Author's response to referee comments – CP-2015-162

Räsänen et al: On the spatial and temporal variability of ENSO precipitation and drought teleconnection in mainland Southeast Asia

Dear editor and referees,

We are very grateful for the thoughtful and constructive comments submitted by the reviewers and editorial board member. We have taken all their comments carefully into account when revising the paper. This document provides our responses to referee comments and a description of the changes we have made to the manuscript. The referees pointed out shortcomings in the manuscript and addressing them helped us to improve the manuscript, in particular with regard to clarification of the seasonal representativeness of the proxy Palmer Drought Severity Index (PDSI) data; the new findings; and the relationship between the precipitation and proxy PDSI analyses. We believe that these changes have resulted in substantial improvements to the paper. We have responded to all suggestions and comments as specified below.

Best regards,

Timo Räsänen

Referee #1 comments	**Author responses**
General comments: I enjoyed reading this carefully written and highly relevant manuscript. The authors clearly state their objectives (improving the understanding of the ENSO-MSEA teleconnection by looking into proxy and instrumental record for a long time-span). Their methodology is well structured and they apply state-of-the-art techniques for detecting correlations, synchronized periodic behaviour or frequencies with significant	Thank you for the encouraging and constructive comments!

coherence. I have nonetheless a major comment regarding one of their conclusions and in general the way the authors refer to dry and wet "years". Most of the times they are referring to dry or wet MAM seasons. I explain my concerns below in detail.	
Major comment: The authors state in the conclusions that "ENSO has affected the region's hydroclimate over the majority (96%) of the 355 year study period". Though there is evidence of a recurring monsoon-ENSO link, this statement seems to be a bit abusive in the light of the results of your manuscript. It would seem that the MAM(1)-ENSO correlation is valid for the whole rainy season, which is not true, as you show in e.g. Figure 2. In fact, what would arguably define a year of drought in most part of MSEA is the failure of the monsoon in JJA, not whether it rained more or less in March-April-May. By looking at Figure 2, I would say that ENSO does not correlate strongly with JJA – meaning that it would be irrelevant for the bulk of the water supply to the Tonle Sap, for flooding the rice paddies in the Mekong delta, for bringing water to the flood plains of Laos or even irrigating the rain-fed agriculture of comparatively drier northeast Thailand. By saying that "ENSO has affected the region's hydroclimate over the majority (96 %) of the 355 year study period", you are extrapolating your results to the whole rainy	We agree with the referee's major comment and are pleased that the referee brought this up. Our intention was not to claim that the proxy PDSI for MAM season is representative for the whole rainy season, so the framing of our findings and conclusion clearly needed clarification. The referee suggests revising our manuscript so that the text in results and conclusions section better reflect what the analyses truly reveal. In other words, it should be clarified that our results concern the MAM season and not the whole rainy season. We fully agree with the reviewer and we have revised our manuscript accordingly. The referee also suggests looking at "how representative is MAM of the rainy season. To test this, we now conducted a correlation analysis for MAM and JJA precipitation in the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$ (see areas in Figure 1 of the manuscript) and did not find a statistically significant correlation between the two seasons. This provides evidence to support our intuition, and the reviewer's argument, that

season. Another way how to put it is "how representative is MAM of the rainy season?" I suggest carefully handling this issue throughout the paper before it being considered for publishing. In my view, the paper per se is worth publishing even if the results sound weaker (a dry MAM season vs. a dry year). A more moderate language concerning the results and conclusions won't be as appealing as the current version of the manuscript, but it will certainly be truer and still of great value. I encourage you to address this issue not only in the conclusions, but also in the "results" section (section 3)	results for MAM do not necessarily apply to the latter part of the rainy season. However, we do not feel that having results that apply to the whole rainy season would necessarily have strengthened the results – it is MAM that we are in fact interested in when it comes to long-term ENSO teleconnection in Mainland Southeast Asia (MSEA). In the following, we argue that MAM is an appropriate season for analysis scientifically, biophysically and societally: • In terms of hydrology, MAM is the appropriate season for detecting ENSO signal in MSEA. Our analyses revealed that the correlation between ENSO and precipitation in MSEA was strongest and statistically significant over largest area in MSEA during the MAM season compared to other seasons. • The proxy PDSI data is most accurate for the MAM season. The tree-ring data has strongest correlation with instrumental PDSI data and provide best verification results for the MAM season (Buckley et al., 2010a;Sano et al., 2008). • Given that precipitation in MAM provides strongest correlation with ENSO and proxy PDSI is most accurate for MAM, we consider that our current approach focusing on the MAM season is the most suitable for detecting and analysing

	variations in the long-term ENSO teleconnection in MSEA. • It should not be forgotten that hydrologically MAM is also an important season, not just the monsoon season proper (JJA). MAM is the transition period from dry to wet season when the monsoon precipitation gradually starts (Adamson and Bird, 2010). The increase in the rainfall after the dry season is observed already in April, but it is commonly considered that the wet monsoon starts in early- to mid-May. In addition, our analyses showed that, in the area of $PDSI_{BDFH}$, the MAM precipitation is 17% of the annual precipitation while for the area of $PDSI_{MCC}$ this is 22%. A dry MAM contributes to moisture deficit that has accumulated during the dry season and thus extends the length of the dry season. This can lead to a drought situation, especially if the monsoon rains of the previous year end early. Räsänen and Kummu (2013) also shows for the Mekong River that during the decay year of the El Niño the flood period is delayed, and during La Niña, advanced. • MAM is also the beginning of the sowing season of rainfed rice in many areas (see e.g. Sawano et al., 2008) and the conditions of the early monsoon affect the transplanting of rice and thus the

	productivity of the crops (Fukai et al., 1998). We have included the preceding justifications for focusing on MAM season in our revised manuscript. **In order to clarify the seasonality issue we have made the following changes to the manuscript**: • Abstract: The research focus of long-term proxy PDSI analysis (1650-2004) on March-May season is stated and in the reporting of results the March-May season is considered. • 1. Introduction: The research focus of long-term proxy PDSI analysis (1650-2004) on March-May season is stated in the last paragraph. • 2. Methodology: Focus of long-term proxy PDSI analysis (1650-2004) on March-May season is stated. The relevance of the March-May season is also now discussed. • 3. Results: The discussion on extreme dry and wet events have been revised to discuss "March-May seasons" instead "years". • 4. Discussion: Focus on MAM season is now stated • 4.1. On the Methodology: The appropriateness of using Proxy PDSI data

	from March-May season for analysing ENSO-teleconnection is discussed in the second paragraph. • 5. Conclusions: the focus on March-May season is considered when discussing research focus and results. • Table captions 2 and 4: The table captions have been revised to state the research focus on March-May season. • Figure captions 4-7: The figure captions have been revised to state the research focus on March-May season.
Referee #2 comments	**Author responses**
General comment: It is quite important to understand the linkages between ENSO and regional climates, which can shed lights on projection of future climate changes. This paper used both of the observational and reconstructed data to study the spatial and temporal linkages between them. The results are sound. I agree with publication after major revision.	Thank you for the constructive review comments! They help us to improve the manuscript.
Major comment 1: It is very important to highlight the new findings from this study, as you also mentioned that several analyses have been done. For example, there are studies on the seasonal responses ENSO for this area. It is better clearly state the new findings in the Abstract and conclusions. I am feeling that you sometimes try to outline all the results or	We agree that the new findings could be highlighted better. We have revised the manuscript accordingly. **The improvements in revised manuscript are:** • Abstract: The abstract states the key findings more clearly.

previous findings, which makes me confusing on the key results and your new findings. Please condense your paper and highlight your new findings.	• 1. Introduction: we have revised the research questions in order to clarify better the new contributions that the research aims to provide. • 4.2. Contribution and comparison to earlier research: this section is revised and explains in detail the new findings of the research by showing the contribution in comparison to existing knowledge. • 5. Conclusions: the new findings are stated on more general level than in Section 4.2., and so that they answer clearly to research questions. We believe this approach highlights the new findings adequately. While referee suggested that we would detail the new findings in Conclusions, we decided to include detail description of those in Discussion and only summarise those in Conclusions. We believe that conclusions section serves now its purpose better, when we provide the conclusion in relatively concise way instead of summarising detailed findings. The reviewer commented also that "*there are studies on the seasonal responses ENSO for this area*" and we want to comment on this. To our knowledge only Juneng and Tangang (2005) have done this. They (Juneng and Tangang, 2005) analysed the seasonal evolution of rainfall anomalies over the Southeast Asia over the development and

	decay phases of El Niño. Our study in turn looked at the evolution of seasonal correlation with ENSO (El Niño and La Niña) and precipitation over *mainland* Southeast Asia and its largest river basins. Thus our analysis provides a description of evolutionary correlation pattern for partly different area. In addition, our results provide more details and information on the evolution of ENSO's effects in MSEA. For example, our analysis shows areas of negative correlation in DJF (0/1) that the Juneng and Tangang (2005) could not show. It is also worth to mention that our findings on the evolutionary pattern is only one out of several new findings.
Major comment 2: This paper has studied the seasonal patterns using the observational data and the long term changes using reconstructions. But the reconstructions do not have seasonal distribution. What are the relationships between the two parts?	It is correct that the PDSI reconstructions do not have seasonal distributions. The PDSI reconstructions represent only the MAM season and the seasonal patterns are analysed only in the precipitation analysis. Given that the reconstruction only reflects one season, the precipitation analysis provides 1) justification for the use of PDSI reconstruction and also 2) context for interpretation of results from reconstructed PDSI data. In addition, together the analysis of the precipitation and PDSI reconstruction 3) provide a more comprehensive picture of ENSO's effects across spatial and temporal scales. We elaborate on these contributions in the following:

	• The precipitation analyses provide verification that the reconstructions for the MAM season are appropriate for detecting ENSO signal in MSEA. The precipitation analysis showed that MAM season has strongest correlation with ENSO and the statistically significant correlations covered largest areas in MSEA during MAM. The reconstructions are located within the areas that showed statistically significant correlation between precipitation and ENSO during MAM. • The precipitation analysis provides important information for the interpretation of the results from the long-term analysis of reconstructions and ENSO. The precipitation analysis revealed that the spatial patterns of rainfall anomalies varied considerably between individual ENSO events. This means that there is a certain degree of uncertainty whether the reconstructions contain the effects of every ENSO events. It is possible that some ENSO events did not affect the area of a reconstruction. • In addition, together the precipitation and reconstruction analyses provide a more comprehensive picture of the spatio-temporal effects of ENSO in MSEA. The precipitation analyses provide understanding of the seasonal evolution of the effects of ENSO and the spatial

	variation in the effects of individual ENSO events. The reconstructions provide long-term inter-annual analysis of the effects of ENSO on the MAM season and to some extent comparison spatial variations in the long-term effects of ENSO. The reconstructions are for two different areas and thus they also provide indication on the spatial variations in the effect of ENSO in MSEA in long-term. **We have improved the clarification of the connection between the precipitation and proxy analyses The following states the improvements to the current manuscript as well as the explanations from the previous version of the manuscript:** • 1. Introduction: we have added a sentence (last paragraph): "The methodology of using both precipitation and proxy PDSI data together aims for providing more coherent view on the spatial and temporal variability in the effects of ENSO." • Section 2. Methodology: The first version of the manuscript already stated: "The precipitation analysis was aimed at improving the understanding of spatial and temporal patterns of ENSO-related precipitation anomalies and at understanding how strongly the hydroclimate in the locations of proxy PDSI data is related to ENSO."

	3.2. ENSO and proxy PDSI 1650-2004: The first version of the manuscript already stated: “The precipitation analyses provided a good understanding of the hydroclimate and its relationship to ENSO in the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$. The $PDSI_{BDFH}$ and $PDSI_{MCC}$ were found to be well located in terms of areas affected by ENSO, and the hydroclimate of the MAM season, which the PDSI data also describes, showed high correlation with ENSO. Therefore, $PDSI_{BDFH}$ and $PDSI_{MCC}$ are considered as good proxies for analysing the long-term teleconnection in MSEA.” 4.2. On the methodology the revised version of the manuscript now discusses the connection between precipitation and proxy analyses. 5. Conclusions: The revised conclusions should now provide better understanding how the precipitation and proxy PDSI analysis contribute together to the improved understanding on the spatio-temporal variability in the effects of ENSO in MSEA.
Minor comment 1: There is still room to polish the language to make it clearer. For example, you mentioned “in northern regions in DJF.” It is better than you clearly state which region. You can also condense some sections to make it clearer. For example, for	**We have polished the text in following way:** 3.1. Analysis of precipitation 1980-2014. We have improved the description of the results throughout this section by stating more accurately the regions where

your analyses of the results, there is no need to detailed descript each correlation, it is better to summarize the correlation patterns that make readers to comprehend the changes in response patterns easily.	particular results apply. For example, instead of using “Southern region” we use “Southern Vietnam”. Regarding the comment on description of correlation, we prefer to keep manuscript as it is. Now the description conveys more information and it highlights the findings that we want the reader to focus on. We believe that the description of the correlation patterns is also clearly written.
Minor comment 2: The spatial coverage of Figure 1 and 2 are different. It would be better to make them consistent	We are not sure what the referee means here. The spatial coverage in terms of latitude and longitude coverage are same in all figures (maps).
Minor comment 3: Please explain MEI when you first mention it. What is the difference for this index?	We have used three ENSO indices: Multivariate ENSO index (MEI), the unified ENSO proxy, and Multi-proxy ENSO event reconstruction. They are now clearly explained in the revised manuscript (see Methodology Section and Table 1). **Changes in the manuscript are:** • 2. Methodology. We use the acronym MEI for the first time in Section 2 and we have now opened the acronym there. • 2.1 Precipitation analysis 1980-2014. We have added explanation on MEI here. We introduce the data that has been used to calculate the MEI.

Minor comment 4: Page 5317, you write “early 90th century”. It is difficult to say how climate would like then.	**Response to minor comment 4:** This is a typo. Corrected.
Minor comment 5: You also mentioned other proxies sensitive to ENSO, such as the study by Xu et al., why you did not consider these series. It is better to use more than one series to study the relationships with ENSO for the whole Southeastern Asia.	We have already used two proxy series from different locations instead of one and together they provide better understanding of ENSO teleconnection in MSEA. We did not use the data from Xu et al. (2013) simply because the data was not available for us. In addition, the PDSI data and the location of the reconstruction of Xu et al. (2013) overlap with ours and therefore the use of data from Xu et al. (2013) would have resulted in some degree of redundancy. The comparison of two different reconstructions for partially same location would have been interesting but we consider it to be outside the scope of this manuscript.
Minor comment 6: Page5320, you mentioned “During the development phase of ENSO events in SON(1)” and “During the peaking months of ENSO events in DJF(1),”. Do you mean SON (0) and DJF (0)?	This comment helped us to spot and correct two mistakes: SON(1) should be SON(0) and DJF(1) should be DJF(0/1). Thank you for noticing these. We intentionally use (0/1) for DJF as the season spans the years 0 (development) and 1 (decay). This is consistent with earlier literature (Juneng and Tangang, 2005;Räsänen and Kummu, 2013).
Minor comment 7: The first paragraph of the Discussion section contains many results, which should be merged in the results section. Some of the results can be condensed as this	The detailed discussion of results has been removed. Instead, the results are discussed in very general level with few sentences.

paragraph, which are clearer.	
Minor comment 8: Page5320, it is not good to state "These results point to a need for further research" at the beginning of the Discussion section. Implications for future studies can be shown at the end of the Discussion.	The sentence has been removed.
Minor comment 9: Page5321, The moving correlation and wavelet analyses are widely used in paleoclimate studies. I think it is not necessary to highlight these methods	We do not highlight the moving correlation and wavelet methods, *per se*. Instead we discuss the benefits and limitations of our overall methodology. We believe this is important as the discussion explains the benefits of our approach and also the limitations that the approach has on interpreting the results. We believe the discussion on how 'the use of two proxies and two analysis methods provided more information on the ENSO teleconnection than single method or single proxy data' is useful for the reader. Similarly we believe that the discussion on the limitations of the methods in defining exact years is important reminder for the reader when interpreting our results. In addition, not all readers are well aware of the used methods (e.g. wavelets).
Minor comment 10: Page5321, "annual dating" should be revised.	"annual dating" has been changed into "years"
Minor comment 11: Page5322, at the end of	We now have stated clearly the improvements

the page, you mentioned "that allows regional and seasonal comparison", please more detailed write the regional and seasonal comparison. It is very important to indicate the improvements of this paper. It appears to me that you have mainly used two previous reconstructions and season comparisons for the reconstructed data do not appear evident to me. Please indicate your improvements in the Abstract also.	of our manuscript for the understanding of ENSO in MSEA in detail in Section 4.2 and in Abstract and in more general level in conclusions as discussed in our response to major comment 1 from referee #2. We hope that the improvements are now more clearly stated and so that they make obvious what the "regional and seasonal comparison" means. We have revised the sentence "that allows regional and seasonal comparison" to be more clear. Now the sentence appears after detailed description of our contributions and it states: "Through these contributions the current research provides more accurate and uniform picture of the spatiotemporal effects of ENSO on precipitation and thus allows a more detailed comparison of effects of ENSO between different regions and seasons in MSEA and its largest river basins."

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On the spatial and temporal variability of ENSO precipitation and drought teleconnection in mainland Southeast Asia

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ABSTRACT

The variability of~~in~~ the hydroclimate over mainland Southeast Asia is strongly influenced by the El Niño-Southern Oscillation (ENSO)~~ phenomenon~~, which has been linked to severe droughts and floods that profoundly influence human societies and ecosystems alike. ~~However,~~Although the significance of ENSO is well understood there are still limitations in the understanding of its effects on hydroclimate, particularly with regard to understanding ~~-~~the spatioal~~al~~ temporal characteristics and the long-term variation of its effects. ~~-and long-term stationarity of ENSO's influence in the region are not well understood. We thus~~Therefore we ~~aim to~~ analysed the seasonal evolution and spatial variations in the effect of ENSO on precipitation over the period of 1980-2013, and the long-term variation in the ENSO-teleconnection using tree-ring derived Palmer Drought Severity Indices (PDSI) for the March-May season that span over the time period ~~from~~-1650-2004. The analyses provided an improved understanding of the seasonal evolution of the precipitation anomalies and during ENSO events. The effects of ENSO were found to be most consistent and expressed over the largest areal extents during the March-May of the year when the ENSO events decay. ~~In~~On a longer time scale, we found that ENSO has ~~significantly~~ affected the region's March-May hydroclimate over the majority (95%) of the 355 year study period and during half (52%) of the time ENSO caused a significant increase in hydroclimatic variability.~~. We found that the majority of the study area is under the influence of ENSO, which has affected the region's hydroclimate over the majority (96%) of the 355-year study period.~~ ~~Th~~The ~~Our results further indicate that there is a pattern of seasonal evolution of precipitation anomalies during ENSO. However,~~~~M~~majority of the extreme wet and dry March-May seasons also occurred during ENSO events. However, considerable variability in the ENSO's influence ~~is~~ was revealed: the spatial pattern of precipitation anomalies

varied between individual ENSO events and the strength of ENSO's influence was found to vary ~~in~~ through time ~~and space, and the different ENSO.~~ ~~events resulted in varying precipitation anomalies. Additional research is needed to investigate how this variation in ENSO teleconnection is influenced by other factors, such as the properties of the ENSO events and other ocean and atmospheric phenomena. In general, the high~~Given the high variability ~~we found~~ in ENSO teleconnection that we described, and the ~~combined with~~ limitations of the~~of~~ current ~~knowledge~~understanding of the effects of ENSO,~~;~~ we suggests that the adaptation to ENSO related ~~extremes in hydroclimate~~extremes in hydroclimate ~~in~~over mainland Southeast Asia needs to recognise uncertainty as an inherent part of adaptation, must go beyond 'predict-and-control',~~ and recognise both uncertainty~~ and should seek adaptation opportunities widely within the society. ~~and complexity as fundamental principles.~~

Key words: El Niño-Southern Oscillation, mainland Southeast Asia, hydroclimate, precipitation, drought, variability, dendrochronology

1 INTRODUCTION

Extremes or changes in the mean state of climate can result in great duress to societies, especially during periods of prolonged drought or flood. A well-known source for droughts and floods on a global scale is the ocean-atmosphere coupled phenomena El Niño-Southern Oscillation (ENSO) (Cane, 2005;Ward et al., 2014). ENSO is an evolving phenomena (Trenberth and Shea, 1987) and it has become increasingly variable over recent decades (McGregor et al., 2013;Cai et al., 2014).

Over mainland Southeast Asia, henceforth MSEA, ENSO explains a large part of the inter-annual hydrological variability (Juneng and Tangang, 2005), and many of the recent severe droughts and floods occurred during ENSO events (see e.g. Räsänen and Kummu, 2013). Changes in ~~mainland Southeast Asia's~~MSEA hydroclimate variability is of great concern to the largely agrarian population of MSEA, as their ~~as the~~livelihoods, economy and food security ~~largely agrarian population and economy are growing rapidly (ADB, 2015;Pech and Sunada, 2008). Therefore regional livelihoods, economic and food security~~ are strongly dependent upon hydroclimatic conditions (MRC, 2010;Keskinen et al., 2010;ADB, 2015;Pech and Sunada, 2008). This dependency has ~~Despite such significance,~~triggered several studies that investigate the hydroclimatic variability and particularly the role of ENSO over MSEA.

~~however, the region's hydroclimate variability and its spatio-temporal connection to ENSO remains poorly understood.~~

Past research has shown that ENSO modulates precipitation~~, temperature~~ and river flows over ~~mainland Southeast Asia~~MSEA (Cook et al., 2012;Anchukaitis et al., In press). Precipitation over MSEA is known to decrease during warm phase (El Niño) events and increase during cool phase (La Niña) events (Juneng and Tangang, 2005;Singhrattna et al., 2005b;Räsänen and Kummu, 2013;Kripalani and Kulkarni, 1997). The effects of El Niño on precipitation has been reported to ~~of ENSO has been reported to~~ evolve over Southeast Asia from south to north during development and decay phases of the events and particularly ~~be strong~~affecte~~r in~~ the southern parts of ~~mainland Southeast Asia~~MSEA ~~particularly~~ ~~, particularly so~~ during the spring when the events decay ~~second year (i.e. decay year) of an event~~ (Räsänen and Kummu, 2013;Juneng and Tangang, 2005)~~.~~. The ENSO's correlation with precipitation is known to be strongest in southern MSEA, weakening towards the north and there are indications of opposite correlation between southern and northern areas (Kiem et al., 2005;Räsänen and Kummu, 2013;Zhang et al., 2007). ~~(Räsänen and Kummu, 2013;Kiem et al., 2005). (Räsänen and Kummu, 2013)~~ These studies have contributed to the understanding on the effects of ENSO on precipitation over MSEA, and they provide~~s~~ either a high resolution view over a smaller area, or a coarse resolution view over a larger area, but they~~does~~ do not provide a high resolution view over the entire MSEA and its largest river basins, particularly on seasonal scales.

~~While El Niño events are associated with higher land surface temperature over the study region, La Niña events are accompanied by lower temperatures (Limsakul and Goes, 2008).~~

~~The relationship between~~ ENSO related hydroclimatic ~~and~~ anomalies over~~hydroclimate~~ MSEA are known to vary through time ~~is not spatially uniform over MSEA~~. In general, during periods when hydrological conditions are below (above) average the effects of El Niño (La Niña) on precipitation are more severe (Kripalani and Kulkarni, 1997). ~~However, P~~Precipitation analyses over Thailand show that the connection between precipitation and ENSO has become stronger in the post-1980 period (Singhrattna et al., 2005b). Variation in the relationship between ENSO and hydroclimate are also found in the river flows. The analyses of the Mekong River show a stronger relationship between ENSO and river flow before the 1940s and after the late 1970s (Räsänen and Kummu, 2013;Darby et al., 2013). The changes in the relationship between ENSO and hydroclimate are linked ~~at least to~~ changes in ENSO's connection to different monsoon components. MSEA lies between the Indian summer monsoon (ISM) and western North Pacific summer monsoon (WNPSM) regions, and since the late 1970s the relationship between ENSO and WNPSM has strengthened while the relationship between ENSO and ISM has weakened (Wang et al., 2008;Hsu et al., 2014). These studies have shown temporal variations in the effects of ENSO in MSEA, but only over the last hundred years or so.

Xu et al. (2013) reconstructed the multivariate ENSO index ~~(MEI)~~ using stable isotopes of Oxygen (^{18}O) from cross-dated tree rings of the Vietnamese cypress (*Fokienia hodginsii*). Their results illustrate the long~~-~~term influence ~~nature~~ of ENSO~~'s influence~~ over the region, identifying at least 121 El Niño and 130 La Niña events between the years of 1605 and 2002. Other hydrological reconstructions also suggest long-term connection between ENSO and the regional hydroclimate, and make an unequivocal linkage between severe droughts and El Niño events (Buckley et al., 2007;Buckley et al., 2010b;Sano et al., 2008;Buckley et al., 2014). However, the studies focusing on the long-term ENSO-teleconnection over MSEA did not investigate the temporal variation systematically.

Altogether, ~~ofthe last on~~

the body research described above shows that ~~While~~ the understanding ~~on~~of the linkage between ENSO and hydroclimate over MSEA has developed rapidly over ~~past~~ recent years, but ~~the~~gaps exist, and there is need to draw a more coherent picture. In this paper we focus on a research need consisting of combined analysis of three aspects:~~.~~ ~~First~~1)~~,~~ high spatial resolution ~~spatial analysis~~understanding of the seasonal evolution of correlation patterns between ENSO and precipitation, covering MSEA and its largest river basins, 2)~~. Second, the analysis of~~ spatial variation in precipitation anomaly patterns between individual ENSO events over MSEA~~.~~, 3) ~~Third, the analysis of~~ long-term temporal variation and stationarity of the ENSO teleconnection over MSEA. A~~ spatial characteristics and long-term stationarity of this linkage is not yet well understood. The a~~dvanc~~ement~~ing ~~of~~ the ~~the~~ knowledge ~~in~~ of these ~~two~~ three aspects would improve the scientific understanding of ENSO teleconnection and thus provide valuable information for adaptation to ENSO-related hydrological variability ~~in~~over MSEA and its largest river basins.

We t~~T~~herefore~~, we~~ aim to analyse the instrumental and proxy records of hydroclimate over the region ~~to improve our understanding of the spatio-temporal variability of ENSO's influence on MSEA's largest river basins~~ (Fig. 1). First we analyse instrumental records of precipitation over the period of 1980-2013 in order to investigate the seasonal evolution and spatial variation in the effect of ENSO on precipitation over the MSEA, and second we analyse tree-ring based proxy ~~records~~ Palmer Drought Severity Index data (PDSI, see Palmer, 1965) for the March-May season ~~(for PDSI see Palmer, 1965)~~ from two ~~locations~~ areas in MSEA that cover time period of 1650-2004 to investigate the long-term variations in ENSO teleconnection. The methodology of using both

~~,~~precipitation and proxy PDSI data together aims ~~for~~to provide a~~ing~~~~intended~~ more coherent view o~~n~~f ~~of~~the spatial and temporal variability in the effects of ENSO.

2 METHODOLOGY

The spatial and temporal analysis of ENSO's influence on hydroclimate is divided into two parts: analysis of seasonal precipitation over~~of~~ the MSEA ~~over~~ for the period 1980-2013, and analysis of proxy ~~Palmer Drought Severity Index (~~PDSI~~)~~ (for PDSI see Palmer, 1965) for the March-May season from two locations in MSEA over the period of 1650-2004.

The precipitation analysis ~~was~~ aimed ~~at improving~~ to improve ~~the~~ our understanding of the spatial and temporal patterns of ENSO-related precipitation anomalies ~~and at~~as well as our understanding of the strength of the relationship between ENSO and hydroclimate over the two proxy-PDSI regions~~how strongly the hydroclimate in the locations of proxy PDSI data is related to ENSO~~. The precipitation was analysed using GPCC data (Schneider et al., 2015), the Multivariate ENSO index (MEI) (Wolter and Timlin, 1993, 1998) ~~-~~and correlation ~~tests~~analyses. ~~Greater emphasis was given to the March-April-May season as proxy PDSI proxy data are designed to describe the hydroclimate of that season.~~

The analyses of proxy PDSI data ~~were aimed at improving~~ aimed to improve the understanding of how the ENSO-hydroclimate teleconnection ~~in~~ over MSEA has varied ~~in~~ through time. Our analyses focus on months of March-May, which span the transition period from dry to wet season, when the monsoon precipitation gradually starts (Adamson and Bird, 2010). March-May is also the beginning of the sowing season of rainfed rice in many areas (see e.g. Sawano et al., 2008) and the conditions of the early monsoon affect the transplanting of rice and thus the productivity of the crops (Fukai et al., 1998). The analyses of proxy PDSI data were based on two tree-ring reconstructions from southern and northern Vietnam (Sano et al., 2008;Buckley et al., 2010b;Cook et al., 2010), the unified ENSO proxy (McGregor et al., 2010) and on correlation and wavelet methods (e.g. Torrence and Compo, 1998). ~~.~~In addition we analysed the co-occurrence of extreme dry and wet ~~years~~ March-May seasons with ENSO events.

2.1 Precipitation analysis 1980-2013

The seasonal precipitation analysis was based on GPCC v.7 data (Schneider et al., 2015), which is an observation-based gridded climatological dataset with temporal coverage of 1901-2013 and spatial resolution of 0.5° (approx. 55 km at the equator). The analysis of precipitation was done on a seasonal basis: June-July-August (JJA), September-October-November (SON), December-January-February (DJF), and March-April-May (MAM). The analysis was limited to the post-1980 period as previous research (Räsänen and Kummu, 2013) has reported that there are considerably fewer ~~a considerable decrease in the number of~~ weather stations in the pre-1980 period. In addition, the post-1980 period ~~reflects the recent period with~~ exhibits a stronger relationship between ENSO and hydrology (Räsänen and Kummu, 2013;Räsänen et al., 2013;Singhrattna et al., 2005b). The datasets used for the precipitation analysis are summarised in Table 1.

We also considered CRU TS v.3.21 (Harris et al., 2014), and APHRODITE (Yatagai et al., 2009;Yatagai et al., 2012) precipitation data for the analyses, but comparisons suggested that GPCC v.7 was the most suitable. CRU TS v.3.21 had major gaps in stations in the region of Myanmar and APHRODITE covers only a time period until 2007 and therefore does not capture the most recent influential ENSO events. The comparison of GPCC v.7 and APHRODITE over their common period provided very similar results.

First the seasonal evolution of ENSO-related precipitation patterns was analysed. ENSO events are generally two-~~-~~year phenomena that~~. They~~ start to develop in spring, mature ~~in~~ late in the same year or early next year and decay in the following summer. Therefore the precipitation was aggregated into JJA(0), SON(0), DJF(0/1), MAM(1), JJA(1) and SON(1) seasonal sums and correlated with the time series of January-February-March value of MEI (NOAA, 2015a) from the second year of each ENSO event (MEI_{JFM}). MEI is a monthly index that describes the phases of ENSO and it is calculated from six variables from the tropical Pacific Ocean: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (NOAA, 2015a). The JFM ~~is the in~~forms part of the peaking period of ENSO events and thus the MEI index values from these months represent the occurrence and strength of individual ENSO events (see e.g. Räsänen and Kummu, 2013;Singhrattna et al., 2005a). ~~Pearson's correlation was used.~~ The notations '0' and '1' in the names of the seasons denote the first year (i.e. developing year) and the second year (i.e. decaying) year of ENSO event, respectively. In a few occasions the ENSO event lasted three years and this third year of ENSO event was denoted with '2'. Pearson's correlation was used to correlate seasonal precipitation and MEI_{JFM} at grid level, resulting in seasonal ~~evolution~~ correlation ~~This and~~ maps~~-correlation analysis provided maps of the seasonal evolution of correlation was produced~~. ~~between MEI_{JFM} and seasonal precipitation.~~

Second, we analysed the seasonal precipitation anomalies for each ENSO event and for each season over~~ the~~ MSEA. Anomalies were calculated as deviations from the 1980-2013 average precipitation and reported ~~in ~~as percentages. This yielded seasonal precipitation anomaly maps of all El Niño and La Niña events ~~in ~~for the period of 1980-2013. In ~~addition~~addition, we analysed the precipitation anomalies in more detail in the locations of proxy PDSI data in order to understand how strongly the hydroclimate at those locations is related to ENSO. This helps to assess ~~would provide understanding of ~~how well the PDSI proxies are suited for analysing long-term ENSO teleconnection. ~~The datasets used in the precipitation analysis are summarised in Table 1.~~

2.2 Proxy PDSI analysis 1650-2004

The temporal variability of ENSO's teleconnection to MSEA was analysed using two tree-ring based PDSI reconstructions developed by Sano et al. (2008) and Buckley et al. (2010b), for northern and southern Vietnam, respectively. These two reconstructions marked the first two successful calibration-verification model schemes from tropical tree rings, both from the long-lived Vietnamese cypress (*Fokienia hodginsii*) of the family Cupressaceae, regressed against the PDSI data~~-~~set of Dai et al. (2004). In both cases the season of reconstruction was the three-month monsoon onset period of March-~~—~~May, which is strongly influenced by the ENSO phenomenon (see Buckley et al., 2010b;Buckley et al., 2014). Together these two reconstructions cover a large portion of MSEA over Vietnam, Laos, Thailand and Cambodia. The PDSI reconstructions are referred to hereafter as $PDSI_{BDFH}$ (Buckley et al., 2010b) and $PDSI_{MCC}$ (Sano et al., 2008) based on the names of the study areas in the original publications~~according to names of tree-ring study areas~~. The datasets used in the proxy PDSI analysis are summarised in Table 1.

We used the Unified ENSO proxy (UEP), an index based on the ten most commonly used ENSO proxies that was ~~originally ~~published by McGregor et al. (2010), to describe ENSO behaviour over the period 1650-2005~~ period~~. The original UEP is annual data and covers the time period from 1650 to 1977. We extended the UEP up to the year 2004 by using MEI in order to match the time period of the PDSI data. To do so we scaled the UEP variance to match the variance of MEI (UEP × $\sigma_{MEI}/\sigma_{UEP}$) over the common period 1951-1977 for the annual average (July-June) of the two datasets, similarly to McGregor et al. (2010). The correlation between UEP and MEI over their common period is 0.81 ($p<0.001$). The extended UEP is referred to hereafter as $ENSO_{UEP}$.

The $PDSI_{BDFH}$, $PDSI_{MCC}$ and $ENSO_{UEP}$ and their relationships were analysed using moving window correlation and wavelet methods (see e.g. Torrence and Compo, 1998;Grinsted et al., 2004). Moving window correlations were used to examine the temporal variation in the correlation between ENSO$_{UEP}$ and PDSI data. Pearson's correlation was used with a window width of 21 years, which was deemed sufficiently insensitive to short term variation. The statistical significance of correlations in each moving window was tested using the one-tailed Student's t-test with 5% significance level. ~~Other window sizes were also tested but window of 21-years was proven most suitable for detecting continuous periods with statistically significant correlation.~~

The applied wavelet methods included the computation of wavelet power spectrum of single time series, as well as the cross-wavelet power spectrum and wavelet coherence spectrum of two time series together. The computations were done using the *WaveletComp* R-package developed by Rösch and Schmidbauer (2014). The wavelet power spectrum shows the time series in time-frequency space, which allows the examination of variations and their power ~~in~~ with respect to their frequency and occurrence in time, while the cross-wavelet power spectrum shows where the variations of two time~~-~~series have high common power in the time-frequency space. The wavelet coherence spectrum shows the coherence (i.e. localised correlation) between the two time~~-~~series in time-frequency space, while the cross-wavelet power spectrum and the wavelet coherence spectrum also show the phase relationship between the two time series. In the case of correlated phenomena, the phase relationship is expected to be consistent in time. A more complete treatment of the wavelet methods can be found in Torrence and Compo (1998) and Grinsted et al. (2004).

The wavelet methods were used to identify temporal variability in the strength of ENSO's influence on the hydroclimate over MSEA~~, using the PDSI$_{BDFH}$, PDSI$_{MCC}$ and ENSO$_{UEP}$ data, the periods when ENSO had a stronger statistically significant influence on the hydroclimate in MSEA~~. Two categories were used for this identification: *i.* ~~*Strong*~~ *primary ENSO-related variance, and ii. secondary ENSO-related variance* in the hydroclimate of MSEA. These periods were defined according to regions in wavelet power, cross-wavelet power and coherence spectrum that were overlapping in time-frequency space and fulfilled specific criteria. The specific criteria are explained in detail in Table 2. The major difference between the two categories is that in the former the increase of the wavelet power is statistically significant. Non-significant ENSO-related ~~variances~~ increases in wavelet power are also analysed as they reveal periods ~~with~~ that still do have statistical relationship between ENSO and hydroclimate and provide an indication of the variations in the strength of ENSO teleconnection ~~in~~ over MSEA. The wavelet analyses focused on periodicities from 2 to 10 years as they represent the frequencies of inter-annual ENSO variability. The statistical significance of the wavelet power and coherency was tested against white noise at the 5% significance level.

In addition to wavelet analysis, we employed a variance analysis of the PDSI with an 11-year moving window in order to identify periods with high inter-annual variability in the time domain. This process also enabled us to see how well these periods correspond with the high-variability periods identified from wavelet analysis. We chose 11-years in order to capture the band of inter-annual variability without the decadal variability.

The co-occurrence of extreme dry and wet years with ENSO events was based on the Gergis and Fowler (2009) multi-proxy ENSO event reconstruction over the period of 1525-2002. The extreme years were defined from PDSI data using 5th and 95th percentiles, which meant that 10% of all years of PDSI data were defined as extreme. The co-occurrence of extreme years with warm and cool phase ENSO events was then identified by comparing the multi-proxy ENSO event reconstruction and extreme PDSI values. ~~The datasets used in the proxy PDSI analysis are summarised in Table 1.~~

3 RESULTS

3.1 ENSO and ~~Analysis of~~ precipitation 1980-2013

The seasonal correlation analysis of precipitation and MEI$_{JFM}$ shows different spatial correlation patterns for each season as shown in Fig. 2. The most distinctive feature of the seasonal correlations is the evolution of areas of statistically significant negative correlation from SON(0) to JJA(1) (r < –0.339, 5% significance level) in the region of Thailand, ~~Camdodia~~Cambodia, Vietnam and southern Myanmar, and the wide area of statistically significant positive correlation (r > 0.339, 5% significance level) in DJF(0/1) in the region of China, northern Myanmar, northern Vietnam and Lao PDR~~in DJF(0/1)~~. The negative (positive) correlation corresponds to reduced (increased) precipitation during El Niño and increased (reduced) precipitation during La Niña.

Taking a closer look at these patterns, ~~During SON(0)~~ the negative correlations are observed during SON(0) in the southern coastal regions of ~~MSEA~~ MSEA in the west in Thailand and Myanmar and in the east in southern Vietnam and Cambodia. In DJF(0/1) the areas of negative correlation are pushed further south by areas of positive correlations. In MAM(1) the negative correlations are widespread and cover most of~~in~~ the study area, except northern Myanmar and parts of China. In JJA(1) the areas of negative correlations are observed ~~only~~ mainly in western Thailand and in southern Myanmar~~areas~~ and in SON(1) the negative correlations have more or less disappeared. Another interesting feature ~~In addition, an interesting feature is also the areas of~~is the statistically significant positive correlation ~~(r > 0.339, 5% significance level)~~ during the JJA(0) season in the~~the southern parts~~ southern Myanmar and southern Lao PDR and northern Cambodia, separated by ~~with~~ an area of negative correlation in ~~between in~~ Thailand~~of the study area during the JJA(0) season~~.

The analysis of precipitation anomalies shows spatially varying anomaly patterns between ENSO events. This can be observed in Fig. 3 that shows the MAM(1) precipitation anomalies of eight El Niño and four La Niña events during the period of 1980-2013 ~~and~~ (see also~~in the~~ Fig. S1 and S2 in *Supplement* that shows precipitation anomalies for all seasons for the same El Niño and La Niña events as in Fig. 3).

In the case of the El Niño events of 1982-1983, 1986-1987, 1991-1992, 1994-1995, 1997-1998, and 2009-2010 (Fig. 3A-H), the MAM(1) precipitation anomalies are widely negative in large parts of the study area. During the El Niño event of 2002-2003 the negative precipitation anomalies are smaller in magnitude and positive anomalies are observed in some regions, for example in Southern Myanmar and at the border between southern Lao PDR and western Thailand. During the El Niño event of 2006-2007 the precipitation anomalies are mainly positive and thus inconsistent with other El Niño events.

In the case of La Niña events there is greater inconsistency in spatial patterns of MAM(1) precipitation anomalies than in the case of El Niño. During the 1998-1999 La Niña event, the MAM(1) precipitation anomalies are largely positive and cover Thailand, Cambodia, Southern Lao PDR~~-~~, Southern Vietnam and large parts of Myanmar. ~~the southern parts of the study area.~~ During the 1988-1989 event, the positive precipitation anomalies are confined to the eastern part of the study area in Vietnam, in 2007-2008 the precipitation anomalies are smaller but more widespread ~~in the southern parts of the study area but smaller~~and they can be seen particularly in Cambodia and Eastern Thailand, ~~and~~ while in the 2010-2011 event, the positive precipitation anomalies are mainly ~~in the western parts of the study area~~ in Myanmar and in western Thailand.

The time series analysis of MAM(1) precipitation for the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$ (see locations in Fig. 3) show high correlation between precipitation and MEI_{JFM} and high consistency in the direction of precipitation anomalies during El Niño and La Niña events, as shown in Table 3. The Pearson's and Kendall's correlations for MAM(1) precipitation and MEI_{JFM} in the area of $PDSI_{BDFH}$ are -0.79 (p≤~~≈~~0.~~000~~001) and -0.64 (p~~≈~~≤0.~~000~~001), respectively. Similarly for the area of $PDSI_{MCC}$, the Pearson's and Kendall's correlations for MAM(1) precipitation and MEI_{JFM} are -0.69 (p≤~~<~~0.~~000~~001) and -0.5 (p≤~~<~~0.~~000~~001), respectively.

During MAM(1+2) of El Niño events, the precipitation anomalies were negative for the $PDSI_{BDFH}$ area in 80% of the events and for the $PDSI_{MCC}$ area in 70% of the events (Table 3). During MAM(1+2) of La Niña events the precipitation anomalies for the $PDSI_{BDFH}$ and $PDSI_{MCC}$ areas were positive in 100% of the events (Table 3). The strong El Niño events stand out in the magnitude of precipitation anomalies: the precipitation anomalies during the second and third years are on average -32% and -24%, varying in the ranges (-41%, -14%) and (-50%, -1%) for the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$, respectively.

3.2 ENSO and~~of~~ proxy PDSI 1650-2004

The precipitation analyses provided a good understanding of the hydroclimate and its relationship to ENSO in the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$. The $PDSI_{BDFH}$ and $PDSI_{MCC}$ correspond to ~~were~~

~~found to be well located in terms of~~ areas affected by ENSO~~,~~ . ~~and~~ In particular, the hydroclimate of the MAM season, which the PDSI data also describes, showed high correlation with ENSO (see Fig. 2D). Therefore, $PDSI_{BDFH}$ and $PDSI_{MCC}$ are considered as good proxies for analysing the long-term ENSO teleconnection ~~in~~ over MSEA.

The correlation analysis between $ENSO_{UEP}$ and $PDSI_{BDFH}$ and $ENSO_{UEP}$ and $PDSI_{MCC}$ with moving windows ~~in Fig. 4~~ revealed that the correlations vary in time and also differ between $PDSI_{BDFH}$ and $PDSI_{MCC}$~~.~~ (Fig. 4). Statistically significant negative correlations ($p<0.05$) can be observed for $PDSI_{BDFH}$ approximately during 93%, and for $PDSI_{MCC}$ approximately during 67%, of the study period. The longest period of no statistically significant correlation was observed for $PDSI_{MCC}$ during 1885-1948, which interestingly coincides with the period of highest correlation for $PDSI_{BDFH}$. The most recent period of statistically significant correlation started for both $PDSI_{BDFH}$ and $PDSI_{MCC}$ around the mid-20th century. In the early 19~~0~~th century the correlation with $PDSI_{MCC}$ ~~interestingly~~ changes into a strong positive relationship. The periods with statistically significant correlation between PDSI data and $ENSO_{UEP}$ are ~~also~~ listed in Table 4.

The wavelet analyses ~~in Figs. 5-6 also~~ show a connection between ENSO and the hydroclimate of the region throughout the study period (Figs. 5-6). The connection can be observed as a relatively consistent temporal distribution of statistically significant areas in the wavelet coherence spectrum of $ENSO_{UEP}$ and $PDSI_{BDFH}$ (Fig. 5D) and $ENSO_{UEP}$ and $PDSI_{MCC}$ (Fig. 6~~5~~D). However, there are periods when there is no statistically significant coherence and the phase arrows point in inconsistent directions, for example from 1760s to late 1770s, suggesting no connection between ENSO and the hydroclimate.

The wavelet analyses of $PDSI_{BDFH}$ in Fig. 5 show seven periods with ~~strong~~ primary ENSO-related variance and four periods with secondary ENSO-related variance in the hydroclimate. The periods with ~~strong~~ primary ENSO-related variance coincide also with the overall increase in the variance as shown by the moving window analysis in Fig. 5B. For example, three periods with high variance are identified and these coincide with the periods of 1735-1750, 1871-1899 and 1960-1980 with primary ENSO-related variance (Fig. 5). In $PDSI_{BDFH}$ there are also three periods with significant increase in wavelet power that could not be associated with $ENSO_{UEP}$ (Fig. 5B). Thus in the region of $PDSI_{BDFH}$, seven out of ten periods with statistically significant increase in wavelet power can be associated to ENSO. The identified periods with primary and secondary ENSO-related variance in $PDSI_{BDFH}$ are ~~also~~ listed in Table 4.

The wavelet analyses of PDSI$_{MCC}$ ~~in Fig. 6~~ show two periods with primary~~strong~~ ENSO-related variance and ten periods with secondary ENSO-related variance in the hydroclimate (Fig. 6; Table 4). Many of these periods coincide with the general increase in the variance as shown by the moving window variance in Fig. 6~~-~~B, for example in 1703-1745, 1829-1842 and in 1949-1958. Statistically significant increase in wavelet power of PDSI$_{MCC}$ can be observed also during the first half of 19th century (Fig. 6 B), but its association with ENSO$_{UEP}$ is unclear. During this period both ENSO$_{UEP}$ and PDSI$_{MCC}$ show increase in wavelet power (Fig. 6A-B) and statistically significant coherence (Fig. 6D), but the phase arrows are pointing opposite to the general direction. The change in the direction of correlation was observed also in the analysis with moving window correlation in Fig. 4. The identified periods with primary and secondary ~~with~~ ENSO-related variance in PDSI$_{MCC}$ are ~~also~~ listed in Table 4.

The wavelet analyses also reveal that increased variance in ENSO does not always result in increased hydroclimatic~~logical~~ variance over~~in~~ MSEA. For example, the statistically significant increases in wavelet power of ENSO$_{UEP}$ in 1784-1795 (periodicities of about 5 and 8 years), 1901-1906 (periodicity of around 3 years), 1940-1955 (periodicities of about 4 and 6 years) and 1980-1989 (periodicity of 3-6 years) did not result in increase in wavelet power ~~in~~ for PDSI$_{BDFH}$ (Fig. 5B). Similarly, the significant increases in wavelet power of ENSO$_{UEP}$ in 1784-1795 (periodicity of around 8 years) and 1915-1921 and 1981-1989 (periodicity of around 5 years) (Fig. 5A) did not result in increase in wavelet power for~~of~~ PDSI$_{MCC}$ (Fig. 6B). This suggests non-stationarity in the relationship between ENSO and hydroclimate over MSEA.

The analysis of extreme PDSI values in Fig. 5E and Fig. 6E shows that the majority of the most extreme dry and wet ~~years~~ MAM seasons occurred during ENSO events, particularly in the region of PDSI$_{BDFH}$. Altogether 18 years were defined ~~as~~ with extremely dry and 18 years with~~as~~ extremely wet MAM seasons in PDSI$_{BDFH}$ and PDSI$_{MCC}$ using 5th and 95th percentiles. In the case of PDSI$_{BDFH}$, 13 (72%) extremely dry MAM seasons~~years~~ occurred during El Niño events and 13 (72%) extremely wet MAM season~~years~~ occurred during La Niña events. For PDSI$_{MCC}$, the respective figures are 6 (33%) extremely dry MAM seasons~~years~~ that occurred during El Niño events and 10 (56%) extremely wet MAM seasons~~years~~ that occurred during La Niña events. This indicates in general that in the region of PDSI$_{BDFH}$ both extremely dry and wet MAM season~~years~~ tend to co-occur more often with ENSO events than in the region of PDSI$_{MCC}$.

When the results of the moving-window correlation analyses and the wavelet analyses of both PDSI$_{BDFH}$ and PDSI$_{MCC}$ are examined together ~~as in Fig. 8 and Table 4~~, a more coherent picture can be drawn of ENSO's influence over MSEA (Fig. ~~8~~7 and Table 4). There is evidence of ENSO signal in the hydroclimate of the MAM season over MSEA approximately 96% of the time over the 355 year study period, but the strength of this ENSO signal varies across time and space. The wavelet analyses suggest that approximately ~~during~~ 5~~2~~2% of the study period ~~there~~ can be classified as experiencing ~~was~~ ~~strong~~primary ~~in~~ ENSO-related variance and while ~~during~~ 17% experience~~ncing~~ secondary ENSO-related variance ~~in the hydroclimate of the MSEA~~. The periods with ENSO-related variance in $PDSI_{BDFH}$ and $PDSI_{MCC}$ overlap each other relatively well, but there are also differences in the strength, timing and duration. ~~For example, the strength, timing, length and continuity of the periods vary between $PDSI_{BDFH}$ and $PDSI_{MCC}$, consistent with spatial variation in the hydrological effects of ENSO in MSEA.~~

4 DISCUSSION

The ~~findings of this paper provide new information on the spatial distribution and temporal variability of ENSO's influence on the hydroclimate of MSEA.~~research approach ~~that~~used, ~~was~~ based on a combination of precipitation data and proxy PDSI data derived from tree-ring records, provides a more uniform and coherent picture of the spatiotemporal effects of ENSO over MSEA and its largest river basins. The analysis of precipitation data showed how the precipitation anomalies evolve in time during ENSO events and how they vary in space between individual ENSO events. The analysis of proxy PDSI data in turn showed how the effects of ENSO have varied for the monsoon transition period (March-May) over a longer time scale, but also how the effects have varied spatially between northern and southern areas of MSEA. ~~Evolution of statistically significant correlation patterns between precipitation and MEI_{DJF} was observed over MSEAThe negative correlations were most widespread in (cross-ref), over the period of 1980-2013. During the development phase of ENSO events in SON(1), areas of negative correlations are observed in several regions in MSEA. During the peaking months of ENSO events in DJF(1), these areas of negative correlation are then limited to the southernmost parts of the study area by areas of positive correlation in the north. During the decay phase of ENSO events in MAM(1), the majority of the MSEA is covered by negative correlation and the correlations are strong. In JJA(1) negative correlations exists only in eastern part of MSEA and in SON only small and scattered areas of correlation can be observed. The precipitation anomalies between different ENSO events were also found to vary considerably. Over the past 355 years an ENSO signal was observed~~ the ~~approximately 96% of the time, but its strength was found to vary in time and space. Approximately 56% of the time, strong ENSO-related variance was observed in the hydroclimate (cross-ref). was in~~

~~detection of the ENSO signal by identified (cross-ref)Furthermore, the majority of the extreme dry and wet years were found to co-occur with ENSO events, particularly in the southern parts of MSEA. These results point to a need for further research.~~ In ~~-~~the following sections we further discuss~~ the~~ important aspects of the methodology, state our contributions and compare our findings with past research, and suggest directions for future work as well as for adaptation to ENSO-related ~~hydrological~~ hydroclimatic anomalies.

4.1 On the methodology

The analysis of the long-term ENSO-hydroclimate relationship using two methods (moving window correlation and wavelets) and two hydroclimate proxies derived from tree rings ($PDSI_{BDFH}$ and $PDSI_{MCC}$) was found to be a useful approach. The two methods and two hydrological proxies revealed aspects of this relationship that neither of the methods or data could have achieved alone. For example, wavelet methods revealed statistical relationship between ENSO and hydroclimate where the moving window correlations did not (see e.g. Fig. 7). The two hydrological proxies complemented each other by capturing the spatially varying effects of ENSO and thus provided a more complete picture of the relationship between ENSO and hydroclimate.

However, there are certain limitations in the above approach in providing exact ~~annual dating~~years for the periods with connection between ENSO and hydroclimate. First, ~~T~~the proxy PDSI analyses focused only on the MAM season. ~~, but~~ However, this season ~~was discovered to be~~is deemed to be appropriate for detecting an ENSO signal over MSEA, as our ~~. A~~analyses revealed that the correlation between ENSO and precipitation over MSEA was strongest and statistically significant over the largest area of MSEA during the MAM season compared to other seasons (Fig. 2~~)add cross-ref to fig~~). Moreover, the proxy PDSI data is most accurate for the MAM season: the tree-ring data has strongest correlation with instrumental PDSI data and provide best verification results for the MAM season (Sano et al., 2008;Buckley et al., 2010b). As argued in the method section, t~~T~~he MAM season is also hydrologically important. For example, our analyses showed that, in the area of $PDSI_{BDFH}$, the MAM precipitation is 17% of the annual precipitation while for the area of $PDSI_{MCC}$ this is 22%.

Further, the moving window correlation was based on a window size of 21-years, resulting in ambiguity in the dating of the statistically significant periods. ~~Second~~Third, the visual interpretation of the wavelet images involves a certain amount of subjectivity when multiple images are compared simultaneously. For example, subjective judgement was needed when the statistically significant areas in wavelet power, cross wavelet power and coherence spectrum images were of different size and not perfectly overlapping and when the phase arrows varied slightly from the expected direction. In order to minimise the errors from subjectivity, clear rules for consistent interpretation were developed and followed (see Methodology Sect. 2). ~~Third~~Fourth, the size of statistically significant areas in wavelet images depended on parameters of the wavelet analysis. For example, the choice of statistical significance testing method affected the size of the statistically significant areas, which may change the timing and duration of any such identified ENSO periods with so few years. ~~Fourth~~Last, it is likely that the approach used was not able to capture all individual ENSO events that resulted in ~~anomalies in~~ hydroclimate anomalies. Despite these limitations, the results are based upon standard methods in time series analysis and are therefore considered to be reliable estimates of ENSO-related hydrological variability.

4.2 Contribution and c~~C~~omparison to earlier ~~studies~~research

The past research provides a view on the general influence of ENSO on precipitation over MSEA, as discussed in Introduction section. The

~~The general finding that~~ El Niño (La Niña) events result in drier (wetter) conditions over MSEA ~~has been shown by past research~~ (Juneng and Tangang, 2005;Kripalani and Kulkarni, 1997), and at more local scales in Thailand (Singhrattna et al., 2005b), and in the Mekong River basin (Räsänen and Kummu, 2013). ~~. These studies~~These studies also suggest stronger correlation between ENSO and hydroclimate in central and southern parts of MSEA. ~~A.~~ A~~The~~ transition of the influence of ENSO to opposite sign from south to north is also ~~was previously~~ reported for the Mekong River basin (Räsänen and Kummu, 2013), and is supported by studies focusing on the upper reaches of the Mekong and Yangtze River basins (Kiem et al., 2005;Zhang et al., 2007). The precipitation anomalies are also shown to evolve north-eastward during El Niño events from southern parts of Southeast Asia to MSEA (Juneng and Tangang, 2005).

The current research confirms these past findings on the effects of ENSO on precipitation and expands the existing knowledge in three aspects. First, by providing more detailed and informative description of the seasonal evolution of the effects of ENSO in MSEA and by showing this evolution in more northern areas (compared to Juneng and Tangang, 2005) (Fig. 2). Second, by showing the areas and the season when the transition of the influence of ENSO to opposite sign occurs (Fig. 2C). Third, by showing how the spatial patterns of precipitation anomalies have varied between individual ENSO events over MSEA (Fig 3, Fig. S1 and S2). Through these contributions the current research provides a more accurate and uniform picture of the spatiotemporal effects of

ENSO on precipitation and thus allows a more detailed comparison of effects of ENSO between different regions and seasons of MSEA and its largest river basins.

The past research provided either a high resolution for a small area, or coarse resolution for a large area but not both. Moreover, , such that this work provides a more spatially accurate and uniform picture of the distribution of ENSOs influence, allowing comparison between different regions and seasons of MSEA. The research we present here confirms these past findings and provides an improved picture of the spatial and temporal distribution of ENSO's influence that allows regional and seasonal comparison.

The seasonal long-term variation in the hydroclimatic effects of ENSO events is less studied over MSEA. The variation in the magnitude and direction of annual precipitation and discharge anomalies during individual ENSO events are shown at least in the Mekong River basin (Räsänen and Kummu, 2013) for the period of ??. These findings from the Mekong show that not all El Niño (La Niña) events resulted in negative (positive) precipitation and discharge anomalies. However, the study from the Mekong did not specifically analyse differences between individual ENSO events and seasons. The findings of the current research confirm the findings from the Mekong and provide a broader picture at seasonal and MSEA scales. AltogetherIn sum, the findings of the current study show that the precipitation anomalies and their spatio-temporal patterns vary considerably between individual ENSO eventscausing, which makes reliable distinction between ENSO-related and non-ENSO-related rainfall anomalies very difficult.

The long-term relationship of ENSO and hydroclimate in MSEA has been shown to exist at centennial scales by several studies (Xu et al., 2013;Buckley et al., 2007;Buckley et al., 2010b;Sano et al., 2008), but the *variation* of the relationship of ENSO and hydroclimate has been studied only over the past hundred years or so. Studies conducted in Thailand (Singhrattna et al., 2005b) and the Mekong River basin (Räsänen and Kummu, 2013;Räsänen et al., 2013;Darby et al., 2013) report that the most recent periods of stronger relationship between ENSO and hydroclimate occurred during the beginning of the 20th century and lasted until the 1940s, while the second period began around the 1960s-1980s.

-The current research agrees with the findings from Thailand and the Mekong River Basin and suggests a period of weaker relationship between ENSO and hydroclimate during the 1930s-1950s in the Southern parts of the study area ($PDSI_{BDFH}$; see Fig. 1, Fig. 7 and Table 4). The current research further expands the knowledge on the variations in the ENSO's effect on hydroclimate of MSEA in four ways. Firstly, by the research providing provides a view on the variation over the past 355 years: the research shows that ENSO has affected the region's hydroclimate over MAM during the majority (96%) of the study period and during half (52%) of the time ENSO caused significant increase in hydroclimatic variability (i.e. primary ENSO-related variance) (Fig. 7). Second, ~~by revealing~~ non-stationarity is revealed in the ENSO teleconnection over MSEA for the past 355 years: periods with ENSO activity and no response in the March-April hydroclimate over MSEA were observed. Third, ~~by showing the~~ longer-term spatial variation is shown in the effects of ENSO between individual events: the two proxy PDSI data from southern and northern MSEA responded differently to the same ENSO events and periods (Fig. 5, 6 and 7). Fourth, the research provides a quantified estimation of the occurrence of extreme dry and wet MAM season during ENSO events over the past 355 years. For example, in the southern parts of MSEA (areas of $PDSI_{BDFH}$), 72% of extremely dry MAM seasons occurred during El Niño events and 72% of extremely wet MAM seasons occurred during La Niña events. Altogether the long-term analyses improve the understanding of the ENSO teleconnection and its variability over MSEA for the past three and half centuries. ~~But in the central and more northern part of the study area, the period of weak relationship lasted from the beginning of the 20^{th} century until the late 1950s ($PDSI_{MCC}$; see Fig. 1, Fig. 7 and Table 3). The differences in the timing of weak and strong periods may result from the different methodologies and locations of the studies, but they also strengthen our conclusion that the ENSO teleconnection over MSEA is highly variable across space and time. Furthermore, such variability has been evident for at least the past 355 years.~~

It is worthwhile to further highlight t~~T~~hat ~~is~~ the article's demonstration of the strong inverse relationship between the reconstructed drought metric PDSI and ENSO fit within a broader context of studies demonstrating the importance of ENSO. The tree ring studies used here (Sano et al., 2008;Buckley et al., 2010b) ~~illustrate the strong inverse relationship between the reconstructed drought metric PDSI and ENSO,~~focus on ~~for both~~ northern and southern Vietnam~~, respectively~~. Buckley et al. (2014) expands upon this discussion by using tree ring records from all across monsoon Asia and North America, illustrating that the dominant mode of climate variability across both sides of the Pacific is driven by ENSO-like variability, particularly at decadal scales (i.e., the Inter-decadal Pacific Oscillation or IPO – see Meehl and Hu (2006) and Buckley et al. (2010b) for further details). Indeed, other tree ring sites from Thailand (Buckley et al., 2007) and Myanmar (D'Arrigo et al., 2011) confirm the strength of this relationship in these regions as well.

~~4.2~~4.3 Future research directions and implications for adaptation

The findings of the current paper indicate considerable uncertainties in the effects of ENSO on hydroclimate and how this relationship develops through time. For example, clear patterns were found in the seasonal evolution of precipitation anomalies during ENSO events, but at the same time the precipitation anomalies and their spatio-temporal patterns were found to vary considerably between ENSO events. This leads to two potentially useful research directions related to ENSO. The first research direction would explore the physical characteristics (e.g. sea surface temperature, air pressure, wind and moisture fluxes patterns) of each ENSO event~~s~~ and how they translate into anomalies of MSEA ~~in~~ hydroclimate ~~in MSEA~~. For example, it is hypothesised that the placement of the descending limb of the Walker circulation could affect the ENSO teleconnection over MSEA (Singhrattna et al., 2005b). The second direction ~~w~~could be to explore how other climatic and oceanic phenomena interact with the ENSO teleconnection ~~in~~ over MSEA. For example, it is known that the Indian Ocean Dipole (IOD) affects the hydroclimate over MSEA (Darby et al., 2013) and there are good indications of the effect of the Pacific Decadal Oscillation (PDO) (Delgado et al., 2012). In addition, the current research discovered statistically significant positive correlation between precipitation and MEI_{JFM} in the northern regions of MSEA during DJF (0/1) season, but did not investigate it further. To our knowledge ~~this phenomena~~this phenomenon has not been ~~reported~~ investigated before and therefore ~~there is need~~calls for further research.

The findings of this study also provide perspectives for adaptation to extremes in hydroclimate. The findings suggest some degree of statistical predictability of ENSO-related anomalies in hydroclimate, but at the same time the findings revealed large variation and thus uncertainties in the effects of ENSO over~~in~~ MSEA. It is well known that statistical approaches can have ~~severe~~ limitations when it comes to predicting extreme events (see e.g. Nassim, 2010). Thus, given the high variability in the effects of ENSO, limitations in the current knowledge, and statistical approaches we suggest exploration of adaptation approaches that embrace uncertainty and complexity and seek adaptation opportunities in multiple sectors and levels of society (see e.g. Resilience concept: Walker et al., 2004;Walker et al., 2013) while considering ~~other~~ ongoing anthropogenic environmental changes (Keskinen et al., 2010;Lauri et al., 2012;Pech and Sunada, 2008). For example, adaptation only through engineering solutions is likely to aggravate already existing challenges (e.g. Baran and Myschowoda, 2009). The suggested adaptation approaches could further benefit from analysis of the societal impacts of the identified historical events, and the coping mechanisms used to deal with them in the past (Nuorteva et al., 2010;Buckley et al., 2010b).

5. CONCLUSIONS

Hydroclimate v~~V~~ariability ~~in hydroclimate~~ affects various economic activities, local livelihoods and food security across ~~mainland Southeast Asia~~MSEA. This ~~paper~~ ~~resarch~~research ~~aimed at~~sought to improve~~ing~~ ~~the~~ our understanding of the hydroclimate variability ~~in hydroclimate~~ by investigating the spatial and temporal variability of MSEA's ENSO ~~teleconnection~~ over the period of 1650-2013. The investigations were based on analyses of gridded seasonal precipitation data (1980-2013), proxy Palmer Drought Severity Index for March-May season and proxy ENSO data (1650-2004).

~~The research~~These analyses provide~~d~~ a more accurate and uniform picture of the spatiotemporal effects of ENSO on precipitation, and improve our understanding of the long-term ENSO teleconnection and its variability over MSEA. The research reveals new information on the seasonal evolution of the effects of ENSO over MSEA and it shows how the spatial patterns of the effects of ENSO vary between individual events. ~~In~~On a longer time scale, the strength of the effects of ENSO on hydroclimate of the March-April season (the important monsoon transition season with most widespread ENSO effects in MSEA) ~~were~~was shown to vary between periods of weaker and stronger effects. Altogether our findings reinforce the significance of ENSO over MSEA, but they also expand the past knowledge by ~~showing~~describing ~~a~~the high degree of variability and non-stationarity in the effects of ENSO. This described variability implies challenges for understanding and predicting the effects of ENSO over MSEA into the future.

~~In so doing, we revealed~~Ons, ~~that ENSO has affected the region's hydroclimate over the majority (96%) of the 355 year study period and during half (56%) of the time this effect was found to be strong. The precipitation anomalies were found to evolve during the development of ENSO events and they were at their strongest in the spring when the ENSO events decay. In addition, the majority of the extremely wet and dry years were found to have occurred during ENSO events, particularly in the southern parts of the study area. However, the~~Our thus ~~findings suggest a high degree of variability in the effects of ENSO. The magnitudes and spatial patterns of precipitation anomalies varied between individual ENSO events and the strength of the long-term ENSO teleconnection varied in time and space. Our findings thus suggest high uncertainty in the effects of ENSO and limitations in the current knowledge and thus point out a need for further investigations.~~

~~In addition, the findings of the paper provide insights for adaptation to extremes in hydroclimate.~~ Given, the high impact and variability of ENSO, and limitations in the current knowledge and predictive skill, adaptive ~~holistic~~ approaches for~~to~~ mitigating the negative effects of ENSO ~~adaptation~~ are recommended. Adaptation should embrace uncertainty, seek adaptation opportunities within multiple sectors and levels of society and consider climate-related adaptation as part of broader adaptation to ongoing social and environmental changes. Forecasting and engineering based approaches alone are likely to be inadequate and will ~~likelypossibly create~~risk creating further challenges.

DATA AVAILABILITY

The precipitation data (GPCC v.7) is available at DWD (2015), the Multi-variate ENSO Index at NOAA (2015a), the Unified ENSO Proxy at NOAA (2015c), the Multi-proxy ENSO Event Reconstruction at (NOAA, 2015d) and the PDSI proxies can be downloaded from (NOAA, 2015b).

ACKNOWLEDGEMENTS

TAR and VL received funding from *Maa- ja vesitekniikan tuki ry*, JG from Academy of Finland funded project NexusAsia (grant No. 269901), BMB from NSF grants GEO 09-08971 and AGS 130-3976, and MK from Academy of Finland funded project SCART (267463) and Emil Aaltonen Foundation funded project '*eat-less-water*'. Lamont contribution number XXXX.~~.~~

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Tables and ~~Figure~~ table captions

Table 1 Description of the data sets used in the analyses of this study.

Analysis	Name	Data description	Source
Precipitation analysis 1980-2013	Precipitation	GPCC v.7. Observation-based monthly gridded climatological dataset with temporal coverage of 1901-2013 and spatial resolution of 0.5^{o} (approx. 55 km at the equator).	Schneider et al. (2015)
	$\mathrm{MEI}_{\mathrm{JFM}}$	Multivariate ENSO index. Bi-monthly index based on sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and cloudiness data. JFM refers to index months of January-March that were used in this study.	Wolter and Timlin (1993) Wolter and Timlin (1998)
Proxy PDSI analysis 1650-2004	$\mathrm{PDSI}_{\mathrm{BDFH}}$	Tree-ring based Palmer Drought Severity Index reconstruction from Northern Vietnam describing March-May monsoon conditions with temporal coverage of 1250-2008.	Buckley et al. (2010b)
	$\mathrm{PDSI}_{\mathrm{MCC}}$	Tree-ring based Palmer Drought Severity Index reconstruction from Southern Vietnam describing March-May monsoon conditions with temporal coverage of 1470-2004.	Sano et al. (2008)
	$\mathrm{ENSO}_{\mathrm{UEP}}$	Unified ENSO proxy. Proxy index based on the ten most commonly used ENSO proxies with temporal coverage of 1650-1977. In this study the Unified ENSO proxy was extended to cover the time period up to 2004 using MEI, similarly as in McGregor et al. (2010).	McGregor et al. (2010)
	Multi-proxy ENSO event reconstruction	Multi-proxy ENSO event reconstruction. An annual record of El Niño and La Niña events and their strength with temporal coverage of 1525-2002.	Gergis and Fowler (2009)

Table 2. The identification criteria for periods with ENSO-related variance in March-May hydroclimate. Two types of variance periods were identified from Unified ENSO proxy and Palmer Drought Severity Index (PDSI) proxy data: ~~*strong*~~ *primary ENSO-related variance* and *secondary ENSO-related variance* in the hydroclimate. These periods were defined according to regions in wavelet power spectrum (WP), cross-wavelet power (CWP) and coherence spectrum (WC) that were overlapping in time-frequency space and fulfilled the criteria in the table. Variance period refers to period when ENSO had increased influence on the March-May hydroclimate in mainland Southeast Asia.

Identification criteria	Secondary ENSO-related variance in the hydroclimate	~~Strong~~ Primary ENSO-related variance in the hydroclimate
WP of PDSI: Increase in the power	✓	✓ Statistically significant (p<0.05)
WP of $ENSO_{UEP}$: Increase in the power	✓	✓
CWP: Increase in the common power	✓	✓ Statistically significant (p<0.05)
WC: Statistically significant coherence (p<0.05)	✓	✓
CWP and WC: Phase arrows suggest consistent phase lock	✓	✓

Table 3. ENSO events (NOAA, 2015a) and March~~-April~~-May precipitation anomalies in the areas of $PDSI_{BDFH}$ and $PDSI_{MCC}$ over the period of 1980-2013. Locations of PDSI areas are shown in Fig. 2. Strong ENSO events (as in NOAA, 2015a) are highlighted in bold.

Year	ENSO event	Precipitation anomaly for the $PDSI_{BDFH}$ area	Precipitation anomaly for the $PDSI_{MCC}$ area
1980		-11%	-10%
1981		-16%	20%
1982	**Strong El Nino1**	**-12%**	**-12%**
1983	**Strong El Nino2**	**-41%**	**-30%**
1984		4%	-8%
1985		9%	-9%
1986	**Strong El Nino1**	**4%**	**19%**
1987	**Strong El Nino2**	**-39%**	**-27%**
1988	El Nino3/**Strong La Nina1**	**-11%**	**4%**
1989	**Strong La Nina2**	**19%**	**6%**
1990		-7%	18%
1991	**Strong El Nino1**	**-23%**	**-21%**
1992	**Strong El Nino2**	**-39%**	**-50%**
1993	**Strong El Nino3**	**-14%**	**-1%**
1994	El Nino1	9%	15%
1995	El Nino2	-23%	-20%
1996		14%	5%
1997	**Strong El Nino1**	**10%**	**1%**
1998	**Strong El Nino2**/La Nina1	**-24%**	**-7%**
1999	La Nina2	68%	37%
2000	La Nina3	41%	24%
2001		25%	31%
2002	El Nino1	-19%	15%
2003	El Nino2	7%	-14%
2004		-4%	14%
2005		-15%	-20%
2006	El Nino1	8%	5%
2007	El Nino2/La Nina1	22%	4%
2008	La Nina2	31%	17%
2009	**Strong El Nino1**	**46%**	**3%**
2010	**Strong El Nino2/Strong La Nina1**	**-33%**	**-30%**
2011	**Strong La Nina2**	**8%**	**15%**
2012		19%	16%
2013		-14%	-7%

Table 4. Periods with evidence of ENSO teleconnection in March-May hydroclimate ~~in~~ of mainland Southeast Asia over the period of 1650-2004. *Correlation periods* refer to periods with statistically significant correlation in moving window correlation-analysis (Fig. 4~~Figure 4~~) and *Periods with primary and secondary ENSO-related variance in hydroclimate* refer to periods when ENSO had stronger influence on hydroclimate according to wavelet analyses (Figs. 5-6). Statistically significant periods ($p<0.05$) are in bold.

Correlation periods			Periods with primary and secondary ENSO-related variance in hydroclimate			Evidence of ENSO teleconnection mainland Southeast Asia
$PDSI_{BDFH}$	$PDSI_{MCC}$	Combined	$PDSI_{BDFH}$	$PDSI_{MCC}$	Combined	
1667-1765	**1663-1684**	**1663-1814**	**1653-1644**	1655-1666	1653-1666	1663-1814
1767-1814	**1696-1716**	**1817-1940**	**1681-1689**	1681-1699	1681-1699	1817-2004
1817-1839	**1724-1752**	**1943-2004**	**1703-1721**	**1703-1745**	1703-1750	
1842-1940	**1762-1811**		**1735-1750**	1778-1785	1778-1785	
1943-2004	**1821-1884**		1794-1804	1796-1803	1794-1804	
	1949-2004		1829-1841	1829-1842	1829-1842	
			1849-1858	1866-1887	1849-1858	
			1871-1899	1899-1918	1866-1942	
			1904-1925	1933-1942	1947-1980	
			1926-1937	1947-1959	1992-2002	
			1960-1980	1966-1978		
			1992-2002	**1992-2002**		

Figure captions

Figure 1. Map of the study area: mainland Southeast Asia. The spatial variability of ENSO's influence was analysed using annual precipitation data over the period of 1980-2013 with a focus on the area covering Myanmar, Thailand, Lao PDR, Vietnam and Cambodia and the~~its~~ largest river basins, the Irrawaddy, Salween, Chao Phraya, Mekong and Red River. The temporal variability of ENSO's influence was analysed using proxy Palmer Drought Severity Index (PDSI) data for March-May season over the period of 1650-2004 with focus on two regions shown in the figure with rectangles denoting the $PDSI_{MCC}$ and $PDSI_{BDFH}$ reconstruction fields of Sano et al. (2008) and Buckley et al. (2010), respectively.

Figure 2. Map of correlation of January-February-March values of Multivariate ENSO index (MEI_{JFM}) and seasonal precipitation over the period of 1980-2013: A) June-July-August (JJA (0)), B) September-October-November (SON(0)), C) December-January-February (DJF(0/1)), D) March-April-May (MAM(1)), E) June-July-August (JJA (1)) and B) September-October-November (SON(1)). '0' denotes the first (i.e. developing) year and the '1' denotes the second (i.e. decaying) year of ENSO events. Black lines delimit areas of statistically significant correlation ($|r| > 0.339$, 5% significance level).

Figure 3 March-~~April~~ May precipitation anomalies [%] during the second year (MAM(1)) of (A-H) eight El Niño and (I-J) four La Niña events.

Figure 4 Correlations between $ENSO_{UEP}$ and $PDSI_{BDFH}$ and $ENSO_{UEP}$ and $PDSI_{MCC}$ using a 21-year moving window over the period of 1650-2004. PDSI data describe the hydroclimate of March-May season.

Figure 5. Wavelet analysis of the ENSO and $PDSI_{BDFH}$ over the period 1650-2004. Wavelet power spectrum of A) $ENSO_{UEP}$ and B) $PDSI_{BDFH}$, C) cross-wavelet power spectrum and C) wavelet coherence spectrum of $ENSO_{UEP}$ and $PDSI_{BDFH}$, and E) time series of $PDSI_{BDFH}$. Tiles A and B also show total variances of time series calculated with a moving window of 21 years. Dark grey columns indicate periods with ~~strong~~ primary ENSO-related variance and the light grey columns indicate periods with secondary ENSO-related variance in the $PDSI_{BDFH}$ (see definitions in Table 2). Tile E also shows extreme PDSI values that occurred during ENSO events. Extreme values were defined from PDSI data as 5^{th} and 95^{th} percentiles. PDSI data describe the hydroclimate of March-May season.

Figure 6. Wavelet analysis of the ENSO and ~~PDSI$_{BDFH}$~~ PDSI$_{MCC}$ over the period 1650-2004. Wavelet power spectrum of A) ENSO$_{UEP}$ and B) PDSI$_{MCC}$, C) cross-wavelet power spectrum and C) wavelet coherence spectrum of ENSO$_{UEP}$ and PDSI$_{MCC}$, and E) time series of PDSI$_{MCC}$. Tiles A and B show also total variances of time series calculated with moving window of 21 years. Dark grey columns indicate periods with ~~strong~~ primary ENSO-related variance and the light grey columns indicate periods with secondary ENSO-related variance in the PDSI$_{MCC}$ (see definitions in Table 2). Tile E also shows extreme PDSI values that occurred during ENSO events. Extreme values were defined from PDSI data as 5th and 95th percentiles. PDSI data describe the hydroclimate of March-May season.

Figure 7. Periods with evidence of ENSO-related hydrological variability in ~~march~~March-May hydroclimate of mainland Southeast Asia over the period of 1650-2004. The periods with statistically significant correlation between the time series of ENSO$_{UEP}$ and PDSI$_{BDFH}$ and PDSI$_{MCC}$ are shown with thin horizontal lines and the periods with primary and secondary ENSO-related variance (see definitions in Table 2) in PDSI$_{BDFH}$ and PDSI$_{MCC}$ are shown with thick horizontal lines.