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Research Article

PRECIPITATION AND SEA SURFACE TEMPERATURE CHANGES IN THE VICINITY OF THE PHILIPPINES

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ABSTRACT

Precipitation anomalies in the vicinity of the Philippines are described with data covering about two decades that provide information on regional and long-term changes. Zonal mean precipitation data show that maxima are mainly in a belt between 6^0N and 19^0N, but high precipitation is not uniformly distributed. Longitude-averaged data show that low precipitation is concentrated somewhere along 120^0E. High precipitation along the eastern coast of the Philippines demonstrates that almost no correlation is found between sea surface temperature and precipitation, whereas the west coast shows a better correlation between the two parameters. Seasonal data show extensive anomalies in precipitation and are symptomatic for drought and flood conditions. Linear regressions indicate an increase of precipitation for the season from September to February while precipitation in June to August appears to stay rather constant whereas precipitation for March to May suggests a slight decline. Long-term oscillations in precipitation are observed for all seasons except for the period June to August, which shows most probably the impact of typhoon activity. In addition to seasonal differences, considerable temporal complexity is observed that demonstrates that intensity and duration of anomalies vary simultaneously with the monsoon seasons but are not uniform from year to year. Both sea surface temperature and precipitation show similar longtime oscillations, and linear fits show for sea surface temperature an increase of about 0.03^0C y^{-1}, that corresponds approximately to the mean global increase in sea surface temperature. When applying a linear regression to the precipitation data, only a minimal increase is observed, but the linear regression describes a parallel development for both parameters. However, this relationship does not necessarily mean that sea surface defines precipitation, or vice versa. Rather, changes of precipitation and temperature are primarily driven by global increase of temperature and are related to large-scale changes in atmospheric processes. This study showed that large gradients exist between the offshore regions and the coastal environment, and it can be anticipated that even small horizontal fluctuations of the boundaries in connection with the ongoing global change may alter conditions at local levels.

Keywords: *Philippines, Precipitation, Sea Surface Temperature, Inter-Decadal Variability, Regional Trends*

INTRODUCTION

The Philippines’ archipelago is located in the Pacific Ocean typhoon belt and is exposed to the change in Asian monsoon seasons that are characterized by the annual reversal of the prevailing wind regime. The extreme meteorological changes in the Philippines lead to natural disasters, and droughts, typhoons and floods are frequently observed that rank the Philippines as one of the highest risk-countries. The change in wind systems is based on the contrast in differential heating between the immense landmass of Asia and the Indian Ocean that forms a rainy summer and a dry winter. Based on the level of temperature and precipitation, the climate of the Philippines can be divided into a rainy season from June to November, and a dry season that lasts from December to May. However there is geographical variation in the distribution of precipitation because it is heavy during June to September at the western part of the country, whereas between October and March, heavy precipitation is mainly located along the eastern coastal regions. The Philippines are also exposed to severe rainfalls due to tropical cyclones that originate in the Western North Pacific and add to interannual variability of precipitation. The impact of tropical cyclones on precipitation is highest in the northern Philippines, particularly along the western coast of Luzon but it is lowest in the southern islands of Mindanao (Bagtasa, 2017, 2019). Anomalies in high precipitation are related to tropical cyclones northeast of Luzon and strong southwesterly winds that interact with the high Cordillera Mountain ranges along the west coast of Luzon (Cayanan *et al.,* 2011; Olaguera *et al.*, 2020).

The southwest monsoon covers the whole Philippines but in the southern region, the arrival of the monsoon is slightly delayed. The northeast monsoon winds and terrain interaction induce precipitation along the eastern coastal regions of the Philippines that peaks in December, but progressively decreases until February of the following year. Unlike the northeast monsoon, the southwest monsoon winds induce precipitation even in the central and eastern areas of the country. For this reason, the eastern regions do not have a distinctive dry season, unlike the western regions and therefore a sharp gradient exists between precipitation at the west and east coasts during the southwest and northeast monsoon seasons, respectively (Bagtasa, 2020). The island of Luzon receives, on the average, less rain than the southern part of the Philippines. A climatological increase in precipitation on the west coast precedes the southwest monsoon arrival, because tropical cyclones influence in some years the amount of precipitation (Matsumoto, 2020). But in general, the onset of the summer monsoon progresses from south to north in early-to-late May (Arkin and Meisner, 1987) and low-level wind with southwesterly direction signifies the onset of the summer or southwest monsoon season. In the following months of June–September, the rainy season in the Philippines is normally fully developed whereas by September to late October, the precipitation in the western Philippines decreases and signifies the beginning of the northeast monsoon season. Furthermore the El Niño–Southern Oscillation adds to the complex and variable distribution in temperature and precipitation over the Philippines.

Much research has been undertaken on the dynamics of interactions between the various atmospheric conditions and precipitation that are controlled by the monsoonal changes. This includes, inter alia, the spatial difference of precipitation in the Philippines (Akasaka *et al.,* 2007) and abrupt climate shift during the rainy season (Olaguera *et al.,* 2018a). Long-term trends of precipitation in connection with global climate change and extreme precipitation during the southwest monsoon show the intricacy of interpreting precipitation signals over the Philippines (Cinco et al. 2014; Narisma *et al.*, 2013; Matsumoto *et al.*, 2020; Basconcillo *et al.*, 2016). Fluctuations in precipitation can either be consistent with the continuous long-term trends or represent inter-decadal variability (Villafuerte *et al.*, 2014). Global projection of precipitation changes due to global warming shows that an increase of precipitation by about 7% per degree of temperature increase can be anticipated. Estimates for the Philippines show a possible increase of about 4% of rainfall intensity per 1^0C near-surface warming (Villafuerte et al. 2015). In general, the Philippines follow the global trend in temperature increase and the Philippines ocean temperature may in some regions even increase by about 0.5^0C within two decades (Szekielda and Guzman, 2021).

Aside from the monsoon seasons, the level of precipitation and temperature can also be controlled, especially in near coastal regions, by air-sea interaction and currents around the Philippines of which the Mindenao Current and the Kuroshio are the most important ones. These currents are formed by the north Pacific Equatoriqal Current that propagates west until it bifurcates off the coast of the Philippines into the Mindanao Current and towards the north into the Kuroshio Current. During its flow northward, the Kuroshio occasionally bifurcates as westward incursion through the Luzon Strait into the South China Sea. As schematically shown in Figure 1, the Mindanao Current moves towards the equator and interacts with water from the North Equatorial Counter Current, the cyclonic Mindanao Eddy and the Indonesian Throughflow. As the path and intensity of the currents also change in response to the monsoons, oceanographic conditions also have to be considered for a better analysis of precipitation and temperature changes. Traditionally, precipitation data are collected at land-based stations and therefore the data cover only partially the region that may be under the influence of an offshore weather system and anomalies may either go undetected or are not fully recognized. Therefore, the research presented in this paper is analyzing data on precipitation and sea surface temperature in a regional context and identifies anomalies in the vicinity of the Philippines. The data used in the analysis cover about two decades and provide in the first section a general description of the region around the Philippines with averaged data while the second section will provide an analysis of seasonal changes and a describes with time series possible long-term changes.

MATERIALS AND METHODS

The research used data that were retrieved from and processed with Giovanni, a system for multidisciplinary research and was accessed via https://giovanni.gsfc.nasa.gov/ (Acker and Leptoukh 2007). Sea surface temperature data in this system are based on 11µm-measurements with a monthly average at 4 km resolution and are built on data from Aqua MODIS Global Mapped C1615905770-OB_DAACVersion R2019.0. For the analysis of precipitation, the average merged satellite-gauge precipitation estimate were used that have a spatial resolution of 0.1^0 x a0.1^0 at temporal resolution of one month and were retrieved from GPM GPM_3IMERGM v07 and are given in mm h^{-1}. Satellite-derived precipitation data are good estimates, but validation in the Philippines against ground observations show that in general they do not correlate well with ground observations, and satellite-precipitation data perform better in the northern regions of the Philippines, but they do not perform well in the southern Philippines; however, satellite data document better the frequency, magnitude of severe precipitation events (Jamandre and Narisma, 2013).

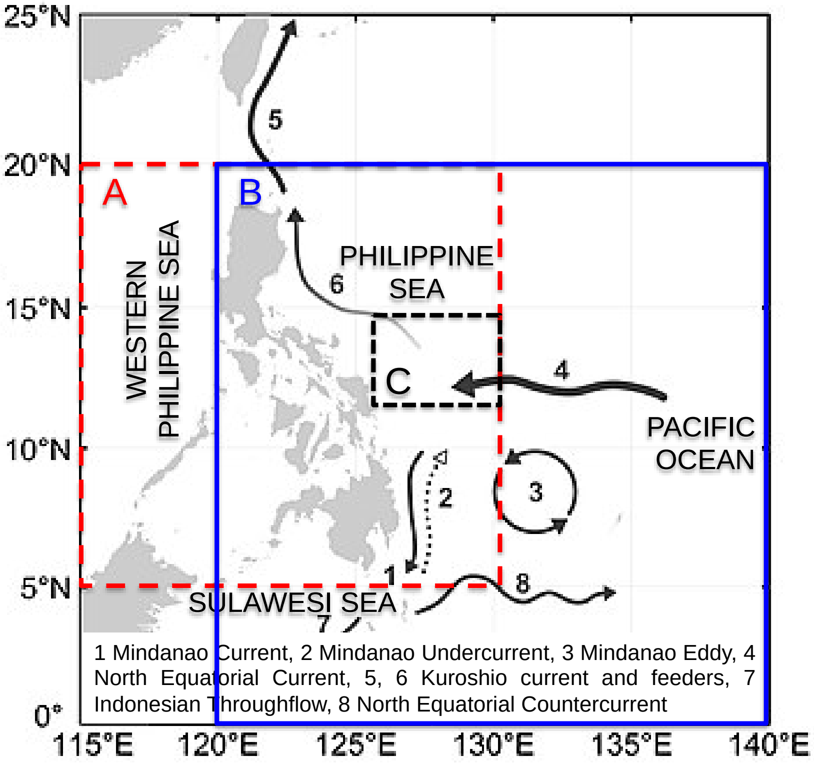

Figure 1: Location of the investigated areas showing the major currents in the vicinity of the Philippines.

The geostrophic surface velocity field was retrieved via the Ocean Virtual Laboratory https://ovl.oceandatalab.com/ of the European Space Agency and consists of the zonal and meridional velocity that is mapped at 1/4 degree. The total velocity fields are based on a combination of satellite-derived geostrophic surface currents and modeled Ekman currents (for more details, see Rio *et al.*, 2014). Two regions were selected for the research and are shown in Figure 1. The main area investigated in this research is shown in red and is located at 5^0N to 20^0N and 115^0E to 130^0E. Region B in blue covers the area that was analyzed to determine the extent and changes of major currents and eddies. Region C shows the approximate location of the bifurcation of the North Equatorial Current.

RESULTS AND DISCUSSION

Average Climatology

Monsoons and typhoons change drastically the level of precipitation and temperature, but climatological averages that combine observations for both monsoon periods, still reveal some of the principals that govern the distribution of precipitation at a regional level and can be used as guidance on specific issues. It is generally assumed that warmer sea surface temperatures result in greater precipitation over the western Philippines, especially under westerly monsoon conditions when a moderate and stronger monsoon regime is developed. However, it is also observed that warmer sea surface temperature is associated with less precipitation, and cooler sea surface temperature is linked to more precipitation due to stronger cooling of surface water by stronger westerly monsoon (Takahashi and Dado, 2018). But the Philippines are located in a region with extreme high precipitation that is not uniformly distributed. As shown in Figure 2 with averaged data, high precipitation is observed in a rather narrow belt between 6^0N and 19^0N and relations between sea surface temperature and precipitation may follow different trends from region to region.

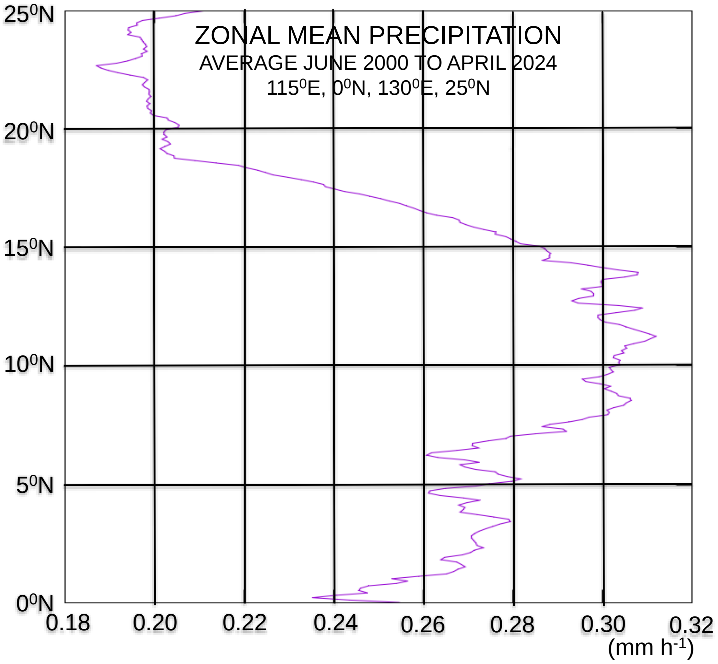

Figure 2: Zonal mean of monthly merged satellite-gauge precipitation estimate (mm h^{-1}) for June 2000 to April 2024. The region covers 0^0N to 25^0N and 115^0E to 130^0E.

The uneven regional distribution of precipitation is highlighted in Figure 3A that shows that the average precipitation is remarkably higher along the east coast compared to precipitation along the west coast of the archipelago. Although most of the precipitation is controlled by seasonal monsoons and tropical cyclones in the winter, convective precipitation caused by topography is common in the country's mountainous terrain, and the spatial pattern is mainly a consequence of interaction of the prevalent winds with topography (Matsumoto *et al.*, 2020). However, the oceanic conditions also affect in particular the coastal precipitation, especially the side towards east of the Philippine Sea where the area is exposed to a climate that is influenced to a high degree by the North Equatorial Current and related wind system. Averaged sea surface temperature distribution shown in Figure 3B and the correlation of sea surface temperature with precipitation shown in Figure 3C seem to demonstrate that sea surface temperature is not directly related to the level of precipitation, rather high precipitation along the eastern coast appears to be more related to the windfield.

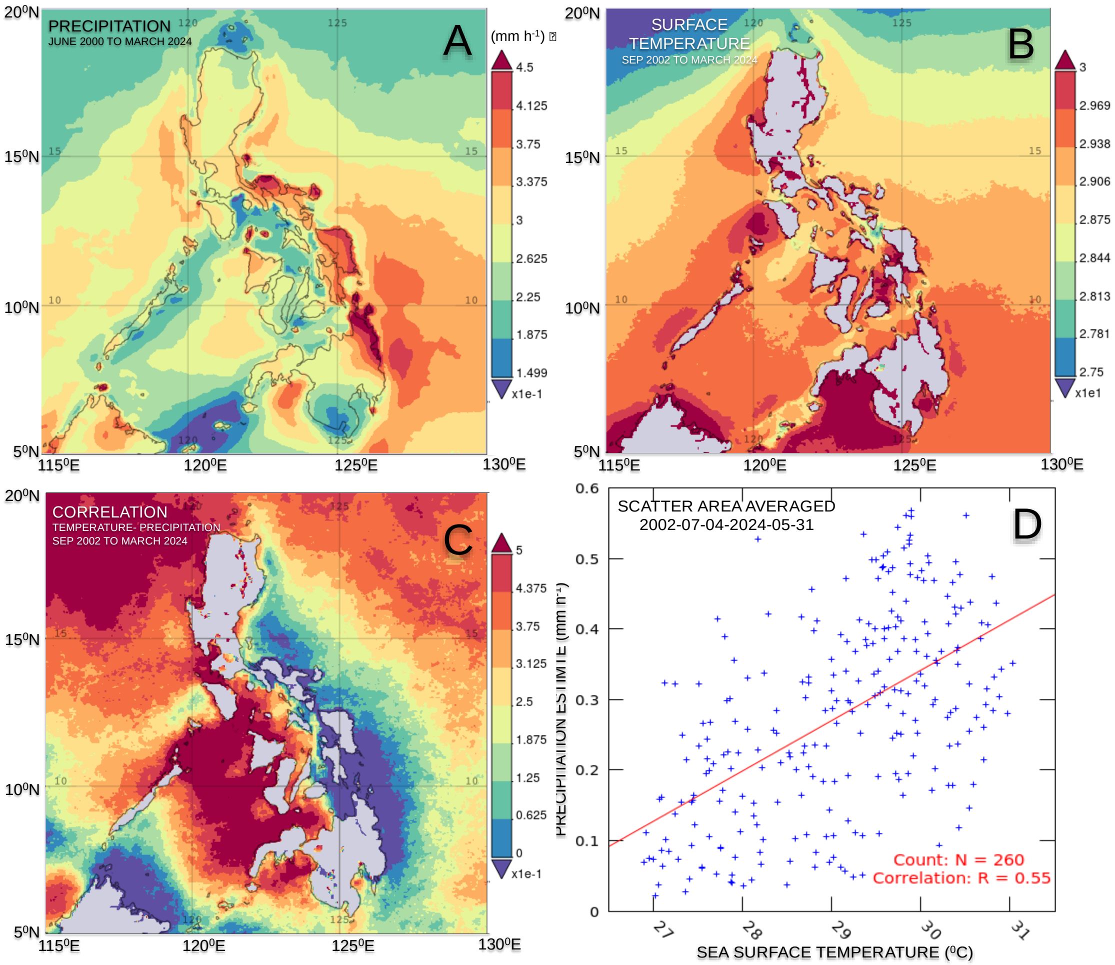

Figure 3: Averaged data of the Philippine region at 5^{0}N to 20^{0}N and 115^{0}E to 130^{0}E for September 2002 to March 2024. A: Average precipitation (mm h^{-1}). B: Averaged sea surface temperature (^{0}C). C: Correlation map of sea surface temperature and precipitation. D: Scatter diagram showing area averaged sea surface temperature and precipitation from July 2002 to July 2024. The linear regression follows Y = 0.0715X-1.803 and RMSE = 0.117.

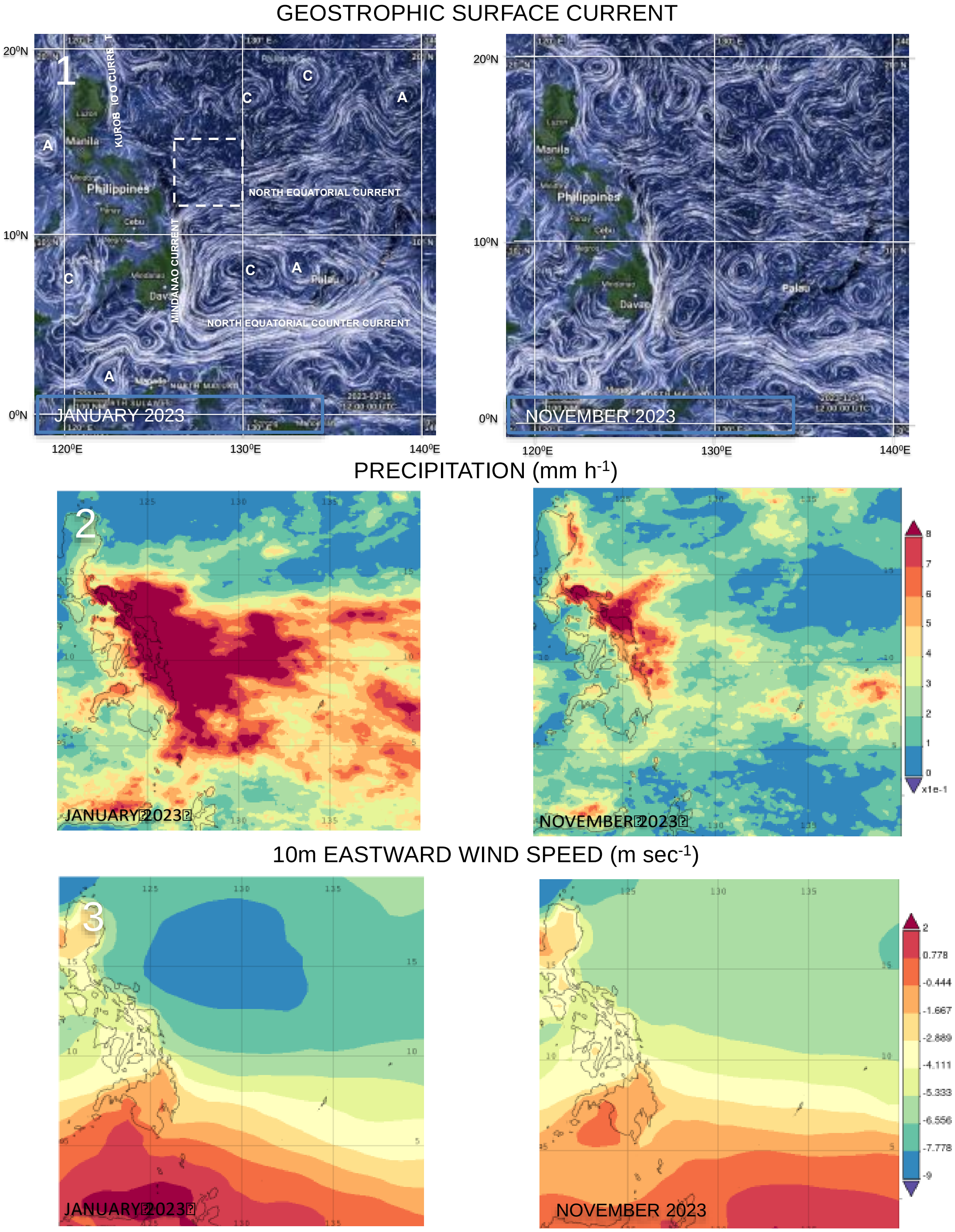

Figure 4: Monthly averaged maps covering 0⁰N to 20⁰N and 120⁰E to 140⁰E. 1: Biweekly geostrophic surface current streamlines for January 2023 (left) and November 2023 (right). The rectangle indicates the approximate location of the North Pacific Equatorial Current bifurcation at around 12⁰N to 15⁰N and 125⁰E to 130⁰E. A indicates anticyclonic water movement, and C shows cyclonic water movements; 2: Precipitation (mm h^{-1}); 3: Eastward wind speed at 10m (m sec^{-1}).

Regional correlation of precipitation and sea surface temperature are summarized in Figure 3D with a scatter diagram of the area-averaged sea surface temperature and precipitation data. The linear regression and the root-mean-square error describe a parallel increase of both parameters. However, this relationship does not necessarily mean that sea surface temperature defines precipitation, or vice versa. Although local currents and air-sea interaction to a high degree also regulate local temperature in the near-coastal regions of the Philippines, the precipitation levels do not reveal a clear relationship with sea surface temperature.

The rather low correlation between sea surface temperature and precipitation was observed throughout the year, although for the period March to May, a better correlation was seen for the northeastern region. Various processes actually control precipitation in the Philippines, but due to the averaging of data, many interannual variations are suppressed. However, Botin et al. (2010), pointed out seasonal variability of the Philippine waters is correlated with sea surface temperature. A negative correlation was observed during the summer monsoon (Trenberth and Shea, 2005), and during the Southwest monsoon, a warmer local sea surface temperature is generally related to a more intense precipitation over the western Philippines (Takahashi and Dado, 2018). Furthermore, precipitation in the northwestern region of the Philippines is modulated by interannual variations in sea surface temperature west of the Philippines that explains 20% to approximately 40% of the precipitation changes in the northwest of the Philippines (Dado and Takahashi, 2017). Figure 3C also shows the low correlation along the east coast of the Philippines close to the North Equatorial Current Bifurcation, whereas the west coast at the same latitude shows a better correlation between the two parameters. Information on the relationship between coastal currents and their impacts on precipitation are limited although significant changes appear especially during the transition of the monsoons. This is demonstrated with Figure 4.1 showing the geostrophic surface current streamlines in January with the well developed Mindanao Eddy, and smaller cyclonic and anticyclonic eddies that are present throughout the year.

The comparison of for January and November shows that the surface circulation of the Mindanao Eddy breaks down by November into smaller eddies, but a yearlong sequence (not shown) indicates that the surface circulation of the eddy is rebuilt after the winter. A qualitative interpretation of the strength and location of the major eddies shows further that near surface circulation and wind speed are connected to precipitation along the east coast of the Philippines. For January, the boundaries of the geostrophic surface flow and the position of the eastward wind speed component are also related to the precipitation distribution, whereas in November, the low level of precipitation coincides with the change in surface circulation of the Mindanao Eddy.

Seasonal precipitation changes

There are major changes in temperature and precipitation during the periodically appearing monsoon seasons and throughout their transitions. This is shown with precipitation variations in Figure 5A to 5D that cover the seasons December to February, March to May, June to August and September to November.

Figure 5A shows the precipitation during the North East monsoon for December to February when maximum precipitation is observed in the east coast extending roughly from 5^0N to about 15^0N. Low levels of precipitation characterize the season March to May, but the western coast of Mindanao is exposed to precipitation during this season as shown in Figure 5B. The summer season shown in Figure 5C for June to August is characterized by heavy precipitation to most of the western part of the archipelago, but high precipitation is also observed east in the offshore region. The period for September to November shows that the eastern region of the Philippines is dominated by high precipitation with maxima along Luzon while the other parts of the Philippines have reduced precipitation. The abrupt changes related to the different monsoon seasons are further modified by changes in the atmospheric circulation over the Pacific that may undergo decadal oscillation (Wu *et al.*, 2019) and it is predictable that precipitation would follow also those changes. In order to validate this assumption, all measurements from December 2001 to March 2022 were grouped into seasonal time series that were subjected to linear and polynomial fits and are shown in Figure 6A and 6B, respectively.

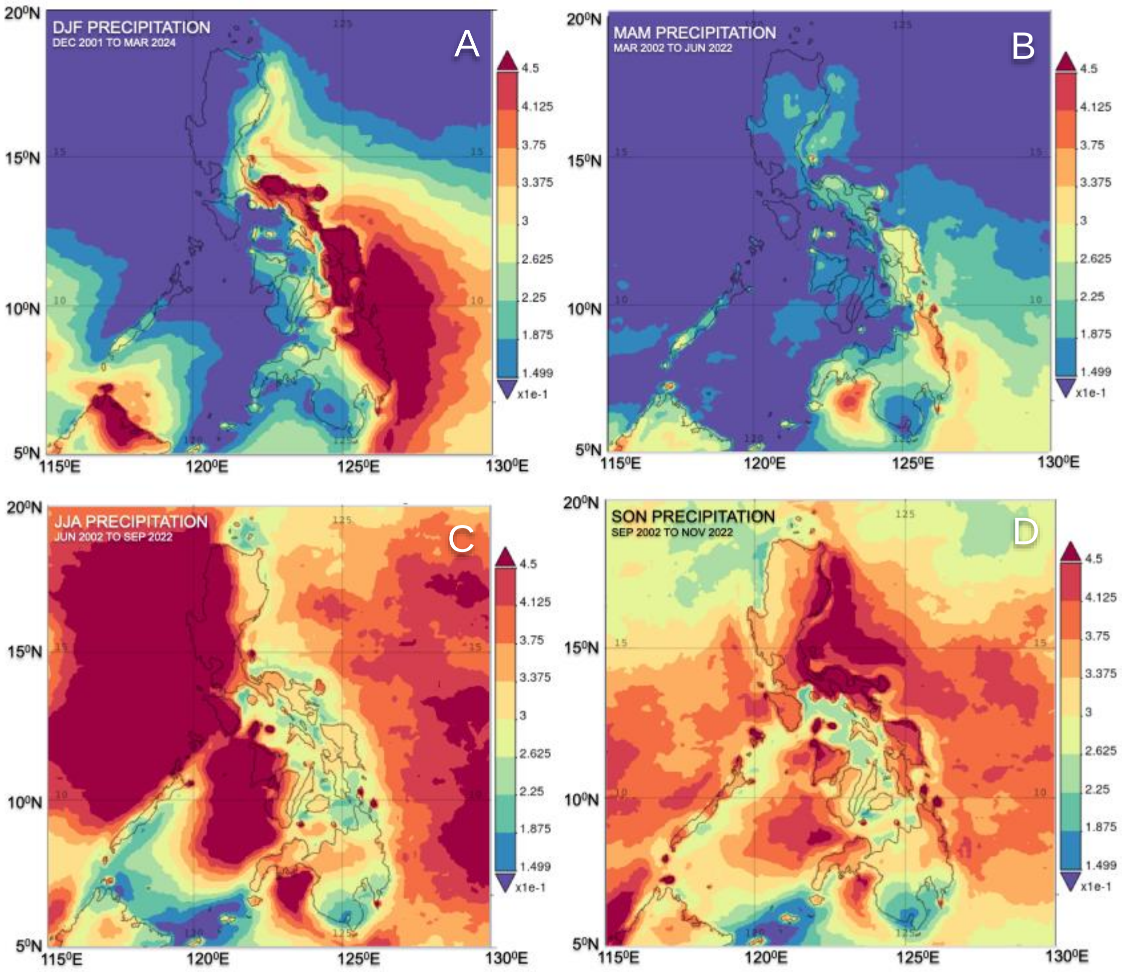

Figure 5: Seasonal distribution of precipitation that is based on averaged data from 2002 to 2022. 5A: December to February that includes the first day of March; 5B: March to May that includes the first day of June; 5C: June to August that includes the first day of September; 5D: September to November. The location of the site is shown as A in Figure 1 and is located at 5⁰N to 20⁰N and 115⁰E to 130⁰E.

Figure 6A shows the actual extremes in precipitation that are symptomatic for drought and flood conditions. The minimum in 2010 for instance, was a La Niña event that explained the low precipitation for the same year. Linear regressions indicate an increase of precipitation for the season September to February, while June to August shows no significant changes, but the season March to May suggests a slight decline. A polynomial fit to the data in Figure 6B shows the same long-term oscillations for all seasons except for the opposite trend for the period June to August. This deviation in trend from the other three seasons is most probably a result of changes and influence of typhoon activity, because the major and strongest typhoons frequently occur in August and September and are attributed to the enhancement of the Asian southwest monsoon. The interannual variability of precipitation is also explained by changes in the duration of monsoon seasons that is linked to El Niño Southern Oscillations (Hilario *et al.*, 2009; Villafuerte *et al.*, 2014).

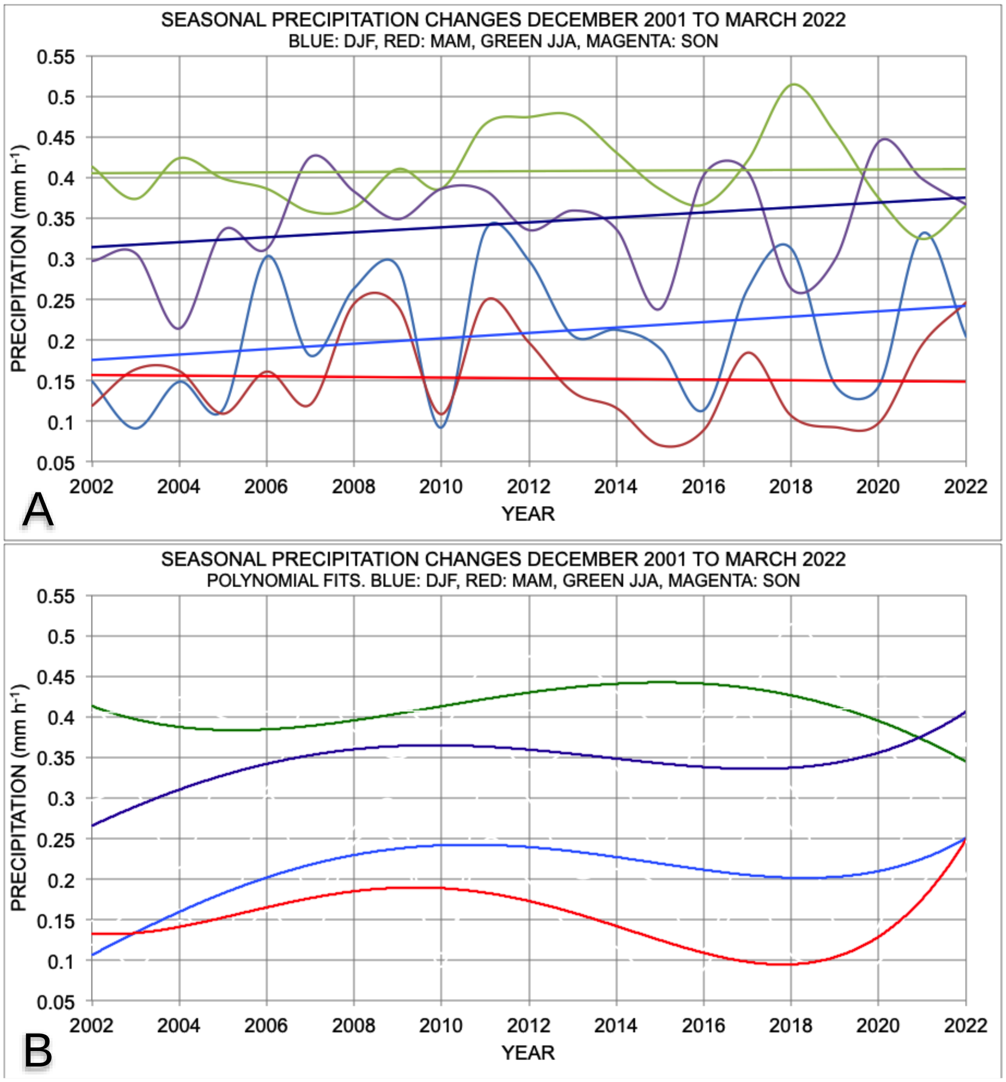

Figure 6: Seasonal precipitation changes (mm h^{-1}) based on measurements from December 2001 to March 2022, the site is located at 5^{0}N to 20^{0}N and 115^{0}E to 130^{0}E as shown in Figure 1A. A: Monthly averaged data with linear regession; B: Polynomial fit of data shown in Figure 6A. Blue: December to February, red: March to May, green: July to August, magenta: September to November. B: Polynomial fits of the same data and with the same color-coding shown in Figure 6A.

The anomalies in precipitation anomalies are further documented with Hovmöller latitude and longitude-averaged observations of which the results are shown in Figures 7A and 7B. The Hovmöller longitude averaged precipitation in Figure 7A shows the asymmetric distribution of low precipitation in the region from 5^{0}N to around 20^{0}N. Minima occur more frequently in the north, and 2010/2011 data showed the dramatic decrease in precipitation during draught conditions at around 15^{0}N. The longitude-averaged data show that the low precipitation is concentrated around 120^{0}E while high precipitation is observed mostly west of 122^{0}E. This is also the region where a positive correlation is observed between sea surface temperatures on the western part of the Philippines. Anomalous high precipitation rate is also related to the region where the passage of typhoons and their landfalls are dominant, and typically higher than the monthly climatological normal are often observed (Olaguera *et al.*, 2020).

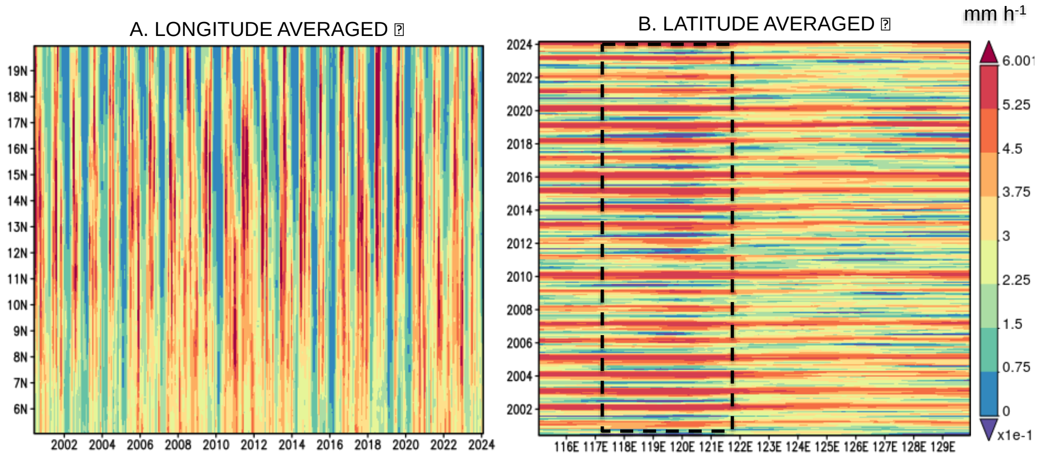

Figure 7: Hovmöller merged satellite-gauge precipitation June 2000 to March 2024 at 5^0N to 20^0N and 115^0E to 130^0E as shown in Figure 1A. A: Hovmöller longitude-averaged; B: Hovmöller latitude-averaged precipitation; the inserted rectangle shows the approximate region where strongest seasonal changes are detected.

The heterogeneity in precipitation is further shown in Figure 8 at higher temporal resolution of Hovmöller averaged precipitation data for June 2020 to March 2024, and it shows the spatial-temporal uneven distribution of maxima precipitation. This irregularity in precipitation is equally noticeable in the latitude-average data minima of precipitation are particularly evident in July 2023.

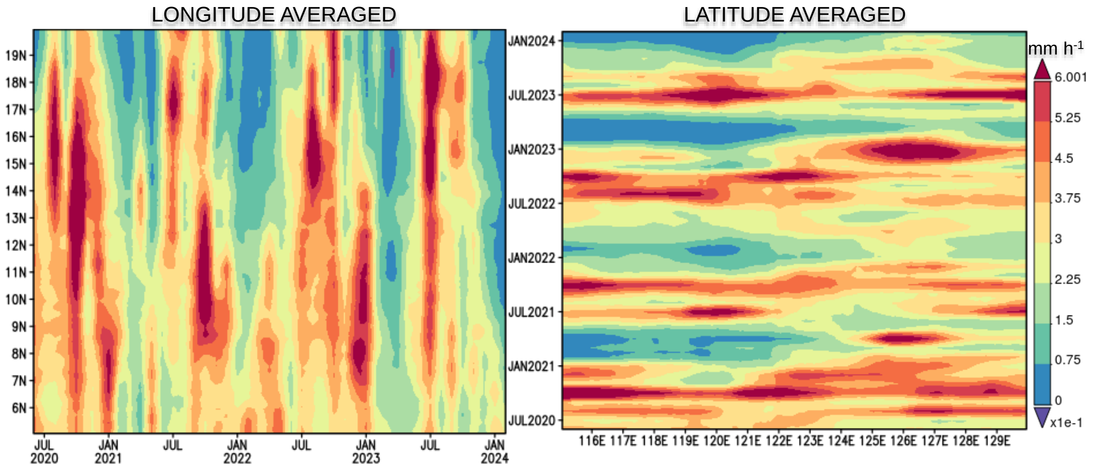

Figure 8: Hovmöller averaged merged satellite-gauge precipitation for June 2020 to March 2024 at 5^0N to 20^0N and 115^0E to 130^0E as shown in Figure 1A.

During 2022 to 2023, several typhoons were reported and the corresponding precipitation is shown in Figure 9 in conjunction with the analysis of typhoon Egay (local Philippine name Doksuri) that passed the region on 21 to 27 July 2023. Before the arrival of Egay, the period February to May had minimum precipitation, whereas in July, Egay produced high precipitation especially along the northwest of Luzon.

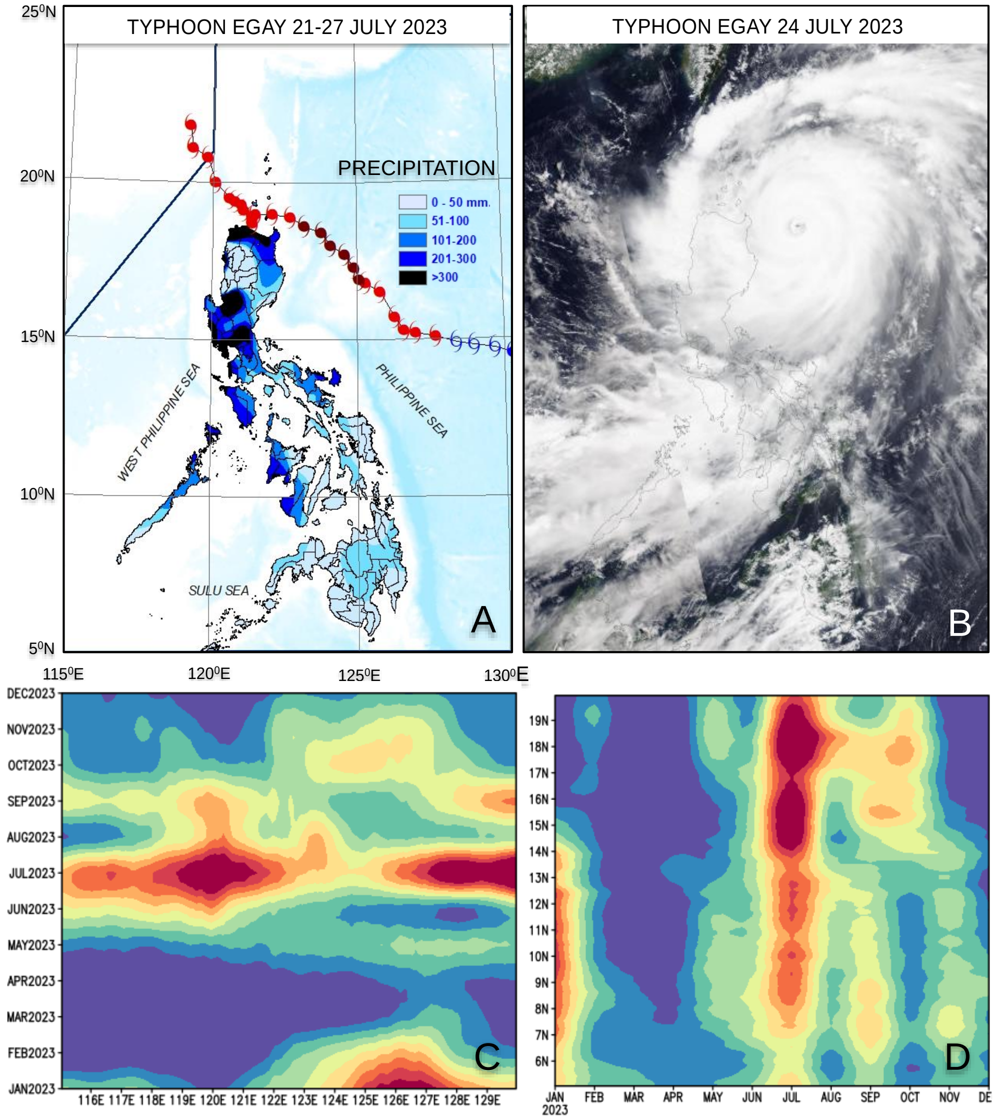

Figure 9: A: Path of typhoon Egay (local Philippine name Doksuri) on 21 to 27 July 2023, the figure is modified from original source PAGASA. B: Typhoon Egay retrieved from Worldview https://worldview.earthdata.nasa.gov. C: Hovmöller monthly latitude-averaged precipitation covering the region 5^0N to 20^0N and 115^0E to 130^0E as shown in Figure 1A. D: Longitude-averaged for the same data used in Figure C.

During the southwest monsoon, Egay developed from a low-pressure system off the eastern coast of Mindanao and during its northwestward progression, strengthened into a typhoon prior to making landfall over the Babuyan Islands. As Figure 9A shows, the northern and central Luzon were exposed to high precipitation, but the typhoon weakened by late July 27, and Egay underwent another round of rapid intensification in the South China Sea. Hovmöller analysis showed that the major affected regions in the Philippines were centered at around 15^0N to 19^0N.

Time series

The spatial-temporal heterogeneity and complexity of precipitation poses a restriction in statistical analysis when limited data sets from land stations are used alone, and spatial fluctuations in the regional distribution of precipitation based on land stations may be misinterpreted. Regional recordings of sea surface temperature and precipitation in Figure 10A and 10B show the large fluctuations in time series. In addition to the seasonal differences, considerable temporal complexity is observed which demonstrates that intensity and duration of anomalies vary with the monsoon seasons but are not uniform from year to year. Interannual variability of precipitation can be partly attributed to El Niño-like sea surface temperature changes and the weakening of the East Asian winter monsoon (Olaguera *et al.,* 2018b). Pacific Decadal Oscillation also features an El Niño-like sea surface temperature change over the Pacific basin, whereas at another time, sea surface temperature could be related to a La Niña-like change. Furthermore, the weakening of the low-level easterly winds, decrease in moisture transport, and decrease in tropical cyclone activity are additional processes that are responsible for variations. However, decrease in mean precipitation can also be attributed to the weakening of the low-level easterly winds that are linked to a decrease in moisture transport and a decrease in tropical cyclone activity as well (Olaguera *et al.,* 2018b).

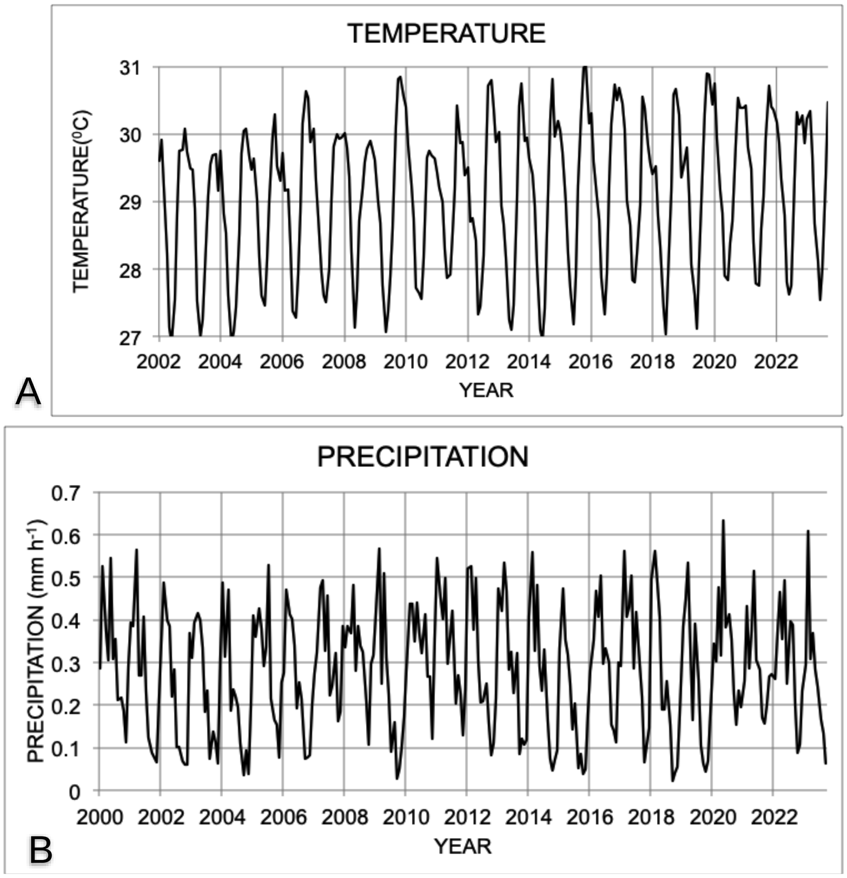

Figure 10: Monthly averaged measurements for sea surface temperature from 2002 to 2023 and precipitation (mm h^{-1}) from 2000 to 2023. The location of the analyzed area is located at 5^0N to 20^0N and 115^0E to 130^0E, site shown Figure 1A.

As the transition periods of the monsoon seasons are not a continuous process, major events at different time scales are recognized. Sea surface temperature and precipitation start to rise quickly at the start of the Southwest monsoon by mid-May, however after reaching the temperature and precipitation peak, temperature and precipitation start their decrease in phases that indicate frequent interruption of the cooling cycle by short-time pulses. Temperature data in Figure 10A show during the transition from the hot season to the cooler season, the irregularities in temperature decrease. The corresponding precipitation data in Figure 10B show even more complexity but they follow the seasonal temperature changes, and the occasional interruption of the cooling cycle indicate the impact of tropical cyclones. The Southwest monsoon begins to retreat from the Philippines by September, but as shown above, the reduction in temperature and precipitation can show regional differences. For instance, precipitation along the western coastal region stays at maximum for about two months, and due to tropical cyclones, shows rather larger post-monsoon precipitation. Towards the northeast monsoon season, the precipitation center at the east coast is located in the northern and central region until mid-December but shifts during the northeast monsoon to the southern region from late December to mid-March (Matsumoto *et al.*, 2020).

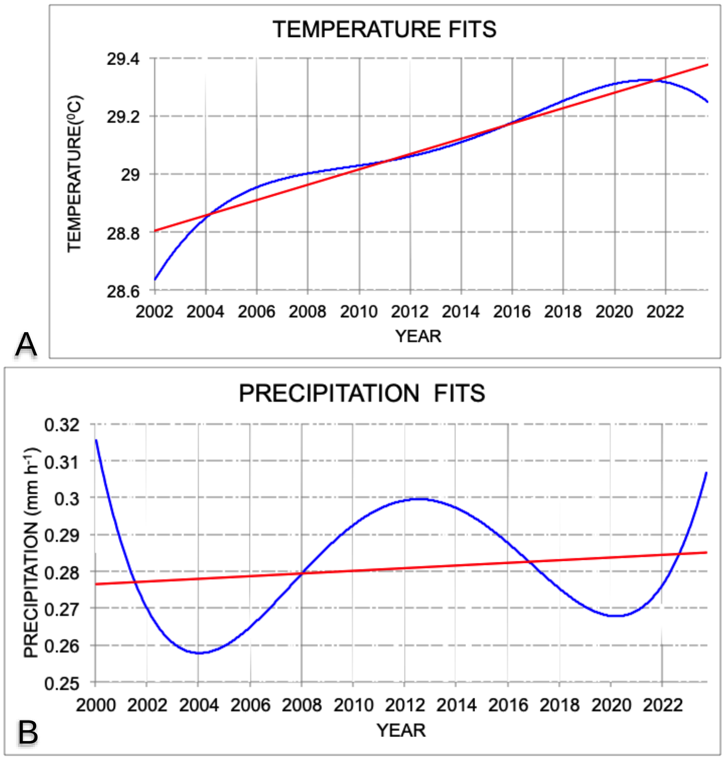

Figure 11: Linear and polynomial fits for sea surface temperature and precipitation for the data shown in Figure 10.

Superimposed to regional and local anomalies in temperature, precipitation shows longtime oscillations that are documented in Figure 11 with linear and polynomial fits. The linear fit for sea surface temperature shows an increase of about 0.03^0C y^{-1} that corresponds approximately to the mean global increase in sea surface temperature. However, when a linear regression is applied to the precipitation data, only a minimal increase is observed because the linear regression smooths out some variations that are related to monsoonal changes and long-term fluctuations. With regards to ENSO and the impact of global change to warming, the polynomial fit in Figure 11B demonstrates that long-term signals at the scale of global change are superimposed on local time scales, whereby the precipitation undulates stronger than the temperature. Although precipitation shows more intensity in fluctuations than temperature, both show an increase over the whole investigated region. Figure 11 shows that precipitation and temperature changes are consistent with global climate change although at the local scale, precipitation anomalies may have different amplitudes. For instance, it is projected for the Cagayan Valley that March to May seem to stay dry, and during the rainy season, July to November, are likely to be exposed to an increase in precipitation. There are also indications of an increase in frequency of heavy precipitation events, prolonged dry spells and the advent of extreme daytime temperatures (Basconcillo *et al.*, 2016).

Final remarks

The time series shown in the present study leads to the conclusion that a combination of several processes interact with each other and seem to be responsible for changes in precipitation and sea surface temperature at different time-space scales. However, the trend in changes seem to be in line with the continuous long-term trends in global change. The present regional study confirms major observations derived from land-based observations, although land-based stations provide only limited observations and are not necessarily connected to the larger regional scenario and local changes that may occur. This study shows further that large gradients exist between the offshore regions and the coastal environment, and it can be anticipated that even small horizontal fluctuations of those gradients, in connection with the ongoing global change, may seriously alter conditions at the local level.

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