacts on climate over the two sites. The authors talked about ENSO and IOD in the manuscripts. Do they change rainfall and rainfall $\text{d}18\text{O}$ similarly at Klang and Flores?

Figure 6 shows the two records are not mirror imaging. This suggests that one or both records recorded changes in addition to ITCZ displacement. A simple subtraction between the two $\text{d}18\text{O}$ records cannot remove these effects. It is ok to propose an index. However, once again, a careful discussion on the index, particularly caveats of the practice, would be helpful.

Reply: Thank this reviewer for pointing out this issue. Editor also raised this question. We discussed sea-level related Sunda Shelf exposure in the revised manuscript on **Lines 426-434**. We wrote: “*Hydroclimate changes based on $\delta^{18}\text{O}$ record of Klang Cave in the western margin of WPWP are dominantly associated with the ISM (Tan et al., 2019). Substantial early to mid-Holocene decreases in the $\delta^{18}\text{O}$ record of Liang Luar Cave are interpreted as an intensification of Australian–Indonesian summer monsoon rainfall in response to deglacial eustatic sea-level rise and flooding of the Sunda Shelf (Griffiths et al., 2009). This new regional ITCZ SI record (Fig. 7A) shows different trends than that of the Cariaco Basin Ti record from 11.0–7.0 kyr BP, especially around 11.0–9.5 kyr BP. This disagreement can likely be attributed to Sunda Shelf exposure due to sea level rise (Griffiths et al., 2009).*”

R2.4. The writing in the manuscript can be significantly improved. For example, in the introduction, Chawchai et al. brought up several scientific questions to be addressed in the manuscript. These questions are all important and timely. I am however surprised that the authors didn't directly address them, at least not effectively in the following discussions. For example, the first paragraph talked about the timing of the onset and strengthening and weakening of the Asian monsoon, which is somewhat unpleasantly debated in the community. I however didn't see discussions on what the Klang record can contribute to this debate. Also, the 2nd paragraph talks about the difference between the Indian summer monsoon and East Asian monsoon. Great, but how does the difference relate to the Klang

d18O interpretation? The connections are somehow missing through the text. Transitions are also needed between paragraphs.

Reply: Thank **Reviewer #2** for pointing out this. We agreed and rewritten the introduction **Lines 70-86** as based on the current discussion.

A few other comments and suggestions:

R2.5. In highlights, not necessary to claim to be the "first" to report the 8.2-ka event in stalagmite records from the tropical Indo-Pacific. The authors might indeed be the first group. However, how exactly does this speleothem d18O shift relate to the 8.2-ka event in Greenland ice cores? It is probably more important to discuss why this event only occurred in southern Thailand, but not in other speleothem records in the region. Simply sample resolution issues, or chronology problems?

Reply: We agreed and lowered down the tune regarding the identification of 8.2 ka event and remove the word "first" from the sentence in *Highlights*. "Stalagmite record of 8.2-ka event in the tropical Indo-Pacific region."

For the linkage between the 8.2 ka event recorded in Greenland ice cores and the $\delta^{18}\text{O}$ shift in our cave record, we have applied the well-accepted mechanism, i.e., through the weakening of AMOC and consequently the southward shift of the ITCZ (**Lines 233-240** in the previous submission).

For clarity, the text has been changed to "*It has been attributed to the last outburst flood from glacial Lake Agassiz (Clarke et al., 2004; Lajeunesse and St-Onge, 2008; Teller et al., 2002), which freshened North Atlantic surface waters, reduced the production of North Atlantic Deep Water and weakened the North Atlantic Meridional Overturning Circulation (AMOC). A weakened AMOC hindered the northward transportation of warm surface waters, caused a southward shift of the ITCZ and reduced Asian monsoon (Cheng et al., 2009; Tan et al., 2020), and consequently a reduction of rainfall at our cave site, which led to a positive shift of $\delta^{18}\text{O}$ in our stalagmite record.*" (**Lines 295-303**)

Regarding why 8.2-ka event has only been observed in southern Thailand, we propose that it can be largely attributed to low-resolution chronologies and sampling, and/or insensitive proxies in existing records. The clear forcing in this region could be related to several factors, e.g. the El Niño-Southern Oscillation, the Indian Ocean Dipole, and the movement of ITCZ. Due to this complexity, our current understanding of hydroclimate changes in this region is still limited. More regional records and simulations are required to address this issue in the future. (**Lines 305-312**)

R2.6. Lines 77-80, what are the exactly differences in the two monsoons? Differences can be caused by land-sea configurations.

Reply: To clarify this issue, we revised this part to "*The Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM), are the main components of the Asian monsoon system. Both interact with each other and are characterised by dissimilarities in the strengths and feedback mechanisms of the summer and winter monsoon regimes in the ISM and EASM regions caused by land-sea configurations, topography, and oceanic circulations (e.g. An et al., 2000; P. Wang et al., 2005; Wang et al., 2017; Y. Wang et al., 2005).*" (**Lines 74-80**)

R2.7. Lines 87-88, what is "It" here?

Reply: The text was corrected from "It" to "The ITCZ".

R2.8. Lines 92-93, it only affected the Atlantic ITCZ.

Reply: We agreed. The text was revised to “*For the North Atlantic, observations during the 20th century link the positions of the ITCZ to an interhemispheric heating imbalance driven by multi-decadal variability in the extratropical sea surface temperature (SST) (Green et al. 2017).*” (Lines 88-91)

R2.9. Lines 187-188. This is likely a wrong statement. Hendy test is to test whether calcite/aragonite precipitates under equilibrium conditions. This test is no longer helpful. Replication test is more robust one.

Reply: The text was revised to “*Hendy tests (Hendy, 1971) were performed on five laminae of the three stalagmites (Supplementary Data Fig. 3) and duplication tests (Dorale and Liu, 2009) were done to decipher whether the speleothems were subject to the same conditions during their growth.*” (Lines 188-191)

R2.10. Lines 202-203, need to reword.

Reply: The text was revised as “ *$\delta^{18}O$ variations of TK7 replicate TK20 during 8.35–7.34 kyr BP and show similar pattern with TK133 (published data of Tan et al., 2019) during the 2.65 to 1.67 kyr BP (Fig. 2)*” (Lines 229-231)

R2.11. Lines 301, which "insolation"? Annual, JJA, or daily? Figure 7 needs to be marked clearly accordingly.

Reply: The text was revised as “*Summer insolation over the northern extratropics (30°N) in June was much stronger between 12.0 and 9.5 kyr BP as compared to the southern extratropics (30°S) in December.*” and marked in Figure 6 in the revised manuscript.

R2.12. Figures

The quality of figures needs to be improved. QSR does not have a strict limitation in publication pages. However, some figures, if not much informative, are better to be deposited in supplementary materials.

For example, it is great that authors show stalagmite photos in Figure 2. However, the images are in rather poor quality. They need to be replaced by better images, so readers can see crystal structures more clearly. Better to move them to supplementary materials. Also helpful to mark a few U/Th dates on sample images.

Reply: The quality of Figure 2 was improved and this figure was moved to Supplementary Data Figure 1. Layers for U-Th dating were marked in the figure images.

R2.13. Figure 3 can be moved to supplementary.

Reply: Figure 3 was moved to Supplementary Data Figure 2A.

R2.14. Figure 4, A and B better also be moved to supplementary. Figure 4C however can be substantially improved, e.g., using different colors for different specimens. U/Th date symbols can be color coded as well.

Reply: Figure 4 A and B were moved to Supplementary Data Figure 3. Figure 4C has been improved in the revised manuscript as new Figure 2.

R2.15. Figure 5 also can be improved. I personally don't enjoy reading many curves in one figure. Figures need to have clean presentation, can convey a clear message.

Reply: This figure was improved as the new Figure 3 in the new manuscript.

R2.16. Table 1. ^{238}U and ^{232}Th concentrations should be in ppb and ppt, respectively. Also, "‰" unit for $\delta^{234}\text{U}$ measured and corrected initial values.

Reply: The text in Table 1 ^{238}U and ^{232}Th concentrations has been changed to ppb and ppt, respectively, and unit ‰ has been added to $\delta^{234}\text{U}$.

Highlights

- Holocene stalagmite $\delta^{18}\text{O}$ record of Thai-Malay Peninsula, southern Thailand.
- Wet conditions/strong rainfall during 11-7 kyr BP and a drying trend since 6 kyr BP.
- Stalagmite record of 8.2-ka event in the tropical Indo-Pacific region.
- A new Holocene ITCZ shift index record for the central Indo-Pacific region.

Hydroclimate variability of central Indo-Pacific region during the Holocene

Sakonvan Chawchai^{1*}, Liangcheng Tan^{2,3,4}, Ludvig Löwemark⁵, Hao-Cheng Wang^{5,6,7}, Tsai-Luen Yu^{5,6,8}, Yun-Chuan Chung^{5,6,7}, Horng-Sheng Mii⁹, Guangxin Liu¹⁰, Maarten Blaauw¹¹, Shou-Yeh Gong¹², Barbara Wohlfarth¹³, Chuan-Chou Shen^{5,6,7*}

¹ *Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA), Department of Geology, The Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand*

² *State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China*

³ *Center for Excellence in Quaternary Science and Global Change, Chinese Academy of Sciences, Xi'an 710061, China*

⁴ *Institute of Global Environmental Change, Xi'an Jiaotong University, 710049 Xi'an, China*

⁵ *Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC*

⁶ *High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC*

⁷ *Research Center for Future Earth, National Taiwan University, Taipei 10617, Taiwan, ROC*

⁸ *Marine Industry and Engineering Research Center, National Academy of Marine Research, Kaohsiung City 80661, Taiwan, ROC*

⁹ *Department of Earth Sciences, National Taiwan Normal University, Taipei 10617, Taiwan, ROC*

¹⁰ *Research Center for Earth System Science, Yunnan University, Kunming 650500, China*

¹¹ *Archaeology and Palaeoecology, School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*

¹² *Department of Geology, National Museum of Natural Science, Taichung 40419, Taiwan, ROC*

¹³ *Department of Geological Sciences, Stockholm University and Bolin Centre for Climate Research, Stockholm University, 10691 Stockholm, Sweden*

*To whom correspondence should be addressed:

Assistant Prof. Dr. Sakonvan Chawchai: Tel: 669-61611187;

E-mail: sakonvan.c@chula.ac.th

Prof. Dr. Chuan-Chou Shen: Tel: 886-2-33665878; Fax: 886-2-33651917;

E-mail: river@ntu.edu.tw

Abstract

Here we present a decadal-resolved hydroclimate record covering the past 11 thousand years based on $\delta^{18}\text{O}$ data of three stalagmites from Klang Cave (TK) on the Thai-Malay Peninsula, southern Thailand. The $\delta^{18}\text{O}$ values indicate wetter conditions/more rainfall during the early Holocene from 11 to 7 thousand years before present (kyr BP). A large increase of 2‰ in $\delta^{18}\text{O}$ is observed from 7.0 to 6.0 kyr BP, indicating a millennial drying period followed by drought conditions between 6.0 and 5.2 kyr BP. After a long hiatus (5.2–2.7 kyr BP), $\delta^{18}\text{O}$ data show a millennium-long trend toward dry conditions. An abrupt positive change of 0.8–1.0‰ in $\delta^{18}\text{O}$ is noticed between 8.29–8.17 kyr BP, reflecting the 8.2-ka event, however; the amplitude of the $\delta^{18}\text{O}$ shift is much smaller when compared to 6.0–5.2 kyr BP. On orbital time-scales, the TK record agrees with insolation-dominated speleothem records in the Asian-Australian monsoon realm. Noticeable inconsistencies among records in the Southeast Asia region (between 8°N and 4°N–8°S) have been documented on multi-centennial scales. Lower $\delta^{18}\text{O}$ values are likely associated with the mean position of the Intertropical Convergence Zone (ITCZ). A new reconstruction of Holocene ITCZ shifts index within the central Indo-Pacific region, based on stalagmite $\delta^{18}\text{O}$ records from Klang Cave (8°N) and Liang Luar Cave (8°S), shows that the ITCZ played an important role in hydroclimate variability in the Asian-Australian monsoon regions. The southward shift of the ITCZ in the central Indo-Pacific region, controlled by the interhemispheric extratropical insolation gradient, may strongly correlate with the El Niño-Southern Oscillation (ENSO) activities in the Holocene.

Keywords: Stalagmite; Thai-Malay Peninsula; Holocene; ITCZ; central Indo-Pacific region

63 **Highlights**

- 64 • Holocene stalagmite $\delta^{18}\text{O}$ record of Thai-Malay Peninsula, southern Thailand.
- 65 • Wet conditions/strong rainfall during 11-7 kyr BP and a drying trend since 6 kyr BP.
- 66 • [Stalagmite record of 8.2-ka event in the tropical Indo-Pacific region.](#)
- 67 • A new Holocene ITCZ shift index record for the central Indo-Pacific region.
- 68

1. Introduction

Numerous geological and biological records, including loess, lake sediments, peat and stalagmites, showed that the strength of the Asian summer monsoon during the Holocene followed insolation patterns, with an increased summer monsoon intensity during the early Holocene and a gradual decline from the mid-Holocene onwards (e.g. Kutzbach, 1981; P. Wang et al., 2005; Y. Wang et al., 2005). The Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM) are the main components of the Asian monsoon system. Both interact with each other and are characterised by dissimilarities in the strengths and feedback mechanisms of the summer and winter monsoon regimes in the ISM and EASM regions, caused by land-sea configurations, topography, and oceanic circulations (e.g. An et al., 2000; Li et al., 2019; P. Wang et al., 2005; Wang et al., 2017; Y. Wang et al., 2005). The boundary between the ISM and EASM regions is generally set at around 105°E (Wang et al., 2003; P. Wang et al., 2005). A further component of the monsoon system is the Intertropical Convergence Zone (ITCZ), which refers to the monsoon trough and trade wind convergence zone and corresponds to the location of maximum persistent rainfall. The ITCZ plays an important role for hydroclimate variability in the Asian monsoon regions (Chao and Chen, 2001; Clift and Plumb, 2008; Gadgil, 2018; Wang, 2009).

Nowadays, a significant annual displacement (summer/winter) of the ITCZ can be observed over the Indian Ocean and the western Pacific Warm Pool (WPWP). For the North Atlantic, observations during the 20th century link the positions of the ITCZ to an interhemispheric heating imbalance driven by multi-decadal variability in the extratropical sea surface temperature (SST) (Green et al. 2017). For Asia, several studies suggested that the position and expansion of the ITCZ over land in the Asian monsoon region are inter-related with monsoon rains and that its mean northward extent is influenced by the strength in summer monsoon (Chiang and Friedman, 2012; Dallmeyer et al., 2013; Fleitmann et al., 2007; Schneider et al., 2014; Yancheva et al., 2007). Over the Pacific Ocean, the ITCZ migrates between 9°N in boreal summer and 2°N in boreal winter, whereas over the Indian Ocean and adjoining land surfaces, the ITCZ shifts between 20°N in boreal summer and 8°S in boreal winter during the observed period (Schneider et al., 2014). However, in paleorecords the ITCZ shifts reached over 25°N in the WPWP (e.g. Liu et al., 2015; Wang et al., 2008; Yancheva et

al., 2007). Annual changes in the migration of the ITCZ therefore strongly affect the regional hydroclimate in large parts of Southeast Asia.

Paleoclimatic records from the northern and southern regions of Southeast Asia document anti-phased rainfall responses to orbital precessional insolation forcing (Griffiths et al., 2020, 2009; Krause et al., 2019; Tan et al., 2019; Wu et al., 2020). Millennial-scale climate events detected by various proxies have been interpreted as latitudinal shifts of the ITCZ during the last deglaciation and the Holocene (e.g. Ayliffe et al., 2013; Chawchai et al., 2013; Denniston et al., 2013; Tan et al., 2019; Tierney et al., 2010; Wurtzel et al., 2018). However, the spatial distribution of paleoclimatic records used for most of these studies are from north of 25°N and from the Indo-Pacific equatorial region, with few records between 5–20°N in the ISM dominated tropics.

The Thai-Malay Peninsula is located between the Indian and Indo-Pacific climate systems. Recently, Tan et al. (2019) suggested that rainfall variations during the last 2,700 years were in-phase between Thai-Malay Peninsula and southern Indo-Pacific region on centennial-to decadal time scales, despite their anti-phase variations on orbital- to suborbital-scales. These results highlight the ITCZ's influence on regional precipitation changes, despite of the impact of the El Niño-Southern Oscillation (ENSO). A better knowledge of how climate varied in the past in this region could thus enhance insight into the interactions between ISM and the western Indo-Pacific Warm Pool (IPWP) over longer timescales.

Here, we present a new hydroclimate record of stalagmite $\delta^{18}\text{O}$ from Klang Cave in southern Thailand (8°20'N, 98°44'E; Fig. 1) from 11.23 to 5.23 thousand year (kyr BP, before 1950 AD) combined with the published record from the same cave of Tan et al. (2019) covering the Holocene. This site fills an important gap in the spatial distribution of tropical paleoclimatic records north of the present-day mean position of the ITCZ (~3°N), and could further develop our understanding of hydroclimate changes, regional differences, and the dynamics in tropical/subtropical Asian monsoon areas.

2. Regional settings

Klang Cave (8°1'N, 98°48'E) is located in the Ao-Luek District, Krabi Province, Thai-Malay Peninsula, southern Thailand (Fig. 1A & C). The regional tower karst developed in the massive Permian limestone and dolomitic limestone of the Ratburi Group (Department of Mineral Resources, 2013). The present-day climate in the region

is characterized by the ISM, the northeast winter monsoon, the ITCZ, and by tropical cyclones from the South China Sea (Thai Meteorological Department, 2017). ISM rainfall occurs during the rainy season, mostly from May to October. The first arrival of the ITCZ to southern Thailand is usually in May. Afterward it moves northwards and is situated across southern China from around June to early July. The ITCZ then moves south again and is located over southern Thailand in September and October. The northeast winter monsoon generally causes abundant regional rainfall in November. The east coast of Thai Peninsula receives additional moisture during the winter monsoon. However, the Khao Luang Mountain Range situated in the middle part of the Peninsula blocks moist air from reaching the west coast where Klang Cave is situated.

Tropical cyclones occur occasionally in October and November. The National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model ensembles depict air-parcel/moisture transport routes, highlighting the contrast between summer monsoon (May-October) and winter monsoon (November-April) seasons (Tan et al., 2019). Mean annual temperatures in Krabi range from 26.5 °C in winter to 28.5 °C in summer and annual precipitation amounts to 2,000–2,800 mm (2010–2018 AD) (Fig. 1B).

3. Materials and methods

3.1. Cave setting and stalagmite sampling

Our first survey of Klang Cave (1100-m-long main passageway) was conducted in 2010. Cave air temperature data were recorded from April 2011 to August 2012 by six temperature loggers, Maxim DS1921H High-Resolution Thermochron®iButton, installed at locations 100–300 m from the cave entrance. The inner part of the cave, 50 m from the entrance, is well enclosed with >95% humidity and a steady cave temperature of 23 °C. The consistency of the temperature records between the six measuring sites indicates a uniform thermal condition in the cave system (Tan et al., 2019). Three broken aragonite stalagmites, TK7, TK20, and TK40 (90–140 cm in length, 4–10 cm in diameter), were collected in 2010 in a chamber 400 m from the cave entrance (Supplementary Data Fig. 1).

3.2. Chronology

The three stalagmites were cut into halves along their growth axes and polished. X-ray diffraction (XRD) analysis at 6 depths (Supplementary data Fig. 1) show that all stalagmites are composed of pure aragonite without mineral transformation. A total of 33 layers, 19, 8 and 6 layers for TK7, TK20 and TK40, respectively, were drilled for U-Th dating (Table 1). U and Th contents and isotopic compositions were analyzed using a multi-collector inductively coupled mass spectrometer, Thermo NEPTUNE, at the High Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), National Taiwan University (NTU) (Shen et al., 2012). The half-lives of the nuclides used for age calculations are given in Cheng et al. (2013). Uncertainties in isotopic data and ^{230}Th dates, relative to 1950 AD, are given at the two-sigma (2σ) level or two standard deviations of the mean ($2\sigma_m$). Both Monte Carlo approach simulated age models StalAge (Scholz and Hoffmann, 2011) and Bacon (Blaauw and Christen, 2011) were used to evaluate the chronology for each stalagmite.

3.3. Stable Isotope Analysis

For $\delta^{18}\text{O}$ isotopic analysis, subsamples were drilled with a hand-held driller from the central axis at 3-mm resolution for TK7 and TK20 and at 10-mm resolution for TK40. Oxygen isotopic ($\delta^{18}\text{O}$) profiles were measured on 701 subsamples on a Thermo MAT 253 isotope ratio mass spectrometer (IRMS) at the Department of Geosciences, NTU, and a Micromass IsoPrime IRMS at the Department of Earth Science, National Taiwan Normal University (NTNU). $\delta^{18}\text{O}$ values are reported in per mil (‰), relative to the Vienna PeeDee Belemnite (VPDB) (Supplementary Data Table 1) and standardization was accomplished using NBS-19 ($\delta^{18}\text{O} = -2.20\text{‰}$). Hendy tests (Hendy, 1971) were performed on five laminae of the three stalagmites (Supplementary Data Fig. 3) and duplication tests (Dorale and Liu, 2009) were done to decipher whether the speleothems were subject to the same conditions during their growth.

3.4 Cave drip water and rain water monitoring

Cave drip water samples were collected daily from active stalactites in the deeper chambers of the Klang Cave system from two periods covering parts of the summer monsoon season during August 16th to September 30th, and parts of the winter monsoon season during October 1st to December 31st in 2013. Rain water samples were collected daily for the same period at the meteorological station at Krabi Airport,

Thailand. For δD and $\delta^{18}\text{O}$ analysis, water samples were collected in 100-ml plastic bottles and tightly sealed to prevent any isotopic alterations due to evaporation. Both cave drip water and rain water samples were analysed in a Picarro L2130-i Isotopic H_2O Analyzer at the Institute of Earth Sciences, Academia Sinica, in Taiwan. The analytical details were following the method for cavity ring-down spectroscopy (Brand et al., 2009; Laskar et al., 2014). δD and $\delta^{18}\text{O}$ values are expressed as ‰ in relative to VSMOW. The precisions of the measurements, evaluated on standards, were better than 1‰ for δD and 0.1‰ for $\delta^{18}\text{O}$.

4. Results

4.1. Chronology and Stalagmite $\delta^{18}\text{O}$

U-Th isotopic data and ages are listed in Table 1. Stalagmites show high uranium contents of up to 16 ppm and low thorium values as low as 21 ppt, which allows for precise U-Th dating with an age uncertainty of ± 6 –43 years. All dates are in stratigraphic order. Two U-Th ages of 2758 ± 20 and 5255 ± 37 yr BP at depths of 18 and 28 mm of stalagmite TK7 indicate that a dark layer at 21 mm is a hiatus (Supplementary Data Fig. 1). For stalagmite chronology, StalAge (Scholz and Hoffmann, 2011) and Bacon (Blaauw and Christen, 2011) give overlapping output results (Supplementary Data Fig. 2A, B). This consistency shows that the U-Th dated stalagmites ages are not sensitive to the choice of a specific age-depth model. Herein, we report the ages derived from the Bacon age model. Within 95% certainty of the age model, stalagmite TK7 grew between 8.35–1.67 kyr BP with a likely hiatus from 5.23–2.73 kyr BP. Stalagmites TK20 and TK40 are dated to 8.88–7.34 and 11.23–8.84 kyr BP, respectively. The high growth rates of 0.3–0.5 mm/yr for TK7, TK20 and TK40 allow the reconstruction of decadal-scale stable isotope records between 11.23 and 5.23 kyr BP (Fig. 2).

The Hendy Test (Hendy, 1971) shows similar coeval $\delta^{18}\text{O}$ values with small variations of ± 0.02 –0.08‰ for all three stalagmites from the centre to the rim of the same layer (Supplementary Data Fig. 3A, B). Systematic offsets between stalagmite $\delta^{18}\text{O}$ records in Klang Cave were reported in Tan et al. (2019). Similar oxygen isotopic discrepancies are not noticeable in this study. $\delta^{18}\text{O}$ variations of TK7 replicate TK20 during 8.35–7.34 kyr BP and show similar pattern with TK133 (published data of Tan et al., 2019) during the 2.65 to 1.67 kyr BP (Fig. 2). The uppermost TK40 $\delta^{18}\text{O}$ values

of -6.03‰ at 8.840 kyr BP match the lowermost $\delta^{18}\text{O}$ values of TK20 between 8.840–8.878 kyr BP (Fig. 2; Supplementary Data Table 1). These agreements indicate that TK7, TK20 and TK40 were most likely deposited under isotopic equilibrium and allow presenting the three records combined.

The combined Holocene TK $\delta^{18}\text{O}$ values range from -7.09 to -4.04‰ (Fig. 2). $\delta^{18}\text{O}$ values of TK40 gradually decreased from -5‰ at 11.23 kyr BP to -7‰ at 10.0 kyr BP. Between 10.0 and 7.0 kyr BP, $\delta^{18}\text{O}$ values range from -7.0 to -5.4‰, but notably relatively high $\delta^{18}\text{O}$ values of $\sim$ -5.7‰ is observed between 8.3 and 8.2 kyr BP.

The composite $\delta^{18}\text{O}$ record in Figure 2 exhibits large changes of $\sim$ 2‰ from 7.0 to 6.0 kyr BP and remain higher than the mean value between 6.0–5.2 kyr BP. Also, color changes are observed in stalagmite petrography during this time period (Supplementary Data Fig. 1). After the hiatus between 5.2 and 2.7 kyr BP, a millennium-long trend to high $\delta^{18}\text{O}$ values of -2.7 to -3.5‰ is recorded in TK133 (Tan et al., 2019).

4.2 Cave drip water and rain water $\delta^{18}\text{O}$

The $\delta^{18}\text{O}$ values of cave drip water for the first period (August-September), roughly corresponding to the latter part of the summer monsoon, display relatively small variability from -7.5 to -3.6‰ with an average of -5.5‰, while the second period (October-December) displays larger variability with values from -6.6 to -0.8‰ and an average of -4.4 ‰ (Fig. 3A). The observed isotopic averages of cave drip water are close to the amount weighted $\delta^{18}\text{O}$ of precipitation of the entire study period (-5.4‰) (Fig. 3B), but do not show any direct relationship to the amount of weighted monthly variations in $\delta^{18}\text{O}$ in precipitation. The isotopic composition of the cave drip water also falls close to the global meteoric water line (GMWL) (Fig. 3C).

5. Discussion

5.1 Climatic significance of $\delta^{18}\text{O}$

The close agreement between drip water $\delta^{18}\text{O}$ at Klang Cave and amount-weighted $\delta^{18}\text{O}$ precipitation suggests that the water recharging the aquifer that feeds the cave is hardly influenced by evaporative processes. While the residence time of the ground water in the aquifer above the cave is unknown, observations in the cave show that drip water increases within hours of major rain events. In particular, several intense

rain events appear to have left distinct imprints in the cave drip water record with a lag of one to two weeks. For example, the powerful storms that struck the peninsula on September 12th and November 21st 2013 seem to have been recorded as distinct depletions in the cave drip water around September 28th and November 25th, respectively (Fig. 3). Therefore, we assume that Klang Cave drip water $\delta^{18}\text{O}$ values generally reflect seasonal or yearly averages precipitation $\delta^{18}\text{O}$.

Negative correlations between monthly rainfall amount and precipitation $\delta^{18}\text{O}$ ($r = -0.64$, $P < 0.01$), as well as between the amount of annual rainfall and weighted mean precipitation $\delta^{18}\text{O}$ ($r = -0.58$, $P < 0.01$), are observed at the Bangkok GNIP station, the longest Global Network of Isotopes in Precipitation station (GNIP) in Thailand (http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html). In addition, the recent study of isotopic composition of precipitation across Thailand during 2013–2015 showed that the lower values of $\delta^{18}\text{O}$ in southern Thailand during December–February and March–May are attributable to the precipitation amount effect dominated by oceanic moisture (Laonamsai et al., 2020). Tan et al. (2019) suggested that local precipitation, as well as the convection and rainfall upstream of Klang Cave could affect the precipitation/stalagmite $\delta^{18}\text{O}$ in this region. As a result, we followed Tan et al. (2019) to interpret the new stalagmite $\delta^{18}\text{O}$ record from Klang Cave as reflecting the rainfall variations in the northern central Indo-Pacific region, with a negative $\delta^{18}\text{O}$ shift representing high amounts of rainfall, and vice versa.

5.2. Holocene rainfall variations and regional comparisons

During the early Holocene, from 11.2–10.0 kyr BP, the combined TK $\delta^{18}\text{O}$ data set shows a general trend towards relatively wetter conditions. The record features a millennial-scale trend towards drier conditions, punctuated by an abrupt enrichment of 0.8–1.0‰ in $\delta^{18}\text{O}$ between 8.3 and 8.2 kyr BP, which could be an expression of the 8.2-ka event (Cheng et al., 2009; Dixit et al., 2014). Increasing $\delta^{18}\text{O}$ values between 7.0 and 5.2 kyr BP reflect overall drying conditions. The increase of ~1.5‰ in $\delta^{18}\text{O}$ is particularly abrupt and prominent at 6.0 kyr BP.

The 8.2-ka event is a noticeable climate event recorded in Greenland ice cores (Rohling and Pälike, 2005; Thomas et al., 2007) and in many paleorecords from across the globe (e.g. Morrill and Jacobsen, 2005; Jin et al., 2007). It has been attributed to the last outburst flood from glacial Lake Agassiz (Clarke et al., 2004; Lajeunesse and St-

Onge, 2008; Teller et al., 2002), which freshened North Atlantic surface waters, reduced the production of North Atlantic Deep Water and weakened the North Atlantic Meridional Overturning Circulation (AMOC). A weakened AMOC hindered the northward transportation of warm surface waters, caused a southward shift of the ITCZ and reduced Asian monsoon (Cheng et al., 2009; Tan et al., 2020), and consequently a reduction of rainfall at our cave site, which led to a positive shift of $\delta^{18}\text{O}$ in our stalagmite record.

The impact of the 8.2-ka event has however remained elusive in the tropical Indo-Pacific region (Chabangborn et al., 2020). Regarding why 8.2-ka event has only been observed in southern Thailand, we propose that it can be largely attributed to low-resolution chronologies and sampling, and/or insensitive proxies in existing records. The clear forcing in this region could be related to several factors, e.g. the El Niño-Southern Oscillation, the Indian Ocean Dipole, and the movement of ITCZ. Due to this complexity, our current understanding of hydroclimate changes in this region is still limited. More regional records and simulations are required to address this issue in the future. Our record clearly identifies the 8.2-ka event and provides evidence that teleconnections between abrupt climate shifts in the North Atlantic and tropical Indo-Pacific climate existed not only during glacial periods (Cheng et al., 2009; Chiang and Friedman, 2012; Gupta et al., 2003), but also during the Holocene.

The shift of stalagmite $\delta^{18}\text{O}$ at ~ 6.00 kyr BP indicates a non-linear response to insolation forcing. To infer spatial patterns of the hydroclimate variability in the central Indo-Pacific region, Figure 4 shows a comparison of Klang Cave data set with speleothem records available in the Asian monsoon region, including (1) Dongge Cave, China (Wang et al., 2005; Dykoski et al., 2005), (2) Mawmluh Cave, India (Berkelhammer et al., 2013; Dutt et al., 2015), (3) Tham Doun Mai Cave, Laos (Griffiths et al., 2020), (4) Secret Cave, Northern Borneo (Carolin et al., 2013; Partin et al., 2007), (5) Tangga Cave, Sumatra (Wurtzel et al., 2018), (6) Gempa Bumi Cave, Sulawesi (Krause et al., 2019), and (7) Liang Luar Cave, Flores, Indonesia (Ayliffe et al., 2013; Griffiths et al., 2009) (see locations in Fig. 1).

The records between 25°N and the Indo-Pacific equatorial region indicate strong rainfall and strengthening of the Asian summer monsoon during the early Holocene, which follows the insolation curve for the wettest summer month (Fig. 4). Noticeable inconsistencies between records from $25^{\circ}\text{N} - 8^{\circ}\text{N}$ and records from $4^{\circ}\text{N} - 8^{\circ}\text{S}$ are, however; observed for the mid-Holocene. Klang Cave stalagmite $\delta^{18}\text{O}$ values increase

rapidly from 7.0 to 6.0 kyr BP, suggesting a shift towards relatively dry conditions in the northern central Indo-Pacific region. A comparable shift in speleothem $\delta^{18}\text{O}$ can be found in Dongge Cave from 7.0 to 6.2 kyr BP (Y. Wang et al., 2005) and from 5.8 to 5.2 kyr BP (Dykoski et al., 2005), and in Mawmluh Cave at 7.0–6.5 kyr BP (Dutt et al., 2015) and 6.0–5.8 kyr BP (Berkelhammer et al., 2013). The sediment sequences of Lake Kumphawapi (17°N; location in Fig. 1) in northeast Thailand also showed multiple hiatuses between 6.5 and 1.4 kyr BP, which are explained by periodic and severe dry time intervals affecting the wetland (Chawchai et al., 2016, 2013; Wohlfarth et al., 2016). A recent study of stalagmite $\delta^{18}\text{O}$ from Laos indicated megadrought in Mainland Southeast Asia between 5 and 3 kyr BP (Griffiths et al., 2020), which could be the possible reason of the observed hiatus at 5.23–2.73 kyr BP in the Klang Cave record (Fig. 2 and 4).

Griffith et al (2020) suggested a major decrease of monsoon rainfall in Mainland Southeast Asia during the mid- to late Holocene, coincident with African monsoon failure during the end of the Green Sahara (Pausata et al., 2020; Shanahan et al., 2015; Tierney et al., 2017; Tierney and deMenocal, 2013). The drying of the Sahara reduced vegetation and increased dust loads shifted the Walker circulation eastward and cooled the Indian Ocean. Previous studies also suggested that warm SSTs in the eastern Pacific shifted the Walker circulation cell eastward, cooled and reduced atmospheric convergence in the eastern Indian Ocean (e.g. Abram et al., 2009; Berry and Reeder, 2013; Tian et al., 2017), causing a reduction in rainfall in the ISM regions during the mid-Holocene.

In contrast, the stalagmite $\delta^{18}\text{O}$ records south of Klang Cave, such as Northern Borneo, Sumatra, Sulawesi, and Flores between 4°N – 8°S, generally display opposite oscillations during the same period. Stalagmite $\delta^{18}\text{O}$ data from Flores show a distinct anti-phase development to Klang $\delta^{18}\text{O}$ record between 7.0 and 6.0 kyr BP. The hydroclimate changes recorded in Klang Cave (8°N) and in Secret Cave from Northern Borneo (4°N) show opposite patterns during the early and middle Holocene, but a similar trend during the late Holocene. For the early and middle Holocene, Secret Cave and records from the southern Indo-Pacific region indicated wet conditions, which implies the climatic equator (mean position of the ITCZ) maintained a position between 4–8 °N. The in-phase variations of the two records during the late Holocene indicate

the climatic equator move further south of 4°N due to the declined northern hemisphere summer insolation.

5.2. A new record of Holocene ITCZ shift index for the central Indo-Pacific region

Over the Holocene, sea level and topography have not been the main factors controlling the hydroclimate change. Instead, insolation appears to be the most important forcing to drive shifts in the position of ITCZ (Tan et al., 2019, and references therein). We used the formula [1] in Tan et al. (2019) to normalize the Klang Cave $\delta^{18}\text{O}$ record (TK) at 8°N and the stalagmite $\delta^{18}\text{O}$ record (LL) of Liang Luar Cave from 8°S.

$$x^* = (x - x_{\min}) / (x_{\max} - x_{\min}), \quad [1]$$

where x is the original $\delta^{18}\text{O}$ value, $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the time series, respectively, and x^* is the normalized data. The ITCZ shift index (SI) was constructed by subtracting the LL record (Fig. 5D) from the TK record (Fig. 5B) (with a 10-yr moving average of normalized data based on different age uncertainties and proxy resolutions). However, the Liang Luar record has a lower resolution (~50 yrs/data point) from 8.4 to ~6.2 kyr BP. The ITCZ SI can only reflect millennial to orbital changes during this time periods. The calculated ITCZ SI record is plotted in Figure 5E.

Relative negative (positive) ITCZ SI values represent more (less) rainfall in the northern central Indo-Pacific as compared to the southern central Indo-Pacific, indicating a northward (southward) shift of the central Indo-Pacific ITCZ during the Holocene (Fig. 5E). The newly reconstructed ITCZ SI record shows that the mean position of the ITCZ in the central Indo-Pacific region maintained its northernmost position between 11.3 and 9.5 kyr BP. Thereafter, it continuously shifted to the south, with centennial- to decadal-fluctuations toward present day (Fig. 5E). The orbital-scale change of the ITCZ in the central Indo-Pacific during the Holocene follows the insolation differences between the extratropical northern and southern hemispheres (Fig. 6A, C), supporting the atmospheric energy balance of the ITCZ mechanism (Schneider et al., 2014). Summer insolation over the northern extratropics (30°N) in June was much stronger between 12.0 and 9.5 kyr BP as compared to the southern extratropics (30°S) in December. This led to a persistent northward cross-equatorial energy flux, resulting in the northernmost ITCZ mean positions in the central Indo-

Pacific region. The insolation differences from north (30°N) in June to south (30°S) in December decreased from 30 W/m^2 at 9.5 kyr BP to 0 W/m^2 at 6.0 kyr BP. After that, insolation in the southern extratropics began exceeding that in the northern part (Fig. 6C), which led to the southward shift of the ITCZ (Fig. 6A).

The orbital-scale southward shift of the ITCZ in the central Indo-Pacific region corresponds to enhanced ENSO activities in the Pacific (Moy et al., 2002) since the mid-Holocene (Fig. 6A, D). Both proxy data and model studies have shown an increase in ENSO activities during the mid-Holocene (6–5 kyr BP) (Clement et al., 2000; Donders et al., 2008; Liu et al., 2000) and a shift toward a more El Niño-like climate state (Chiang et al., 2009; Emile-Geay et al., 2016; Koutavas and Joannides, 2012). Similar conditions - a southward mean position of the ITCZ and enhanced El Niño conditions - are also observed for the last 2 thousand years, i.e. that during the early Medieval Warm Period and the Current Warm Period (Tan et al., 2019). During the strong El Niño events of 1983 and 1998 AD, the ITCZ in the Indo-Pacific also moved to the south (Liu et al., 2012).

Our ITCZ SI record is generally consistent with the ITCZ shift in the tropical Atlantic reconstructed using the Ti content in marine sediments from the Cariaco Basin (10°N , 65°W) (Fig. 6A, B) (Haug et al., 2001). Both records show a long-term southward movement of the mean ITCZ position during the Holocene, which points to coherent variations of ITCZ in the central Indo-Pacific and in the tropical Atlantic. However, discrepancies existed during the early Holocene. The ITCZ in the tropical Atlantic shifted to the north since the beginning of the Holocene to 9.5 kyr BP (its northernmost position) and moved southward thereafter (Fig. 6B). We speculate that the out-of-phase response of the ITCZ in the tropical Atlantic to the insolation was caused by the relative cold sea surface temperature at 12–10 kyr BP in the north Atlantic. Reconstructions reveal an increasing SST in the north Atlantic during the early Holocene (Fig. 6E) (Bard et al., 2000; Jiang et al., 2015). This may explain the increased energy export to the north Atlantic, resulting in a northward shift of the ITCZ in tropical Atlantic region (Schneider et al., 2014). However, on millennial time scales, the dynamics of the eastern equatorial Pacific may differ from the western equatorial Pacific (Trenberth and Stepaniak, 2001). Hydroclimate changes based on $\delta^{18}\text{O}$ record of Klang Cave in the western margin of WPWP are dominantly associated with the ISM (Tan et al., 2019). Substantial early to mid-Holocene decreases in the $\delta^{18}\text{O}$ record of Liang Luar Cave are interpreted as an intensification of Australian–Indonesian summer

monsoon rainfall in response to deglacial eustatic sea-level rise and flooding of the Sunda Shelf (Griffiths et al., 2009). This new regional ITCZ SI record (Fig. 7A) shows different trends than that of the Cariaco Basin Ti record from 11.0–7.0 kyr BP, especially around 11.0–9.5 kyr BP. This disagreement can likely be attributed to Sunda Shelf exposure due to sea level rise (Griffiths et al., 2009).

6. Conclusions

A new composite stalagmite $\delta^{18}\text{O}$ record from Klang Cave, southern Thailand, allows reconstructing regional Holocene hydroclimate variability. Klang Cave $\delta^{18}\text{O}$ values are consistent with the characteristic speleothem records from the Asian monsoon domain and show an increasing trend throughout the Holocene, which is related to the decline of northern hemisphere summer insolation, indicating decreasing rainfall in the northern central Indo-Pacific region. The new stalagmite $\delta^{18}\text{O}$ data set reveals stronger rainfall between 11.23–7.00 kyr BP; dry conditions between 8.3–8.2 and between 7.0–5.2 kyr BP, and a multi-centennial scale trend toward drier conditions for the last 2.7 kyr BP. The 8.2-ka event could be clearly identified in the tropical Indo-Pacific region, indicating a teleconnection of abrupt climate shifts with the North Atlantic region. The reconstructed Holocene ITCZ shift index suggests that the mean location of the ITCZ in the central Indo-Pacific region maintained its northernmost position between 11.2 and 9.5 kyr BP, but moved to the south of 4°N during the late Holocene. The ITCZ variations in the central Indo-Pacific are generally consistent with those in the tropical Atlantic, except for the early Holocene period. Although ENSO may have influenced tropical rainfall dynamics after the mid-Holocene, the effects of ITCZ/insolation forcing, and ENSO are difficult to disentangle.

Credits authorship contribution statement

C-C.S. and B.W. supervised the project and provided resources. S.C. wrote the original draft and made all figures with help from L.T., C-C.S. and B.W. S.C., L.L. and C-C.S. investigated and conducted a field survey and sampling. S.C. and H-C.W. performed sample preparation and Hendy Test. H-C.W., T-L.Y., Y.-C.C. and H-S.M. did U-Th dating and isotope analysis. G.L., M.B. and S-Y.G. contributed some ideas and helped to improve the manuscript. All authors discussed the results, reviewed and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure captions

Figure 1: (A) Locations of Klang Cave (red star) and other sites: (1) Dongge Cave, China [25°N, 108°E] (Dykoski et al., 2005; Y. Wang et al., 2005), (2) Mawmluh Cave, India [25°N, 91°E] (Berkelhammer et al., 2013; Dutt et al., 2015), (3) [Tham Doun Mai Cave, Laos \[20°N, 102°E\] \(Griffiths et al., 2020\)](#), (4) Secret Cave, Northern Borneo [4°N, 114°E] (Carolin et al., 2013; Partin et al., 2007), (5) Tangga Cave, Sumatra [0°21'S, 100°E] (Wurtzel et al., 2018), (6) Gempa Bumi Cave, Sulawesi [5°S, 120°E] (Krause et al., 2019) and (7) Liang Luar Cave, Flores, Indonesia [8°S, 120°E] (Ayliffe et al., 2013; Griffiths et al., 2009), and lake sediment (8) Lake Kumphawapi [17°N, 102°E] (Chawchai et al., 2016, 2013; Wohlfarth et al., 2016). **(B)** Mean monthly rainfall

and temperatures (2010-2018 AD) for Krabi airport station, situated 45 km SE of Klang Cave. (C) A chamber with speleothem 50 m from the entrance of Klang Cave.

Figure 2: Integrated $\delta^{18}\text{O}$ records of TK7, TK20 and TK40 (this study), and of TK133 (Tan et al., 2019). U-Th ages and errors are color-coded by stalagmite.

Figure 3: (A) Cave drip water $\delta^{18}\text{O}$ during August-December 2013. (B) Rainwater $\delta^{18}\text{O}$ during August-December 2013 and (C) Stable isotope composition of drip water compared to Global Meteoric Water Line (GMWL). Inset map shows simplified outline of Klang Cave and the position of the drip water sampling station. Blue bars in (B) indicate weighted monthly average $\delta^{18}\text{O}$.

Figure 4: Comparison of stalagmite $\delta^{18}\text{O}$ records between Klang Cave and (A) Dongge Cave, China (Dykoski et al., 2005; Y. Wang et al., 2005); (B) Mawmluh Cave, India (Berkelhammer et al., 2013; Dutt et al., 2015); (C) Tham Doun Mai Cave, Laos (Griffiths et al., 2020); (D) Klang Cave (This study); (E) Secret Cave, Northern Borneo (Carolin et al., 2013; Partin et al., 2007); (F) Tangga Cave, Sumatra (Wurtzel et al., 2018); (G) Gempa Bumi Cave, Sulawesi (Krause et al., 2019) and (H) Liang Luar Cave, Flores, Indonesia (Ayliffe et al., 2013; Griffiths et al., 2009). See also location in Figure 1A.

Figure 5: Reconstruction of the ITCZ Shift Index (SI) for the Holocene. (A) Composite TK $\delta^{18}\text{O}$ record. (B) Normalized annual TK $\delta^{18}\text{O}$ record. (C) Original $\delta^{18}\text{O}$ record Liang Luar Cave (LL) from Flores, Indonesia (Ayliffe et al., 2013; Griffiths et al., 2009). (D) Normalized annual LL $\delta^{18}\text{O}$ record. Black lines in B and D are 10-yr moving averages of the normalized TK and LL records, respectively. (E) The reconstructed ITCZ SI series (green line) results from subtracting the smoothed LL dataset from the TK record.

Figure 6: Comparison of (A) the reconstructed ITCZ SI series in the central Indo-Pacific region (this study) with (B) Ti content of the marine sediments in the Cariaco Basin (Haug et al., 2001), (C) Summer insolation differences between 30°N in June and 30°S in December (Berger and Loutre, 1991), (D) ENSO frequency in the Pacific

reconstructed from Laguna Pallcacocha (Moy et al., 2002), and (E) North Atlantic (NA) SST reconstructed from Iberian margin core SU8118 (Bard et al., 2000).

Table captions

Table 1: Stalagmite U-Th dating results.

Supplementary Data Table 1: Time series TK7, TK20 and TK40 $\delta^{18}\text{O}$ record for this study and TK133 (Tan et al., 2019) and The ITCZ shift index (SI).

Supplementary Data Figure 1: Polished quartered/halved sections of stalagmites TK7, TK20, and TK40. Six brown layers represent the depths for X-ray diffraction analysis (XRD). Red horizons are layers for U-Th dating and determined ages are given by layers. Blue lines are the subsampling routes for oxygen isotope analysis. A dashed line at 2.1 mm of TK7 denotes a hiatus.

Supplementary Data Figure 2A: StalAge age models for TK7, TK20, and TK40. Black square shapes show the U–Th dates with errors. Green lines indicate the StalAge model. Red lines are the 95% confidence ranges.

Supplementary Data Figure 2B: Bacon age models for TK7, TK20, and TK40. The blue shapes show the dates with two standard deviations, the green line indicates the likely age model, and the red lines show the 95% confidence ranges of the age models.

Supplementary Data Figure 3: Hendy Test on coeval subsamples of (A) TK07, and (B) TK20 and TK40.

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Figure 1-6
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Table

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author statement

C-C.S. and **B.W.** supervised the project and provided resources. **S.C.** wrote the original draft and made all figures with help from **L.T.**, **C-C.S.** and **B.W.** **S.C.**, **L.L.** and **C-C.S.** investigated and conducted a field survey and sampling. **S.C.** and **H-C.W.** performed sample preparation and Hendy Test. **H-C.W.**, **T-L.Y.**, **Y.-C.C.** and **H-S.M.** did U-Th dating and isotope analysis. **G.L.**, **M.B.** and **S-Y.G** contributed some ideas and helped to improve the manuscript. All authors discussed the results, reviewed and edited the manuscript.

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