Precipitation stable isotopic signatures of tropical cyclones in Metropolitan Manila, Philippines show significant negative isotopic excursions

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Abstract

Tropical cyclones have devastating impacts on the environment, economies, and societies, and may intensify in the coming decades due to climate change. Stable water isotopes serve as tracers of the hydrological cycle, as the fractionation process may leave distinct precipitation isotopic signatures. Here we present a record of daily precipitation isotope measurements from March 2014 to October 2015 for Metropolitan Manila, which is a first of a kind dataset for the Philippines and Southeast Asia, and analyze the isotopic variation related to tropical cyclones. The most negative shift in $\delta^{18}O$ value (-13.84 ‰) leading to a clear isotopic signal was caused by Typhoon Rammasun, which directly hit Metropolitan Manila. The average $\delta^{18}O$ value of precipitation associated with tropical cyclones is -10.24 ‰, whereas the mean isotopic value for rainfall associated with non-cyclone events is -5.29 ‰. Further, the closer the storm track to the sampling site, the more negative the isotopic values, indicating that in-situ isotope measurements can provide a direct linkage between isotopes and typhoon activities in the Philippines.

1. Introduction

The Philippine archipelago, with its fast-growing population clustered along the coastline, is one of the most vulnerable countries to climate change (Cinco et al., 2014). It is especially prone to the devastating effects of tropical cyclones. Thus, it is considered a hotspot region for hydrometeorological disasters (Cinco et al., 2014; Cruz et al., 2013; Takagi and Esteban, 2016). There is a clear need for developing a better understanding of tropical cyclone (TC) dynamics and cyclone histories in the context of prediction that may allow government agencies to implement proper mitigation and adaptation policies. Nine TCs per year made landfall on average between 1951 to 2013 in the Philippines. The number of TCs not making landfall but reaching Philippine waters is substantially higher with 19.4 per year (Cinco et al., 2016). Changing climate and associated warming of the surface ocean, will likely increase the intensity of tropical cyclones in the future (Emanuel, 2005; Webster and Holland, 2005; Woodruff et al., 2013).

The Philippines were struck by several devastating TCs in recent years (Table 1). Typhoon Haiyan (2013) which tracked over the Visayas has been the costliest TC to date (~ 2.06 billion USD in 2013), with strong winds and intense storm surges inundating coastal areas resulting in more than 6000 fatalities (Alojado and Padua, 2015; Lagmay et al., 2015; Soria et al., 2016). Typhoon Rammasun, which made landfall in July 2014, is ranked number 3 with ~ 880 million USD in 2014 (Alojado and Padua, 2015; NDRRMC, 2014). Eighty percent of the strongest typhoons making landfall in the Philippines over the last three decades developed during higher than average sea surface temperatures (SST), which supports evidence that TC intensities are projected to rise in the future due to an increase in global temperatures (Guan et al., 2018; Webster and Holland, 2005; Takagi and Esteban, 2016). For example, SST was found to be anomalously high and reaching 29.6 °C during the formation of Typhoon Haiyan (Takagi and Esteban, 2016). The average Philippines' ocean SST we have calculated for the period 1945 to 2014 (basin between 6° – 18° N, 120° – 140° E) is ~ 28.5 °C based on National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature Dataset, Version 5 (NOAA ERSST v5) (Takagi and Esteban, 2016). By the end of the 21st century, average typhoon intensity in the low-latitude northwestern Pacific is predicted to increase by 14 % due to warming ocean temperatures (Mei et al., 2015).

A few studies have demonstrated the potential to investigate tropical cyclones using stable water isotopes (Good et al., 2014; Lawrence et al., 2002; Munksgaard et al., 2015; Pape et al., 2010). Stable water isotopes (δ^2H and $\delta^{18}O$) serve as dynamic tracers of hydrological processes and can provide insights into the water and energy budgets of TCs (Good et al., 2014; Lawrence and Gedzelman, 1996). For regions with general TC occurrence, significantly lower δ^2H and $\delta^{18}O$ are associated with TC rainfall due to strong fractionation processes, compared to other tropical rain events (Lawrence, 1998; Lawrence and Gedzelman, 1996). Furthermore, δ^2H and $\delta^{18}O$ have been used successfully to interpret TC history from paleoarchives, such as tree rings and speleothems (Oliva et al., 2017). For instance, tree-ring cellulose isotope proxies have recorded the recent 220 years of cyclones in the southeastern USA (Miller et al., 2006); similarly, high-resolution isotopic analysis of tree-rings from the eastern US revealed the occurrence of hurricanes in 2004 (Li et al., 2011); a 23-year stalagmite record from Central America was used to reconstruct past TC activity (Frappier et al., 2007), and isotope signals from a 800-year stalagmite record were used to reconstruct past TC frequencies in northeastern Australia (Nott et al., 2007). Interpretation of TC history in paleotempestology from paleoarchives is based on the fact that TCs leave distinct isotopic signatures on precipitation, possibly providing information on TC's evolution and structure (Lawrence et al., 2002).

The depletion in isotopes is attributed to the high condensation levels, strong isotopic exchanges between inflowing water vapour and falling raindrops in cyclonic rainfall bands, resulting in a temporal decrease of isotopic values throughout a rain event (i.e. amount effect) (Lawrence, 1998; Lawrence and Gedzelman, 1996). Isotopic depletion is further enhanced by TC's thick, deep clouds, relatively large storm size and longevity (Lawrence, 1998). Furthermore, while isotopic depletion increases inwards towards the eye wall of the storm (Lawrence and Gedzelman, 1996), isotope ratios inside the inner eye wall region are relatively enriched, likely due to an intensive isotopic moisture recharge with heavy isotopes from sea spray (Fudeyasu et al., 2008; Gedzelman et al., 2003). These findings are based on work conducted in the 1990s in Puerto Rico and on the southern and eastern coasts of the United States. More recently, these previous findings have been confirmed by studying TCs which occurred in a few other regions, such as in China or Australia (Chakraborty et al., 2016;

Fudeyasu et al., 2008; Good et al., 2014; Munksgaard et al., 2015; Xu et al., 2019).

The above-mentioned studies are geographically limited to a few locations globally, with no studies in Southeast Asia and the Philippines in particular. In this manuscript, we present the first such study for the Philippines, with daily isotope measurements of precipitation from Metropolitan Manila (the National Capital Region) spanning from March 2014 to October 2015. During the study period, nine tropical cyclones passed by or made landfall within 500 km of the sampling site (Fig. 1). The major objective of this research is the following:

- To understand if there is an isotopic variation in precipitation associated to the TC landfall in the Philippines and if tropical cyclones leave clear isotopic signals.
- To identify the isotopic signals measured for Metropolitan Manila and the intensity of the isotopic depletion associated to TC activities, and to identify how it is represented spatially.
- To understand the isotopic variation with distance from the TC track in the Philippines.

Our findings provide a baseline dataset for reconstruction of typhoon activities using stable isotopes and contribute to a better understanding of past and future TC activities in the Philippines.

2. Materials and methods

2.1 Site description

The Philippines is a Southeast Asian country comprising more than 7000 islands located in the Northwest Pacific between 4° 40′ N and 21° 10′ N, and 116° 40′ E and 126° 34′ E (Fig. 1). The country experiences an average annual rainfall of about 2000 mm, influenced by two monsoon seasons, the northeast monsoon from November to April and the southwest monsoon from May to October (Cinco et al., 2014). About 35 % of the annual rainfall is related to TC activity, while that number rises to about 50 % for Luzon and decreases to 4 % for the southern island of Mindanao (Cinco et al., 2016). Part of the rainfall amount in the Philippines is of orographic nature due to north-south oriented mountain ranges of more than 1000 m spanning the largest islands of Luzon and Mindanao (Villafuerte et al., 2014). The majority of the steadily growing population in the Philippines (101 million 2017 census) live in densely populated, low-elevation areas close to the coastlines (Cinco et al., 2014, 2016; Philippine Statistics Authority, 2017).

2.2 Isotopic data

In total, 186 daily precipitation samples were collected from 10 March 2014 to 26 October 2015 using a PALMEX collector (Gröning et al., 2012) at the Marine Science Institute of the University of the Philippines Diliman located in Quezon City, which is part of Metropolitan Manila. The rain collection station was installed on the rooftop of the Marine Science Institute (14°39'02.5"N, 121°04'08.6"E), which is centrally situated in the campus and surrounded by trees and various green spaces. The rooftop location proofed ideal for rainwater collection as it allowed for unobstructed access to rainwater without any potential sources of contamination. Samples were collected daily at 10 am, and transferred without headspace to 30-ml HDPE bottles made by AZLON for storage prior to analysis. Samples were sent to the Earth Observatory of Singapore, Nanyang Technological University, Singapore and were analyzed for stable isotopes using a Picarro L1240-*i* laser spectroscopy instrument. We followed the procedures described by Van Geldern and Barth (2012) for post-run corrections and calibration. Three in-house water standards used for calibration include KONA (0.02 ‰ of $\delta^{18}O$; 0.25 ‰ of $\delta^{2}H$), TIBET (-19.11 ‰ of $\delta^{18}O$; -143.60 ‰ of $\delta^{2}H$), and ELGA (-4.25 ‰ of $\delta^{18}O$; -27.16 ‰ of $\delta^{2}H$). They are calibrated against the international reference water VSMOW2 and SLAP2. Long-term analysis of our QA/QC standards yields precision of 0.04 ‰ for $\delta^{18}O$ and 0.2 ‰ for $\delta^{2}H$.

2.3 Cyclone track data

The International Best Track Archive for Climate Stewardship (IBTrACS) dataset contains global TC best-track data, and is a joint effort of various regional meteorological institutions and centers that are part of the World Meteorological Organization (WMO). The data is publicly available, and comprises information on storm eye/center with its coordinates, wind speed, and pressure, etc., with a temporal resolution of six hours (Knapp et al., 2010; Rios

Gaona et al., 2018). Apart from visualization of cyclone paths, we used the dataset to calculate the spatial distance between the storm's eye coordinates and our sampling site.

2.4 Satellite precipitation data

We used the IMERG Version 5 Final daily product, a remotely-sensed precipitation dataset from satellites to highlight cyclonic tracks and precipitation patterns of several TC's passing by Metropolitan Manila, and to identify which rainfall events were not affected by cyclonic activity, and instead were associated with local or other regional convection activities. Such datasets are beneficial as they provide quasi-global grid-based rainfall estimates for land and the oceans (Poméon et al., 2017). The Integrated Multi Satellite Retrievals for GPM (IMERG) from the Global Precipitation Measurement (GPM) programme with a fine 0.1-degree grid size (Huffman et al., 2017) has been available since March 2014, and provides precipitation data in different temporal resolutions, such as half-hourly or daily. Such satellite rainfall data has been previously utilized to show TC tracks and related rainfall intensities (Rios Gaona et al., 2018; Villarini et al., 2011).

2.5 Rainfall, temperature and relative humidity data

Daily rainfall, mean daily relative humidity and mean daily temperature data was obtained from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), which maintains a rainfall monitoring station about 2.7 km away from our sampling site. The data is freely available for the period 2013 to 2017, and can be accessed on the Philippines Freedom of Information website (www.foi.gov.ph).

3. Results

3.1 Isotopic variation of stable isotopes in precipitation

The stable isotope composition during the 19 months study period spanning from 10 March 2014 to 27 October 2015 shows large seasonal isotopic variability in Metropolitan Manila. One hundred and eighty-six daily precipitation samples have been collected and analyzed in total (Fig. 2). $\delta^{18}O$ ranges from 4 ‰ to -13.84 ‰, and $\delta^{2}H$ from 16.84 ‰ to -99.1 ‰. The highest $\delta^{18}O$ value of 4 ‰ was observed on 9 April 2014 during the annual dry period, whereas the lowest $\delta^{18}O$ value of -13.84 ‰ was observed on 16 September 2014 in association with TC activity. The mean $\delta^{18}O$ of precipitation at the study site is -5.29 ‰ for non-TC rain systems, while TCs, as large regional convective systems, have the potential to cause a change in δ-values of up to almost 9 ‰ relative to the mean. The average $\delta^{18}O$ value of the nine TCs that tracked within <500 km from the sampling site is -10.24 ‰ (STDEV of 2.11), a factor of 2 larger than the mean from non-TC precipitation (average is -5.29 ‰, STDEV of 2.64).

An inter-annual variation of stable isotopes in precipitation is observed in the time series of Metropolitan Manila, where the generally rainfall intensive and humid summer months exhibit lower isotope values compared to the rest of the year (Fig. 2). The precipitation isotopes are chararacterized by slightly higher values during winter and spring, when temperatures and relative humidity are lower and rainfall is less frequent. Especially early 2015 shows drier conditions with sporadic rainfall and relative humidity levels of about 60 % to 70 %. This is also reflected in $\delta^{18}O$ and $\delta^{2}H$ for instance on 1 March 2015 with 0.01 ‰ and 9.8 ‰ respectively. Deuterium excess, which is defined as d-excess = $\delta^{2}H - 8^{*}\ \delta^{18}O$, is commonly regarded to reflect evaporation conditions of moisture source regions. In contrast to the other parameters, d-excess shows less variability throughout the time series and mainly clusters in a relatively small range of 5 ‰ to 15 ‰. To be precise, the d-excess values range from -15.18 ‰ to 24.31 ‰.

Based on the daily isotope measurements of rainfall events between 2014 and 2015, we determined the LMWL (local meteoric water line) for the study site as $\delta^{2}H= 7.2674 \times \delta^{18}O + 5.4103$ (Fig. 3), indicating that slope and intercept of the LMWL are lower due to the influence of tropical precipitation compared to the GMWL (global meteoric water line) with $\delta^{2}H= 8 \times \delta^{18}O + 10$ (Craig, 1961).

In order to assess meteorological controls on the isotopic composition of daily precipitation at Metropolitan Manila, we investigated the correlation between $\delta^{18}O$, daily precipitation amount, daily mean temperature and daily mean relative humidity. Additionally, $\delta^{18}O$ is compared to d-excess (n=187) (Fig. 4). A weak correlation was found between $\delta^{18}O$ and d-excess (R^2=0.2187) and between $\delta^{18}O$ with precipitation amount (R^2=0.1087) and between $\delta^{18}O$ with relative humidity (R^2=0.1323). There is no association between $\delta^{18}O$ and temperature (R^2=0.0338).

In order to get further insights into the seasonal variations, we also calculated the average values for each month in the time series for every isotopic and climatic parameter (Table 2). $\delta^{18}O$ is relatively low during the summer months, for instance with -7.29 ‰ in September 2014 compared to the months of winter and spring with -0.53 ‰ in April 2014 or -0.66 ‰ in February 2015. Similarly, the average monthly rainfall is less in winter and spring with 4.3 mm in March 2014 and 5.8 mm in January 2015 compared to the summer months such as July and August 2014 with 19 mm and 20 mm respectively. As mentioned before regarding the daily measurements, we also observe on the monthly scale conditions which are more humid in the summer. We calculated the correlation to investigate the relationship between the isotopic composition of precipitation ($\delta^{18}O$) with meteorological parameters (average monthly rainfall, relative humidity and temperature) on a monthly scale. $\delta^{18}O$ and $\delta^{2}H$ are strongly correlated with r=0.96 (n=18, p-value=<0.0001 and 99% confidence level), whereas the relationship between $\delta^{18}O$ and d-excess yields an r of -0.64 (n=18, p-value=0.003). A negative correlation was clearly determined between $\delta^{18}O$ and precipitation with r=-0.77 (n=18, p-value=0.0002) and between $\delta^{18}O$ and relative humidity with r=-0.85 (n=18, p-value=<0.0001). $\delta^{18}O$ and temperature are not correlated with r=0.04 (n=18, p-value=0.87).

3.2 Precipitation isotope evolution during TC events

Overall, precipitation isotopes associated with TCs mark the lower range of $\delta^{18}O$ values during the study period. Especially during the 2014 season, most of the very low precipitation isotope values occurred throughout passage of TCs. For instance, Rammasun led to the lowest δ-value (Fig. 5, point a, -13.84 ‰) of the whole study period, while other TCs such as Fung-Wong (Fig. 5, point c, -12.16 ‰), Kalmaegi (Fig. 5, point b, -11.39 ‰), or Hagupit (Fig. 5, point d, -9.88 ‰) caused other negative excursions in isotopic values. The 2015 season is characterized by on average a slightly higher isotopic enrichment during the rainfall intensive summer months. Nonetheless, a similar noticeable isotope signal is visible with low $\delta^{18}O$ isotopes, clustered along the lower end of the sample range, for example, caused by Linfa

(Fig. 5, point f, -8.5 ‰) or Koppu (Fig. 5, point i, -8.7 ‰). The other TCs that occurred during the study period and were investigated by us were Mekkhala (Fig. 5, point e, -10.77 ‰), Twelve (Fig. 5, point g, -7.7 ‰) and Mujigae (Fig. 5, point h, -7.5 ‰). However, relatively negative isotope samples (Fig. 5) also originated from non-TC rainfall systems. Those events are discussed below.

Out of the nine TCs that occurred within a 500 km radius from the sampling site, Rammasun and Kalmaegi left clearly observable, distinct isotopic signatures during their approach and dissipation, which we will therefore present in more detail in the next paragraphs. Typhoon Hagupit (Fig. 5, point d) similarly lead to a clear isotopic evolution pattern during its time of occurrence in the Philippines and is shown in the supplementary (S1).

Typhoon Rammasun's rainfall intensities based on the IMERG precipitation data together with its track from IBTrACKS is shown in Fig. 6a. Typhoon Rammasun stands out in our study period as it moved straight towards the National Capital Region of the Philippines, resulting in a direct hit. Rammasun, locally named Glenda, made landfall in the Bicol region of southern Luzon on 15 July, with wind speeds of about 160 km/h. On 16 July, it passed south of Metropolitan Manila 50 km from our sampling site, with maximum winds of 130 km/h, gradually losing strength over land. As Rammasun approached on 15 July, the precipitation has shown relatively high $\delta^{18}O$ of -4 ‰ while rainfall was weak (Fig. 7a). On 16 July, $\delta^{18}O$ shifted to -13.84 ‰, while the typhoon's track was the closest to our sampling site and rainfall amount was high. As Rammasun moved away, precipitation isotopes became more positive, and rainfall amount decreased. The characteristic isotopic evolution related to Rammasun's distance and rainfall intensities as a function of time can be seen in Fig. 8a, where the different radii indicate the distance to the sampling site, and the strong isotopic depletion observed on 16 July is also evident. As Rammasun with its storm center tracked towards the northwest and away from Metropolitan Manila, our precipitation samples were relatively isotopically enriched for the following two days, namely -9,12 ‰ on 17 July and -6,26 ‰ on 18 July.

Typhoon Kalmaegi, locally named Luis, was the first typhoon to make landfall in the Philippines two months after Rammasun. Kalmaegi reached typhoon intensity on 13 September, making landfall the following day in northern Luzon, with maximum wind speeds of about 120 km/h. Kalmaegi tracked relatively far away from the sampling site (about 350 km), but the accumulated rainfall it produced was centered south of the track, placing it considerably closer to the National Capital Region (Fig. 6b). Despite the distance of the eye from the sampling site, a characteristic isotopic pattern was visible, with the most negative $\delta^{18}O$ value of -11.39 ‰ on 15 September, coincident with the highest rainfall (Fig. 7b). The following day, $\delta^{18}O$ values returned to higher values with the increase in distance from the eye. This is also seen in a spatial representation in Fig. 8b, visualizing the track of Kalmaegi and the respective $\delta^{18}O$ values. Kalmaegi was first approaching the sampling site on 14 September and passed away on 15 and 16 September. The lowest $\delta^{18}O$ was measured on 15 September and is indicated in the figure in dark blue colour.

4. Discussion

4.1 Stable isotopes of precipitation – a possible tracer for TCs

As stable water isotopes fractionate during the physical process of evaporation and condensation, they serve as effective tracers in the hydrological cycle (Dansgaard, 1964; He et al., 2018; Risi et al., 2008; Tremoy et al., 2014). Here, we have demonstrated that stable water isotopes can possibly be used to identify TC activity in the Southeast Asian region by excursions in $\delta^{18}O$, providing evidence and supporting the hypothesis that TCs may leave a clear isotopic signal in the Philippines. The strong isotopic depletion is due to high condensation efficiencies in cyclonic convective rain bands, leading to extensive fractionation. This is particularly pronounced in intense, large-scale TCs (Lawrence, 1998; Lawrence and Gedzelman, 1996). In the previous section, we have presented our findings of precipitation isotope ratios associated with typhoon activities affecting Metropolitan Manila during the study period of March 2014 to October 2015. Based on our time series, we therefore argue that for the Philippines, the lowest measured isotope value likely indicates the occurrence of a TC, such as is the case for Typhoon Rammasun (Fig. 5). Similarly, other anomalously low $\delta^{18}O$ values at our site are caused by TC making landfall or passing by.

Individual TCs (Rammasun and Kalmaegi) were characterized by consistent isotopic excursions to very negative values in a range of up to -9 ‰ compared to the mean isotopic value of -5.29 ‰ (Fig. 7 and 8). A TC approaching the sampling site had relatively higher isotope values than at its later stages when it was closest to the site in Metropolitan Manila. When at its closest, strong rainfall together with increased fractionation depleted precipitation isotopes, leading to a distinct drop in isotope value. Such a strong negative isotopic shift in precipitation has been previously observed in other regions (Fudeyasu et al., 2008; Lawrence and Gedzelman, 1996; Munksgaard et al., 2015; Xu et al., 2019). As the TC moved away and rainfall intensities weakened, $\delta^{18}O$ in precipitation became again more positive, likely due to evaporative effects (Munksgaard et al., 2015; Xu et al., 2019).

As the strongest TC in terms of wind speeds, damage costs, and fatalities, Typhoon Rammasun reduced the isotope values most during our study period, to -13.84 ‰. Similarly, Typhoon Kalmaegi lead to extensive damage and caused a significantly negative excursion in precipitation isotopes to -11.39 ‰, suggesting that the lowest isotope values might indicate the occurrence of the strongest TC at that time at our site in the Philippines. We note that our isotopic measurements are similar to observations elsewhere. For example, the range of $\delta^{18}O$ values caused by Typhoon Shanshan affecting the subtropical Ishigaki island was -6 to -13 ‰, (Fudeyasu et al., 2008); Tropical Cyclone Ita led to a range of -4.8 to -20.2 ‰ in northeastern Australia (Munksgaard et al., 2015); several TCs which made landfall in Texas resulted in isotope values from -3.9 to -14.3 ‰ (Lawrence and Gedzelman, 1996); or hurricanes that affected Puerto Rico and southern Texas were found to deplete $\delta^{18}O$ up to -18 ‰ (Lawrence, 1998). The lowest value resulting from Typhoon Phailin on the Andaman Islands was reported to be -5.5 ‰, and Typhoon Lehar depleted the precipitation sample to -17.1 ‰ (Chakraborty et al., 2016). For TCs within a distance of up to 500 km from the sampling site at the University of the Philippines Diliman in Metropolitan Manila we measured an isotopic range of -7.7 ‰ (Typhoon Koppu) to -13.84 ‰ (Typhoon Rammasun). Despite the overall comparability to our measurements, differences exist. The lowest values observed in some studies are considerably more negative than at our site (Lawrence, 1998; Munksgaard et al., 2015). However, we attribute these differences to a variety of features, such as the specific climatic condition at each site, differences in temperature, humidity, and altitude or latitude, which are likely contributing factors to the observed isotopic variation by altering isotopic fractionation. Further, rainout history, location of typhoon tracks, topography, respective strength of each TC, as well as its distance to the sampling site most likely have a significant influence as well (Fudeyasu et al., 2008; Good et al., 2014; Munksgaard et al., 2015; Xu et al., 2019).

In order to assess why other very low isotopic excursions occurred on various days (Fig. 5) we used IMERG satellite precipitation data. IMERG data with its fine spatio-temporal resolution allows the identification of convective rainfall areas and the passage of TCs and other rain systems (Fig. 6). Our analysis shows that precipitation events with anomalously low isotope signals unassociated with TCs are largely related to local, strong convective rainfall events or large scale and slow-moving rain areas passing over the National Capital Region. Therefore, the degree of convection is responsible to produce the other observed low $\delta^{18}O$ value outliers that are not related to cyclone rainfall, as strong convection and long stratiform rainfall leads to intense fractionation (He et al., 2018; Risi et al., 2008; Tremoy et al., 2014). Contrarily, we speculate that the more positive isotope values which cluster along the higher end of the sample spectrum around 0 ‰, are associated with local, short convective rainfall events and light intensity rain as confirmed with IMERG satellite precipitation data. Additionally, the PAGASA rain gauge data indicates that rainfall amounts are very low during days with such very enriched isotope samples, such as 0.3 mm/day for the highest recorded sample of 4 ‰ on 9 April 2014. Interestingly, TCs at our site were found to be related with low isotope values together with high rainfall amounts (Fig. 5), while the majority of other low isotopic values unassociated with TCs were characterized by on average lesser rainfall amounts. This possibly indicates that TCs in the Philippines, besides using for instance modern-day satellite or radar data, can be detected using these two parameters, i.e. strong isotopic depletion coupled with high rainfall amounts.

The aforementioned local convective precipitation events have the potential to induce a signal of very negative $\delta^{18}O$ values which are not related to TC activities. We therefore label such a signal as a “false non-TC signal”, as it is induced by non-TC rainfall. This results in the fact that TCs occurring during our study period do not entirely cluster along the lowest range of isotope values as seen in figure Fig. 5. Nevertheless, Typhoon Rammasun caused a clear drop in isotopes and stands out in the dataset. This might be the case because Rammasun’s track and heavy rainfall comes in closest proximity (50 km) to the sampling site. Other TCs occurring within the 500 km radius did not lead to such a clear negative isotopic signature, likely because these typhoons did not pass the sampling site at all or heavy rainfall occurred elsewhere within the TC rainfall system (see S 2 for their tracks and accumulated rainfall areas). Some of these TCs have intense rainfall areas over other parts of the Philippines and are characterized by a variable track, likely influenced by land interactions. Land interaction reduces TC strength and can lead to rain out due to orographic effects induced by the north-south oriented mountain ranges (Park et al., 2017; Xie and Zhang, 2012; Xu et al., 2019). Especially Typhoon Koppu rained out before making landfall and abruptly changed its track, instead of passing by the Metropolitan Manila. Similarly, Typhoon Mekkhala's intense rainfall occurred along the eastern coasts, before it started to dissipate. Evidently, due to these factors the isotope values associated with those TCs were not as negative as during Rammasun. Therefore, a TC which is relatively far away from the sampling site produces an isotope signal that is not as clear and as negative, thus averaging out between the other low values from rain systems unassociated with TC.

4.2 Drivers of isotopic variation at Metropolitan Manila

As presented in section 3.1, the isotopic parameters ($\delta^{18}O$, $\delta^{2}H$, d-excess) show seasonal variabilities and are influenced by several climatic factors (precipication amount, temperature and relative humidity). The scale of influence varies depending on daily or monthly values. The results indicate that $\delta^{18}O$ on daily levels is not influenced by temperature, relative humidity or precipitation amount (Fig. 2) as drivers of isotopic variability. Instead, we speculate that other processes, such as large scale convection and processes at the moisture source region might influence stable isotopes of precipitation at our study site (Conroy et al., 2016; He et al., 2018; Kurita, 2013). Interestingly, $\delta^{18}O$ is not affected by precipitation amount on short timescales (Fig. 4), which has also been previously confirmed in other tropical regions, suggesting that the tropial amount effect is not reflected on daily timescales (Belgaman et al., 2016; Dansgaard, 1964; He et al., 2018; Kurita et al., 2009; Marryanna et al., 2017; Permana et al., 2016). However, comparing monthly $\delta^{18}O$ to $\delta^{2}H$ and d-excess and to monthly average precipitation, relative humidity and temperature, the results are clearly different (Table 2). These monthly observations show close relationships with each other, especially $\delta^{18}O$ and precipitation amount are closely linked. The close relationship between these two parameters can be attributed to the tropical amount effect (Aggarwal et al., 2012;

Bowen, 2008; Conroy et al., 2016). The close relationship with r=-0.77 between monthly $\delta^{18}O$ and monthly precipitation might be likely due to the influence of regional convective activities on the isotopic composition of precipition (Bony et al., 2008; He et al., 2018; Moerman et al., 2013; Risi et al., 2008).

4.3 Distance of TCs from Metropolitan Manila

Our observations provide details on spatial distance from collection site towards TCs' centers, as our findings indicate that the distance from the storm center to the sampling site impacts the isotopic value. The TCs' distance of up to 500 km to sampling site and the precipitation isotope value are correlated with r=0.55 (n=16, p-value=<0.05 and 99% confidence level). This relationship weakens with an increase in the distance from the sampling site: a distance of 500 to 1000 km yields an r of 0.2 (n=19, p-value=0.41), the distance of 1000 to 1500 km yields an r of 0.18 (n=24, p-value=0.40), while a 1500 to 2000 km distance results in an r of 0.1 (n=21, p-value=0.69). This suggests that a TC more than 500 km away from the sampling site has no influence on precipitation isotopes (Munksgaard et al., 2015). Thus, the closer the TC is to the sampling site, the more negative the isotope signal and the larger the δ-change. This relationship might provide information on storm structure and intensity, as the intensity increases with proximity of the TC to the sampling location. We thus confirm that the isotope value at our location is a function of the closest approach of the storm's center to the sampling site (Lawrence and Gedzelman, 1996).

Figure 8 displays all the precipitation samples associated with TC presence and activities within a 2000 km radius from Metropolitan Manila, and further highlights the relationship between distance and isotopic depletion, additionally providing a spatial indication of TC's quadrants and their tracks relative to the location of the sampling site. Strongest depletion occurs within the 500 km radius. However, two relatively negative outliers are located within a 1000 to 1500 km radius in the northwest quadrant (see points a and b in Fig. 9). These two samples were taken during the passage of tropical storm Kujira on 22nd and 23rd of June 2015 (Fig. 5), which was more than 1000 km away from Metropolitan Manila travelling east along the coast of Vietnam as seen with IBTrACKS data. We investigated these two samples with IMERG satellite precipitation data and identified them as a part of a mesoscale system, with strong convective cells delivering intense rainfall, leading to distinct isotopic depletion and inducing a “false non-TC signal” of very negative $\delta^{18}O$ which is not related to TC activity.

4.4 Cyclone track’s rainfall intensity

IMERG satellite precipitation data also identify that the highest rainfall intensities occur at the left side of the TC track for all the TC within the 500 km radius, except for Hagupit and Mekkhala, which are more complex cases (Fig. 6a, b, supplementary S 2). This is in contrast to the results from Villarini et al. (2011), stating that the largest rainfall accumulation appears on the right side of the hurricane tracks. They also noted that large rainfall amounts occur far away from the storm’s track, which we can confirm and quantify with our observations. The largest rainfall totals vary in a range of 50 to 150 km away from the storm’s center depending on the TC. For Kalmaegi the intense rainfall areas are up to 150 km away from the storm’s center. These areas with the highest rainfall totals should most likely coincide with the most negative isotope value, indicating that the strongest depletion occurs in the outer cyclonic rain bands. This is consistent with previous findings (Gedzelman et al., 2003; Lawrence and Gedzelman, 1996; Munksgaard et al., 2015). However, Fudeyasu et al. (2008) observed the highest isotope values in the inner eye wall, i.e. in close proximity to the storm’s center. We could not investigate this further as no TC passed by our site in a distance of about 20 km, which is the size of a typical typhoon’s eye (Weatherford and Gray, 1988).

4.5 Implications for paleoclimate studies

Isotope proxies from paleoarchives such as tree rings and speleothems have been utilized to reconstruct past cyclone activities (Frappier, 2013; Frappier et al., 2007; Miller et al., 2006; Nott et al., 2007). For instance, stalagmites yielded a record of weekly temporal resolution with negative isotopic excursions related to TC activity (Frappier et al., 2007). Such a high temporal resolution from stalagmites makes our in-situ measurements very comparable, highlighting the potential to use both in conjunction. Similarly, high-resolution tree ring isotope analysis identified the occurrence of Hurricane Ivan and Hurricane Frances in 2004, which both resulted in the lowest observed precipitation isotope values for that year (Li et al., 2011). Nevertheless, it is important to consider possible limitations at the study site that arise in paleotempestology, such as sea level change or disruption of sedimentological records through floods or tsunamis. These need to be evaluated when comparing precipitation isotopes related to TCs with other proxy records such as speleothems and coastal deposits and when choosing the study area (Oliva et al., 2017). However, the aforementioned paleotempestology studies suffer from uncertainty regarding parameters such as TC intensity and distance to the storm's center affecting the isotope signal. With our study, we provide further information on these parameters as we hypothesize that immediate proximity of a TC results in very low $\delta^{18}O$. Therefore, we might aid with a better interpretation of paleoarchives. Moreover, these studies are limited in number and only focus on a few regions affected by TCs, such as Central America and the Southeastern USA (Frappier et al., 2007; Miller et al., 2006). However, more paleotempestology studies investigating paleoarchives related to typhoon footprints covering different regions and countries would provide a better understanding of past TC activity, ultimately resulting in better and more accurate climate reconstructions. TC projections related to climate change could also be improved, which is especially relevant for decision makers dealing with TC related impacts and damages. Our in-situ isotope measurements provide baseline data input in an understudied tropical region, providing isotopic data of TC occurrence and quantifying the isotopic depletion associated with TC activity. Further, our 19-month dataset suggests that the lowest measured isotope value at the Philippines study site is associated with TC activity, resulting in the distinct negative isotopic shift in the time series (Fig. 5). As rain out history, topography, distance of track or rainfall unassociated with TCs can induce a weak or "false non-TC signal", it is important to choose stalagmites or trees as archives based on their location, ideally covering a spatial gradient thus capturing a TC in its full size.

5. Conclusions

As presented with our dataset, a strong, high-energy TC with a track directly approaching and hitting the sampling site leads to a clear isotopic signal in a time series in the Philippines. If the TC is further away, such as more than 500 km from the site, or heavy TC rainfall occurred elsewhere prior of making landfall, the signal is not as clear and might average out between other rainfall events. Other strong convective rainfall events unassociated with TCs may result in similarly low isotope values, and we label these as a weak or "false non-TC signal".

Therefore, our data suggests that distance of TC to the sampling site is a key factor in influencing the isotope signal and that such a spatial component needs to be considered when interpreting the isotope signal. However, a longer time series isotope record would help to better constrain controlling factors, such as the influence of topography on high-energy TCs. To what extent mountain ranges and low elevation coastal areas shape the TC induced isotope signal needs further investigation. Based on our findings we conclude that the location of precipitation sample collection needs to be chosen strategically. Ideally, several rainwater collection stations should be operated, covering a wide geographical range such as stretching from northern Luzon to its south. If such a spatial gradient was covered, a TC would likely be captured in its full size. Consequently, we aim to expand our time series spatially and temporally.

Previous studies conducted in other regions found that TCs can leave detectable isotopic signals of very negative $\delta^{18}O$ values in precipitation (Good et al., 2014; Munksgaard et al., 2015; Xu et al., 2019). Daily precipitation isotope samples confirm the hypothesis that TC activities using isotopes can also be identified in the tropical Philippines. A total of 186 daily precipitation samples spanning 10 March 2014 to 27 October 2015 from Metropolitan Manila were analyzed for their isotopic composition, resulting in seasonal isotopic variability and in TC related isotopic signatures. The mean isotopic value for the study period is -5.29 ‰ for rain events unassociated with TC, whereas the average TC induced isotope value is -10.24 ‰ for TCs occurring within 500 km. The lowest recorded value is -13.84 ‰, which is a δ-change of almost -9 ‰ compared to the mean, and it was sampled during the closest approach of Typhoon Rammasun to the National Capital Region of the Philippines. Similarly, individual TCs such as the intense and costly Rammasun that struck the Philippines in July 2014 or Kalmaegi left characteristic isotopic signatures. During their approach, $\delta^{18}O$ values were relatively high but once they moved closer to the collection site the isotopes became more depleted alongside increasing rainfall amounts. Once they moved away their remnants lead again to higher values. The distance of TC center to sampling site plays a key role in determining the observed isotope signals. Correlation between isotopes and distance of up to 500 km was found, though this relationship significantly weakens with increasing distance. Information on storm structure and intensity can be derived from the interconnectedness of distance and isotopic depletion, due to the fact that strong rainfall leads to increased isotopic fractionation

(He et al., 2018; Tremoy et al., 2014; Xu et al., 2019). The closer the TC is to the sampling location, the stronger the rainfall intensities and the more negative the $\delta^{18}O$ in precipitation. Additionally, we found that the degree of convection can induce a “false non-TC signal” of very low isotope values not associated with TC activity. Other factors which limit the strength and clarity of the isotope signal are distance of TC towards the sampling side, rain out history, TC track and topography. Our dataset is the first of such record in the Philippines and provides much needed data in scarcely sampled Southeast Asia. It can be used as a baseline in paleotempestology studies reconstructing past TC history, in conjunction with tree ring and speleothem datasets, as our data suggest that for Metropolitan Manila the lowest measured isotope value is caused by typhoon activity. A higher precipitation sampling frequency on sub-daily levels at several locations would yield more detailed constraints on TC parameters such as storm structure, which we aim to realize in the future.

Data availability

The underlying research data can be accessed via the supplementary document.

Author Contributions

Dominik Jackisch analyzed the data and wrote the manuscript. Bi Xuan Yeo contributed to data analysis and improved the manuscript. Adam D. Switzer conceived the idea, reviewed and improved the manuscript. Shaoneng He provided advice, reviewed and improved the manuscript. Danica Cantarero and Fernando P. Siringan collected the precipitation samples and improved the manuscript. Nathalie F. Goodkin reviewed and improved the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Figures and Captions

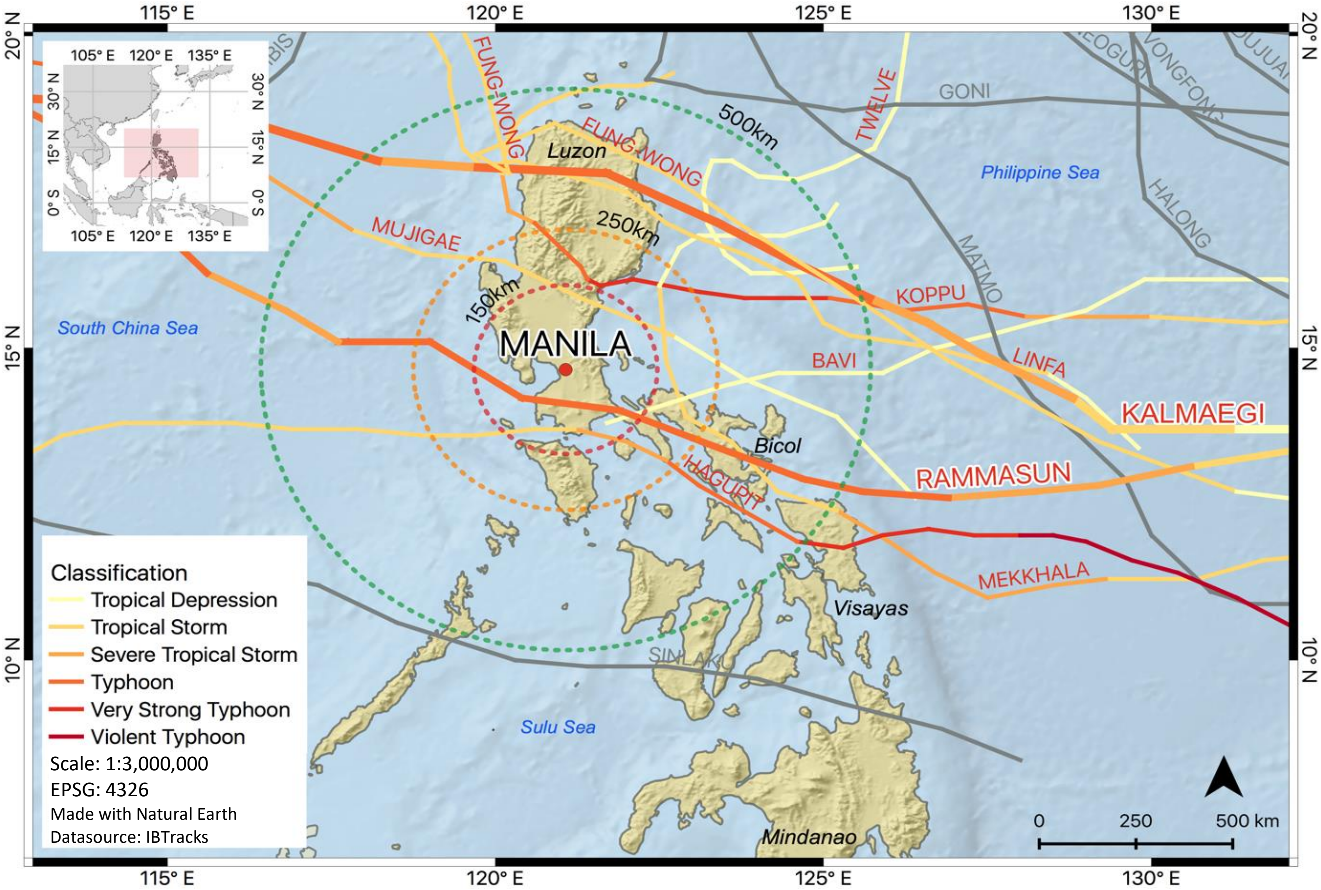

Figure 1 Metropolitan Manila sampling site and TC tracks of 2014 and 2015 seasons. Three different sized circles indicate the distance to the sampling site with the outermost one being 500 km in radius. Cyclone tracks are color coded according to the typhoon classification from Regional Specialized Meteorological Center (RSMC) Tokyo. Cyclones in gray color refer to TC outside the 500 km radius.

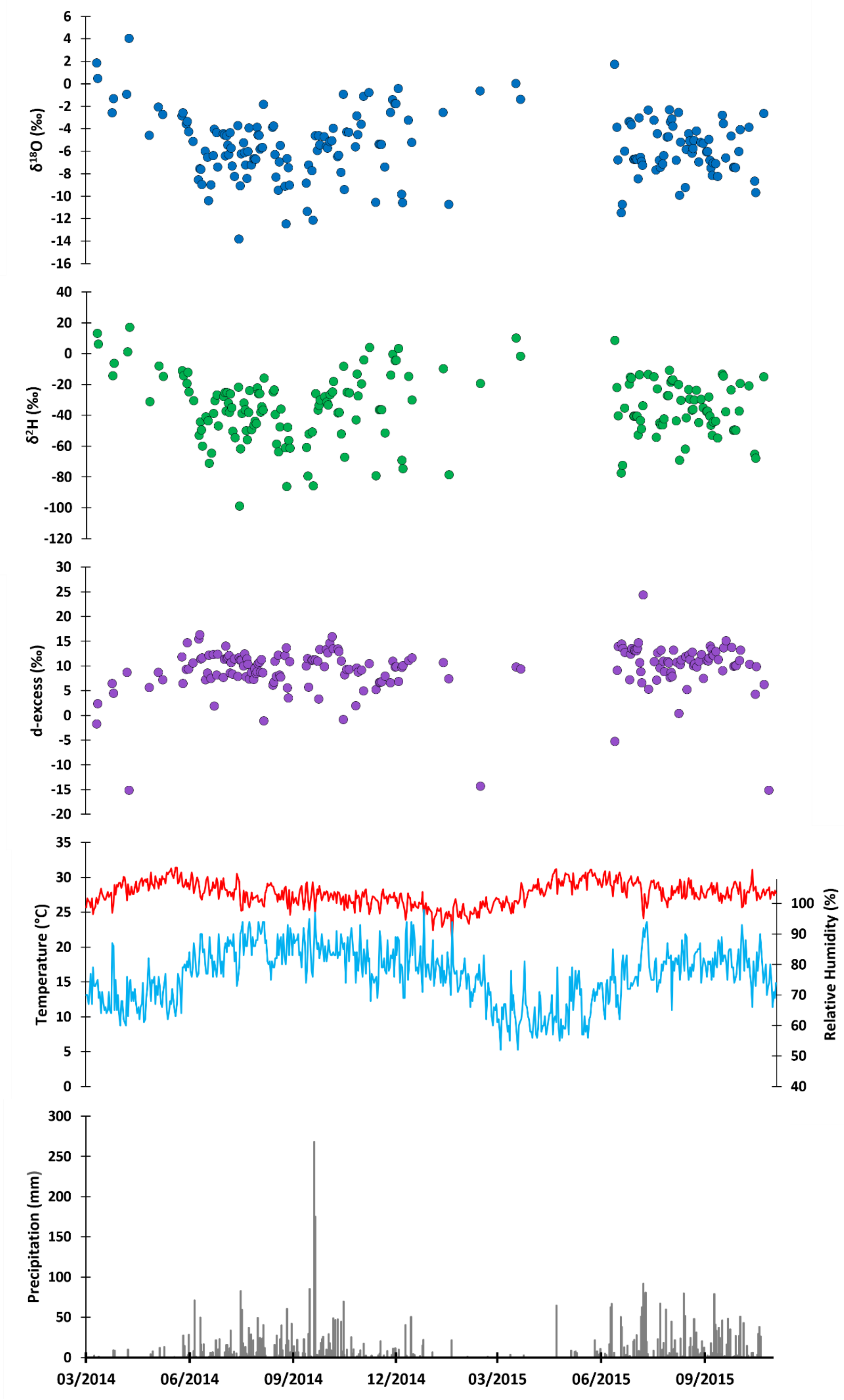

Figure 2 Time series of daily variations of $\delta^{18}O$, $\delta^{2}H$, d-excess, temperature, relative humidity and precipitation amount at Metropolitan Manila, Philippines.

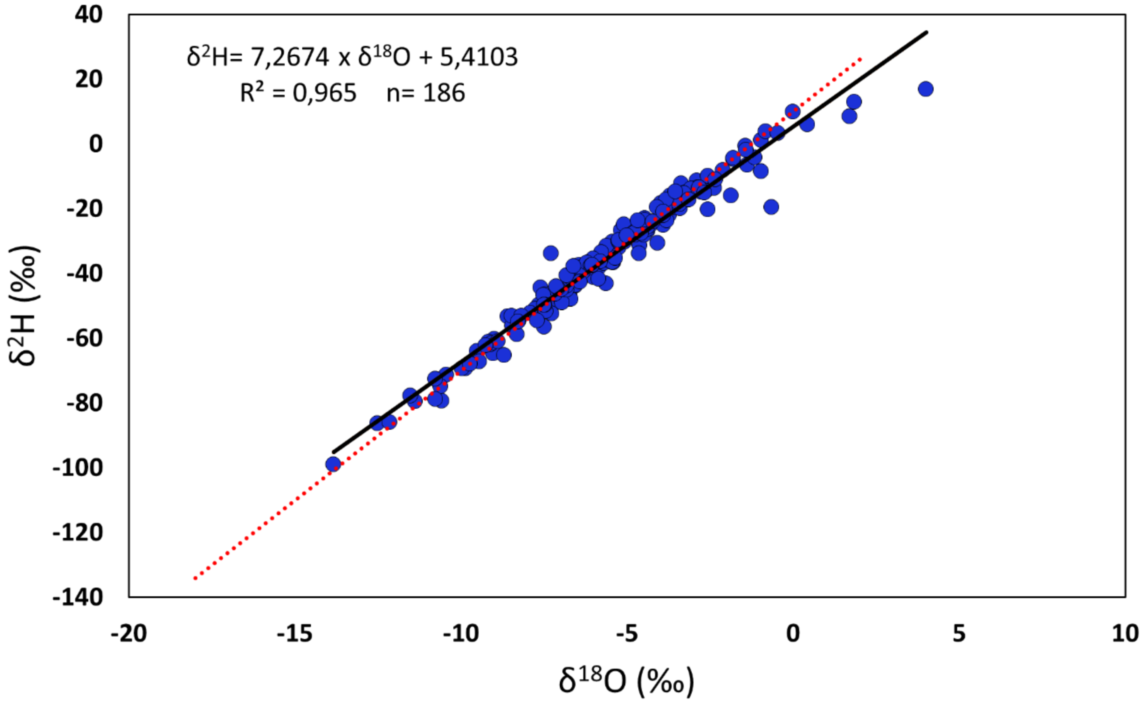

Figure 3 Local meteoric water line (LMWL) established for Metropolitan Manila, Philippines. The red dotted line represents the global meteoric water line (GMWL) ($\delta^2H = 8 \times \delta^{18}O + 10$; Craig, 1961).

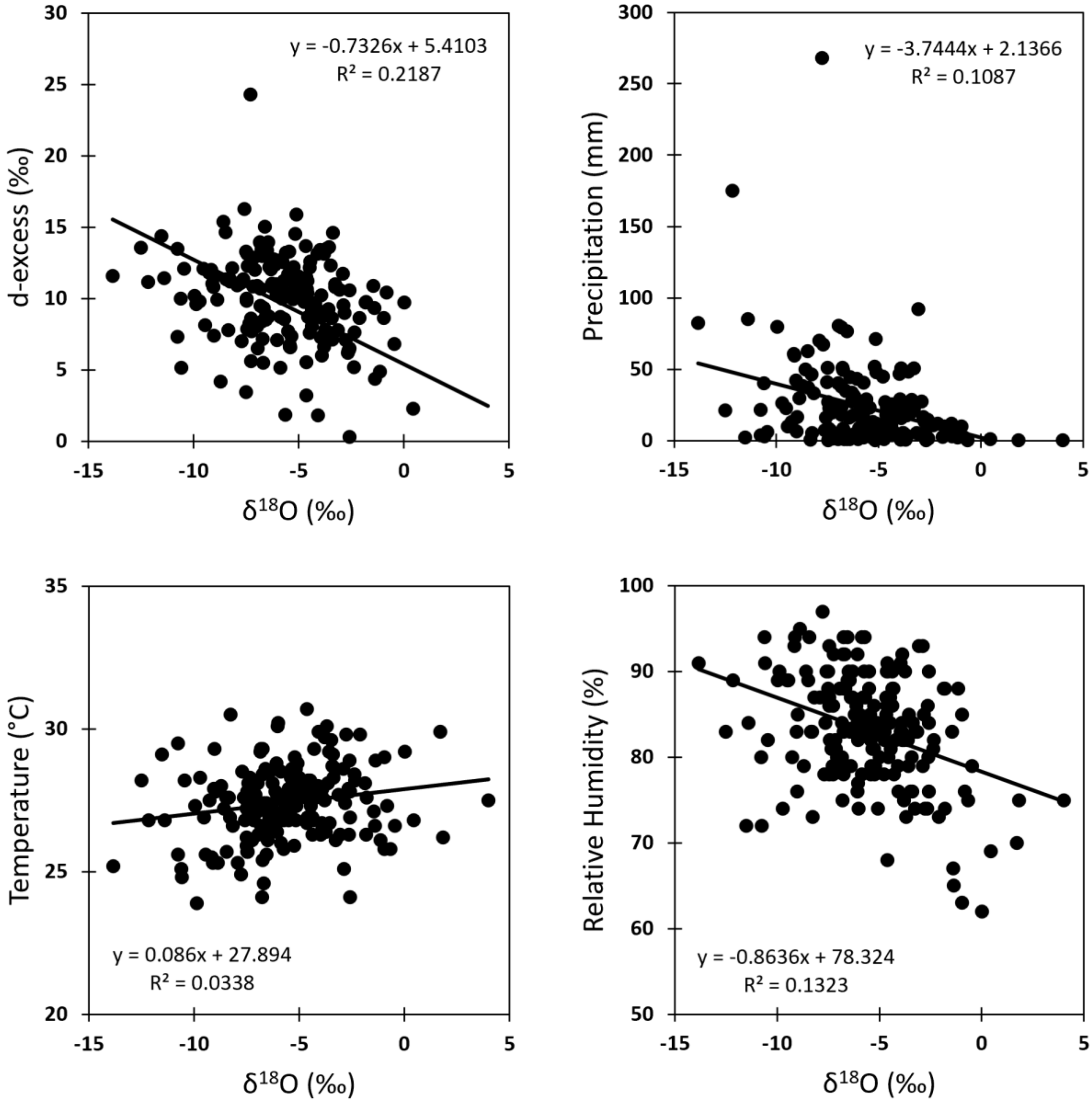

Figure 4 Correlations between daily $\delta^{18}O$ values and daily values of d-excess, precipitation amount, temperature and relative humidity. Linear regression line, correlation coefficient (R^2), slope and intercept are shown in each plot.

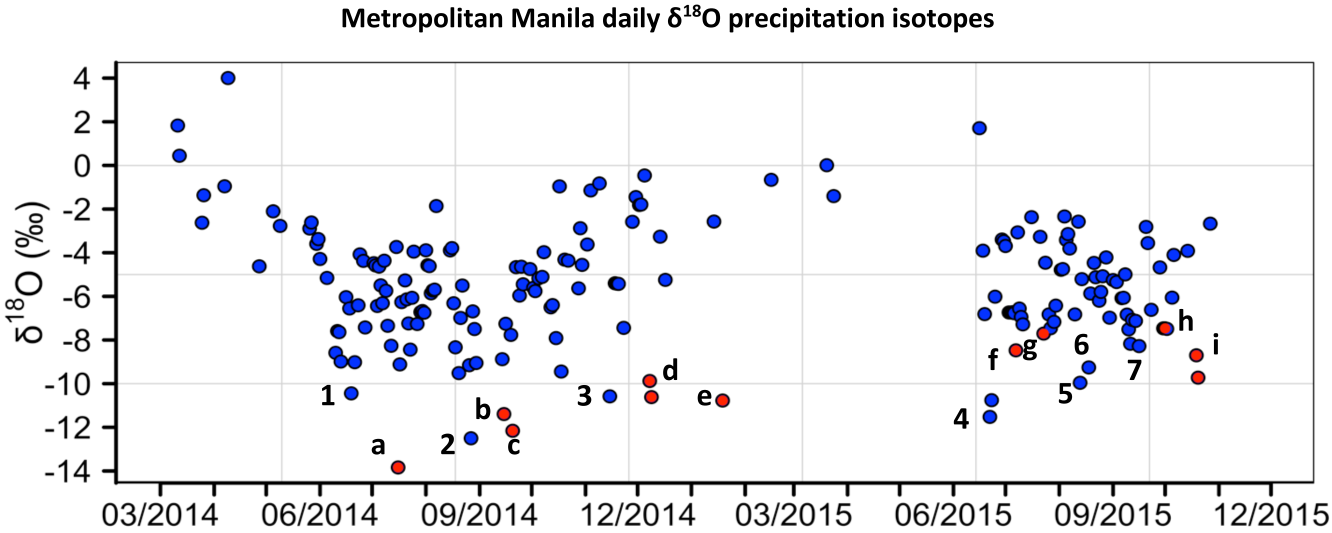

Figure 5 Complete time series of 186 precipitation samples taken between 10 March 2014 to 27 October 2015. δ ^{18}O data points associated with TC activity are colored in red. Other anomalously low δ^{18}O values were investigated using IMERG satellite precipitation data. a: Rammasun 16/07/14, -13.84 ‰, 83 mm. b: Kalmaegi 15/09/14, -11.39 ‰, 85 mm. c: Fung-Wong 20/09/14, -12.16 ‰, 175 mm. d: Hagupit 8-9/12/14, -9.88 ‰, -10.62 ‰, 40 mm. e: Mekkhala 19/1/15, -10.77 ‰, 22 mm. f: Linfa 07/07/15, -8.5 ‰, 63 mm. g: Twelve 23/07/15, -7.7 ‰, 68 mm. h: Mujigae 01/10/15, -7.5 ‰, 51 mm. i: Koppu 19-20/10/15. -8.7 ‰, -9.72 ‰, 38 mm, 26 mm. 1: storm passing by 19/06/14, -10.44 ‰, 6 mm. 2: large rain areas 27/08/14, -12.5 ‰, 21 mm 3: storm passing by 15/11/14 -10.58 ‰, 3 mm. 4: large rain areas, 22-23/06/15 -10.76 ‰, -11.52 ‰, 2 mm, 4 mm. 5: heavy rainfall 13/08/15, -9.96 ‰, 80 mm. 6: heavy rainfall 18/08/15, -9.26 ‰, 13 mm. 7: local convection 16/09/15, -8.28 ‰, 47 mm.

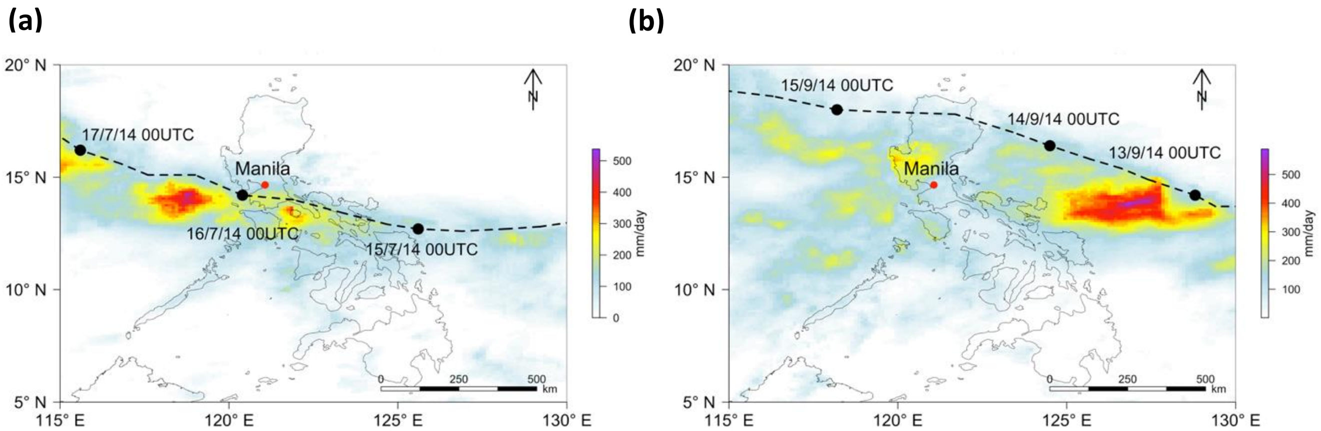

Figure 6 Accumulated precipitation from IMERG satellite data and TC tracks from IBTrACKS for a) Rammasun with precipitation accumulation for 14-17 July 2014, b) Kalmaegi with accumulated precipitation for 12-15 September 2014. Made with base layers from Natural Earth.

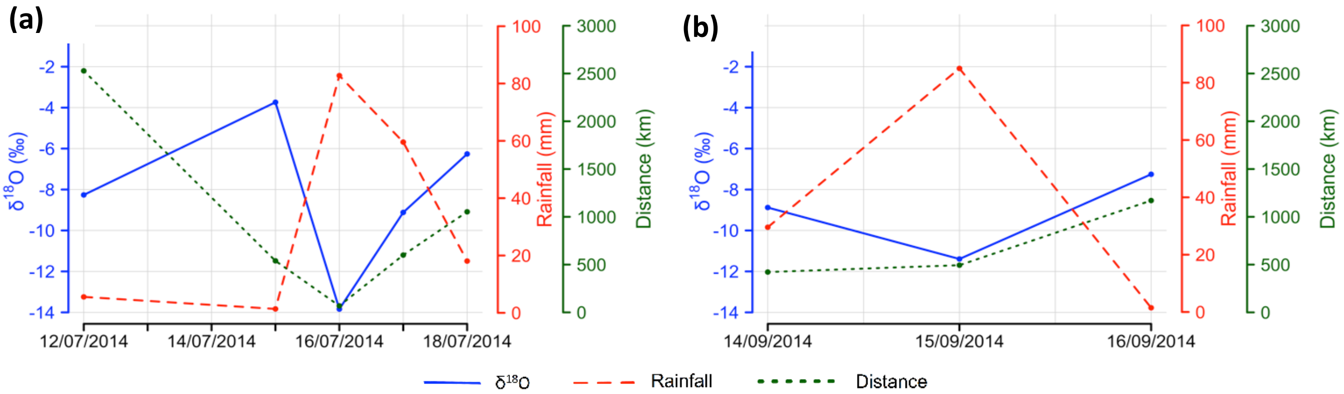

Figure 7 Isotopic signature from TCs during their passage to the Metropolitan Manila sampling site. $\delta^{18}O$ (blue color), distance from storm center to sampling location (green) and daily rainfall amount (red). a) Rammasun, b) Kalmaegi

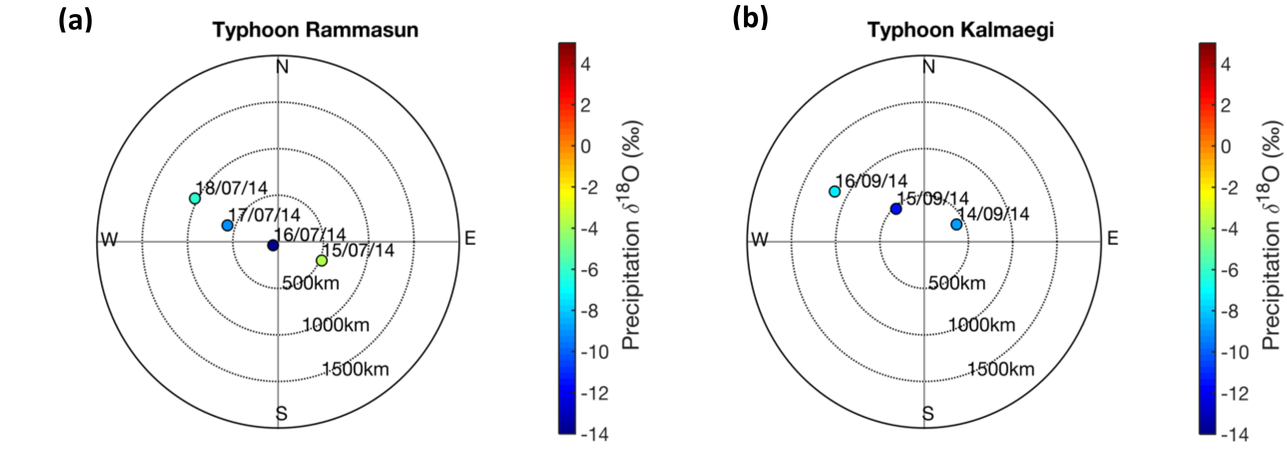

Figure 8 Spatio-temporal evolution of $\delta^{18}O$ isotopes. Centered on Metropolitan Manila collection site, different radii provide information on distance between storm's center to Metropolitan Manila. $\delta^{18}O$ values are color coded. a) Rammasun, b) Kalmaegi

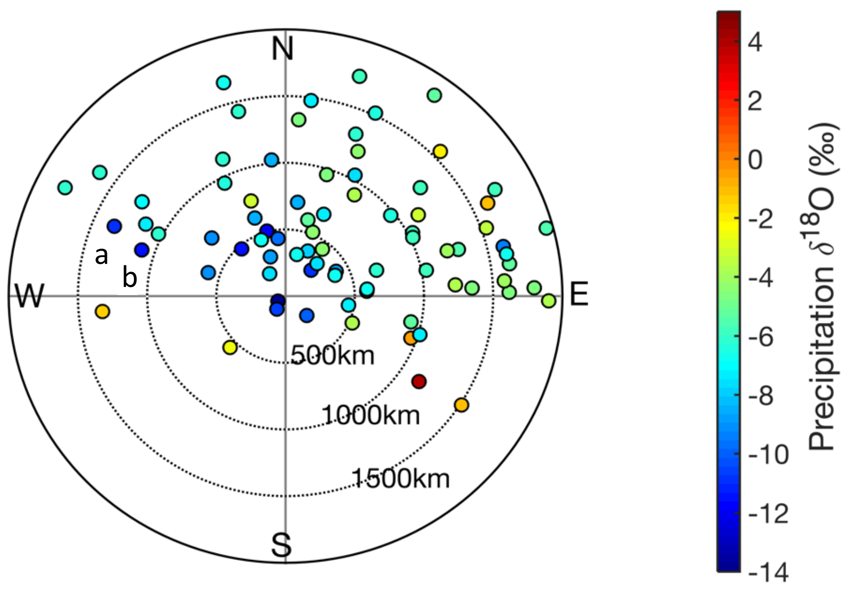

Figure 9 Spatio-temporal variation of isotopes related to TC activity within 2000 km, with different radii indicating the distance towards Metropolitan Manila. $\delta^{18}O$ values are color coded.

Tables

Table 1 Costliest typhoons in the Philippines. Two devastating typhoons, Rammasun and Koppu (ranking 3 and 7), occurred during our study period and made landfall. Damage in USD based on each time of TC occurrence (not adjusted to current inflation rates).

Rank	Name (local name)	Category (Saffir Simpson scale)	Period of occurrence	Damage in USD	Fatalities	Part of our dataset
1.	Haiyan (Yolanda)	Category 5	2-11 November 2013	~ 2.06 billion USD	~ 6000	No
2.	Bopha (Pablo)	Category 5	2-10 December 2012	~ 977 million USD	1067	No
3.	Rammasun (Glenda)	Category 5	12-17 July 2014	~ 880 million USD	106	Yes
7.	Koppu (Lando)	Category 4	12-21 October 2015	~ 310 million USD	62	Yes
References: Alojado and Padua, 2015; Lagmay et al., 2015; NDRRMC, 2012, 2014, 2015; Soria et al., 2016						

Table 2 Monthly average values of the 19-month time series of $\delta^{18}O$, $\delta^{2}H$, d-excess and meteorological parameters (precipitation amount, temperature and relative humditiy).

Month	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)	Precipitation (mm)	Temperature (°C)	Relative humidity (%)
Mar 14	-0.43	-0.62	2.82	4.3	27.1	70.0
Apr 14	-0.53	-4.54	-0.33	4.5	28.8	68.9
May 14	-2.89	-13.50	9.63	10.1	29.8	71.7
Jun 14	-6.90	-44.90	10.28	14.6	28.7	81.2
Jul 14	-6.46	-41.68	10.04	19.0	27.5	86.6
Aug 14	-6.39	-42.63	8.51	20.0	27.4	85.7
Sep 14	-7.29	-48.57	9.76	32.1	27.4	85.3
Oct 14	-5.24	-31.73	10.19	19.4	26.9	84.2
Nov 14	-4.39	-27.64	7.48	6.5	26.9	80.0
Dec 14	-4.72	-28.00	9.79	14.1	26.0	81.4
Jan 15	-6.67	-44.41	8.97	5.8	24.6	77.8
Feb 15	-0.66	-19.70	-14.41	0.7	25.5	70.7
Mar 15	-0.70	3.95	9.54	3.3	26.8	62.9
Apr 15				64.8	29.1	62.0
May 15				7.5	29.7	68.4
Jun 15	-5.52	-34.47	9.71	19.3	29.3	73.1
Jul 15	-6.04	-36.69	11.61	28.6	27.8	80.5
Aug 15	-5.25	-32.28	9.74	18.4	28.0	81.1
Sep 15	-6.12	-37.07	11.86	18.5	28.0	81.0
Oct 15	-6.27	-40.80	6.60	16.7	27.8	78.0