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

Dominik Jackisch[1], Bi Xuan Yeo[2], Adam D. Switzer[1,2], Shaoneng He[1], Danica Linda M. Cantarero[3], Fernando P. Siringan[3] and Nathalie F. Goodkin[1,2,4]

[1] Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798

[2] Asian School of the Environment, Nanyang Technological University, Singapore 639798

[3] Marine Science Institute, University of the Philippines Diliman, Quezon City 1101, Philippines

[4] American Museum of Natural History, New York 10024, USA

Correspondence to: Adam D. Switzer (aswitzer@ntu.edu.sg)

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 if there is an isotopic response to tropical cyclones. The most negative shift in δ^{18}O value (-13.84 ‰) leading to a clear isotopic signal was caused by Typhoon Rammasun, which directly hit Metropolitan Manila. The average δ^{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 in the future. 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).

64

A few studies have demonstrated the potential to investigate tropical cyclones using stable water isotopes (e.g. Good et al., 2014; Lawrence et al., 2002; Munksgaard et al., 2015). Stable water isotopes (δ^2H and δ^{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 δ^{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 δ^{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;

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

97

98   The above-mentioned studies are geographically limited to a few locations globally, with no

99   studies in Southeast Asia and the Philippines in particular. In this manuscript, we present the

100   first such study for the Philippines, with daily isotope measurements of precipitation from

101   Metropolitan Manila (the National Capital Region) spanning from March 2014 to October

102   2015. During the study period, nine tropical cyclones passed by or made landfall within 500

103   km of the sampling site (Fig. 1). The major objective of this research is to understand if there

104   is an isotopic response of precipitation to TC activities in the Philippines, and if so – what

105   signal do we measure and how is it represented spatially? Further, we aim to understand the

106   isotopic variation with distance from the TC track. Our findings provide a baseline dataset for

107   reconstruction of typhoon activities using stable isotopes and contribute to a better

108   understanding of past and future TC activities in the Philippines.

109

110

111   **2.   Materials and methods**

112

113   **2.1 Site description**

114

115   The Philippines is a Southeast Asian country comprising more than 7000 islands located in the

116   Northwest Pacific between 4° 40' N and 21° 10' N, and 116° 40' E and 126° 34' E (Fig. 1). The

117   country experiences an average annual rainfall of about 2000 mm, influenced by two

118   monsoon seasons, the northeast monsoon from November to April and the southwest

119   monsoon from May to October (Cinco et al., 2014). About 35 % of the annual rainfall is related

120   to TC activity, while that number rises to about 50 % for Luzon and decreases to 4 % for the

121   southern island of Mindanao (Cinco et al., 2016). Part of the rainfall amount in the Philippines

122   is of orographic nature due to north-south oriented mountain ranges of more than 1000 m

123   spanning the largest islands of Luzon and Mindanao (Villafuerte et al., 2014). The majority of

124   the steadily growing population in the Philippines (101 million 2017 census) live in densely

125   populated, low-elevation areas close to the coastlines (Cinco et al., 2014, 2016; Philippine

126   Statistics Authority, 2017).

127

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 allows 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 δ^2H), TIBET (-19.11 ‰ of $\delta^{18}O$; -143.60 ‰ of δ^2H), and ELGA (-4.25 ‰ of $\delta^{18}O$; -27.16 ‰ of δ^2H). 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 δ^2H.

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

160   We used the IMERG Version 5 Final daily product, a remotely-sensed precipitation dataset

161   from satellites to highlight cyclonic tracks and precipitation patterns of several TC's passing

162   by Metropolitan Manila, and to identify which rainfall events were not affected by cyclonic

163   activity, and instead were associated with local or other regional convection activities. Such

164   datasets are beneficial as they provide quasi-global grid-based rainfall estimates for land and

165   the oceans (Poméon et al., 2017). The Integrated Multi Satellite Retrievals for GPM (IMERG)

166   from the Global Precipitation Measurement (GPM) programme with a fine 0.1-degree grid

167   size (Huffman et al., 2017) has been available since March 2014, and provides precipitation

168   data in different temporal resolutions, such as half-hourly or daily. Such satellite rainfall data

169   has been previously utilized to show TC tracks and related rainfall intensities (Rios Gaona et

170   al., 2018; Villarini et al., 2011).

171

172   **2.5 Rainfall data**

173

174   Daily rainfall data was obtained from the Philippine Atmospheric, Geophysical and

175   Astronomical Services Administration (PAGASA), which maintains a rainfall monitoring station

176   about 2.7 km away from our sampling site. The data is freely available for the period 2013 to

177   2017, and can be accessed on the Philippines Freedom of Information website

178   (www.foi.gov.ph).

179

180

181   **3. Results**

182   **3.1 Precipitation isotope evolution during TC events**

183

184   The stable isotope composition during the 19 months study period spanning from 10 March

185   2014 to 26 October 2015 shows large seasonal isotopic variability in Metropolitan Manila.

186   One hundred and eighty-six daily precipitation samples have been collected and analyzed in

187   total (Fig. 2). $\delta^{18}O$ ranges from 4 ‰ to -13.84 ‰, and δ^2H from 16.84 ‰ to -99.1 ‰. The

188   highest $\delta^{18}O$ value of 4 ‰ was observed on 9 April 2014 during the annual dry period, whereas

189   the lowest $\delta^{18}O$ value of -13.84 ‰ was observed on 16 September 2014 in association with

190   TC activity. The mean $\delta^{18}O$ of precipitation at the study site is -5.29 ‰ for non-TC rain systems,

191   while TCs, as large regional convective systems, have the potential to cause a change in δ-

192   values of up to almost 9 ‰ relative to the mean. The average $\delta^{18}O$ value of the nine TCs that

193   tracked within <500 km from the sampling site is -10.24 ‰ (STDEV of 2.11), a factor of 2 larger

194   than the mean from non-TC precipitation (average is -5.29 ‰, STDEV of 2.64).

195

196   Overall, precipitation isotopes associated with TCs mark the lower range of $\delta^{18}O$ values during

197   the study period. Especially during the 2014 season, most of the very low precipitation

198   isotope values occurred throughout passage of TCs. For instance, Rammasun led to the lowest

199   δ-value (Fig. 2, point a, -13.84 ‰) of the whole study period, while other TCs such as Fung-

200   Wong (Fig. 2, point c, -12.16 ‰), Kalmaegi (Fig. 2, point b, -11.39 ‰), or Hagupit (Fig. 2, point

201   d, -9.88 ‰) caused other negative excursions in isotopic values. The 2015 season is

202   characterized by on average a slightly higher isotopic enrichment during the rainfall intensive

203   summer months. Nonetheless, a similar noticeable isotope signal is visible with low $\delta^{18}O$

204   isotopes, clustered along the lower end of the sample range, for example, caused by Linfa

205   (Fig. 2, point f, -8.5 ‰) or Koppu (Fig. 2, point i, -8.7 ‰). The other TCs that occurred during

206   the study period and were investigated by us were Mekkhala (Fig.2, point e, -10.77 ‰),

207   Twelve (Fig.2, point g, -7.7 ‰) and Mujigae (Fig. 2, point h, -7.5 ‰). However, relatively

208   negative isotope samples (Fig. 2) also originated from non-TC rainfall systems. Those events

209   are discussed below.

210

211   Out of the nine TCs that occurred within a 500 km radius from the sampling site, Rammasun

212   and Kalmaegi left clearly observable, distinct isotopic signatures during their approach and

213   dissipation, which we will therefore present in more detail in the next paragraphs. Typhoon

214   Hagupit (Fig. 2, point d) similarly lead to a clear isotopic evolution pattern during its time of

215   occurrence in the Philippines and is shown in the supplementary (S1).

216

217   Typhoon Rammasun's rainfall intensities based on the IMERG precipitation data together

218   with its track from IBTrACKS is shown in Fig. 3a. Typhoon Rammasun stands out in our study

219   period as it moved straight towards the National Capital Region of the Philippines, resulting

220   in a direct hit. Rammasun, locally named Glenda, made landfall in the Bicol region of southern

221   Luzon on 15 July, with wind speeds of about 160 km/h. On 16 July, it passed south of

222   Metropolitan Manila 50 km from our sampling site, with maximum winds of 130 km/h,

223   gradually losing strength over land. As Rammasun approached on 15 July, the precipitation

224   has shown relatively high δ^{18}O of -4 ‰ while rainfall was weak (Fig. 4a). On 16 July, δ^{18}O

225   shifted to -13.84 ‰, while the typhoon's track was the closest to our sampling site and rainfall

226   amount was high. As Rammasun moved away, precipitation isotopes became more positive,

227   and rainfall amount decreased. The characteristic isotopic evolution related to Rammasun's

228   distance and rainfall intensities as a function of time can be seen in Fig. 5a, where the different

229   radii indicate the distance to the sampling site, and the strong isotopic depletion observed on

230   16 July is also evident. As Rammasun with its storm center tracked towards the northwest

231   and away from Metropolitan Manila, our precipitation samples were relatively isotopically

232   enriched for the following two days, namely -9,12 ‰ on 17 July and -6,26 ‰ on 18 July.

233

234   Typhoon Kalmaegi, locally named Luis, was the first typhoon to make landfall in the

235   Philippines two months after Rammasun. Kalmaegi reached typhoon intensity on 13

236   September, making landfall the following day in northern Luzon, with maximum wind speeds

237   of about 120 km/h. Kalmaegi tracked relatively far away from the sampling site (about 350

238   km), but the accumulated rainfall it produced was centered south of the track, placing it

239   considerably closer to the National Capital Region (Fig. 3b). Despite the distance of the eye

240   from the sampling site, a characteristic isotopic pattern was visible, with the most negative

241   δ^{18}O value of -11.39 ‰ on 15 September, coincident with the highest rainfall (Fig. 4b). The

242   following day, δ^{18}O values returned to higher values with the increase in distance from the

243   eye. This is also seen in a spatial representation in Fig. 5b.

244

245

246   **4. Discussion**

247   **4.1 Stable isotopes of precipitation – a possible proxy for TCs**

248

249   As stable water isotopes fractionate during the physical process of evaporation and

250   condensation, they serve as effective tracers in the hydrological cycle (Dansgaard, 1964; He

251   et al., 2018; Risi et al., 2008; Tremoy et al., 2014). Here, we have demonstrated that stable

252   water isotopes can possibly be used to identify TC activity in the Southeast Asian region by

253   excursions in δ^{18}O, providing evidence and supporting the hypothesis that TCs may leave a

254   clear isotopic signal in the Philippines. The strong isotopic depletion is due to high

255   condensation efficiencies in cyclonic convective rain bands, leading to extensive

256   fractionation. This is particularly pronounced in intense, large-scale TCs (Lawrence, 1998;

257   Lawrence and Gedzelman, 1996). In the previous section, we have presented our findings of

258   precipitation isotope ratios associated with typhoon activities affecting Metropolitan Manila

259   during the study period of March 2014 to October 2015. Based on our time series, we

260   therefore argue that for the Philippines, the lowest measured isotope value likely indicates

261   the occurrence of a TC, such as is the case for Typhoon Rammasun (Fig. 2). Similarly, other

262   anomalously low $\delta^{18}O$ values at our site are caused by TC making landfall or passing by.

263

264   Individual TCs (Rammasun and Kalmaegi) were characterized by consistent isotopic

265   excursions to very negative values in a range of up to -9 ‰ compared to the mean isotopic

266   value of -5.29 ‰ (Fig. 4 and 5). A TC approaching the sampling site had relatively higher

267   isotope values than at its later stages when it was closest to the site in Metropolitan Manila.

268   When at its closest, strong rainfall together with increased fractionation depleted

269   precipitation isotopes, leading to a distinct drop in isotope value. Such a strong negative

270   isotopic shift in precipitation has been previously observed in other regions (Fudeyasu et al.,

271   2008; Lawrence and Gedzelman, 1996; Munksgaard et al., 2015; Xu et al., 2019). As the TC

272   moved away and rainfall intensities weakened, $\delta^{18}O$ in precipitation became again more

273   positive, likely due to evaporative effects (Munksgaard et al., 2015; Xu et al., 2019).

274

275   As the strongest TC in terms of wind speeds, damage costs, and fatalities, Typhoon Rammasun

276   reduced the isotope values most during our study period, to -13.84 ‰. Similarly, Typhoon

277   Kalmaegi lead to extensive damage and caused a significantly negative excursion in

278   precipitation isotopes to -11.39 ‰, suggesting that the lowest isotope values might indicate

279   the occurrence of the strongest TC at that time at our site in the Philippines. We note that

280   our isotopic measurements are similar to observations elsewhere. For example, the range of

281    $\delta^{18}O$ values caused by Typhoon Shanshan affecting the subtropical Ishigaki island was -6 to -

282   13 ‰, (Fudeyasu et al., 2008); Tropical Cyclone Ita led to a range of -4.8 to -20.2 ‰ in

283   northeastern Australia (Munksgaard et al., 2015); several TCs which made landfall in Texas

284   resulted in isotope values from -3.9 to -14.3 ‰ (Lawrence and Gedzelman, 1996); or

285   hurricanes that affected Puerto Rico and southern Texas were found to deplete $\delta^{18}O$ up to -

286   18 ‰ (Lawrence, 1998). The lowest value resulting from Typhoon Phailin on the Andaman

287   Islands was reported to be -5.5 ‰, and Typhoon Lehar depleted the precipitation sample to

288 -17.1 ‰ (Chakraborty et al., 2016). For TCs within a distance of up to 500 km from the
289 sampling site at the University of the Philippines Diliman in Metropolitan Manila we measured
290 an isotopic range of -7.7 ‰ (Typhoon Koppu) to -13.84 ‰ (Typhoon Rammasun). Despite the
291 overall comparability to our measurements, differences exist. The lowest values observed in
292 some studies are considerably more negative than at our site (Lawrence, 1998; Munksgaard
293 et al., 2015). However, we attribute these differences to a variety of features, such as the
294 specific climatic condition at each site, differences in temperature, humidity, and altitude or
295 latitude, which are likely contributing factors to the observed isotopic variation by altering
296 isotopic fractionation. Further, rainout history, location of typhoon tracks, topography,
297 respective strength of each TC, as well as its distance to the sampling site most likely have a
298 significant influence as well (Fudeyasu et al., 2008; Good et al., 2014; Munksgaard et al., 2015;
299 Xu et al., 2019).

300

301 In order to assess why other very low isotopic excursions occurred on various days (Fig. 2) we
302 used IMERG satellite precipitation data. IMERG data with its fine spatio-temporal resolution
303 allows the identification of convective rainfall areas and the passage of TCs and other rain
304 systems. Our analysis shows that precipitation events with anomalously low isotope signals
305 unassociated with TCs are largely related to local, strong convective rainfall events or large
306 scale and slow-moving rain areas passing over the National Capital Region. Therefore, the
307 degree of convection is responsible to produce the other observed low $\delta^{18}O$ value outliers
308 that are not related to cyclone rainfall, as strong convection and long stratiform rainfall leads
309 to intense fractionation (He et al., 2018; Risi et al., 2008; Tremoy et al., 2014). Contrarily, we
310 speculate that the more positive isotope values which cluster along the higher end of the
311 sample spectrum around 0 ‰, are associated with local, short convective rainfall events and
312 light intensity rain as confirmed with IMERG satellite precipitation data. Additionally, the
313 PAGASA rain gauge data indicates that rainfall amounts are very low during days with such
314 very enriched isotope samples, such as 0.3 mm/day for the highest recorded sample of 4 ‰
315 on 9 April 2014. Interestingly, TCs at our site were found to be related with low isotope values
316 together with high rainfall amounts (Fig. 2), while the majority of other low isotopic values
317 unassociated with TCs were characterized by on average lesser rainfall amounts. This possibly
318 indicates that TCs in the Philippines, besides using for instance modern-day satellite or radar

319 data, can be detected using these two parameters, i.e. strong isotopic depletion coupled with

320 high rainfall amounts.

321

322 The aforementioned local convective precipitation events have the potential to induce a

323 signal of very negative $\delta^{18}O$ values which are not related to TC activities. We therefore label

324 such a signal as a "false non-TC signal", as it is induced by non-TC rainfall. This results in the

325 fact that TCs occurring during our study period do not entirely cluster along the lowest range

326 of isotope values as seen in figure Fig. 2. Nevertheless, Typhoon Rammasun caused a clear

327 drop in isotopes and stands out in the dataset. This might be the case because Rammasun's

328 track and heavy rainfall comes in closest proximity (50 km) to the sampling site. Other TCs

329 occurring within the 500 km radius did not lead to such a clear negative isotopic signature,

330 likely because these typhoons did not pass the sampling site at all or heavy rainfall occurred

331 elsewhere within the TC rainfall system (see S 2 for their tracks and accumulated rainfall

332 areas). Some of these TCs have intense rainfall areas over other parts of the Philippines and

333 are characterized by a variable track, likely influenced by land interactions. Land interaction

334 reduces TC strength and can lead to rain out caused by orographic effects induced by the

335 north-south oriented mountain ranges (Park et al., 2017; Xie and Zhang, 2012; Xu et al., 2019).

336 Especially Typhoon Koppu rained out before making landfall and abruptly changed its track,

337 instead of passing by the Metropolitan Manila. Similarly, Typhoon Mekkhala's intense rainfall

338 occurred along the eastern coasts, before it started to dissipate. Evidently, due to these

339 factors the isotope values associated with those TCs were not as negative as during

340 Rammasun. Therefore, a TC which is relatively far away from the sampling site causes an

341 isotope signal that is not as clear and as negative, thus averaging out between the other low

342 values from rain systems unassociated with TC.

343

344 **4.2 Distance of TCs from Metropolitan Manila**

345

346 Our observations provide details on spatial distance from collection site towards TCs' centers,

347 as our findings indicate that the distance from the storm center to the sampling site impacts

348 isotopic value. The TCs' distance of up to 500 km to sampling site and the precipitation isotope

349 value are correlated with r=0.55, n= 16, p-value= <0.0001 and 99% confidence level. This

350 relationship weakens with an increase in the distance from the sampling site: a distance of

351   500 to 1000 km yields an r of 0.2 with n=19, p-value= 0.019, the distance of 1000 to 1500 km

352   yields an r of 0.18 with n=24, p-value= 0.087, while a 1500 to 2000 km distance results in an

353   r of 0.1 with n=21, p-value= 0.65. This suggests that a TC more than 500 km away from the

354   sampling site has no influence on precipitation isotopes (Munksgaard et al., 2015). Thus, the

355   closer the TC is to the sampling site, the more negative the isotope signal and the larger the

356   δ-change. This relationship might provide information on storm structure and intensity, as

357   the intensity increases with proximity of the TC to the sampling location. We thus confirm

358   that the isotope value at our location is a function of the closest approach of the storm's

359   center to the sampling site (Lawrence and Gedzelman, 1996).

360

361   Figure 6 displays all the precipitation samples associated with TC presence and activities

362   within a 2000 km radius from Metropolitan Manila, and further highlights the relationship

363   between distance and isotopic depletion, additionally providing a spatial indication of TC's

364   quadrants and their tracks relative to the location of the sampling site. Strongest depletion

365   occurs within the 500 km radius. However, two relatively negative outliers are located within

366   a 1000 to 1500 km radius in the northwest quadrant. These two samples were taken during

367   the passage of tropical storm Kujira on 22nd and 23rd of June 2015 (Fig. 2), which was more

368   than 1000 km away from Metropolitan Manila travelling east along the coast of Vietnam as

369   seen with IBTrACKS data. We investigated these two samples with IMERG satellite

370   precipitation data and identified them as a part of a mesoscale system, with strong convective

371   cells delivering intense rainfall, leading to distinct isotopic depletion and inducing a "false

372   non-TC signal" of very negative rainfall unassociated with TC activity.

373

374   **4.3 Cyclone track's rainfall intensity**

375

376   IMERG satellite precipitation data also identify that the highest rainfall intensities occur at the

377   left side of the TC track for all the TC within the 500 km radius, except for Hagupit and

378   Mekkhala, which are more complex cases (Fig. 3a, b, supplementary S 2). This is in contrast

379   to the results from Villarini et al. (2011), stating that the largest rainfall accumulation appears

380   on the right side of the hurricane tracks. They also noted that large rainfall amounts occur far

381   away from the storm's track, which we can confirm and quantify with our observations. The

382   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).

4.4 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

415 provide a better understanding of past TC activity, ultimately resulting in better and more
416 accurate climate reconstructions. TC projections related to climate change could also be
417 improved, which is especially relevant for decision makers dealing with TC related impacts
418 and damages. Our in-situ isotope measurements provide baseline data input in an
419 understudied tropical region, providing isotopic data of TC occurrence and quantifying the
420 isotopic depletion associated with TC activity. Further, our 19-month dataset suggests that
421 the lowest measured isotope value at the Philippines study site is associated with TC activity,
422 resulting in the distinct negative isotopic shift in the time series (Fig. 2). As rain out history,
423 topography, distance of track or rainfall unassociated with TCs can induce a weak or "false
424 non-TC signal", it is important to choose stalagmites or trees as archives based on their
425 location, ideally covering a spatial gradient thus capturing a TC in its full size.

426

427 **5. Conclusions**

428

429 As presented with our dataset, a strong, high-energy TC with a track directly approaching and
430 hitting the sampling site leads to a clear isotopic signal in a time series in the Philippines. If
431 the TC is further away, such as more than 500 km from the site, or heavy TC rainfall occurred
432 elsewhere prior of making landfall, the signal is not as clear and might average out between
433 other rainfall events. Other strong convective rainfall events unassociated with TCs may result
434 in similarly low isotope values, and we label these as a weak or "false non-TC signal".
435 Therefore, our data suggests that distance of TC to the sampling site is a key factor in
436 controlling the isotope signal and that such a spatial component needs to be considered when
437 interpreting the isotope signal. However, a longer time series isotope record would help to
438 better constrain controlling factors, such as the influence of topography on high-energy TCs.
439 To what extent mountain ranges and low elevation coastal areas shape the TC induced
440 isotope signal needs further investigation. Based on our findings we conclude that the
441 location of precipitation sample collection needs to be chosen strategically. Ideally, several
442 rainwater collection stations should be operated, covering a wide geographical range such as
443 stretching from northern Luzon to its south. If such a spatial gradient was covered, a TC would
444 likely be captured in its full size. Consequently, we aim to expand our time series spatially and
445 temporally.

446

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 26 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.

Acknowledgments

This study is supported by the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence Initiative. It is Earth Observatory of Singapore contribution no. 188. This study is also the part of IAEA Coordinated Research Project (CRP Code: F31004) on "Stable isotopes in precipitation and palaeoclimatic archives in tropical areas to improve regional hydrological and climatic impact model" with IAEA Research Agreement No. 17980.

References

Alojado, D. and Padua, D. M.: Costliest Typhoons of the Philippines (1947 - 2014), [online] Available from: https://www.typhoon2000.ph/stormstats/WPF_CostliestTyphoonsPhilippines_2015E d.pdf (Accessed 17 September 2019), 2015.

Chakraborty, S., Sinha, N., Chattopadhyay, R., Sengupta, S., Mohan, P. M. and Datye, A.: Atmospheric controls on the precipitation isotopes over the Andaman Islands, Bay of Bengal, Sci. Rep., 6, 1–11, doi:10.1038/srep19555, 2016.

Cinco, T. A., de Guzman, R. G., Hilario, F. D. and Wilson, D. M.: Long-term trends and extremes in observed daily precipitation and near surface air temperature in the Philippines for the period 1951-2010, Atmos. Res., 145–146, 12–26, doi:10.1016/j.atmosres.2014.03.025, 2014.

Cinco, T. A., de Guzman, R. G., Ortiz, A. M. D., Delfino, R. J. P., Lasco, R. D., Hilario, F. D., Juanillo, E. L., Barba, R. and Ares, E. D.: Observed trends and impacts of tropical cyclones in the Philippines, Int. J. Climatol., 36(14), 4638–4650, doi:10.1002/joc.4659, 2016.

Cruz, F. T., Narisma, G. T., Villafuerte, M. Q., Cheng Chua, K. U. and Olaguera, L. M.: A climatological analysis of the southwest monsoon rainfall in the Philippines, Atmos. Res., 122, 609–616, doi:10.1016/j.atmosres.2012.06.010, 2013.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16(4), 436–468, doi:10.3402/tellusa.v16i4.8993, 1964.

Emanuel, K.: Increasing destructiveness of tropical cyclones over the past 30 years, Nature, 436(7051), 686–688, doi:10.1038/nature03906, 2005.

Frappier, A. B.: Masking of interannual climate proxy signals by residual tropical cyclone rainwater: Evidence and challenges for low-latitude speleothem paleoclimatology, Geochemistry, Geophys. Geosystems, 14(9), 3632–3647, doi:10.1002/ggge.20218, 2013.

Frappier, A. B., Sahagian, D., Carpenter, S. J., González, L. A. and Frappier, B. R.: Stalagmite stable isotope record of recent tropic cyclone events, Geology, 35(2), 111–114, doi:10.1130/G23145A.1, 2007.

Fudeyasu, H., Ichiyanagi, K., Sugimoto, A., Yoshimura, K., Ueta, A., Yamanaka, M. D. and

543   Ozawa, K.: Isotope ratios of precipitation and water vapor observed in typhoon

544   Shanshan, J. Geophys. Res. Atmos., 113(12), 1–9, doi:10.1029/2007JD009313, 2008.

545 Gedzelman, S., Lawrence, J., Gamache, J., Black, M., Hindman, E., Black, R., Dunion, J.,

546   Willoughby, H. and Zhang, X.: Probing Hurricanes with Stable Isotopes of Rain and

547   Water Vapor, Mon. Weather Rev., 131(6), 1112–1127, doi:10.1175/1520-

548   0493(2003)131<1112:PHWSIO>2.0.CO;2, 2003.

549 Van Geldern, R. and Barth, J. A. C.: Optimization of instrument setup and post-run

550   corrections for oxygen and hydrogen stable isotope measurements of water by

551   isotope ratio infrared spectroscopy (IRIS), Limnol. Oceanogr. Methods, 10, 1024–

552   1036, doi:10.4319/lom.2012.10.1024, 2012.

553 Good, S. P., Mallia, D. V., Lin, J. C. and Bowen, G. J.: Stable isotope analysis of precipitation

554   samples obtained via crowdsourcing reveals the spatiotemporal evolution of

555   superstorm sandy, PLoS One, 9(3), doi:10.1371/journal.pone.0091117, 2014.

556 Gröning, M., Lutz, H. O., Roller-Lutz, Z., Kralik, M., Gourcy, L. and Pöltenstein, L.: A simple

557   rain collector preventing water re-evaporation dedicated for δ 18O and δ 2H analysis

558   of cumulative precipitation samples, J. Hydrol., 448–449, 195–200,

559   doi:10.1016/j.jhydrol.2012.04.041, 2012.

560 Guan, S., Li, S., Hou, Y., Hu, P., Liu, Z. and Feng, J.: Increasing threat of landfalling typhoons

561   in the western North Pacific between 1974 and 2013, Int. J. Appl. Earth Obs. Geoinf.,

562   68(7), 279–286, doi:10.1016/j.jag.2017.12.017, 2018.

563 He, S., Goodkin, N. F., Jackisch, D., Ong, M. R. and Samanta, D.: Continuous real-time

564   analysis of the isotopic composition of precipitation during tropical rain events:

565   Insights into tropical convection, Hydrol. Process., 32(11), 1531–1545,

566   doi:10.1002/hyp.11520, 2018.

567 Huffman, G. J., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., Kidd, C., Nelkin, E. J.,

568   Sorooshian, S., Tan, J. and Xie, P.: Algorithm Theoretical Basis Document (ATBD) of

569   Integrated Multi-satellitE Retrievals for GPM (IMERG), version 4.6, Nasa [online]

570   Available from:

571   https://pmm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V4.6.pdf

572   (Accessed 11 September 2019), 2017.

573 Knapp, K. R., Levinson, D. H., Kruk, M. C., Howard, J. H. and Kossin, J. P.: The International

574   Best Track Archive for Climate Stewardship (IBTrACS), Bull. Am. Meteorol. Soc., 91,

363–376, doi:10.1007/978-90-481-3109-9_26, 2010.

Lagmay, A. M. F., Agaton, R. P., Bahala, M. A. C., Briones, J. B. L. T., Cabacaba, K. M. C., Caro, C. V. C., Dasallas, L. L., Gonzalo, L. A. L., Ladiero, C. N., Lapidez, J. P., Mungcal, M. T. F., Puno, J. V. R., Ramos, M. M. A. C., Santiago, J., Suarez, J. K. and Tablazon, J. P.: Devastating storm surges of Typhoon Haiyan, Int. J. Disaster Risk Reduct., 11, 1–12, doi:10.1016/j.ijdrr.2014.10.006, 2015.

Lawrence, J. R.: Isotopic spikes from tropical cyclones in surface waters: Opportunities in hydrology and paleoclimatology, Chem. Geol., 144(1–2), 153–160, doi:10.1016/S0009-2541(97)00090-9, 1998.

Lawrence, J. R. and Gedzelman, S. D.: Low stable isotope ratios of tropical cyclone rains, Geophys. Res. Lett., 23(5), 527–530, 1996.

Lawrence, J. R., Gedzelman, S. D., Gamache, J. and Black, M.: Stable isotope ratios: Hurricane Olivia, J. Atmos. Chem., 41(1), 67–82, doi:10.1023/A:1013808530364, 2002.

Li, Z. H., Labbé, N., Driese, S. G. and Grissino-Mayer, H. D.: Micro-scale analysis of tree-ring $\delta 18O$ and $\delta 13C$ on α-cellulose spline reveals high-resolution intra-annual climate variability and tropical cyclone activity, Chem. Geol., 284(1–2), 138–147, doi:10.1016/j.chemgeo.2011.02.015, 2011.

Mei, W., Xie, S. P., Primeau, F., McWilliams, J. C. and Pasquero, C.: Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures, Sci. Adv., 1(4), 1–8, doi:10.1126/sciadv.1500014, 2015.

Miller, D. L., Mora, C. I., Grissino-Mayer, H. D., Mock, C. J., Uhle, M. E. and Sharp, Z.: Tree-ring isotope records of tropical cyclone activity., Proc. Natl. Acad. Sci. U. S. A., 103(39), 14294–14297, doi:10.1073/pnas.0606549103, 2006.

Munksgaard, N. C., Zwart, C., Kurita, N., Bass, A., Nott, J. and Bird, M. I.: Stable Isotope Anatomy of Tropical Cyclone Ita, North-Eastern Australia, April 2014, PLoS One, 10(3), 1–15, doi:10.1371/journal.pone.0119728, 2015.

NDRRMC: SitRep No. 38 re Effects of Typhoon "Pablo" (Bopha), [online] Available from: http://www.ndrrmc.gov.ph/attachments/article/2245/SitRep_No_38_Effects_of_Typhoon_PABLO_as_of_25DEC2012_0600H.pdf (Accessed 18 September 2019), 2012.

NDRRMC: Final Report re Effects of Typhoon "Glenda" (RAMMASUN), [online] Available from:

607   http://ndrrmc.gov.ph/attachments/article/1293/Effects_of_Typhoon_Glenda_(RAM

608   MASUN)_Final_Report_16SEP2014.pdf (Accessed 17 September 2019), 2014.

609 NDRRMC: Final Report re Preparedness Measures and Effects of Typhoon "Lando" (I.N.

610   Koppu), [online] Available from:

611   http://ndrrmc.gov.ph/attachments/article/2607/FINAL_REPORT_re_Preparedness_

612   Measures_and_Effects_of_Typhoon_LANDO_KOPPU_as_of_14_-_21OCT2015.pdf

613   (Accessed 17 September 2019), 2015.

614 Nott, J., Haig, J., Neil, H. and Gillieson, D.: Greater frequency variability of landfalling tropical

615   cyclones at centennial compared to seasonal and decadal scales, Earth Planet. Sci.

616   Lett., 255, 367–372, doi:10.1016/j.epsl.2006.12.023, 2007.

617 Oliva, F., Peros, M. and Viau, A.: A review of the spatial distribution of and analytical

618   techniques used in paleotempestological studies in the western North Atlantic Basin,

619   Prog. Phys. Geogr., 41(2), 171–190, doi:10.1177/0309133316683899, 2017.

620 Park, M. S., Lee, M. I., Kim, D., Bell, M. M., Cha, D. H. and Elsberry, R. L.: Land-based

621   convection effects on formation of tropical cyclone Mekkhala (2008), Mon. Weather

622   Rev., 145(4), 1315–1337, doi:10.1175/MWR-D-16-0167.1, 2017.

623 Philippine Statistics Authority: Philippine Population Surpassed the 100 Million Mark

624   (Results from the 2015 Census of Population), [online] Available from:

625   http://www.psa.gov.ph/population-and-housing/node/120080 (Accessed 15

626   September 2019), 2017.

627 Poméon, T., Jackisch, D. and Diekkrüger, B.: Evaluating the performance of remotely sensed

628   and reanalysed precipitation data over West Africa using HBV light, J. Hydrol., 547,

629   doi:10.1016/j.jhydrol.2017.01.055, 2017.

630 Rios Gaona, M. F., Villarini, G., Zhang, W. and Vecchi, G. A.: The added value of IMERG in

631   characterizing rainfall in tropical cyclones, Atmos. Res., 209, 95–102,

632   doi:10.1016/j.atmosres.2018.03.008, 2018.

633 Risi, C., Bony, S., Vimeux, F., Descroix, L., Ibrahim, B., Lebreton, E., Mamadou, I. and Sultan,

634   B.: What controls the isotopic composition of the African monsoon precipitation?

635   Insights from event-based precipitation collected during the 2006 AMMA field

636   campaign, Geophys. Res. Lett., 35(24), 1–6, doi:10.1029/2008GL035920, 2008.

637 Soria, J. L. A., Switzer, A. D., Villanoy, C. L., Fritz, H. M., Bilgera, P. H. T., Cabrera, O. C.,

638   Siringan, F. P., Maria, Y. Y. S., Ramos, R. D. and Fernandez, I. Q.: Repeat storm surge

639   disasters of typhoon haiyan and its 1897 predecessor in the Philippines, Bull. Am.

640   Meteorol. Soc., 97(1), 31–48, doi:10.1175/BAMS-D-14-00245.1, 2016.

641   Takagi, H. and Esteban, M.: Statistics of tropical cyclone landfalls in the Philippines: unusual

642   characteristics of 2013 Typhoon Haiyan, Nat. Hazards, 80(1), 211–222,

643   doi:10.1007/s11069-015-1965-6, 2016.

644   Tremoy, G., Vimeux, F., Soumana, S., Souley, I. and Risi, C.: Clustering mesoscale convective

645   systems with laser-based water vapor d18O monitoring in Niamey (Niger), J.

646   Geophys. Res. Atmos. Res., 5079–5103, doi:10.1002/2013JD020968.Received, 2014.

647   Villafuerte, M. Q., Matsumoto, J., Akasaka, I., Takahashi, H. G., Kubota, H. and Cinco, T. A.:

648   Long-term trends and variability of rainfall extremes in the Philippines, Atmos. Res.,

649   137, 1–13, doi:10.1016/j.atmosres.2013.09.021, 2014.

650   Villarini, G., Smith, J. A., Baeck, M. L., Marchok, T. and Vecchi, G. A.: Characterization of

651   rainfall distribution and flooding associated with U.S. landfalling tropical cyclones:

652   Analyses of Hurricanes Frances, Ivan, and Jeanne (2004), J. Geophys. Res. Atmos.,

653   116(23), 1–19, doi:10.1029/2011JD016175, 2011.

654   Weatherford, C. L. and Gray, W. M.: Typhoon Structure as Revealed by Aircraft

655   Reconnaissance. Part I: Data Analysis and Climatology, Mon. Weather Rev., 116(5),

656   1032–1043, doi:10.1175/1520-0493(1988)116<1032:TSARBA>2.0.CO;2, 1988.

657   Webster, P. J., Holland, G. J., Curry, J. A. and Chang, H.-R.: Changes in Tropical Cyclone

658   Number, Duration, and Intensity in a Warming Environment, Science (80-.)., 309(4),

659   1844–1846, doi:10.1126/science.1116448, 2005.

660   Woodruff, J. D., Irish, J. L. and Camargo, S. J.: Coastal flooding by tropical cyclones and sea-

661   level rise, Nature, 504(7478), 44–52, doi:10.1038/nature12855, 2013.

662   Xie, B. and Zhang, F.: Impacts of typhoon track and Island topography on the heavy rainfalls

663   in Taiwan associated with Morakot (2009), Mon. Weather Rev., 140(10), 3379–3394,

664   doi:10.1175/MWR-D-11-00240.1, 2012.

665   Xu, T., Sun, X., Hong, H., Wang, X., Cui, M., Lei, G., Gao, L., Liu, J., Lone, M. A. and Jiang, X.:

666   Stable isotope ratios of typhoon rains in Fuzhou , Southeast China , during 2013 –

667   2017, J. Hydrol., 570, 445–453, doi:10.1016/j.jhydrol.2019.01.017, 2019.

668

669

670

Figures and Captions

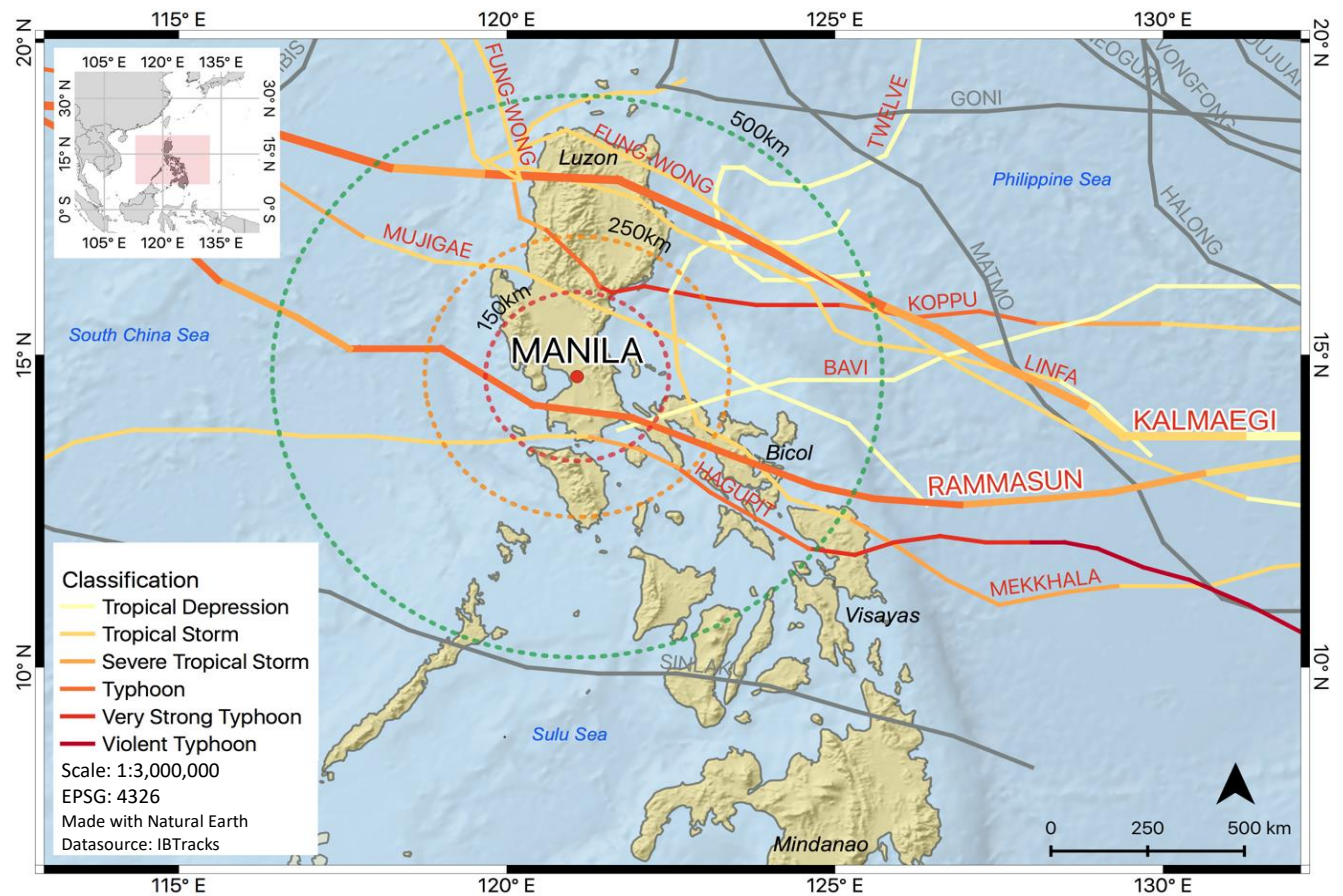



Figure 1 Metropolitan Manila sampling site and TC tracks of 2014 and 2015 seasons. Three different sized circles indicate the distance to the sampling site with the outermost one being 500 km in radius. Cyclone tracks are color coded according to the typhoon classification from Regional Specialized Meteorological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

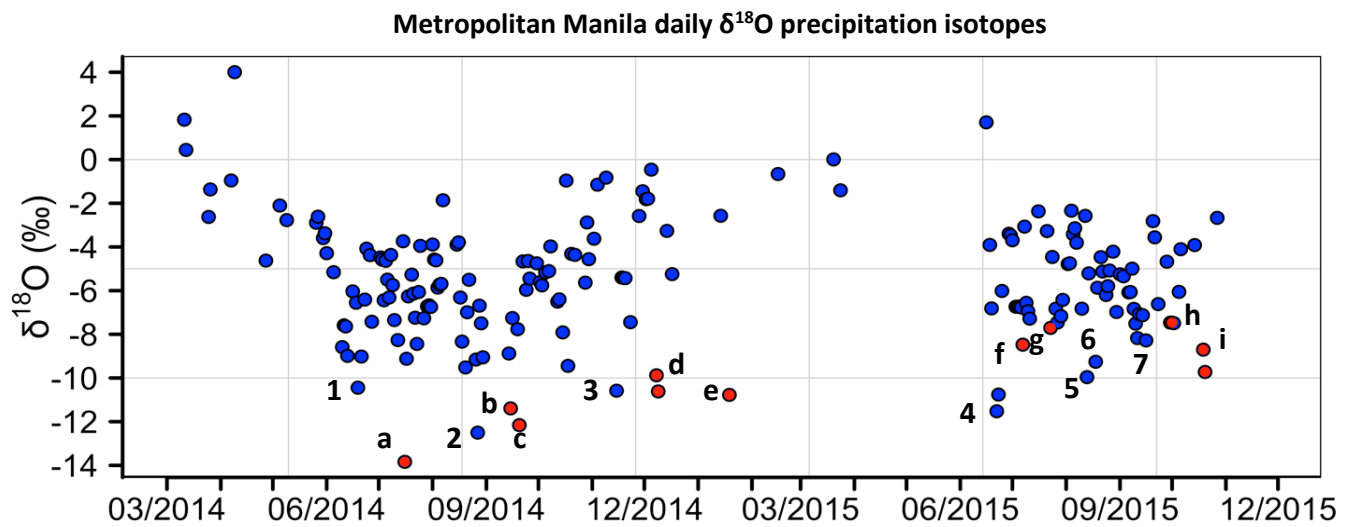



Figure 2 Complete time series of 186 precipitation samples taken between 10 March 2014 to 26 October 2015. δ ^{18}O data points associated with TC activity are colored in red. Other anomalously low δ^{18}O values were investigated using IMERG satellite precipitation data. a: Rammasun 16/07/14, -13.84 ‰, 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.

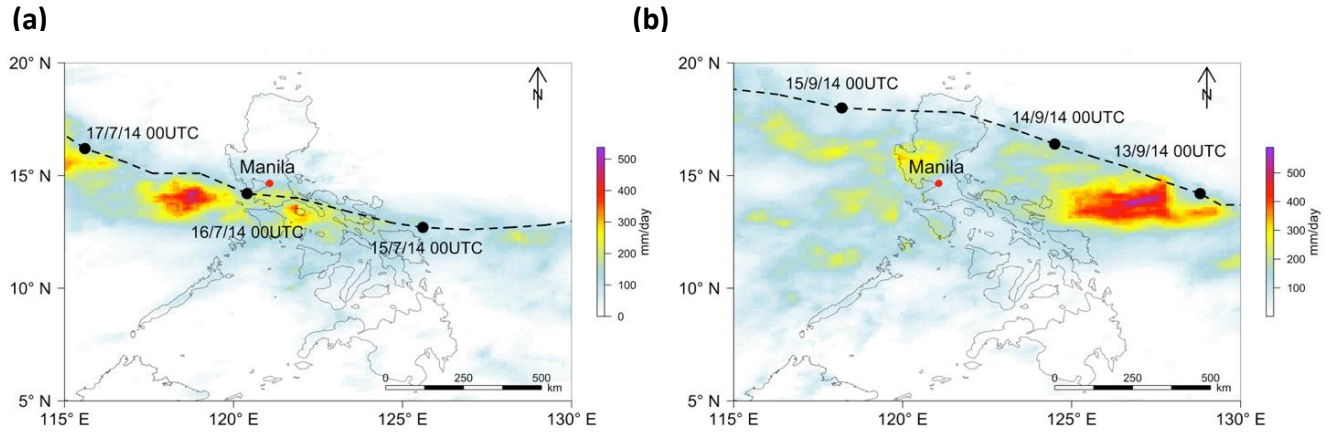



Figure 3 Accumulated precipitation from IMERG satellite data and TC tracks from IBTrACKS for a) Rammasun with precipitation accumulation for 14-17 July 2014, b) Kalmaegi with accumulated precipitation for 12-15 September 2014. Made with base layers from Natural Earth.

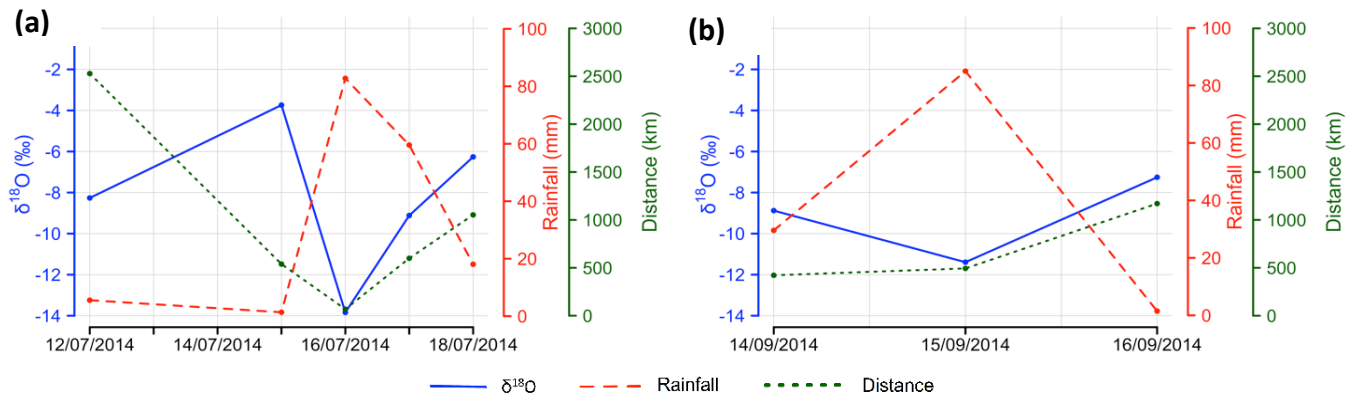



Figure 4 Isotopic signature from TCs during their passage to the Metropolitan Manila sampling site. $\delta^{18}O$ (blue color), distance from storm center to sampling location (green) and daily rainfall amount (red). a) Rammasun, b) Kalmaegi

767

768

769

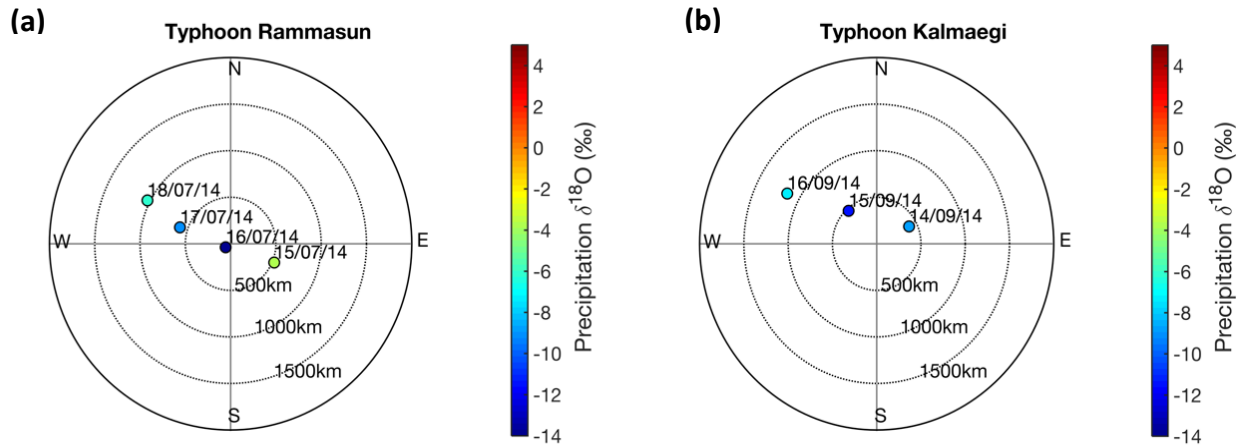
770

771

772

773

774

775

776 **Figure 5 Spatio-temporal evolution of δ¹⁸O isotopes**. Centered on Metropolitan Manila collection site, different radii provide information on distance between storm's center to Metropolitan Manila. δ¹⁸O values are color coded. a) Rammasun, b) Kalmaegi

777

778

779

780

781

782

783

784

785

786

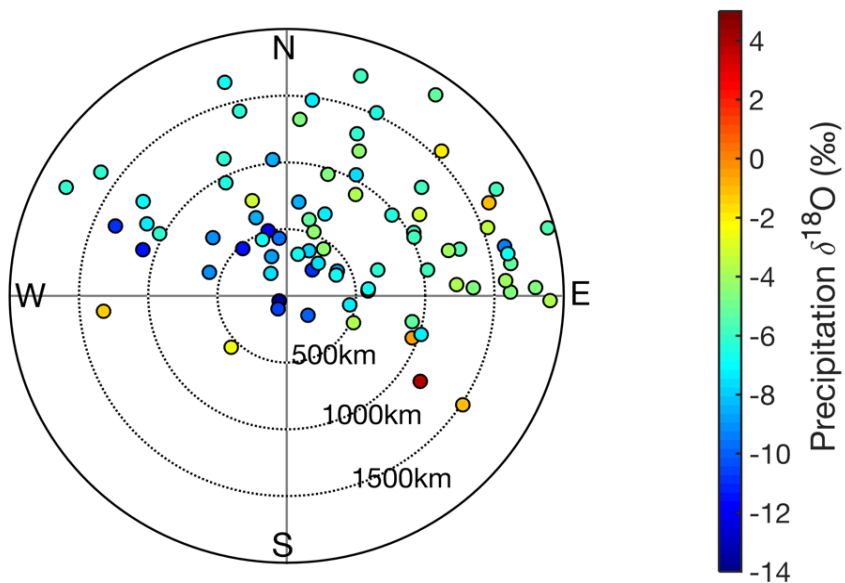
787

788

789

790

791

792

793 **Figure 6 Spatio-temporal variation of isotopes** related to TC activity within 2000 km, with different radii indicating the distance towards Metropolitan Manila. δ¹⁸O values are color coded.

794

795

796

797

798

799 **Tables**

800

801 **Table 1 Costliest typhoons in the Philippines.** Two devastating typhoons, Rammasun and Koppu (ranking 3 and 7),
802 occurred during our study period and made landfall. Damage in USD based on each time of TC occurrence (not adjusted to
803 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						

804