The Regional Hadley Cells Response to the Sea Surface Temperature Distribution Across the Indo-Pacific Ocean

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Abstract. Hadley Cells are thermally driven cell in the tropics. On its occurrence, these cells are strongly influenced by the sea surface temperature (SST) distribution across the tropical ocean or the Pacific Ocean as the investigated location in this study. The SST shifting in the Pacific Ocean is mainly due to the ENSO. An opposite SST polarity between the western and eastern Pacific Ocean are captured during ENSO events. This means that ENSO could trigger an anomalous regional Hadley Cells that behave oppositely between Indonesia or the western Pacific and the eastern Pacific. This study examines the strength of the regional Hadley Cells related to the ENSO event across the Indonesian region and the Pacific Ocean. A significant correlation between the Hadley Cells and ENSO as the tropical climate variability in the Pacific Oceans are found. The strength of the Hadley Cells associated with ENSO event is examined by using the zonally average vertical velocity across the Pacific Ocean. During La Nina, the regional Hadley Cells over Indonesia or the western Pacific strengthened, whereas the regional cells over the eastern Pacific weakened. In contrast, during El Nino where the warm pool shifted to the eastern Pacific, the regional cell in the eastern Pacific strengthened, while the cell over the western Pacific weakened. These anomalous conditions clearly show that the meridional temperature gradient is strongly affecting the regional Hadley Cells strength. The stronger the meridional temperature gradient, the stronger the regional Hadley Cells.

Keyword: Hadley Cell, El Nino, La Nina, sea surface temperature, precipitation

1. Introduction
As a thermally driven meridional cells in the tropics, Hadley Cells play an important role in distributing energy from low to high latitude as well as from southern to northern hemisphere and vice versa. The annual average of this cells shows two symmetric cells in equator with ascending branch in tropics and descending branch in subtropics. However, the southern and northern hemisphere are not heated equally for the entire year, especially for the solstitial season. During the boreal summer, the northern hemisphere receives more heat than the southern hemisphere, in contrast, during the boreal winter, the southern hemisphere receives more heat than the northern hemisphere. This condition leads to asymmetric Hadley Cells about the equator where the ascending branch located in the summer hemisphere and descending branch located in the winter hemisphere [1]. This means that the cells over the winter hemisphere are more dominant and stronger than the cells over the summer hemisphere. This is because the winter hemisphere is cooler than the summer hemisphere which makes the meridional temperature gradient in this hemisphere greater. As the thermal wind balance concept, the
stronger the meridional temperature, the stronger the meridional wind. Since the distribution of the heat affecting the Hadley Cells strength, the Indo-Pacific SST distribution will also do the same.

The unevenly distributed SST across the Indo-Pacific Ocean will significantly affect the cells. ENSO is the most important interannual climate variability that occur in the Pacific Ocean. The occurrence of this event causes the Indo-Pacific warm pool shift across this ocean. El Nino as the warm phase of this event leads to the shifting of warm pool to the eastern Pacific Ocean, whereas La Nina as the cold phase of ENSO cause the warm pool in the western Pacific Ocean strengthen [2]. When the warm pool over the western Pacific is enhanced during the occurrence of La Nina, the convective activity over this region is also enhanced which cause above normal rainfall over this region as well as Indonesia. In contrast, during the occurrence of El Nino, where the convective activity over the western Pacific is suppressed, Indonesia experiencing below normal rainfall and even drought. When ENSO occurred, the SST variability in the Indo-Pacific Ocean will shows an opposite dipole between the eastern and the western Pacific Ocean. Since Hadley Cells is significantly affected by the heat distribution, the unevenly distributed SST in the Indo-Pacific Ocean could make the regional Hadley Cells behave differently from the global mean Hadley circulation. The distribution of SST in the tropics has an important effect on the variation of the Hadley Cells [3]. For instance, the vertical motion in the lower troposphere is affected by the meridional distribution of SST in tropics [4]. Another study also supported this result, that the vertical ascent of the Hadley Cells is coincide with the zero value of the meridional SST distribution, which means that the symmetric cells about the equator are accompanied with the symmetric distribution of SST about the equator [5].

Regarding the significant influence of tropical SST distribution to the behaviour of regional Hadley Cells, the opposite polarity of SST during ENSO event could cause an opposite response of the regional Hadley Cells in the eastern and the western Pacific Ocean. By examining the distribution of SST across the Indo-Pacific region, this study will evaluate the strength of the regional Hadley Cells over the western and eastern Pacific Ocean. This study will also evaluate the impact of the changing SST variability related to ENSO on the rainfall variability in Indonesia. The data and method used to analyse the strength of the regional Hadley Cells in the equatorial Pacific are presented in Sect. 2. Sections 3 explore and discuss the relationships between the distribution of SST across the Pacific Ocean with the regional Hadley Cells and the impact of its changing variability to the rainfall pattern in Indonesia. Concluding remarks are provided in Sect. 4.

2. Data and Method

In order to conduct this study, it is necessary to find a suitable dataset. Secondary data will be used for this study as shown in Table 1. and ENSO events are defined by using the Nino3.4 indices. The climate dataset from 1981 to 2010 will be used to analyse the climatological condition of SST and rainfall, then the datasets from 1989 to 2019 will be used to select ENSO events and analyse the anomalous condition. The SST data were retrieved from NOAA Optimum Interpolation (OI) Sea Surface Temperature V2 (NOAA OI SST V2). The NOAA OI SST V2 will be used to calculate the climatological condition of SST across the Indo-Pacific Ocean and to show the anomalous SST distribution during the occurrence of ENSO. Then the vertical velocity (omega) and the meridional wind were collected from the NCEP/NCAR Reanalysis. The vertical velocity data will be used to demonstrate the vertical motion of the regional cells as well as the strength of the Hadley Cells.

This study will analyse the causal relationship of the SST distribution related to ENSO on the Hadley Cells’ strength and on rainfall variability in Indonesia. The first step is selecting El Nino and La Nina based on the Nino3.4 indices. El Nino event will be selected if the Nino3.4 ≥ 0.5°C, whereas La Nina if Nino3.4 ≤ -0.5°C. The events selected in this study is pure ENSO or a neutral event and not in a simultaneous occurrence with the IOD events in the Indian ocean. The years of El Nino are 1992, 2002, 2004, 2009, and 2014, while the years for La Nina are 1995, 1999, 2000, 1007, 2011, and 2017. Then the data listed in the Table 1. will be processed to perform composite analysis and will be investigated by using comparative study to find out the regional Cells response. Since the changing distribution of sea surface temperature is related to the changing of the cells’ energy source, it is important to analyse the SST anomaly during ENSO occurrence. The shifting of SST will result in a different response from the cells. Before evaluating the regional cells response, in order to know the
relation between the Hadley Cells and ENSO, correlation between the vertical velocity in 500hPa and the sea surface temperature in Nino3.4 domain will be performed. This step is essential since the vertical velocity data shows the upward and downward motion of the cells and will be used to analyse the regional Hadley Cells strength. Lastly, the impact of SST shifting and changing behaviour of the regional Hadley Cells to the weather variability over Indonesia will be investigated through the rainfall data. The CHIRPS v2p0 monthly global precipitation from UCSB (UC Santa Barbara) will be used to see the rainfall anomalies over Indonesia.

| Variables                  | Data Name          | Spatial resolution | Data access / Information         |
|----------------------------|--------------------|--------------------|-----------------------------------|
| ENSO indices               | Nino3.4            | -                  | https://www.psl.noaa.gov          |
| Sea surface temperature    | NOAA OI SST V2     | 1° x 1°            | https://psl.noaa.gov               |
| Vertical velocity (omega) v-wind | NCEP / NCAR Reanalysis | 2.5° x 2.5°       | https://psl.noaa.gov               |
| Monthly rainfall           | CHIRPS v2p0        | 0.05° x 0.05°      | https://iridl.ldeo.columbia.edu   |

3. Results and Discussion

El Nino Southern Oscillation (ENSO) is the significant climate variability that occur in the equatorial Pacific. This event arises from the feedback mechanism of the sea surface temperature and the trade-wind across this region. El Nino start to develop when the warm pool over the western Pacific travels to the east in the form of Kelvin wave for several months [6], the trade-wind that normally blows from east to west in the tropics weaken and even change direction. After several months, the sea surface temperature shift to the central and eastern Pacific causes a rise in SST and sea levels in this region, thus result in El Nino occurrence. During this event, the Indonesian and the western Pacific region experiencing cool SST anomaly, while the central and eastern Pacific has warm SST anomaly (as in Figure 1.a). The conditions where the weaker trade-wind can enhance the SST anomaly in the equatorial Pacific called the positive Bjerknes feedback [2].

Figure 1. Composite SST and horizontal wind anomaly for a) El Nino and b) La Nina during SON season

In contrast, air-sea interaction in the equatorial Pacific shows a negative feedback during the occurrence of La Nina. The Bjerknes negative feedback describes as the negative SST anomaly in the eastern Pacific Ocean can enhance the east-west SST gradient and hence strengthen trade-wind in the tropics [7]. These strengthened trade-wind then further reduce the SST in the eastern Pacific. As a
result, the eastern Pacific has a negative SST anomaly, whereas the western Pacific has a positive SST anomaly as shown in Figure 1.b. This feedback mechanism also related to the equatorial Rossby wave, after the Kelvin wave reach the western coast of South America and generate sea level to rise, Rossby waves then generated and propagates back to the western Pacific. The propagation of the Rossby waves to the western Pacific cause sea level in the eastern Pacific decrease and transfer the warm SST from the eastern Pacific back to the western Pacific. Thus, returning the SST variability across the Pacific Ocean to normal or to the cold phase of ENSO or La Nina.

The sea surface temperature shows a dipolar pattern during the occurrence of ENSO as in Figure 1. The changes in the ocean or sea states could influence the atmosphere condition above it. Hadley Circulation is one of the atmospheric circulations in the tropics that has function as a tropical meridional circulation. Because these cells are thermally driven cells, the changes in the SST distribution across the Pacific Ocean could affect the behaviour of this cells. In order to prove this statement, we need to know the relationship between the Hadley Cells and ENSO. The correlation between vertical velocity in the 500hPa and sea surface temperature in the Nino3.4 domain then performed. The value of vertical velocity or omega in this study has been times by -1, so the positive value indicates an upward motion, while the negative value indicates a downward motion. The correlation shown in Figure 2. indicates that the Indonesian region and the eastern Pacific has opposite correlation coefficient. This figure shows that Indonesia and its surrounding has a medium-strong negative correlation (-0.4 to -0.6) with the SST in Nino3.4 region, whereas the eastern Pacific has a strong positive correlation (0.6 to 0.85) with the SST in Nino3.4 domain. When the SST in Nino3.4 warms up, Indonesia experiencing anomalous downward motion in the middle of troposphere, in contrast, eastern Pacific has anomalous upward motion.

![Figure 2](image)

**Figure 2.** Correlation between vertical velocity in 500hPa and sea surface temperature in Nino3.4 region

The globally average Hadley Cells has upward motion in the tropics, flows to the poles in the upper troposphere, sinks in the subtropics, then flows back to the tropics in the lower troposphere. However, the unevenly distributed SST across the Pacific during ENSO lead to anomalous behaviour of the regional cells. According to the spatial correlation that has been performed, the positive SST anomaly in the eastern Pacific Ocean led to a weaker Hadley circulation in the Indonesian region and also western Pacific. This condition is the interpretation of the anomalous downward motion of vertical velocity above this region as in Figure 3.a. Since the normal Hadley Cell has upward motion in the tropics, so if the regional cell shows more negative value of vertical velocity, it means that the regional cells over that region is weakened. In contrast, when the Nino3.4 region warms up, the eastern Pacific regional cell is strengthened. To support this finding, the previous study also show a negative correlation between the Hadley Cells in the western Pacific with the Nino3 SST anomalies, with the correlation of -0.56 [8]. While the eastern Pacific has a positive correlation with the Nino3 SST anomalies, with the value of 0.75. Thus, these evident indicates that during El Nino or the warm
The opposite response of regional Hadley Cells over the western and the eastern Pacific is due to the difference in the meridional SST gradient and also the energy source over that region. The shifting of the warm SST to the eastern Pacific causes the east-west SST gradient in the equator weaken, which also lead to the meridional SST gradient in the western Pacific weaken. When the meridional SST weaken, the pressure gradient also weaken thus leads to a weakening of the regional Hadley circulation over the western Pacific Ocean. Moreover, when the western Pacific has negative SST anomaly, the convective energy to supply the meridional circulation in this region also decrease, hence causes the regional meridional circulation weakened. This condition also related to the upper-level convergence in the western Pacific and the upper-level divergence in the eastern Pacific [8]. The upper-level divergence is normally related to the huge convective clouds, because the upper-level outflows help to maintain the existence of the cloud system. In other word, the western Pacific Ocean has a low-level divergence and an anomalous downward motion that weakened the regional Hadley Cells, while the eastern Pacific has a low-level convergence and an anomalous upward motion that strengthen the regional Cells.

The anomalous strength of the regional Hadley Cells depend on the anomalous variation of SST [9]. The anomalous strength of SST in the Pacific Ocean has stages, the lowest amplitude is during the onset and decay phase, while the highest amplitude is during the mature phase. In other word, when the variation of SST reaches its maximum amplitude, the regional Hadley Cells’ strength also shows its maximum value. However, the strength of the regional Hadley Circulation also depends on each
region’s climate variability. Indonesia that located close to the Pacific Ocean is strongly influenced by the heating variation in this ocean which are influenced by ENSO as the interannual climate variability.

The strength of the regional Hadley circulations is affecting the convective activity in that specific region. Since the energy in the western Pacific is decreased due to the warm SST shifting to the eastern Pacific, the convective activity in this region is suppressed and result in the reduction of precipitation in western Pacific. The suppression of the convection activity over the western Pacific Ocean is in agreement with the weakening of the regional Hadley circulation over this region. The reverse mechanism is applied for the convective activity over the eastern Pacific. In contrast, during the occurrence of La Nina, where the western Pacific shows positive SST anomaly, the convective activity in this region is enhanced, thus result in positive anomaly of rainfall over this region. While the eastern Pacific receive negative anomaly of rainfall during La Nina. This means that during the occurrence of El Nino where the regional Hadley circulation in western Pacific weakened, Indonesia gets negative precipitation anomaly, in contrast, during La Nina where the western regional cell is strengthened, Indonesia gets positive precipitation response as in Figure 4. In this figure, most of Indonesia receive negative precipitation response during El Nino, and positive response during La Nina. In the extreme condition, El Nino could cause drought and even forest fire, while La Nina could cause heavy rainfall that leads to floods in some region in Indonesia.

4. Conclusion
The purpose of this research was to examine the behaviour of the regional Hadley Cells, especially the strength of the cell, during the occurrence of ENSO. In normal year, where the warm pool located in the western Pacific Ocean, the regional cells over this region is stronger than the regional cells over the eastern Pacific due to the excess of energy supply from the warm SST region to the cells. However, during the occurrence of ENSO, SST distribution in the Pacific Ocean is changes. The changes of the SST distribution could influence the strength of the Hadley Cells since these cells are a thermally driven cell. The strength of this cells is depending on the meridional SST gradient and the heat supply in that certain region. The greater the meridional SST gradient, the stronger the regional cells. Based on this study result, we found that vertical velocity in the western Pacific shows a positive anomaly during the occurrence of La Nina, where the warm pool in the western Pacific becomes warmer than the normal year. This means that the regional Hadley Cells over the western Pacific is strengthen during the occurrence of La Nina because the meridional SST gradient between the equator and the high latitude is higher.

In contrast, during the occurrence of El Nino, the regional cells over the western Pacific are weakened. While the regional cells over the eastern Pacific is strengthened due to the SST shifting to the eastern Pacific during El Nino. This condition makes the meridional SST gradient in the eastern

**Figure 4.** Precipitation responds in percent (%) during a) El Nino and b) La Nina
Pacific greater, while the meridional SST gradient in the western Pacific is weaker. The correlation between the vertical velocity and the SST in Nino3.4 domain also supports this result. A negative correlation is observed in the western Pacific, while a strong positive correlation is observed in the eastern Pacific. In other word, the western Pacific regional Cells will be strengthened if the SST in Nino3.4 region is cooler than normal, while the regional Cells over the eastern Pacific will be weakened.

The strength of the regional Hadley Cells also influences the convective activity in that specific region. The convective activity in the western Pacific or Indonesia is enhanced when the regional cells over this region is strengthened. This is due to a great supply of heat energy to the cells and the existence of the upper-level convergence that helps to maintain the cloud system. Thus, makes Indonesia has positive rainfall respond. In the other hand, if the regional Hadley Cells is weakened, the convective activity is also suppressed, thus leads to a negative rainfall anomaly. Since the regional Hadley circulation behaviour depend on its regional condition especially the heat distribution, having a better understanding about the background condition that could leads to the Hadley cells’ changing behaviour is important. Moreover, the changing behaviour of this cells also related to the rainfall variability that could have an impact to the society activity. That is why it is important to have a better knowledge about this cell mechanism and relationship with other phenomena to be able to estimate or predict the socio-economic impacts.

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