NOTES AND CORRESPONDENCE

Relationship between Sea Surface Temperature and Rainfall in the Philippines during the Asian Summer Monsoon

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Abstract

We offer a new perspective on a relationship between sea surface temperature (SST) over the windward region of the Philippines and rainfall in the western Philippines during the Asian summer monsoon season, which has been known as the negative correlation, using observational daily SST, rainfall, and atmospheric circulation datasets. This study focuses on the local SST effect rather than the remote effect. A warmer local SST results in greater rainfall over the western Philippines under similar monsoon westerlies conditions, particularly during moderate and relatively stronger monsoon regimes. This result is obtained after selecting only the moderate or relatively stronger monsoon days, because the positive effect of SST on rainfall is masked by the apparent negative correlation between SST and rainfall. The warmer SSTs being associated with less rainfall correspond to weaker cooling by weaker monsoon westerlies and the cooler SSTs being associated with more rainfall correspond to stronger cooling by stronger monsoon westerlies. The cooler SSTs are the result of stronger monsoon cooling and are not the cause of the greater rainfall, which is the apparent statistical relationship. This also implies that the monsoon westerly is the primary driver of the variation in rainfall in this region. We conclude that the local SST makes a positive contribution toward rainfall, although it does not primarily control rainfall. This conclusion can be applicable to coastal regions where, climatologically, rainfall is controlled by winds from the ocean.

Keywords apparent statistical relationship; local SST effect; monsoon westerlies; evaporative cooling; water vapor; rainfall

1. Introduction

Over the tropics, sea surface temperature (SST) is a key factor controlling the local and remote variation in rainfall over various timescales. Many previous studies have investigated the impact of SST anomalies, such as the El Niño-Southern Oscillation (ENSO), on tropical and extratropical climates. Across the Asian monsoon region, the relationship between the ENSO
and monsoons is very important (e.g., Webster et al. 1998). Compared to studies on the remote SST effect, fewer studies have considered the local or nearby SST effect on local or regional climates. In this study, we use the term “local SST effect” to represent the impact of local and nearby SST on local and regional climates.

Previous studies have investigated the relationship between local SST and rainfall using observational datasets and numerical experiments for the Asian monsoon region (e.g., Trenberth and Shea 2005; Wang et al. 2005). A negative relationship between local SST and rainfall, which can be associated with changes in solar radiation and evaporative cooling over the sea surface, has been observed and simulated (e.g., Trenberth and Shea 2005; Wang et al. 2005; Roxy 2014). These studies suggest that SST is mainly controlled by the atmosphere and that an understanding of strong air-sea coupling processes is crucial to predicting monsoon rainfall.

Although the local SST cannot be the primary driver of the observed variation in rainfall across the Asian monsoon region, it is important to note that these previous studies have not investigated the influence of local SST on rainfall. Although remote SST effects are very important for the prediction of monsoon rainfall in Asia, the monsoon rainfall is controlled by many factors, including local and remote SST (e.g., Hendon 2003), land-surface conditions (e.g., Douville 2002; Takahashi et al. 2010; Sugimoto and Takahashi 2017), and aerosol loading (e.g., Nakajima et al. 1999; Yamaji and Takahashi 2014). An understanding of the influence of each factor on the variation in rainfall is necessary for more precise predictions of monsoon rainfall in the Asian monsoon region. Thus, this study focuses on the local SST effect on rainfall in the tropical Asian monsoon region.

Although the following example does not consider a tropical region, the nature of the physical processes is likely to be similar. In mid-latitudes in winter, specifically in the Sea of Japan, a similar negative correlation between SST and rainfall has been observed using monthly datasets (Matsumura and Xie 1998). This can be explained as the result of an atmospheric impact on the oceans. This explanation is consistent with results obtained in the tropics (e.g., Trenberth and Shea 2005; Wang et al. 2005). Takahashi and Idenaga (2013) used a daily observational dataset to show that a local warm SST results in large amounts of rainfall over the downstream land region in the mid-latitudes in winter. They suggest that strong air-sea coupling processes mask the local SST effects. Over the same region, results of numerical experiments driven by observational SSTSs, using a high-resolution non-hydrostatic atmospheric regional model, have been consistent with observations (Takahashi et al. 2013). Thus, even over regions with an apparent negative correlation between SST and rainfall, the impact of local SST on rainfall may be important.

The negative correlation between SST and rainfall, which is the result of air-sea interaction, has been analyzed using observational datasets in previous studies (Matsumura and Xie 1998; Takahashi and Idenaga 2013). Takahashi and Idenaga (2013) emphasized that a SST-rainfall relationship varies with the timescales considered. The negative correlations between SST and precipitation are observed on monthly or seasonal timescales. Over the Sea of Japan in winter, the positive effect of SST can only be found on timescales of less than one month. Hendon (2003) investigated the remote and local SST effects over the Maritime Continent with time periods over one month. The current study examines shorter timescales.

Theoretically, under the same atmospheric conditions, a warm SST will provide high vapor pressure conditions at the sea surface based on the Clausius-Clapeyron equation, which results in a large latent heat flux from the sea surface into the atmosphere. The increase in atmospheric water vapor under such conditions should induce more rainfall over downstream regions.

Across the Asian monsoon region, the Philippines is very likely to be affected by local SST because the country is surrounded by ocean. A negative correlation between monthly SST and rainfall has been observed over and around the Philippines (Trenberth and Shea 2005; Wang et al. 2005). Thus, in this study, we focus on the SST effect from the South China Sea, which is located on the windward side of the Philippines during the Asian summer monsoon season.

We investigate the impact of the local SST on rainfall in the western Philippines during the Asian summer monsoon season. Because the impact of monsoon winds on rainfall is more predominant than that of SST, we investigate the impact of local SST under similar low-level monsoon westerlies conditions. We emphasize that the SST is not the primary factor controlling the variation in rainfall in this region. Section 2 documents the data used in this study. Section 3 shows the negative and positive correlations between SST and rainfall. A discussion of the apparent negative correlation is given in Section 4, and conclusions are given in Section 5.
To understand the relationship between the SST west of the Philippines and rainfall in the western Philippines, the Global Precipitation Climatology Project 1° Daily Precipitation (GPCP-1DD; Huffman et al. 2001, version 1.2) dataset is used. This provides daily, global 1° × 1° gridded fields for total precipitation from October 1996 to October 2015. We also use the global high-resolution Optimum Interpolation SST (OISST; Reynolds et al. 2007) Version 2 dataset, which has a spatial resolution of 0.25° and daily temporal resolution. To identify the effects of SST including high-frequency variability, such as synoptic and intraseasonal timescales, we select daily rainfall and SST datasets.

We define the rainfall region as the western Philippines (WP; land region of 118–122°E, 12–18°N; Fig. 1), because the rainfall in this region likely occurs under strong monsoon westerlies due to orographic uplift of moist air. To create an index of SSTs west of the Philippines, we average the OISST values on the windward side of the Philippines (Fig. 1; oceanic region of 110–120°E, 10–18°N). The SST region is referred to as the wSST region in Fig.1. The water vapor accounting for the rainfall in the WP is likely to be supplied from this region and more upstream regions of the low-level monsoon westerlies.

To examine the atmospheric circulation over and around the Philippines, we use the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) dataset, specifically zonal and meridional winds (u, v) at 850 hPa. We use the 1.25° product. To select similar strong and moderately strong monsoon westerly regimes, we define the key region of the monsoon westerlies over the South China Sea, which is the same as the wSST region.

To connect SST and rainfall physically, we also use the daily Objectively Analyzed Air–Sea Fluxes (OAFlux) dataset (Yu and Weller 2007), which diagnose air–sea heat fluxes using observational and reanalysis datasets. The spatial resolution is 1°.

The analysis period covers 17 years from 1998 to 2014, which is established based on the availability of all of the datasets. We focus our analysis on the Asian summer monsoon months from May to September.

To understand the relationships among SSTs, rainfall and the low-level monsoon westerlies, we focus on a several-day timescale. In this region, rainfall varies on an intraseasonal timescale (Wand and Xue 1997), including tropical disturbances (Takahashi and Yasunari 2008; Takahashi et al. 2015). Thus, we show the results of 7-day running mean values for all meteorological variables. In addition, we confirmed that the conclusion is unchanged when we use 5-, 9-, and 11-day running mean values. To avoid double counting, the events studied are at least 7 days apart. Moreover, because day-to-day variations in rainfall are extremely irregular, smoothing is necessary for our analyses.

3. Results

3.1 Apparent negative relationship between SST and rainfall

First, we reconfirmed the relationship between SST over the wSST region and rainfall in the WP during the Asian summer monsoon season. Figure 2a shows a clear negative correlation between SST and rainfall, although the variance was considerable. This negative correlation was statistically significant at the 99% confidence level according to Student’s t-test. It is noteworthy that the negative correlation coefficient between SST over the wSST region and rainfall in the WP was strongest when we used all atmospheric conditions. This likely implies that the negative correlation was strongly affected by the contrast between a warm SST with little rainfall and a cool SST with large amounts of rainfall.

On the other hand, there was little rainfall under weak monsoon conditions (see the different markings in Fig. 2a), whereas more rainfall occurred during relatively strong monsoon conditions. This indicates that
the two opposite rainfall conditions occurred under very different low-level monsoon conditions. Thus, the negative correlation can be strengthened under two different low-level monsoon conditions.

While the negative correlation between SST and rainfall can be explained by the dominant atmospheric processes, a basic understanding of the physical processes regarding the impact of SST on rainfall is needed. As mentioned in Section 1, warmer SSTs supply more water vapor to the atmosphere under the same atmospheric conditions, which in turn results in increased rainfall in the downstream regions of basic flows.

3.2 Positive correlation between SST and rainfall under the same monsoon westerlies

To understand the physical processes between SST and rainfall, we examined the effects of the monsoon westerlies on rainfall in this region. Figure 2b shows a clear positive correlation between the low-level monsoon westerlies over the wSST region and rainfall over the WP region, indicating that the variation in rainfall in the WP is primarily controlled by the low-level monsoon westerlies. It is possible that the primary effects of monsoon westerlies on rainfall mask the effects of SST, as explained in a previous study (Takahashi and Idenaga 2013).

To examine only the effects of SST, we exclude the effects of the monsoon westerlies on the variation in rainfall over the Philippines. To do so, we chose events with similar monsoon westerlies conditions, as defined by the strength of monsoon westerlies. Specifically, we determined the threshold values of the 850-hPa westerlies over the wSST regions to be 8–10 m s\(^{-1}\) to represent strong monsoon conditions. To check that the determined 8–10 m s\(^{-1}\) threshold value of the 850-hPa westerlies was appropriate, we composited the selected atmospheric circulations (Fig. 3). The strong monsoon westerlies penetrate the Philippines from the South China Sea to the Philippine Sea, which indicates that the threshold value of the 850-hPa westerlies over the wSST region was suitable in representing the monsoon westerlies conditions for the analysis of SST impact. These low-level winds then transport the water vapor over the wSST region to the WP region. In addition, air over the wSST region will be transported from wSST to the WP regions within a few days based on a scale analysis of low-level winds. The horizontal wind speed of 8 m s\(^{-1}\) approximately corresponds to a transport of 700 km day\(^{-1}\). This suggests that a series of physical processes occurs within a few days. Using 7-day running mean values, the time-lag of the physical processes was negligible.

Figure 4 examines the relationship between SST
and rainfall under similar westerlies conditions. A positive correlation between local SST over the wSST and rainfall in the WP \( (r = 0.44; \text{p-value} = 0.0044) \) was found (Fig. 4a). The correlation coefficients for each individual month were also positive, although we did not examine the months with a small sample number (see values on the upper-right side of Fig. 4a). This indicates that the local SST over the wSST positively contributed to the rainfall in the WP.

To confirm that the relationship persists under other low-level westerlies conditions, we also calculated the correlation coefficient between SST over the wSST and rainfall in the WP for 5 months (May–September). We defined the monsoon conditions of the 850-hPa westerlies as 10–1 m s\(^{-1}\), 8–10 m s\(^{-1}\), 6–8 m s\(^{-1}\), 4–6 m s\(^{-1}\), and 2–4 m s\(^{-1}\) over the wSST region (Figs. 4b–e). The correlation coefficients were 0.55, 0.44, 0.26, 0.25, and 0.00 under the 10–1 m s\(^{-1}\), 8–10 m s\(^{-1}\), 6–8 m s\(^{-1}\), 4–6 m s\(^{-1}\), and 2–4 m s\(^{-1}\) conditions, respectively. These results show that the positive relationship holds under moderate monsoon conditions, which weakens under weak monsoon conditions.

We examined the physical processes connecting the SST over the wSST region to rainfall in the WP. The water vapor that was evaporated from the sea surface of the wSST region under warm SST conditions was eventually transported to the WP region. The transported water vapor resulted in rainfall by uplifting due to the orography of the Philippines or by a low-level convergence due to tropical cyclonic disturbances.

Figure 5a shows the relationship between SST over the wSST and the latent heat flux (positive from the ocean to the atmosphere) over the same region. There was a clear positive correlation between SST and latent heat flux from the ocean to the atmosphere over the wSST region. This indicates that the warmer SST provides more water vapor to the atmosphere under the similar monsoon conditions.

The figure also shows a scatter diagram between latent heat flux over the wSST region and rainfall in the WP region under relatively strong monsoon conditions. A positive correlation between the latent heat flux and rainfall was apparent (Fig. 5b). This implies that an increase in the amount of evaporated water vapor would result in greater rainfall in the WP.

4. Discussion

4.1 Apparent negative correlation due to air-sea interactions

The relationship between local SST and rainfall has been investigated under all atmospheric conditions in most previous studies (e.g., Trenberth and Shea 2005; Wang et al. 2005). As monsoon winds become stronger, more rainfall is generated through increased latent heat flux, while weaker monsoon winds are associated with less rainfall. At the same time, strong monsoon winds can generate substantial cooling of the sea surface through evaporative cooling, while weaker monsoon winds reduce the cooling effects. This results in the apparent negative correlation between the combination of the substantially cooled SST and large amounts of rainfall and the combination of the slightly cooled SST and lesser amounts of rainfall. In other words, there is little rainfall generated by very weak monsoon winds, which in turn produces warm SSTs. It is important to understand that cooler SSTs do not directly induce more rainfall.

Moreover, changes in downward shortwave radiation at the surface can contribute to SST variations. The strong (weak) monsoon can increase (decrease) cloud cover, which in turn reduces (increases) downward shortwave radiation at the surface. Note that the sign of response of shortwave radiation to the strength of monsoon westerlies is probably the same as that of evaporative cooling to monsoon. The effect of shortwave radiation does not change our conclusion. Both cooling effects should be quantitatively estimated in future studies.
Fig. 4. Scatter diagrams indicating the relationship between SST over the wSST and rainfall in the WP, under the conditions that the 850-hPa zonal wind speed averaged (a) 8–10 m s\(^{-1}\), (b) 10– m s\(^{-1}\), (c) 6–8 m s\(^{-1}\), (d) 4–6 m s\(^{-1}\), and (e) 2–4 m s\(^{-1}\) over the wSST region. The symbols in each panel indicate monthly differences. Correlation coefficients and sample numbers are shown in the upper left corner. The correlation coefficient was omitted for categories with fewer than five data points.
We considered the impact of local SST on rainfall in the WP under the same atmospheric conditions. To assume the same atmospheric conditions, we considered only relatively strong monsoon regimes. When we analyzed only the relatively strong monsoon regimes, the warm SST was found to provide a large latent heat flux from the sea surface to the atmosphere, which eventually resulted in large amounts of precipitation (Fig. 5a). At the same time, the sea surface was cooled by evaporation. This strong air-sea interaction hid the positive correlation between SST and rainfall. In addition, Dado and Takahashi (2017) recently demonstrated local SST effects on rainfall over a similar region using a high-resolution regional climate model. The results were consistent with our observational facts that warm SST resulted in increased latent heat flux and rainfall over the western Philippines under the same atmospheric conditions.

5. Conclusions

We have demonstrated a positive correlation between nearby SST and rainfall in the Philippines and have provided a physical explanation of the apparent negative correlation between SST in the wSST region and rainfall in the WP, using only observation datasets.

When we examined the relationship between SST over the wSST region and rainfall in the WP region under similar monsoon westerlies conditions, a positive correlation was found between SST and rainfall. This suggests that the local effects of SST contribute to variations in rainfall although the SST effect is not the primary cause of this variation. This is consistent with previous results obtained by numerical models and theoretical explanations.

A negative correlation was identified between low SSTs with a strong monsoon and large amounts of rainfall, and high SSTs with a weak monsoon and little rainfall. However, we cannot explain the physical mechanism whereby a low (warm) SST results in large (small) amounts of rainfall. Because the primary contributing factor of variation in rainfall in this region is low-level monsoon westerlies, the effects of local SSTs were hidden by the effects of variation in the monsoon and the related air-sea interaction.

Because this study showed only the qualitative results between local SST and rainfall over the Southeast Asian monsoon region, future studies should quantify the effects of SST with other datasets or numerical experiments. In addition, the timescales of the air-sea interactions over the region should be investigated.

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