**Theoretical and Applied Climatology**

**The Influence of El Nino-Southern Oscillation on Boreal Winter Rainfall over Peninsular Malaysia**

---Manuscript Draft---

<table>
<thead>
<tr>
<th>Manuscript Number:</th>
<th>TAAC-D-17-00026R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Title:</td>
<td>The Influence of El Nino-Southern Oscillation on Boreal Winter Rainfall over Peninsular Malaysia</td>
</tr>
<tr>
<td>Article Type:</td>
<td>Original Paper</td>
</tr>
<tr>
<td>Corresponding Author:</td>
<td>Sandra Richard</td>
</tr>
<tr>
<td></td>
<td>University of Melbourne</td>
</tr>
<tr>
<td></td>
<td>AUSTRALIA</td>
</tr>
<tr>
<td>Corresponding Author's Institution:</td>
<td>University of Melbourne</td>
</tr>
<tr>
<td>First Author:</td>
<td>Sandra Richard</td>
</tr>
<tr>
<td>First Author Secondary Information:</td>
<td>Sandra Richard</td>
</tr>
<tr>
<td>Order of Authors:</td>
<td>Sandra Richard</td>
</tr>
<tr>
<td></td>
<td>Kevin J.E Walsh</td>
</tr>
<tr>
<td>Order of Authors Secondary Information:</td>
<td>ARC Centre of Excellence for Climate System Science</td>
</tr>
<tr>
<td></td>
<td>Jabatan Perkhidmatan Awam Malaysia (MY)</td>
</tr>
<tr>
<td>Funding Information:</td>
<td>ARC Centre of Excellence for Climate System Science</td>
</tr>
<tr>
<td></td>
<td>Jabatan Perkhidmatan Awam Malaysia (MY)</td>
</tr>
<tr>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>Miss Sandra Richard</td>
</tr>
<tr>
<td>Abstract:</td>
<td>Multi-scale interactions between El Nino-Southern Oscillation (ENSO) and the Boreal Winter Monsoon contribute to rainfall variations over Malaysia. Understanding the physical mechanisms that control these spatial variations in local rainfall is crucial for improving weather and climate prediction and related risk management. Analysis using station observations and ERA-interim reanalysis reveals a significant decrease in rainfall during El Nino (EL) and corresponding increase during La Nina (LA) particularly north of 2ºN over Peninsular Malaysia (PM). It is noted that the southern tip of PM shows a small increase in rainfall during El Nino although not significant. Analysis of the diurnal cycle of rainfall and winds indicates that there are no significant changes in morning and evening rainfall over PM that could explain the north-south disparity. Thus, we suggest that the key factor which might explain the north-south rainfall disparity is the moisture flux convergence (MFC). During the December to January (DJF) period of EL years, except for the southern tip of PM, significant negative MFC causes drying as well as suppression of uplift over most areas. In addition, lower specific humidity combined with moisture flux divergence results in less moisture over PM. Thus, over the areas north of 2ºN, less rainfall (less heavy rain days) with smaller diurnal rainfall amplitude explains the negative rainfall anomaly observed during DJF of EL. The same MFC argument might explain the dipolar pattern over other areas such as Borneo if further analysis is performed.</td>
</tr>
<tr>
<td>Response to Reviewers:</td>
<td>Please refer to the attachment</td>
</tr>
</tbody>
</table>

*Powered by Editorial Manager® and ProduXion Manager® from Aries Systems Corporation*
The Influence of El Nino-Southern Oscillation on Boreal Winter Rainfall over Peninsular Malaysia

Sandra Richard* and Kevin J. E. Walsh

The University of Melbourne, Melbourne, Victoria, Australia

For submission to the Journal of Theoretical and Applied Climatology

Corresponding author address:

Sandra Richard, School of Earth Sciences, The University of Melbourne, Melbourne, Victoria, Australia

E-mail: srichard@student.unimelb.edu.au

ACKNOWLEDGEMENT

This research was funded by the Jabatan Perkhidmatan Awam Malaysia (JPA) and the ARC Centre of Excellence for Climate System Science (ARCCSS). We are grateful to the Malaysian Meteorological Department for generously providing the hourly data for the purpose of this study. We thank the anonymous reviewers for their insightful comments on the manuscripts.
ABSTRACT

Multi-scale interactions between El Nino-Southern Oscillation (ENSO) and the Boreal Winter Monsoon contribute to rainfall variations over Malaysia. Understanding the physical mechanisms that control these spatial variations in local rainfall is crucial for improving weather and climate prediction and related risk management. Analysis using station observations and ERA-interim reanalysis reveals a significant decrease in rainfall during El Nino (EL) and corresponding increase during La Nina (LA) particularly north of 2°N over Peninsular Malaysia (PM). It is noted that the southern tip of PM shows a small increase in rainfall during El Nino although not significant. Analysis of the diurnal cycle of rainfall and winds indicates that there are no significant changes in morning and evening rainfall over PM that could explain the north-south disparity. Thus, we suggest that the key factor which might explain the north-south rainfall disparity is the moisture flux convergence (MFC). During the December to January (DJF) period of EL years, except for the southern tip of PM, significant negative MFC causes drying as well as suppression of uplift over most areas. In addition, lower specific humidity combined with moisture flux divergence results in less moisture over PM. Thus, over the areas north of 2°N, less rainfall (less heavy rain days) with smaller diurnal rainfall amplitude explains the negative rainfall anomaly observed during DJF of EL. The same MFC argument might explain the dipolar pattern over other areas such as Borneo if further analysis is performed.
1. INTRODUCTION

The climate of Malaysia is affected by the El Nino Southern Oscillation (ENSO) phenomenon, the South East Asian Monsoon and the Madden-Julian Oscillation. These multi-scale interactions give rise to varying weather patterns across Malaysia. Understanding their influence on Malaysian weather and climate is crucial for weather and climate prediction and related risk management, and their influence over the Maritime Continent (MC) has been studied extensively by many researchers. To date, most studies over the MC are concentrated over the Indonesian archipelago with less research on the Malaysian region (Tangang and Liew 2004).

Malaysia, situated in the MC, comprises a peninsula (Peninsular Malaysia) and part of Borneo (East Malaysia) which are separated by the South China Sea. Peninsular Malaysia (PM), discussed in this paper, is located between 1°N – 7°N and 99°E – 125°E. The major topographic features of Peninsular Malaysia (PM) are the Western Range, Central Valley and the Eastern Range (Figure 1). Its weather is characterised by a humid tropical climate with temperature ranging from 21°C to 32°C. During the Boreal Winter Monsoon (December to February, DJF), higher rainfall occurs over the east coast of PM compared to other areas of PM. Maximum rainfall occurs during November – December along the east coast of PM (Chen et al. 2013; Wong et al. 2009). Over the east coast of PM, rainfall occurs throughout the entire day with a small maximum in the morning, while an afternoon maximum is noted over other areas of PM (Oki and Mushiak 1994; Richard 2010).

Like most of the regions of the MC, Malaysia generally experiences drier than normal conditions during El Nino (EL) while wet conditions persist during La Nina (LA). Despite this general association, the influence of ENSO over the MC demonstrates considerable spatial and strong seasonal variation (Chang et al. 2004; Haylock and McBride 2001; Juneng and Tangang 2005; McBride et al. 2003; Tangang and Liew 2004). Tangang and Liew (2004) compared the seasonal behaviour of ENSO-related rainfall anomalies between Malaysian rainfall and Indonesian rainfall. While the ENSO-Malaysia rainfall relationship strengthens during DJF, the ENSO-Indonesian rainfall correlations decreased (Tangang and Liew 2004). The DJF rainfall anomalies associated with ENSO are influenced by the existence of a low-level (850 hPa) anomalous cyclonic circulation in the South China Sea, near northern Borneo and the Philippines (Chang et al. 2004; Tangang and Liew 2004). Tangang and Liew (2004) proposed that this anomalous cyclonic circulation advects moisture from the warm Philippines Sea and provides moisture convergence into the Malaysian region and the southern Philippines, thus modulating the Malaysian rainfall anomalies. Importantly, the relationship between ENSO-Malaysia rainfall also changes from one season to another with DJF having the strongest correlation compared to other seasons (Tangang and Liew 2004). In terms of spatial variations, PM is less prone to the influence of ENSO compared to East Malaysia during both the summer and winter monsoon (Cheang 1993). Using yearly rainfall data, Wong et al. (2009) noted that the wet and dry conditions, or the annual rainfall averages, over PM are not primarily controlled by ENSO events. However, due to the seasonal variation of ENSO influences of rainfall across the MC, the averaging of rainfall across seasons with varying correlation might contribute to the resulting lower correlation of ENSO-PM annual rainfall.
Over the islands of the MC, the geographically diverse influence of ENSO on the Boreal Winter rainfall and mechanisms that contribute to this relationship have been pointed out by several studies (Chang et al. 2004; Juneng and Tangang 2005; Qian et al. 2010, 2013; Rauniyar and Walsh 2013). These studies show that a localised north-south difference in the ENSO-related rainfall anomalies exists over Borneo, Java and Papua New Guinea, with most regions having less rainfall during EL, but some regions having more rainfall. Physical explanations for this effect include the presence of anomalous cyclonic circulation over the South China Sea and the Sulu Sea and interaction between land-sea breezes (and/or valley-mountain breeze) and the large-scale circulation. These opposing correlations between ENSO and rainfall have also been shown for DJF (Chang et al. 2004; Lau and Nath 2000; Rauniyar and Walsh 2013). Chang et al. (2004) found only weak correlations between an index of ENSO and PM rainfall. In contrast, Rauniyar and Walsh (2013) suggest that there is a link between rainfall anomalies and moisture convergence that could explain the reason behind areas with rainfall above normal during EL and areas with rainfall below normal during LA. During EL years, although the mid troposphere is drier compared to LA years, low-level moisture convergence and mid-level ascent may be providing a favourable environment for isolated deep convection over areas of the MC (such as south Borneo, Java and Papua New Guinea) with above normal rainfalls during the EL years (Rauniyar and Walsh 2013). In contrast, during LA years when the mid-troposphere is more humid, low-level moisture divergence and mid-level descents may be hindering the development of deep convection, leading to areas with below normal rainfall (over south Borneo, Java and Papua New Guinea) during LA (Rauniyar and Walsh 2013). Over the mountains of southwest Java, Qian et al. (2010) found that both mean rainfall and diurnal amplitude are higher there during EL years. Qian et al. (2010) showed that during EL, the enhanced sea-valley breeze convergence due to less interference from the weaker monsoonal westerly winds produced higher sea breeze-related rainfall. During LA years, the stronger westerly winds suppressed the sea-valley breeze convergence resulting in a smaller mean rainfall and diurnal amplitude compared to EL years (Qian et al. 2010). Over the Malaysian region, studies on the causes of rainfall anomalies during the different phases of ENSO reveal that moisture flux convergence (MFC) is a factor in explaining the different response in rainfall during EL and LA. However, no study has been done to demonstrate the influence of the diurnal cycle of rainfall and winds during the different phase of ENSO using station analysis.

Thus, the aim of the present paper is to re-examine the role of local scale circulations and large-scale circulations during the different phases of ENSO using a dataset from station observations over PM. This dataset contains more stations with hourly rainfall and surface winds and a longer period compared to previous studies. Most of the analyses of land-sea breeze (valley-mountain breeze) in previous studies over the MC have been performed using model output (Qian et al. 2010, 2013). However, local winds from modeling output may suffer from simulation error. Thus, the present analysis of surface wind anomalies was performed using station observations, which has not been done before over the Malaysia region. As will be seen later, the moisture flux convergence (MFC) is one of the key factors explaining the influence of ENSO on the PM rainfall. In addition, we want to determine whether previous relationships between ENSO and PM rainfall derived from Tropical Rainfall Measuring Mission (TRMM) satellite-based rainfall (e.g. Rauniyar and Walsh 2013) are still seen when a high-resolution station rainfall data set is analysed.
The analyses of local scale and large-scale circulations were performed by utilising the available high temporal resolution station data and satellite observations. Section 2 describes the data and methodology. Results from analysis of large-scale circulations, such as the 850 hPa winds, humidity, vertically integrated MFC (VIMFC) and vertical velocity (omega), and also local scale circulation are presented in section 3. The last section discusses and summarises the major findings and possible explanations for the observed results of this study. Finally, suggestions for future work are also included.

2. DATA AND METHODS

2.1 Datasets

Hourly rainfall and surface winds observations that span a period up to 46 years from 1968 to 2014 were provided by the Malaysia Meteorological Department (MetMalaysia) (Table 1). A total of 23 stations that have observations for more than 20 years are selected for this study (Figure 1). Missing data are excluded from the calculation of means. Means of the remaining data were calculated once the missing data are removed.

Data for winds, specific humidity, vertical velocity (omega) and surface pressure were extracted from the ERA-Interim reanalysis (Dee et al. 2011) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Large scale analyses from 1979 to 2014 at a horizontal resolution of 0.75° x 0.75° using the 6-hourly data were used in this study to compare with the station observations from MetMalaysia.

This study also utilises the monthly TRMM 3B43 (V7) data from 1998 to 2014 for comparison of DJF rainfall analysis with ERA-Interim rainfall over the MC. The TRMM 3B43 (V7) were released by NASA in December 2010 with a spatial resolution of 0.25° x 0.25°.

2.2 Methodology

In this study, seasonal means of rainfall and surface winds for the Boreal Winter Monsoon are calculated from December of the preceding year to February of the current year (DJF). ENSO phases are defined based on a threshold of ±0.5°C for the Ocean Nino Index (ONI, http://www.cpc.ncep.noaa.gov/)(Huang et al. 2015). The ONI is calculated using a 3-month running mean of ERSST.v4 SST anomalies in the Niño 3.4 region (5°N – 5°S, 120° – 170°W). EL (LA) occurs when the ONI is above +0.5°C (below -0.5°C) for a minimum of three consecutive overlapping 3-month seasons. Based on this definition, DJF seasons are partitioned into 16 EL episodes and 15 LA episodes (Table 2). Further partitioning of EL and LA by intensity (weak, moderate and strong) is also made for the analysis of hourly rainfall using station rainfall. The intensity threshold is broken down into weak (0.5 to 0.9), moderate (1.0 to 1.4) and strong (above 1.5) events.

A heavy rainfall day is calculated and defined as a day with rainfall of equal to or greater than 50 mm day⁻¹. In addition to examining differences in mean rainfall caused by ENSO variations, we have also
examined differences in the morning (0000 LT – 1100 LT) and evening (1200 LT – 2300 LT) rainfall mean and amplitude between ENSO phases. The rationale for this analysis is that land-based, CAPE-driven convective rainfall in this region typically peaks in the afternoon, while precipitation of oceanic origin typically peaks in the morning (Dai 2001; Mori et al. 2004; Qian 2008). Thus changes in morning or evening rainfall amounts will give an indication of changes in the relative contribution of these two mechanisms to ENSO-related rainfall. The DJF diurnal rainfall for each station was also analysed and stations that have similar diurnal rainfall patterns were grouped together for further analysis. Composites of hourly mean for each group were then used to calculate the morning and evening rainfall mean and amplitude. The amplitude of morning peak and evening peak is calculated by subtracting minimum hourly rainfall from the maximum hourly rainfall during the corresponding interval for each year. The mean morning and evening amplitudes are then calculated for each ENSO phases and their climatology mean. The rationale for this analysis is that a substantial increase in the morning or evening rainfall amplitude would indicate an increase in the hourly peak rainfall in the respective period, and thus this may provide a more sensitive diagnostic for changes in rainfall-producing mechanisms than simply using mean changes.

The hourly wind for each station is calculated for DJF of climatology, EL and LA. The difference between afternoon surface wind (1500 LT) and morning surface wind (1000 LT) have been calculated to remove the influence of background monsoonal northeasternly winds. The rationale for this analysis is that the changes in the land-sea breeze (or mountain-valley breeze) would help explain the changes in the observed diurnal cycle of rainfall.

The ENSO-related anomaly values in this paper are calculated by subtracting LA values from EL values (EL – LA). To assess the statistical significance of the anomalies (rainfall and surface winds), we used a bootstrap method to calculate the anomaly (EL-LA) values since we only have a small number of EL and LA episodes (Efron and Tibshirani 1986).

Horizontal moisture flux convergence (MFC) is calculated using the equation given below.

\[ MFC = -\nabla \cdot (q \nabla_h) = -V_h \cdot \nabla q - q \nabla \cdot V_h \]  \hspace{1cm} (1)

\[ MFC = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \]  \hspace{1cm} (2)

In the above equations, \( V_h = (u,v) \) and q is the specific humidity. In (2), the advection term represents the horizontal advection of specific humidity while the convergence term represents the product of specific humidity and horizontal mass convergence (Banacos and Schultz 2005). Using (2), the advection term, convergence term and MFC were calculated using the derived horizontal winds and specific humidity from the ERA-Interim reanalyses. The values of MFC, advection terms and convection terms are then vertically integrated between the surface and the 700 hPa. The results from vertically integrated MFC (VIMFC) and 850 hPa winds during DJF are used to determine the importance of large scale versus small scale influences in rainfall variations during ENSO phases.
3. RESULTS

3.1 Seasonal rainfall anomaly

During DJF, mean seasonal rainfall exhibits substantial spatial variations from the east to west of PM (Figure 2). The east coast stations of PM received higher rainfall (≥ 300 mm month⁻¹) compared to other areas. During this season, Kuantan (KN) recorded over 400 mm month⁻¹ rainfall. In contrast, Chuping (CP) and Alor Setar (AS) over northwestern PM received less than 100 mm month⁻¹ during the same season.

The impact of ENSO on rainfall during DJF was examined through analysis of the seasonal rainfall anomaly (EL – LA). During EL years, most stations located north of 2°N exhibit a negative rainfall anomaly (Figure 3). More than half of the stations with negative rainfall anomaly show a significant reduction in DJF rainfall (statistically significant above 95% according to the bootstrap test). Larger and significant anomalies (up to 150 mm month⁻¹ at 95% confidence level) are noted over the northeast coast of PM. However, most stations located south of 2°N show a small non-significant positive anomaly during EL years. This outcome supports the TRMM analysis of 12 DJF Tropical Rainfall Measuring Mission (TRMM) from 1998 – 2010 by Rauniyar and Walsh (2013). In their Figure 2c, Rauniyar and Walsh (2013) calculated rainfall anomaly (EL – LA) over the MC and Australia and showed that negative anomalies (EL – LA) were observed over the central and northern areas of PM whereas the southern tip of PM shows no significant change in rainfall.

The number of heavy rain days (≥ 50 mm day⁻¹) has been investigated to determine if the rainfall anomaly over PM is caused by the occurrence of heavy rainfall events. During DJF, the heavy rain days anomaly (EL – LA) pattern (Figure 4) agrees well with the seasonal rainfall anomaly (Figure 3). During EL years, stations with less heavy rain days are mostly stations with a negative DJF mean rainfall anomaly, while stations with more heavy rain days have a positive anomaly. Interestingly, stations over the southern tip of PM, which show a small non-significant positive anomaly, also show no notable difference in the number of heavy rain days during EL years compared to LA years. Tangang et al. (2017) analysed the precipitation total (total precipitation in wet days where rainfall ≥ 1 mm day; PRCPTOT) and the number of extremely heavy precipitation days (number of days with precipitation ≥ 50 mm; R50mm) during EL and LA compared to the neutral condition. They found that a significant increase in PRCPTOT is coherent with a significant increase in R50mm for stations over the south of PM (Senai, Kluang and Mersing) during EL compared to the neutral condition (refer to their Figure 3(c) and 6(c)) (Tangang et al. 2017). However, Tangang et al. (2017) show that a non-significant increase in both PRCPTOT and R50mm (except for Kluang with a non-significant decrease in R50mm) during LA compared to the neutral condition (their Figure 7(c) and Figure 9(c)). This might explain why over the southern of PM, the EL-LA rainfall anomaly is not significant (Figure 3 and Figure 4).
3.2 Seasonal Large Scale Anomalies

3.2.1 850 hPa wind

During DJF, northeasterly flow dominates the Malaysian region and South China Sea (SCS) (Figure 5). Stronger north easterlies (4 – 6 ms\(^{-1}\)) lie north of 5\(^\circ\)N over the SCS and become more zonal as they pass through the northern part of PM. South of 5\(^\circ\)N, northeasterly flow turns northerly towards the equator with wind difluence over the west coast of PM between 3\(^\circ\)N and 5\(^\circ\)N.

Between EL and LA years, significant changes in wind speed occur throughout the entire PM and coastal waters around it (Figure 6). Similar to other findings (Qian et al. 2010; Rauniyar and Walsh 2013), westerly winds at 850 hPa around the Indonesian archipelago weaken significantly (up to 6 ms\(^{-1}\)) during EL compared LA. However, larger westerly wind anomalies (up to 3 ms\(^{-1}\)) are observed south of 4\(^\circ\)N than north of this latitude.

3.2.2 Specific Humidity and Moisture Flux Convergence

Specific humidity and moisture flux convergence (MFC) are analysed to show potential areas of large scale deep convection and rainfall during ENSO years. During DJF, the specific humidity increases gradually from 10 g kg\(^{-1}\) to 12 g kg\(^{-1}\) from north to south of the Malaysian region (Figure 7). Specific humidity is higher over the central and west coast region of PM compared to the east coast of PM. During EL, a reduction in specific humidity can be seen over most areas of PM except the central west coast of PM (Figure 8). The largest reduction which is also significant (at 95% confidence level) in specific humidity (1.0 g kg\(^{-1}\)) occurs over the coastal areas of northeast PM and SCS.

During DJF, an area of negative VIMFC (moisture flux divergence) is mostly confined to the east coast of PM while an area of positive VIMFC covers most of the west coast of PM (Figure 9a). The largest moisture flux divergence (negative VIMFC) is located between 4\(^\circ\)N and 6\(^\circ\)N over the east coast of PM. In contrast, the largest moisture flux convergence (positive VIMFC) is located between 5\(^\circ\)N and 8\(^\circ\)N over the west coast of PM. The VIMFC pattern during EL and LA is similar to the long-term average (figure not shown). However, there is an inconsistency in the DJF rainfall (Figure 2) with the specific humidity (Figure 7) and the VIMFC (Figure 9) over the northeastern part of PM. Over the northeast coast of PM, the localised maximum rainfall coincides with an area of moisture flux divergence and high moisture (~10 g kg\(^{-1}\)). This is rather baffling as an area of divergence normally brings a low rainfall and vice versa. To shed light to this inconsistency in rainfall and VIMFC, we compared the ERA-Interim rainfall to TRMM rainfall over the MC. We found that ERA-Interim largely underestimated rainfall over PM, Borneo, the Philippines and North Australia compared to TRMM (Figure 10a and Figure 10b). An important feature during DJF, which is the localised maxima, over the east coast of PM, northeast of Borneo, west of Borneo and east of the Philippines Island is clearly not present compared to the TRMM rainfall analysis. However, the local maxima over the Indonesian region and Papua New Guniea are present in the ERA-Interim rainfall analysis although the intensity is a bit lower compared to the TRMM rainfall. Surprisingly, there is a good agreement in the rainfall.
anomaly (EL-LA) for both ERA-Interim and TRMM (Figure 10a and Figure 10b). Over North PM, both ERA-Interim and TRMM show a significant negative anomaly although the intensity is much lower in the ERA-Interim rainfall compared to TRMM. This indicates that the ERA-Interim rainfall assimilation model is still not able to resolve the rainfall over the areas mentioned above. Thus, we suspect that the values in calculated fields such as moisture convergence and specific humidity will be underestimated too. This might explain why we have a negative VIMFC (moisture divergence) over the localised rainfall maxima over PM (Figure 2 and Figure 9a).

The analysis of the VIMFC anomaly (EL-LA) shows that there is a significant increase in moisture flux divergence during EL over the central and northern PM (Figure 9b). Interestingly, the south part of PM generally shows no significant change in VIMFC, albeit showing a negative VIMFC (Figure 9b). The result of VIMFC is consistent with the lack of significant change in rainfall anomaly (Figure 3) between ENSO phases over PM. The vertical integrated horizontal mass convergence of specific humidity (VI Q Con) (Figure 12a) anomaly pattern is not only closely similar to the VIMFC anomaly but also larger in values (by a factor of 3) compared to the vertically integrated moisture advection (VI Q adv) (Figure 12b). This suggests that the VIMFC over the Malaysia and its surrounding region is mainly contributed by the horizontal mass convergence of specific humidity rather than moisture advection.

The opposite sign of VIMFC can also be observed over Borneo and Sumatera (Figure 9b). Over Borneo, an area of negative VIMFC covers most regions east of 115°E except over the central areas of Borneo. In contrast, the positive VIMFC area covers most areas west of 115 °N over Borneo. The VIMFC pattern over Borneo also coincides with the rainfall anomaly associated with ENSO calculated using the TRMM dataset and Global Precipitation Climatology Centre (GPCC) reanalyses (Qian et al. 2013; Rauniyar and Walsh 2013). Qian et al. (2013) (refer to their Figure 2d and 2f) and Rauniyar and Walsh (2013) (refer to their Figure 2c) show that a negative rainfall anomaly is observed over the northeastern part of Borneo during EL while a positive rainfall anomaly occurs over the southwestern part of Borneo. The northeast-southwest disparity in rainfall anomaly is reversed during LA years with negative anomaly observed over the northeastern Borneo and positive anomaly over the south-western Borneo (Qian et al. 2013; Rauniyar and Walsh 2013). A similar pattern is observed here in the VIMFC field.

In addition, we also analysed the vertical velocity (omega) to show the effect of dynamic forcing such as orographic lifting during the different phase of ENSO. During DJF, it can be shown that the entire MC experience upward motion (negative omega) that coincide with the rainfall higher rainfall over the MC compared to areas over the higher latitude (Figure 13a). However, it is noted that over areas with localised rainfall maxima such as PM, Borneo and the Philippines do not show a localised maxima in an upward motion. This might also be due to unresolved vertical velocity in model assimilation which caused underestimate of vertical velocity values over these areas. However, the vertical velocity anomaly (EL-LA) is consistent with the rainfall anomaly over the MC (Figure 11b and Figure 13b). Over areas with negative rainfall anomaly, low-level divergence (negative VIMFC) and mid-level descent (positive omega) combined with lower specific humidity may be hindering deeper convection from developing.
3.3 Diurnal cycle anomalies

3.3.1 Diurnal Cycle of Rainfall (DCR)

To analyse the changes in DCR that possibly contribute to the spatial variations in the rainfall anomaly during EL and LA years, we grouped the stations according to their diurnal rainfall patterns, location and rainfall anomalies. In the preliminary analysis, the hourly rainfall for each station are analysed and six regions have been identified (Table 3). The climatology mean of each hour has been calculated according to their groups and shown in Figure 14 (bottom panel). Group 1 and Group 6 stations, located over the coastal areas of east PM, experiences a weak DCR with rainfall occurring throughout the entire day during DJF (Figure 14). In contrast, the other group (Group 2–5) has a clear DCR with a rainfall maximum during the late afternoon or early evening (1700–1900 LT).

During DJF of EL year, rainfall is suppressed for both morning and evening for Group 1–4 (Table 3). The suppression of rainfall over this region (Group 1–4) is consistent with the negative rainfall anomaly (EL–LA) (Figure 3) and a smaller number of heavy rain days (Figure 4) during EL of DJF. Over the southern part of PM, an increase in both morning and evening mean rainfall is noted for Group 5 and 6. Although the increase in morning and afternoon rainfall is not significant, it is consistent with the positive DJF rainfall anomaly (EL–LA) (Figure 3) and a higher number of heavy rain days (Figure 4) during EL years.

Between EL and LA years, there appear to be no phase changes in DCR over all groups (Table 4); for instance, regions that are dominated by high afternoon rainfall peaks, like region 3, remain dominated by them in both phases of ENSO. However, some changes in DCR amplitude (either more enhanced or suppressed) are noted in DJF during EL and LA years. Rainfall is suppressed through the entire day for stations located over the east, inland and west of PM (Group 1, 2 and 3) during EL. In contrast, there is no significant change in amplitude between EL and LA for stations over the south and coastal areas of the west coast of PM. It is noted that the amplitude of maximum rainfall over the southern stations (Group 5 and 6) is suppressed during EL years. However, the suppression of rainfall in the morning for Group 6 is mostly balanced by amplification of the evening peak. The results from the mean rainfall and the amplitude anomalies in morning and evening suggest that the DJF rainfall anomaly (EL–LA) might be due the large scale rainfall changes (enhanced or suppressed) rather than changes in the diurnal cycle of rainfall.

3.3.2 Diurnal cycle of surface winds (DCW)

Hourly winds are analysed to determine the changes in surface winds that might change the mechanism of rainfall locally. During DJF, a land-sea breeze pattern is evident over PM. Surface winds during selected hours (1000 LT and 1500 LT) for DJF are shown in (Figure 15). The strongest land breeze appears to occur at 1000 LT (Figure 15a) while the strongest sea-breeze occurs around 1500 LT (Figure 15b). However, the land breeze appears to be overridden by the monsoonal northeasterly at 1000 LT over the east coast,
northwestern coast and the southern tip of PM (Figure 15b). There appears to be a minimal change in local circulation (sea-land breeze and mountain-valley breeze) over the entire peninsula between EL and LA years (Figure 16).

Further analysis has been done to analyse the changes in land-sea breeze during DJF each period (CL, EL and LA). With the removal of background northeasterly winds (1500 LT minus 1000 LT), the sea-breeze is stronger than the land-breeze throughout the entire peninsula during all periods (CL, EL and LA) (Figure 17). Between EL and LA years, there is no significant difference in land-sea breeze circulation over the east coast and northwest coast of PM except at KN and BL (Figure 18). However, an easterly wind anomaly up to 0.5 ms⁻¹ occurs during EL over the southwestern coast of PM (Figure 18). Thus, stronger northeasterly are noted over the southwestern coast of PM during EL compared to LA at 1000 LT and 1500 LT (Figure 16).

3.3.3 Diurnal cycle of rainfall (DCR) during different intensities of EL and LA

Motivated by the recent study of Tangang et al. (2017), we extend our analysis using hourly station rainfall to determine if there are any changes in mean rainfall anomaly patterns during the different phases of ENSO compared to the composite of ENSO phases. We found that while the weak EL and LA cause a mixed response in rainfall anomaly, the moderate events (EL and LA) have an opposite impact on rainfall anomaly compared to the strong events of ENSO. During the weak ENSO events, the rainfall anomaly (weak EL-weak LA) shows a mixed response over PM (Figure 19a). Over stations with a negative rainfall anomaly (EL – LA), both morning and evening mean and also amplitude are reduced during weak EL compared to weak LA (figure not shown). During the moderate phases of ENSO (EL and LA), all stations over PM experience a higher rainfall during moderate LA compared to moderate EL (Figure 19b). During moderate EL, both mean rainfall (Figure 20a and Figure 20b) and amplitude (Figure 20c and Figure 20d) in the morning and evening show that there is a consistent reduction of rainfall mean and amplitude over most of the stations compared to moderate LA. The fact that there are reductions in both morning and evening means and also amplitudes indicates that there are no changes in the diurnal cycle of rainfall over this region during moderate EL and moderate LA. Thus, we suggest that the changes in rainfall mean are mostly due to the large scale circulation changes such as the VIFMC over this region.

Interestingly, during the strong events of EL and LA, we found that most stations show higher rainfall during strong EL compared to strong LA (Figure 19c). Stations over the north east coast of PM mostly show a significant increase in rainfall during strong EL compared to strong LA. Analysis of the morning and evening means shows that over the northeast PM, both morning and also evening means are mostly significantly higher during strong EL compared to strong LA (Figure 21a and Figure 21b). In addition, during the strong EL, the morning and evening amplitudes are also larger compared to the strong LA events (Figure 21c and Figure 21d). Again, the increase in rainfall (significant over the northeast of PM) during the strong events are more likely to be caused by large-scale circulation (such as VIFMC) instead of changes in the diurnal circulation of winds (land-sea breeze).
Our findings during the strong ENSO events are different from Tangang et al. (2017). While we found that higher rainfall occurs during strong EL compared to strong LA, Tangang et al. (2017) found that both strong EL and LA caused a reduction in rainfall extremes when compared to the neutral condition. Using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, Tangang et al. (2017) calculated the composite of the anomalous low-level moisture flux and moisture flux divergence for EL and LA. Tangang et al. (2017) show that during the strong EL events, significant moisture divergence contributes to a significant reduction in rainfall extremes (R50mm) in most stations compared to the neutral condition (refer to their Figure 12b and Figure 16). During strong LA, Tangang et al. (2017) explained that PM experiences moisture divergence (although not significant) resulting in a reduction of extreme rainfall (R50mmmm) compared to the neutral condition (refer to their Figure 13b and Figure 17b).

The analysis of moisture flux convergence during the different ENSO intensities using ERA-Interim has not been done as it is beyond our scope of studies. However, we attempt to replicate the analysis of Tangang et al. (2017) using their definition of rainfall anomaly (strong EL minus neutral and strong LA minus neutral) but for daily means to determine the contribution of the diurnal cycle to the rainfall anomaly during the strong EL and strong LA events. Using their definition of strong EL years and strong LA years, we calculated the composite of daily rainfall mean, morning mean and evening mean. We found that during strong EL years, the east coast of PM shows an increase of daily rainfall while the west coast of PM experiences reduction in rainfall means when compared to the neutral condition (Figure 22a). During strong EL, the reduction in mean rainfall over the west coast of PM is quite consistent with the reduction in heavy rainfall (R50mm) (refer to their Figure 12b) in Tangang et al. (2017). Interestingly, while we found that there is an increase in mean rainfall during strong EL over all stations on the east coast of PM (significant over the northeast PM (Figure 22a), Tangang et al. (2017) showed a mixed signal (mostly not significant) in their R50mm analysis (refer to their figure 12b) during the strong EL events. We found that the increased rainfall over the east of PM is caused by an increase in morning and afternoon rainfall during the strong EL events (Figure 23a). This indicates that the increase in rainfall means over the east coast of PM is largely contributed by large-scale circulation (presumably MFC) rather than changes in the diurnal cycle. However, Tangang et al. (2017) showed that the entire PM experiences moisture divergence during strong EL compared to neutral condition (refer to their Figure 16b).

During the strong LA events, most stations over PM experience a decrease in rainfall due to a decrease in the morning and afternoon rainfall (Figure 22b, Figure 23c and Figure 23d). This is almost consistent with Tangang et al. (2017), where an area of moisture divergence (albeit not significant) covering the entire PM (refer to their Figure 17b) explains why there is a decrease in mean rainfall during the strong LA events. However, we found that during strong LA there are stations that show a significant decrease in mean rainfall (Figure 22b) but there is no significant moisture divergence there (Figure 17b of Tangang et al. (2017)). Importantly, the depicted moisture divergence over PM in Tangang et al. (2017) contradicts the outcome of our analysis of mean rainfall during strong EL. We suspect that the NCEP/NCAR reanalysis is not able to resolve the moisture flux convergence over the PM since the area of moisture divergence is not consistent with the increase in station rainfall mean, although it is clear that there is an increase in both morning and

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65
afternoon rainfall over the east coast of PM. Roads (2003) compared the estimates for the tropical atmospheric hydrologic cycle (including moisture convergence) from the NCEP/NCAR reanalysis, the NCEP-Department of Energy reanalysis (NCEP/DOE) and the TRMM dataset. Roads (2003) found that there large differences between both NCEP/NCAR and NCEP/DOE with TRMM estimates which can have errors in moisture convergence (also rainfall and evaporation). Thus, we suggest that analysis of moisture field and the diurnal cycle of winds using station observations should be done in the future to confirm the result of this analysis. It might be worthwhile to reproduce the moisture flux convergence analysis during the different intensity of ENSO using ERA-Interim dataset as a comparison.

4. DISCUSSION AND CONCLUSION

The influence of ENSO on DJF rainfall over PM has been analysed using surface observations and ERA-Interim reanalyses. We found that the weather during ENSO phases is controlled more by the large-scale circulation, particularly by MFC, rather than changes in the diurnal cycle of rain and wind. During DJF, northeasterly dominate the entire PM at 850 hPa (Figure 5). During the same period, the east coast of PM receives higher rainfall compared to the west coast of PM. Under the influence of ENSO variations, the DJF rainfall pattern over PM responds differently from north to south. During EL years, significant rainfall decrease occurs north of 2°N over PM while the southern tip appears not affected (in fact showing a small positive anomaly) (Figure 3). This finding supports the DJF rainfall anomaly calculated from TRMM rainfall by Rauniyar and Walsh (2013) (their Figure 2c). Analysis of the number of heavy rainfall day anomalies shows a similar pattern that matches the DJF rainfall anomaly. Also, a smaller number of heavy rainfall days is also observed over stations with negative rainfall anomalies. In contrast, more heavy rainfall days are observed over stations with positive rainfall anomaly during EL years.

During EL years, analysis of the 850 hPa winds shows that there is a significant change in the northeasterly flow throughout the entire PM. However, the largest easterly wind anomaly occurs south of 4°N where there is a small positive rainfall anomaly (Figure 3 and Figure 6). EL years also bring a lower specific humidity over the whole PM compared to LA years (Figure 8). We speculate that although specific humidity is lower during EL years, MFC may play an important role compared to the land-sea breeze and monsoonal wind interactions in explaining the rainfall anomaly pattern in PM. The analysis of VIMFC and mid-level vertical velocity (500 hPa omega) shows that areas of moisture divergence with sinking motion over most of PM and are statistically significant over the north and central PM (Figure 9b and Figure 13b). Most of the VIMFC comes from moisture convergence (specific humidity convergence) compared to advection of moisture from other regions (Figure 12a and Figure 12b). Thus, during EL years, the amplitude of DCR over the east, inland and west of PM is smaller due to a higher moisture divergence (with less vertical motion) and an associated reduction in the morning and evening rainfall peak compared to that in the LA years. Table 3 shows that both morning and evening amplitude is reduced in Group 1 to Group 3, indicating a large-scale drying effect rather than as a result of changes in local scale diurnal winds and rainfall. In addition, stronger on-shore winds over the east coast of PM (Group 1 and 2) do not amplify the hourly rainfall over all stations during the EL years. Thus, this suggests that the VIMFC is the main physical explanation for the pattern of the DJF rainfall anomaly compared to changes in the diurnal cycle over PM.
We also support the findings of previous studies (Juneng and Tangang 2005; Tangang and Liew 2004; Tangang et al. 2017) on the contribution of MFC in explaining the observed rainfall anomaly over PM.

Motivated by the recent outcome of different response in rainfall extreme during different ENSO intensity by Tangang et al. (2017), we further analyse the mean rainfall during weak, moderate and strong ENSO events. We found that there is a striking difference between mean rainfall response during the moderate and strong ENSO events. During DJF, moderate EL brings a lower rainfall over PM compared to moderate LA (Figure 19b). Oppositely, strong DJF brings a higher rainfall mean over PM as compared to the strong LA (Figure 19c). We showed that the negative anomaly in rainfall means is contributed by both negative anomalies in morning and evening means (also morning and evening amplitude) (Figure 20 and Figure 21). We suggest that the rainfall anomaly over PM during different ENSO phases and intensities are largely controlled by the large-scale circulation compared to the local circulation (such as land-sea breeze).

Tangang et al. (2017) found that moderate and strong LA events during DJF had an opposing impact on rainfall extreme over PM. On the contrary, the different intensities of EL (weak, moderate and strong) had a similar in impact in the reduction of rainfall extreme in the most station over PM. They pointed out that during moderate LA, moisture convergence enhanced rainfall over PM associated with a narrow anomalous cyclonic circulation and shifted westward) (Tangang et al. 2017). On the other hand, moisture divergence which leads to a reduction of rainfall over PM during strong LA is associated with a broader and notable anomalous cyclonic over the east of Philippines Island. During moderate and strong EL, Tangang et al. (2017) point out that an area of moisture divergence covers all of PM (refer to their Figure 16b) compared to the neutral condition. This should cause a reduction in rainfall over PM during strong EL compared to the neutral condition. However, this outcome could not explain why we have a higher rainfall during strong EL compared to strong LA. Thus, we attempt to replicate Tangang et al. (2017) and found that there is evidence that the increase in rainfall means over the east coast of PM during strong EL compared to neutral might be due to a large-scale circulation presumably due to moisture flux converge. We suggest that further analysis on the physical mechanism during the different ENSO intensity should be done using station observation or compared to ERA-Interim reanalysis.

This outcome should be reliable as it uses ground truth from a long period and hourly resolution dataset of observations from 23 stations, compared to satellite rainfall estimates used in previous studies. This study on the influence of ENSO over PM not only analysed rainfall measurements but also surface winds from the same stations, which has not been done before over PM or Malaysia. Secondly, although there are only 16 EL years and 15 LA years, hourly data and bootstrap sampling were used, so the results are statistically robust.

A limitation of this study is that the database suffers from a lack of stations in the inland areas, where Malaysia is covered by dense forest and inaccessible mountain ranges. Results for this study fill a gap in research on the influence of ENSO over the MC as previous studies mainly concentrated on the Indonesian archipelago. Large-scale factors, particularly the MFC, are seen to affect PM rainfall strongly compared to the small-scale circulation (land-sea breeze and mountain-valley breeze). This might also explain the dipolar structure of rainfall over Borneo. Qian et al. (2013) found that there are more quiescent days over the south of Borneo during EL years which leads to enhancement of DCR and DCW. We speculate that the significant
high MFC over the south of Borneo might also be one of the causes of positive rainfall anomaly during EL years, but this hypothesis would need to be tested using station data from Borneo. We also found that the ERA-Interim rainfall is largely underestimating the observed rainfall over PM during the DJF period. Thus, analysis of other calculated fields using ERA-Interim might also lead to underestimating of their actual values.

In conclusion, we found that the EL period caused a substantial decrease in rainfall over PM particularly north of 2°N, while no effect is seen over the southern tip during DJF. Analysis of the diurnal cycle of rainfall and winds indicates that there are no significant changes on the diurnal cycle of rainfall over PM that could explain the north-south disparity. The key factor which might explain the north-south rainfall disparity is the MFC. During DJF of EL years, significant negative MFC causes drying as well as suppression of uplift over most areas except for the southern tip of PM. During EL, lower specific humidity combined with moisture flux divergence results in less moisture over PM. Thus, less rainfall (less heavy rain days) with smaller diurnal rainfall amplitude explains the negative rainfall anomaly observed during DJF of EL over the areas north of 2°N. The same MFC argument might better understand the dipolar pattern over other areas such as Borneo, if further analysis is performed.
REFERENCES


——, 2013: Diurnal Cycle in Different Weather Regimes and Rainfall Variability over Borneo Associated with ENSO. Journal of Climate, 26, 1772-1790.


Richard, S., 2010: The Diurnal Variations of Rainfall and Winds Over Malaysia, University of Hawaii at Manoa.


Table 1 The Malaysian Meteorological Department (MetMalaysia) stations that were used in this study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48615</td>
<td>Kota Bharu</td>
<td>KB</td>
<td>6.17</td>
<td>102.28</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>48618</td>
<td>K. Terengganu Airport</td>
<td>KT</td>
<td>5.38</td>
<td>103.10</td>
<td>1985</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>48619</td>
<td>Kajiklim.Terengganu</td>
<td>KI</td>
<td>5.33</td>
<td>103.13</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>48657</td>
<td>Kuantan</td>
<td>KN</td>
<td>3.78</td>
<td>103.22</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>48616</td>
<td>Kuala Krai</td>
<td>KR</td>
<td>5.53</td>
<td>102.20</td>
<td>1985</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>48618</td>
<td>K. Terengganu Airport</td>
<td>KT</td>
<td>5.38</td>
<td>103.10</td>
<td>1985</td>
<td>29</td>
</tr>
<tr>
<td>7</td>
<td>48623</td>
<td>Lubok Merbau</td>
<td>LM</td>
<td>4.80</td>
<td>100.90</td>
<td>1993</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>48625</td>
<td>Ipoh</td>
<td>IP</td>
<td>4.57</td>
<td>101.10</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>9</td>
<td>48616</td>
<td>Kuala Krai</td>
<td>KR</td>
<td>5.53</td>
<td>102.20</td>
<td>1985</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>48623</td>
<td>Lubok Merbau</td>
<td>LM</td>
<td>4.80</td>
<td>100.90</td>
<td>1993</td>
<td>21</td>
</tr>
<tr>
<td>11</td>
<td>48625</td>
<td>Ipoh</td>
<td>IP</td>
<td>4.57</td>
<td>101.10</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>48632</td>
<td>Cameron Highlands</td>
<td>CH</td>
<td>4.47</td>
<td>101.37</td>
<td>1983</td>
<td>31</td>
</tr>
<tr>
<td>13</td>
<td>48647</td>
<td>Subang</td>
<td>SB</td>
<td>3.12</td>
<td>101.55</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>14</td>
<td>48648</td>
<td>Petaling Jaya</td>
<td>PJ</td>
<td>3.10</td>
<td>101.65</td>
<td>1974</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>48665</td>
<td>Malacca</td>
<td>ML</td>
<td>2.27</td>
<td>102.25</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>16</td>
<td>48601</td>
<td>Bayan Lepas</td>
<td>BL</td>
<td>5.30</td>
<td>100.27</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>17</td>
<td>48602</td>
<td>Butterworth</td>
<td>BW</td>
<td>5.47</td>
<td>100.38</td>
<td>1985</td>
<td>29</td>
</tr>
<tr>
<td>18</td>
<td>48620</td>
<td>Sitiawan</td>
<td>ST</td>
<td>4.22</td>
<td>100.70</td>
<td>1968</td>
<td>46</td>
</tr>
<tr>
<td>19</td>
<td>48649</td>
<td>Muadzam Shah</td>
<td>MS</td>
<td>3.05</td>
<td>103.08</td>
<td>1983</td>
<td>31</td>
</tr>
<tr>
<td>20</td>
<td>48670</td>
<td>Batu Pahat</td>
<td>BP</td>
<td>1.87</td>
<td>102.99</td>
<td>1992</td>
<td>22</td>
</tr>
<tr>
<td>21</td>
<td>48672</td>
<td>Kluang</td>
<td>KG</td>
<td>2.02</td>
<td>103.32</td>
<td>1974</td>
<td>40</td>
</tr>
<tr>
<td>22</td>
<td>48679</td>
<td>Senai</td>
<td>SN</td>
<td>1.63</td>
<td>103.67</td>
<td>1975</td>
<td>39</td>
</tr>
<tr>
<td>23</td>
<td>48674</td>
<td>Mersing</td>
<td>MG</td>
<td>2.45</td>
<td>103.84</td>
<td>1968</td>
<td>46</td>
</tr>
</tbody>
</table>
Table 2 List of EL and LA years and their corresponding ONI

<table>
<thead>
<tr>
<th>Year</th>
<th>Intensity</th>
<th>Year</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968/69</td>
<td>W</td>
<td>1967/68</td>
<td>W</td>
</tr>
<tr>
<td>1969/70</td>
<td>W</td>
<td>1970/71</td>
<td>M</td>
</tr>
<tr>
<td>1972/73</td>
<td>S</td>
<td>1971/72</td>
<td>W</td>
</tr>
<tr>
<td>1976/77</td>
<td>W</td>
<td>1973/74</td>
<td>S</td>
</tr>
<tr>
<td>1977/78</td>
<td>W</td>
<td>1974/75</td>
<td>W</td>
</tr>
<tr>
<td>1979/80</td>
<td>W</td>
<td>1975/76</td>
<td>S</td>
</tr>
<tr>
<td>1982/83</td>
<td>S</td>
<td>1984/85</td>
<td>W</td>
</tr>
<tr>
<td>1986/87</td>
<td>M</td>
<td>1988/89</td>
<td>S</td>
</tr>
<tr>
<td>1987/88</td>
<td>M</td>
<td>1995/96</td>
<td>W</td>
</tr>
<tr>
<td>1991/92</td>
<td>M</td>
<td>1998/99</td>
<td>M</td>
</tr>
<tr>
<td>1994/95</td>
<td>W</td>
<td>1999/00</td>
<td>M</td>
</tr>
<tr>
<td>1997/98</td>
<td>S</td>
<td>2000/01</td>
<td>W</td>
</tr>
<tr>
<td>2002/03</td>
<td>M</td>
<td>2007/08</td>
<td>M</td>
</tr>
<tr>
<td>2004/05</td>
<td>W</td>
<td>2010/11</td>
<td>M</td>
</tr>
<tr>
<td>2006/07</td>
<td>W</td>
<td>2011/12</td>
<td>W</td>
</tr>
<tr>
<td>2009/10</td>
<td>M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3 The morning (0000 LT – 1100 LT) and evening (1200 LT – 2300 LT) rainfall mean for each group. Values that were underlined and bold are significant at 95% confident level according to bootstrap method.

<table>
<thead>
<tr>
<th>Group</th>
<th>Location</th>
<th>Stations</th>
<th>CL AM</th>
<th>CL PM</th>
<th>EL-LA AM</th>
<th>EL-LA PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>East Coast</td>
<td>KB, KT, KI, KN</td>
<td>0.46</td>
<td>0.39</td>
<td>-0.17</td>
<td>-0.16</td>
</tr>
<tr>
<td>2</td>
<td>Inland East Coast</td>
<td>KR, BE, TM</td>
<td>0.18</td>
<td>0.34</td>
<td>-0.09</td>
<td>-0.14</td>
</tr>
<tr>
<td>3</td>
<td>West Coast</td>
<td>AS, CP, LM, IP, CH, SB, PJ, ML</td>
<td>0.07</td>
<td>0.35</td>
<td>-0.04</td>
<td>-0.07</td>
</tr>
<tr>
<td>4</td>
<td>Coastal West Coast</td>
<td>BL, BW, ST</td>
<td>0.12</td>
<td>0.22</td>
<td>-0.01</td>
<td>-0.06</td>
</tr>
<tr>
<td>5</td>
<td>South East Coast</td>
<td>MS, BP, KG, SN</td>
<td>0.19</td>
<td>0.39</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>South</td>
<td>MG</td>
<td>0.58</td>
<td>0.45</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Table 4  The morning (0000 LT – 1100 LT) and evening (1200 LT – 2300 LT) rainfall amplitude for each group. Values that were underlined and bold are significant at 95% confidence level according to bootstrap method.

<table>
<thead>
<tr>
<th>Group</th>
<th>Location</th>
<th>CLIM</th>
<th></th>
<th>EL-LA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AM</td>
<td>PM</td>
<td>AM</td>
<td>PM</td>
</tr>
<tr>
<td>1</td>
<td>East Coast</td>
<td>0.45</td>
<td>0.42</td>
<td>-0.15</td>
<td>-0.03</td>
</tr>
<tr>
<td>2</td>
<td>Inland East Coast</td>
<td>0.21</td>
<td>0.56</td>
<td>-0.10</td>
<td>-0.17</td>
</tr>
<tr>
<td>3</td>
<td>West Coast</td>
<td>0.16</td>
<td>0.82</td>
<td>-0.03</td>
<td>-0.09</td>
</tr>
<tr>
<td>4</td>
<td>Coastal West Coast</td>
<td>0.31</td>
<td>0.50</td>
<td>0.03</td>
<td>-0.04</td>
</tr>
<tr>
<td>5</td>
<td>South East Coast</td>
<td>0.26</td>
<td>0.77</td>
<td>0.02</td>
<td>-0.10</td>
</tr>
<tr>
<td>6</td>
<td>South</td>
<td>0.86</td>
<td>0.79</td>
<td>-0.13</td>
<td>0.12</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1  The topography and major topographic features of PM (top panel). The location of MetMalaysia principal stations (bottom panel). Terrain height is in meters (m) and acquired from the Land Processes Distributed Active Archive Center (LP DAAC), located at USGS/EROS, Sioux Falls, SD. (http://lpdaac.usgs.gov) .......................................................... 23
Figure 2  The DJF climatological mean rainfall (mm month$^{-1}$) from 1968 to 2014 using station observations from MetMalaysia dataset. The terrain is plotted at 200m intervals .......................................................... 24
Figure 3  The DJF rainfall anomaly (EL – LA) in mm month$^{-1}$. The size of the circle represents the anomaly value (mm month$^{-1}$). The blue (red) circles represent positive (negative) anomalies. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests. The terrain is plotted at 200m intervals .......................................................... 25
Figure 4  The same as Figure 3 but for the number of heavy rain days anomaly (EL – LA) in percent (%). 26
Figure 5  The DJF climatological 850 hPa wind (ms$^{-1}$) from 1979 to 2014 from ERA-Interim reanalyses. Wind speed plotted at 2 ms$^{-1}$ intervals ........................................................................ 27
Figure 6  The DJF 850 hPa wind anomaly (EL – LA) from ERA-Interim reanalyses. Wind speed plotted at 1 ms$^{-1}$ interval. Winds are plotted when they are equal or more than the 95% confidence level according to Student’s t-test .......................................................... 28
Figure 7  As in Figure 5, but for specific humidity. Contour interval is 1.0 g kg$^{-1}$ ........................................ 29
Figure 8  The DJF specific humidity anomaly (EL - LA) from ERA-Interim reanalyses. The blue (red) shadings represent the positive (negative) anomaly. Contour interval is 0.2 g kg$^{-1}$. Values significant at or above 95% are stippled........................................................................ 30
Figure 9  The DJF climatological Vertical Integrated Moisture Flux Convergence (VIMFC) (mm day$^{-1}$) between the surface and 700 hPa from 1979 to 2014 using ERA-Interim reanalyses for (a) the long term mean (CLIM) and (b) the anomaly (EL – LA). The blue (red) shadings denote convergence (divergence) ........................................... 31
Figure 10  The DJF rainfall climatological (mm day$^{-1}$) using (a) ERA-Interim from 1979 to 2014 dataset and (b) TRMM from 1998 to 2014 dataset ........................................................................ 32
Figure 11  The DJF rainfall anomaly (EL-LA) in mm day$^{-1}$ using (a) ERA-Interim from 1979 to 2014 dataset and (b) TRMM from 1998 to 2014 dataset ........................................................................ 33
Figure 12  The Vertically integrated (surface to 700 hPa) (a) Moisture Convergence (VI Q Con) anomaly (EL-LA) and (b) Moisture Advection (VI Q Adv) anomaly (EL-LA) between the surface and 700 hPa. The blue (red) shadings denote positive (negative) convergence and advection. Values significant at or above 95% confidence level are stippled ........................................................................ 34
Figure 13  The mid-level (500 hPa) (a) vertical velocity (omega) during DJF and (b) vertical velocity anomaly (EL-LA). The upward motion denotes in red shades and downward motion in blue shades ........... 35
Figure 14  The location of each group (top panel) and the mean hourly rainfall for each region (bottom panel) ................................................................................................................................. 36
Figure 15  Climatology of surface winds at (a) 1000 LT and (b) 1500 LT. Each full barb represents 1 ms$^{-1}$ 37
Figure 16  As in Figure 15 but for (a), (b) EL and (c), (d) LA ........................................................................ 38
Figure 17  The difference between 1500 LT and 1000 LT for surface winds during (a) CL, (b) EL and (c) LA. Each full barb represents 1 ms$^{-1}$ .................................................................................. 39
Figure 18  The 1500 LT minus 1000LT wind anomaly (EL-LA). Each full barb represents 1 ms$^{-1}$  .......... 40

Figure 19  The DJF mean anomaly for (a) weak EL minus weak LA, (b) moderate EL minus moderate LA and (c) strong EL minus strong LA. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests ............... 41

Figure 20  The moderate EL minus moderate LA (a) morning mean, (b) evening mean, (c) morning amplitude and (d) evening amplitude. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests .......... 42

Figure 21  As in Figure 20, but for strong EL minus strong LA events ........................................... 43

Figure 22  The rainfall mean anomaly for (a) the strong EL minus neutral and (b) the strong LA minus neutral. Strong EL years define as 1972/73,1982/83 and 1997/98. Strong LA years define as 1973/74, 1975/76 and 1988/89. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests ......................... 44

Figure 23  The strong EL minus neutral for (a) morning mean and (b) evening mean. The strong LA minus neutral for (c) morning mean and (d) evening mean. Strong EL and LA are defined as Figure 22 according to Tangang et al. (2017). The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests ......................... 45
Figure 1  The topography and major topographic features of PM (top panel). The location of MetMalaysia principal stations (bottom panel). Terrain height is in meters (m) and acquired from the Land Processes Distributed Active Archive Center (LP DAAC), located at USGS/EROS, Sioux Falls, SD. (http://lpdaac.usgs.gov)
Figure 2  The DJF climatological mean rainfall (mm month$^{-1}$) from 1968 to 2014 using station observations from MetMalaysia dataset. The terrain is plotted at 200m intervals
Figure 3  The DJF rainfall anomaly (EL – LA) in mm month\(^{-1}\). The size of the circle represents the anomaly value (mm month\(^{-1}\)). The blue (red) circles represent positive (negative) anomalies. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests. The terrain is plotted at 200m intervals.
Figure 4  The same as Figure 3 but for the number of heavy rain days anomaly (EL – LA) in percent (%)
Figure 5  The DJF climatological 850 hPa wind (ms⁻¹) from 1979 to 2014 from ERA-Interim reanalyses. Wind speed plotted at 2 ms⁻¹ intervals.
Figure 6  The DJF 850 hPa wind anomaly (EL – LA) from ERA-Interim reanalyses. Wind speed plotted at 1 ms$^{-1}$ interval. Winds are plotted when they are equal or more than the 95% confidence level according to Student’s t-test.
Figure 7  As in Figure 5, but for specific humidity. Contour interval is 1.0 g kg$^{-1}$
Figure 8  The DJF specific humidity anomaly (EL - LA) from ERA-Interim reanalyses. The blue (red) shadings represent the positive (negative) anomaly. Contour interval is 0.2 g kg\(^{-1}\). Values significant at or above 95% are stippled.
Figure 9  The DJF climatological Vertical Integrated Moisture Flux Convergence (VIMFC) (mm day\(^{-1}\)) between the surface and 700 hPa from 1979 to 2014 using ERA-Interim reanalyses for (a) the long term mean (CLIM) and (b) the anomaly (EL – LA). The blue (red) shadings denote convergence (divergence)
Figure 10  The DJF rainfall climatological (mm day$^{-1}$) using (a) ERA-Interim from 1979 to 2014 dataset and (b) TRMM from 1998 to 2014 dataset
Figure 11  The DJF rainfall anomaly (EL-LA) in mm day^{-1} using (a) ERA-Interim from 1979 to 2014 dataset and (b) TRMM from 1998 to 2014 dataset
Figure 12  The Vertically integrated (surface to 700 hPa) (a) Moisture Convergence (VI Q Con) anomaly (EL-LA) and (b) Moisture Advection (VI Q Adv) anomaly (EL-LA) between the surface and 700 hPa. The blue (red) shadings denote positive (negative) convergence and advection. Values significant at or above 95% confidence level are stippled.
Figure 13  The mid-level (500 hPa) (a) vertical velocity (omega) during DJF and (b) vertical velocity anomaly (EL-LA). The upward motion denotes in red shades and downward motion in blue shades.
Figure 14  The location of each group (top panel) and the mean hourly rainfall for each region (bottom panel)
Figure 15  Climatology of surface winds at (a) 1000 LT and (b) 1500 LT. Each full barb represents 1 ms$^{-1}$.
Figure 16  As in Figure 15 but for (a), (b) EL and (c), (d) LA
Figure 17  The difference between 1500 LT and 1000 LT for surface winds during (a) CL, (b) EL and (c) LA. Each full barb represents 1 ms$^{-1}$
Figure 18 The 1500 LT minus 1000LT wind anomaly (EL-LA). Each full barb represents 1 ms⁻¹
Figure 19  The DJF mean anomaly for (a) weak EL minus weak LA, (b) moderate EL minus moderate LA and (c) strong EL minus strong LA. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests.
Figure 20  The moderate EL minus moderate LA (a) morning mean, (b) evening mean, (c) morning amplitude and (d) evening amplitude. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests.
Figure 21  As in Figure 20, but for strong EL minus strong LA events
Figure 22  The rainfall mean anomaly for (a) the strong EL minus neutral and (b) the strong LA minus neutral. Strong EL years define as 1972/73, 1982/83 and 1997/98. Strong LA years define as 1973/74, 1975/76 and 1988/89. The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests.
Figure 23 The strong EL minus neutral for (a) morning mean and (b) evening mean. The strong LA minus neutral for (c) morning mean and (d) evening mean. Strong EL and LA are defined as Figure 22 according to Tangang et al. (2017). The blue (red) circle denotes positive (negative) anomaly. The stars represent statistically significant values at the 95% confidence level according to bootstrap tests.
Reviewer #1 (Formal Review for Authors)

We thank the reviewers for their constructive comments and we have made an earnest effort to address them.

Reviewer #1

Major Comments

1. I am encouraged when the author presented the results on how ENSO affects the rainfall and winds diurnal and concluded that the anomalous rainfall over Peninsular Malaysia was mainly associated moisture flux convergence driven by the large-scale circulation. However, I feel that the manuscript does not sufficiently advance understanding on how ENSO affecting anomalous rainfall from those of much earlier papers e.g. Tangang and Juneng (2004), Juneng and Tangang (2005). In Juneng and Tangang (2005), moisture flux convergence modulated by the anomalous anticyclones over western North Pacific was already described as the factor that explained the anomalous rainfall over the region including Peninsular Malaysia.

A comment has been added to justify the need for this current study on Page 4 Line 36-42. The result of the analysis of surface winds in PM shows that there is no significant change in land-sea breeze circulation during the different phases of ENSO. This finding has also been added in the abstract on Page 2 Line 12-15 and Page 15 Line 10-13.

2. In fact, the author adopted the same methodology used in Juneng and Tangang (2005) i.e. using the EL – LA composite. This approach assumes perfect symmetry of El Nino and La Nina influence. However, our latest paper (in press) shows this is not the case. In fact, El Nino (or La Nina) of different strength would have different effects and the anomalous SST in the Maritime Continent region would have different pattern of moisture convergence.

I suggest the authors consider some of these issues that would advance understanding of how ENSO affect anomalous precipitation over Malaysia.

We believe that using EL-LA composite as used in previous studies (e.g. Juneng and Tangang (2005) and Rauniyar and Walsh (2013)) is still valuable as it could indicate areas where there is a significant change in rainfall during the opposing ENSO phases. In addition, for best comparison with previous work we need to perform this analysis using our new dataset. Nevertheless, motivated by the reviewer's comment and Tangang et al. (2017), we further analyse the different intensity of ENSO by comparing strong EL to strong LA, moderate EL to moderate LA and weak EL and weak LA. The outcome of this analysis has been added in Section 3.3.3 on Page 11 Line 19 to Page 13 Line 10.
Reviewer #2 (Formal Review for Authors)

We thank the reviewers for their constructive comments and we have made an earnest effort to address them.

Reviewer #2

Major Comments

1. My main concern is the lack of consistency in the patterns of large-scale climatology of MFC and specific humidity with the rainfall climatology over Peninsular Malaysia (PM). For example: the positive area of MFC (Fig. 9) and higher specific humidity (Fig. 8) are mostly confined to the west coast (line 31, page 9, Fig. 9) of PM, but the stations with relatively higher rainfall are located over the east coast of PM. This also contradicts the author's statement given on line 54, page 8 "area of divergence over the west coast of PM".

We have addressed the lack of consistency in the patterns of MFC and specific humidity with the east coast of PM rainfall through additional analysis. We recalculate the values of MFC, moisture convergence and moisture advection using vertical integration from surface to 700 hPa (Page 6 Line 53-55), as previous work has indicated that this will be better related to the precipitation pattern. Changes to figures show vertically integrated MFC (Figure 9 on Page 31), vertically integrated moisture convergence and moisture advection (Figure 12 on Page 34). Results from this analysis have been added to Page 8 Line 36 to Page 9 Line 24. We also made a comparison between ERA-Interim and TRMM rainfall and its ENSO anomaly (Page 8 Line 48 to Page 9 Line 9). It can be shown that the ERA-Interim rainfall is different from the TRMM rainfall pattern. While the moisture convergence and vertical velocity explain the ERA-Interim rainfall pattern well, they could not explain the observed local maxima in TRMM rainfall or station observations for DJF (climatology). We suspect that the values in the calculated fields such as moisture convergence and specific humidity as well as rainfall are not resolved in ERA-Interim particularly over PM. Finally, we analyse the vertical velocity at 500 hPa to demonstrate the dynamic forcing contribution over PM (Page 9 Line 44-58).

We also changed to “with wind diffluence over the west coast of PM between 3°N and 5°N” at Page 8 Line 11 for better clarity.
2. It is not clear to me how the amplitude of morning rainfall peak and evening rainfall peak is calculated as the values in table 4 does not match the fig. 13. For example, compare the morning or evening amplitude. For example, compare the morning or evening amplitude values for group 3 from table 4 and Fig. 13. A more sensitive diagnostic for changes in rainfall-producing mechanisms can also be evaluated by comparing the rainfall pdfs of alternate phases of ENSO for morning and evening periods separately as shown in Fig. 6 of Nguyen et al. (2015) QJRMS (A regional forecast model evaluation of statistical rainfall properties using the CPOL radar observations in different precipitation regimes over Darwin, Australia).

The suggestion on using rainfall pdfs is noted for future study. However, we did not calculate rainfall pdfs for this analysis as we feel that our simple analysis is sufficient to demonstrate the changes in the morning and afternoon rainfall mechanisms.

To address the reviewer’s comment about the apparent disagreement between Table 4 and Figure 13, we have improved the explanation of morning and evening rainfall amplitude calculation on Page 6 Line 9-15. For Figure 14 (Figure 13 in the old text), we calculate the mean rainfall for each hour to represent the diurnal cycle of each group. However, for calculation of morning (AM) and evening (PM) rainfall amplitude in Table 4, we calculate the amplitude morning and evening rainfall for each year. After that, we calculate the climatology (and ENSO anomaly mean) of AM and PM amplitude for each group. Thus, the values shown in Figure 14 must be different from Table 4.

For example, Group 3 has a minimum rainfall in the morning and maximum rainfall during the evening (peak at 1800LT) (Figure 14). The morning amplitude is smaller than the evening amplitude (Table 4). The values of AM and PM amplitude for Group 3 were not calculated directly from Figure 14 but by the method described above. During EL, both mean (Table 3) and amplitude (Table 4) of morning and evening rainfall show a decrease in mean and amplitude for Group 3 compared to LA. The same explanation could also be used for Group 1 and 2. The decrease in both morning and evening means and amplitudes suggest that there is a decrease in large-scale rainfall throughout the day as opposed to a decrease in evening rainfall, which would indicate a change in the diurnal cycle.

Minor Comments

1. Delete 'and' before index of ENSO in line 38 page 4.

2. Lines 46-56 (page 4): Areas of above normal rainfall during EL years in Rauniyar and Walsh (2013) are the same where below normal rainfall occurs during LA years or different?
Yes, they are the same area. We have added the areas on Page 4 Line 23-24 and Page 4 Line 29.
3. **Line 25, page 5 expand the first occurrence of acronym TRMM.**
   Full name added on Page 4 Line 58.

4. **Section 2.1 lacks the information on the handling of missing data (if any) in this study. In addition, add the temporal resolution of ERA-interim reanalysis used in this study.**
   Handling of missing data described on Page 5 Line 22-25. The temporal resolution of ERA-Interim added on Page 5 Line 32.

5. **Line 32, page 6: differences in the morning (0000LT - 1100 LT) and evening rainfall (1200LT-2300LT). I suppose this is difference between mean of the morning period rainfall and mean of the evening period rainfall.**
   Correction been made on Page 6 Line 1-2.

6. **Fig. 4 (paragraph 2, page 8): Since, the number of EL and LA episodes are very different and also vary from one station to another based on the availability of data (Table1, and 2), I suggest to re-compute the heavy rainfall days statistics using relative frequency, if not done previously. As from the text, it appears to be absolute number of heavy rain days. For example, line 36, page 8: 4% .... reduction .... during EL, compared to what?**
   We have not made any changes in Figure 4. We have deleted the whole sentence “4% .... reduction .... during EL”. We have added “compared to LA years” on Page 7 Line 38. We believe that it would not change the meaning of the whole paragraph. However, the suggestion is noted for future study.

7. **Line 14, page 9: Change 1.5 x 10-2 to 15 x 10-3 for consistency and easy comparison**
   Numbers have been changed on Page 8 Line 27.

8. **Fig.8: do you mean stippled instead of shaded? Hardly see any stippled regions.**
   Figure 8 have been corrected and changed to show the stippling on Page 30. A new description added on Page 8 Line 32-34 to reflect the new changes.

9. **As per equation 2, the sum of Fig. 12 a and b panels should represent the Fig. 11, but It seems that the authors forgot to multiply by -1 in Fig. 12 or correct the captions accordingly**
   Figure 12(a) and 12 (b) have been corrected. We have also incorporated some changes in the new figure by showing the vertically integrated values from surface to 700 hPa on Page 34.

10. **Line 40, page 10: During DJF ...., You may mean to EL years (?), if so correct the sentence to reflect the meaning as I cannot see any suppression in morning and evening rainfall during DJF.**
    Added the word “of EL year” on Page 10 Line 19.

11. **Add location column in table 4.**
    Location added in Table 4 on Page 20.
12. Line 60, page 10, "Rainfall is suppressed through the entire day...", but which ENSO phase, complete the sentence.
   Added “during EL” on Page 10 Line 37.

13. Fig. 13, hard to distinguish the colour lines, especially for groups 4 and 5.
   Figure 13 changed to Figure 14 in the new text on Page 36. Improvement on colour lines has been done by changing line style.

14. Line 27, page 11: ‘land breeze appears to be …’ or sea breeze? I don’t think land breeze occurs at 1500 LT.
   Changed to “1000 LT” on Page 10 Line 58.

15. Line 1, page 12: southeast coast of PM or west coast?
   Corrected to “west” on Page 13 Line 22.