

Contribution of tropical cyclones to atmospheric moisture transport and rainfall over East Asia

Article

Accepted Version

Guo, L., Klingaman, N. P. ORCID: https://orcid.org/0000-0002-2927-9303, Vidale, P. L. ORCID: https://orcid.org/0000-0002-1800-8460, Turner, A. G. ORCID: https://orcid.org/0000-0002-0642-6876, Demory, M.-E. and Cobb, A. (2017) Contribution of tropical cyclones to atmospheric moisture transport and rainfall over East Asia. Journal of Climate, 30 (10). pp. 3853-3865. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-16-0308.1 Available at https://centaur.reading.ac.uk/68809/

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To link to this article DOI: http://dx.doi.org/10.1175/JCLI-D-16-0308.1

Publisher: American Meteorological Society

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1	Contribution of Tropical Cyclones to atmospheric moisture transport and
2	rainfall over East Asia
3	Liang Guo*
4	National Centre for Atmospheric Science, Department of Meteorology, University of Reading,
5	Reading, United Kingdom
6	Nicholas P. Klingaman
7	National Centre for Atmospheric Science, Department of Meteorology, University of Reading,
8	Reading, United Kingdom
9	Pier Luigi Vidale
10	National Centre for Atmospheric Science, Department of Meteorology, University of Reading,
11	Reading, United Kingdom
12	Andrew G. Turner
13	National Centre for Atmospheric Science and Department of Meteorology, University of Reading,
14	Reading, United Kingdom
15	Marie-Estelle Demory
16	National Centre for Atmospheric Science, Department of Meteorology, University of Reading,
17	Reading, United Kingdom

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Department of Physics, Imperial College, London, United Kingdom

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²⁰ **Corresponding author address:* Department of Meteorology, University of Reading, P.O. Box 243,

²¹ Earley Gate, Reading, UK.

²² E-mail: l.guo@reading.ac.uk

ABSTRACT

The coastal region of East Asia (EA) is one of the regions with the most fre-23 quent impacts from tropical cyclones (TCs). In this study, rainfall and moisture transports related to TCs are measured over the EA, and the contribution 25 of TCs to the regional water budget is compared with other contributors, es-26 pecially the mean circulation of the EA summer monsoon (EASM). Based on 27 ERA-Interim re-analysis (1979–2012), the trajectories of TCs are identified 28 using an objective feature tracking method. Over 60% of TCs occur from 29 July to October (JASO). During JASO, TC rainfall contributes 10-30% the 30 of monthly total rainfall over the coastal region of EA; this contribution is 31 highest over the south/southeast coast of China in September. TCs make a 32 larger contribution to daily extreme rainfall (above the 95th percentile): 50-33 60% over the EA coast and as high as 70% over Taiwan island. Compared with the mean EASM, TCs transport less moisture over the EA. However, as 35 the peak of the mean seasonal cycle of TCs lags two months behind that of the EASM, the moisture transported by TCs is an important source for the water 37 budget over the EA region when the EASM withdraws. This moisture trans-38 port is largely performed by westward-moving TCs. These results improve 39 our understanding of the water cycle of EA and provide a useful test bed for 40 evaluating and improving seasonal forecasts and coupled climate models. 41

42 **1. Introduction**

East Asia (EA) is affected by one of the most intense monsoon systems; its rainfall and water 43 budget are dominated by the East Asia summer monsoon (EASM). Meanwhile, the Western North 44 Pacific (WNP) basin and the coast of EA are regions that have the most frequent impacts from 45 tropical cyclones (TCs). Landfall of TCs is accompanied by destructive winds, storm surges and 46 heavy rainfall that threatens the lives and socioeconomic systems of hundreds of millions of people 47 living along the EA coast. Forming over the western Pacific warm pool, TCs that move across the 48 EA region bring warm and moist air into land. TCs, therefore, could be a key contributor to the 49 rainfall and water budget over the EA, especially over China. Quantifying these contributions of 50 TCs would improve understanding and prediction of water cycle variability over the EA, which is 51 essential to agriculture and the local economy. 52

TC variability has been extensively studied on a variety of temporal scales. Over the WNP 53 and EA regions, studies have covered scales from intra-seasonal to decadal. TC variability has 54 been linked with the Madden-Julian Oscillation (Feng et al. 2013; Kim et al. 2008; Camargo 55 et al. 2007b), the El Niño–Southern Oscillation (Chan 2000; Wang and Chan 2002; Chia and 56 Ropelewski 2002; Camargo et al. 2007a), the Quasi-Biennial Oscillation (Ho et al. 2009) and 57 the Pacific Decadal Oscillation (Lee et al. 2012). In general, there are several key aspects of the 58 background state and large-scale circulation over the EA that have been linked to TCs on different 59 temporal scales, e.g., sea surface temperature (SST), vertical wind shear, and the positions and 60 intensities of the monsoon trough/Intertropical Convergence Zone (ITCZ) and the Western North 61 Pacific Subtropical High (WNPSH). 62

⁶³ While the drivers of TC variations over EA have been widely studied, the contributions of TCs to ⁶⁴ the EA water cycle have received less attention, even in terms of their climatologies. Contributions

of TCs to total and extreme rainfall over the EA have been investigated using gauge data (Chen 65 et al. 2010, 2012; Ren Fumin 2002; Ren et al. 2006; Wu et al. 2007; Wang and Chen 2008). A 66 typical contribution of TCs to the total annual rainfall along the southeastern coastal region is 20– 67 40%, with the largest impact over Hainan Island off the south China coast (Ren et al. 2006; Wu 68 et al. 2007). During the second half of the 20th century, the number of TCs that affect China shows 69 a downward trend, which is accompanied by a decreasing trend in the contribution of TC rainfall 70 to the total rainfall (Ren et al. 2006). Over Taiwan Island, TC rainfall accounts for 40% of total 71 rainfall during late summer to early autumn (Wang and Chen 2008). Over other TC-active regions, 72 the contribution of TC rainfall to the total rainfall varies; however, along the coastal regions, the 73 TC rainfall contribution is 10–40% (Prat and Nelson 2013; Dare et al. 2012; Prat and Nelson 74 2016). The contribution of TCs to Australian extreme rainfall and to United States flooding has 75 been analysed by Villarini and Denniston (2015) and Villarini et al. (2014). Over Australia, more 76 than half of the highest annual rainfall events associated with TCs are over the coastal regions 77 and in particular in Western Australia (Villarini and Denniston 2015). TC rainfall accounts for 78 20–40% of total rainfall over northwest Australia during the Southern Hemisphere warm season 79 (Dare et al. 2012). TC rainfall is also a major cause of floods in the eastern United States (Villarini 80 et al. 2014). There are about 14% of total onshore flux over the coast of the North America is 81 attributed to the Atlantic TCs (Xu et al. 2016). 82

The aforementioned studies suggest that TCs have the potential to make a substantial contribution to the water cycle over EA. The fact that TC contributions to the atmospheric moisture budget have received little attention may be explained by the perceived dominance of the EASM, one of the most intense monsoon systems on the planet. The water budget is thus dominated by the EASM, which explains why most studies have been concentrating on this aspect, while the role played by TCs in the water cycle has been neglected. This study is therefore an attempt to the gap ⁸⁹⁹ between studies of the impact of TCs on rainfall and those of the role of the EASM in the moisture
⁹⁰⁰ budget. As our study will show, due to differences in the timing of the seasonal cycles of TCs
⁹¹ and the EASM, the contribution of TCs to the water cycle is non-negligible, even compared to
⁹² the substantial transport by the EASM, and is particularly important to the EA during the EASM
⁹³ withdrawal phase.

In this study, we decompose the total rainfall and moisture transport into contributions from TCs and from the mean flow. Then, we calculate the contributions of TCs to the rainfall and water budgets and compare these with the EASM in terms of climatology. Data and methods are introduced in Section 2; the statistics of TCs over the EA are shown in Section 3; TC contributions to both total and extreme rainfall are discussed in Section 4; the comparison of moisture transport from TCs with that from the EASM is shown in Section 5. Finally, the conclusion and discussion are given in Section 6.

101 2. Data and Methods

¹⁰² a. Observation and Re-analysis data

To evaluate the contribution of TCs to rainfall over the EA, we use the satellite-derived Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 (v7) rainfall analyses (Huffman and Bolvin 2012). It is a 3-hourly $0.25^{\circ} \times 0.25^{\circ}$ gridded rainfall dataset produced from 1998 onwards. The spatial coverage is 50° S – 50° N, 180° W – 180° E. Chen et al. (2013) showed that TRMM 3B42 v7 has improved skill at detecting intense TC rainfall, with good correlations and spatial patterns that agree with rain gauge observations. This skill is higher over ocean than land, and it is least skilful over land with high elevation. Therefore, we will interpret our results with caution.

The ERA-Interim re-analysis dataset (Berrisford et al. 2011; Dee et al. 2011) from the European 110 Centre for Medium-Range Weather Forecasts (ECMWF) is used in this study for TC trajectory 111 identification and moisture transport calculations. It produces 6-hourly analyses at 00, 06, 12, 18 112 UTC. Variables used in this study include temperature, winds, vorticity and specific humidity on 113 pressure levels and vertically integrated moisture fluxes and their divergence. Variables provided in 114 the original truncation (truncation at wavenumber 255; T255) are used to identify TC trajectories; 115 variables for the moisture transport calculations are gridded onto a 512 longitude \times 256 latitude 116 regular grid with a resolution of $0.7^{\circ} \times 0.7^{\circ}$. 117

118 b. TC feature tracking methodology

TC trajectories used in this study are obtained from an objective feature tracking method. This 119 method has been developed and described fully in Hodges (1994, 1995, 1999) and Bengtsson 120 et al. (2007). The method is applied to 6-hourly ERA-Interim re-analysis data. It uses the vertically 121 averaged vorticity at the levels 850, 700 and 600 hPa and truncated to T63 with the planetary scales 122 removed (total wave-number $n \leq 5$). This was found to provide more coherent tracks including 123 the pre-TC stages (e.g., Easterly Waves) and post-TC stages following extra-tropical transition 124 (Serra et al. 2010; Hodges and Emerton 2015). At this stage all tropical disturbances are tracked. 125 To identify TCs, additional information is added to the tracks in the form of vorticity at T63 126 resolution at multiple levels across 850–250 hPa. This allows for checking for the presence of a 127 warm core and a coherent vertical structure. The criteria used for checking are the same as used 128 in Bengtsson et al. (2007) and other studies (Strachan et al. 2013; Bell et al. 2013; Roberts et al. 129 2015). 130

¹³¹ TC tracks identified from the ERA-Interim reanalysis have been compared with observations ¹³² in previous studies. The average annual TC numbers identified from the ERA-Interim reanalysis

agree well with the International Best Track Archive for Climate Stewardship (IBTrACS) over the 133 period of 1979-2002 (Strachan et al. 2013). A recent study by Hodges and Vidale (personal com-134 munication) matches TC tracks identified from the ERA-Interim reanalysis to the IBTrACS data 135 in 1979-2012. 95% of the TCs in the IBTrACS data are identified in the ERA-Interim reanalysis 136 in the Northern Hemisphere and 93% in the Southern Hemisphere. The interannual variability of 137 TC numbers is also well correlated between the ERA-Interim reanalysis and the IBTrACS data. 138 Over the Western Pacific region, the correlation coefficient is 0.57, which is significant at the 95%139 confidence level; the correlation coefficients are similar or higher over other TC basins, e.g., the 140 North Atlantic and the South Indian Ocean (Strachan et al. 2013). The lower correlation coeffi-141 cient over the Western Pacific region compared to other regions is largely due to uncertainties of 142 identifying the weaker storms. This is partly due to the tracking method and the uncertainties in 143 the ERA-Interim reanalysis, but there may also be contributions from uncertainties in the obser-144 vations for weak storms and whether reporting agencies are consistent in the types of storms they 145 include in the TC datasets used for IBTrACS (Hodges and Vidale 2017). The spatial distribution 146 of TC tracks identified from the ERA-Interim reanalysis also agrees well with the IBTrACS. Stra-147 chan et al. (2013) shows strong agreement between the ERA-Interim reanalysis and the IBTrACS 148 in terms of TC track density, as well as TC genesis and lysis density. 149

c. Decomposition of mean-flow and eddy moisture fluxes related to TCs

To investigate the contribution of TCs to moisture transport over the EA, first the moisture flux is decomposed into time-mean and eddy (deviation from the mean) terms, using the 6-hourly ERA-Interim re-analysis during 1979–2012 (Eq. 1). In Eq. 1, **v** is horizontal wind, q is the specific humidity, both are available on the 6-hourly time interval during 1979–2012; $\bar{\mathbf{v}}$ and $\bar{\mathbf{q}}$ are monthly climatologies over 1979–2012, **v**' and **q**' are eddies (or deviations from the time-mean values)

calculated as $\mathbf{v}' = \mathbf{v} - \bar{\mathbf{v}}$ and $q' = q - \bar{q}$ using 6-hourly ERA-Interim re-analysis. The first term on 156 the righthand side of Eq. 1, $\mathbf{\bar{v}} \cdot \mathbf{\bar{q}}$, is the transport of mean moisture by the mean horizontal wind. 157 We call this term the mean moisture transport or the mean-flow moisture flux afterwards. The 158 second to the fourth terms, $\bar{\mathbf{v}} \cdot q'$, $\mathbf{v}' \cdot \bar{q}$ and $\mathbf{v}' \cdot q'$, are the transport of eddy moisture by the mean 159 horizontal wind, the transport of mean moisture by the eddy horizontal wind and the transport of 160 eddy moisture by the eddy horizontal wind, respectvely. Altogether, we call these terms the eddy 161 moisture transport or eddy moisture flux. Then, by using the TC location information obtained 162 from the feature tracking method, a mask with a 5° geodesic radius around each TC eye at each 163 6-hr time step is applied to the eddy terms to identify eddies that are related to the TC and mask 164 out those that are not related (Eq. 2). Therefore, the eddy terms in Eq. 1 are further decomposed 165 into TC-related terms and non-TC related terms in Eq. 2. In the following analysis, we focus on 166 the mean-flow moisture flux and the eddy moisture fluxes that are related to TCs. Although the 167 size of a TC varies from storm to another, the choice of a 5° radius is an established method of 168 differentiating TC-related features from their surroundings that has been discussed and applied by 169 previous studies (Englehart and Douglas 2001; Larson et al. 2005; Jiang and Zipser 2010; Prat and 170 Nelson 2013). 17

$$\mathbf{v} \cdot \mathbf{q} = (\bar{\mathbf{v}} + \mathbf{v}') \cdot (\bar{\mathbf{q}} + \mathbf{q}')$$
$$= \bar{\mathbf{v}} \cdot \bar{\mathbf{q}} + \bar{\mathbf{v}} \cdot \mathbf{q}' + \mathbf{v}' \cdot \bar{\mathbf{q}} + \mathbf{v}' \cdot \mathbf{q}'$$
(1)

$$\mathbf{v} \cdot \mathbf{q} = (\bar{\mathbf{v}} + \mathbf{v}_{TC}' + \mathbf{v}_{non-TC}') \cdot (\bar{\mathbf{q}} + \mathbf{q}_{TC}' + \mathbf{q}_{non-TC}')$$

$$= \bar{\mathbf{v}} \cdot \bar{\mathbf{q}} + \underbrace{\bar{\mathbf{v}} \cdot \mathbf{q}_{TC}' + \mathbf{v}_{TC}' \cdot \bar{\mathbf{q}} + \mathbf{v}_{TC}' \cdot \mathbf{q}_{TC}'}_{\text{TC related}}$$

$$+ \underbrace{\bar{\mathbf{v}} \cdot \mathbf{q}_{non-TC}' + \mathbf{v}_{non-TC}' \cdot \bar{\mathbf{q}} + \mathbf{v}_{non-TC}' \cdot \mathbf{q}_{non-TC}'}_{\text{non TC related}}$$
(2)

Similar to the method for decomposing the moisture flux, the mask with 5° geodesic radius around each TC eye at each time step is also applied to 3-hourly TRMM 3B42 rainfall to separate TC-related rainfall from non-TC-related rainfall. Note that the temporal interval of the tracked TC position is 6 hours; therefore when filtering 3-hourly TRMM 3B42 rainfall, the same mask is applied to two consecutive time steps of TRMM rainfall. We assume that the movement of a TC is small within 6 hours, relative to the diameter of the masking circle.

The extreme daily rainfall on each grid is defined as the daily rainfall above the 95th percentile of rainfall in each month during 1998–2012.

180 3. Statistics of TCs over East Asia

There are 851 TCs tracked over the WNP and EA during 1979–2012. These TCs are divided into 181 two groups according to their propagation directions: westward and northward. The westward-182 moving TCs are generated over the Pacific warm pool east of the Philippines, then move west-183 ward/northwestward in a straight line and make landfall along the coasts of south China or the 184 Indochina peninsula. The northward-moving TCs are also generated over the Pacific warm pool, 185 but instead of hitting the coast and moving further west, these TCs curve toward the north and 186 make landfall over the eastern China, the Korean peninsula or Japan. This division is similar to 187 that in Camargo et al. (2007a), who used cluster analysis to divide TC trajectories over the WNP 188 and EA into seven clusters which can be further grouped as straight-movers and recurvers. In 189 general, westward-moving TCs are similar to the straight-movers in Camargo et al. (2007a), and 190 northward-moving TCs are similar to the recurvers. Camargo et al. (2007a) found that the seven 191 clusters in their analysis show different characteristics in terms of genesis position and lifetime. 192 However, when comparing the difference in landfall locations, the seven clusters merged into two 193 groups according to their trajectories (straight-mover or recurver). As we focus on the contribu-194

tion of TCs to precipitation and moisture fluxes over the EA landmass, this remerging of the seven
 clusters into two groups based on landfall location, gives us confidence to use the much simpler
 straight-mover/recurver (westward/northward) classification to carry out our study.

The number of TCs in each month and in each group over the period of 1979-2012 is shown 198 in Figure 1. There are more northward-moving TCs than westward-moving TCs in each month, 199 which is consistent with results shown in other datasets e.g., IBTrACS (Camargo et al. 2007a). TC 200 activity over the WNP and EA shows a single peak in the mean seasonal cycle. More in detail, 20 westward-moving TCs are rare from January to May, then increase from July to October (JASO) 202 with the highest number in October; northward-moving TCs show a similar seasonal cycle, being 203 inactive from December to April and active during JASO, with the highest number occurring in 204 September. 58% of all TCs over the WNP and EA occur during JASO. After peaking, TC activity 205 over the WNP and EA decreases rapidly. 206

These seasonal features over the WNP and EA are similar to those for global TCs, which are due to a number of factors, e.g., the mean seasonal cycle SST, which is positively correlated with mean seasonal cycle of TC frequency; a low vertical wind shear in the atmosphere and the existence of a monsoon trough or easterly waves. However, other features, such as the division of westward and northward trajectories, are unique and relate to the positions of the EA summer monsoon trough and the WNPSH. We find similar statistics to 1979–2012 for the 1998–2012 period of the TRMM rainfall record (not shown). During season JASO, there are 14.6 TCs/season over the period 1979–2012 and 14.0 TCs/season over the period 1998–2012.

4. Fractional contribution to rainfall

The monthly mean fractional contribution of TC rainfall to total rainfall during 1998–2012 is shown in Figure 2. TC rainfall makes larger fractional contributions during JASO over both the WNP and the coast of the EA. In other months, the TC contribution is small and confined to the WNP warm pool. Only the Indochina peninsula is affected by TCs in November–January. Note that there are some spotted contributions over the mid-latitudes in December–February. This is caused by mid-latitude disturbances that have been identified as TCs and thus been included in the analysis here. However, the contributions from these mid-latitude disturbances are negligible.

During JASO, the average contribution of TC rainfall over the southeastern coast of China is 10– 223 30%. The contribution is larger at lower latitudes, especially over islands, e.g., Taiwan, Hainan 224 island and the Philippines, where the contribution is as high as 40-50%. At higher latitudes, e.g., 225 the Bohai Bay, the Korean Peninsula and the southern Japan, TCs make a substantial contribution 226 to total rainfall only in August and September. The spatial pattern of the contribution of TC 227 rainfall matches closely with the TC number shown in Figure 1. With most northward-moving TCs 228 occurring in September, the impact of TCs reaches as far north as 45°N in that month; since most 229 westward-moving TCs occur in October, the TC rainfall contribution also reaches its maximum 230 over the Indochina peninsula in October. 23

Heavy rainfall caused by TCs after landfall can cause flooding and other losses. Therefore, 232 it is necessary to quantify the TC contribution to extreme rainfall over the EA. We define an 233 extreme rainfall day as the occurrence of daily rainfall above a threshold of the 95th percentile; 234 the threshold is computed for each month and gridpoint using data for 1998–2012. We compute 235 the contribution of TCs to both the occurrence and amount of extreme rainfall during JASO. (In 236 other months, these contributions are negligible over the EA.) For occurrence, at each gridpoint 237 we compute the percentage of extreme rainfall days on which a TC is within the area defined by a 238 circle with a 5° geodesic radius around that gridpoint. If there were no relationship between TCs 239 and extreme rainfall occurrence, this percentage would be 5%. For amount, at each gridpoint we 240 compute the percentage of the total amount of extreme rainfall (summed over all extreme days) that 241

occurs on TC days. The contribution of TCs to extreme rainfall occurrence is shown in the upper 242 panels of Figure 3. In general, the contribution of TCs to extreme rainfall occurrence is higher 243 than to total rainfall, which indicates that rainfall intensity during TCs is above average. Over 244 the ocean, the contribution to occurrence is over 70%, which means that on over 70% of days on 245 which daily rainfall exceeds the 95th percentile there is a TC within a 5°-radius of the grid-point; 246 this contribution is over 90% in September and October, especially to the east of Taiwan and the 247 Philippines. Over Taiwan, TCs appear on more than 70% of extreme rainfall days; this contribution 248 can also reach 60% over Hainan island and the northern Philippines. Along the southern China 249 coast and the Indochina peninsula, this contribution is also over 50%, which is higher than the TCs 250 contribution to total rainfall. 251

The contribution of TCs to extreme rainfall amount is shown in the lower panel of Figure 3. 252 Comparing the TC contributions to occurrence and amount allows us to measure whether extreme 253 rainfall related to TCs is heavier than extreme rainfall that is unrelated to TCs. If this were the 254 case, then the TC contribution to extreme rainfall amount would be higher than the contribution 255 to extreme rainfall occurrence. As shown in Figure 3, the spatial distribution of contributions 256 to extreme rainfall amount is similar to the contributions to extreme rainfall occurrence (the pat-257 tern correlation between maps of these diagnostics for each month varies between 0.8 and 0.99). 258 However, there are regions where the contributions to extreme rainfall amount are higher than 259 the contributions to extreme rainfall occurrence. For example, over the Anhui Province of China 260 $(30^{\circ}N, 117^{\circ}E)$ in September, the contributions to extreme rainfall occurrence are about 30–40%, 261 while the contributions to extreme rainfall amount are about 50%. This difference indicates that 262 TC-related extreme rainfall over these regions is heavier than extreme rainfall that is unrelated to 263 TCs. 264

5. Moisture flux: relative contributions of eddy (TC) transport and mean flow

As EA is affected by one of the most prominent monsoon systems, the warm and moist monsoonal flow brings a large amount of moisture over land. Generated over the warm and moist ocean, TCs also gather and transport moisture along their paths. With TC landfalls, moisture convergence associated with TCs is therefore a contributor to the water budget over the EA.

To compare the roles of TCs and the EASM in the process of moisture transport, Figure 4 shows 270 monthly accumulated moisture flux divergence due to both the mean, $\nabla \cdot (\bar{\mathbf{v}} \cdot \bar{\mathbf{q}})$, and the TC eddy 27 moisture transport, $\nabla \cdot (\bar{\mathbf{v}} \cdot q'_{TC} + \mathbf{v}'_{TC} \cdot \bar{q} + \mathbf{v}'_{TC} \cdot q'_{TC})$. The mean-flow moisture flux divergence 272 shows features arising from the EASM (the upper panel of Figure 4), i.e., a moisture convergence 273 band which represents the Mei-Yu front (shown in Figure 4 by the ridge of the WNPSH at 500 hPa) 274 stretches from central China to Japan in July and August, then shifts southward to the southern 275 China in September; the band then withdraws further south to the Indochina Peninsula in October 276 and eventually fades away from the most of the EA landmass. 277

The TC eddy moisture flux divergence is smaller in amplitude and also in spatial extent com-278 pared to the mean-flow moisture flux divergence (the lower panel of Figure 4). However, TC 279 moisture flux divergence shows a different seasonal cycle from the mean EASM moisture flux 280 divergence, i.e., the mean-flow moisture flux convergence prevails over the EA during JJA, while 28 the TC moisture flux convergence affects the EA during JASO. The spatial patterns of moisture 282 flux convergence are also different between the EASM and TCs. The position of the Mei-Yu 283 front, where the mean-flow moisture flux convergence dominates, depends on the positions of the 284 monsoon trough and the ridge of the WNPSH, while the pattern of TC moisture flux convergence 285 depends on the number and trajectories of TCs. 286

Therefore, the TC moisture flux convergence is not negligible with respect to the mean-flow 287 moisture flux convergence; their contributions to the water cycle come in different regions and at 288 different times. In July, when the Mei-Yu front is located at around 30°N, the mean-flow moisture 289 flux comes from the south and converges along the Mei-Yu front. Meanwhile, southern China 290 loses moisture due to mean-flow moisture flux divergence. However, for TCs, there are more 291 westward-moving TCs moving into southern China in July, which import moisture that is required 292 to maintain rainfall over this region. In August, when the the inensity of the NWPSH weakens 293 and the Mei-Yu front deflects to the south, the mean-flow moisture flux convergence becomes the 294 main moisture supplier over southern China again. For TCs, there are more northward-moving 295 TCs in August, which bring moisture to higher latitudes including the Baohai Bay, Korean Penin-296 sula and Japan; the TC moisture flux replaces the mean-flow moisture flux as the main supplier 297 of moisture over the northern China. TCs reach their peak in September, when the mean-flow 298 moisture flux weakens and the Mei-Yu front withdraws further south to the south coast of China 299 and the Indochina Peninsula, and play a more important role in transporting moisture to the north. 300 In October, when the EASM has completely faded away from the EA, TCs remain as the main 301 moisture supplier to the EA, especially along the coast. TCs are able to transport moisture beyond 302 the coastal regions to further inland, but their reach does not extend as far inland as that of the 303 mean flow. 304

The seasonal cycle of monthly mean vertically integrated moisture flux passing through the coastal boundaries of the EA is shown in Figure 5. Two boundaries are defined, shown in the inner panel of Figure 5: an eastern (meridional) boundary at 121°E between 21°-43°N, and a southern (zonal) boundary at 21°N between 100°-121°E. Because there is little moisture transported from the north, we do not use a northern boundary. Although there is significant mean moisture transported from the west during the Indian monsoon season, the TC moisture transported from the west remains small as most TCs move westward or northward over the EA. Therefore, moisture transported into the EA region from the west is not included in this comparison of the mean flow and TCs.

The seasonal cycles of the mean-flow moisture fluxes on both boundaries show a clear EASM 314 cycle. At the southern boundary, moisture is transported into the EA between February and Au-315 gust. This period can be further divided into two sub-phases. From late February to early May, 316 the mean-flow moisture influx is small and supplies moisture for the Spring Rainfall (Tian and 317 Yasunari 1998) over southeastern China; from late May to August, the mean-flow moisture influx 318 increases and supplies moisture for the EASM. This moisture is brought in by both the westerly 319 flow from the Indian Ocean, extending from the Indian monsoon circulation, and the western flank 320 of the WNPSH, which are the dominant features defining the EASM. From September to Decem-321 ber, the winter monsoon brings dry and cold air from the north, and the mean-flow moisture flux at 322 the southern boundary is negative. At the eastern boundary, the mean-flow moisture flux is almost 323 opposite to that at the southern boundary. Moisture imported to the EA via the southern boundary 324 is exported from the eastern boundary. This outflow is particularly important to several East Asian 325 regions, i.e. the Korean Peninsula and Japan, as it is the main moisture supply during JJA. 326

The TC moisture fluxes on both boundaries are an order of magnitude smaller than the mean 327 fluxes. However, the seasonal cycles of TC moisture fluxes on both boundaries are different 328 from the mean-flow fluxes. In general, instead of showing a maximum moisture flux during JJA, 329 TC moisture fluxes peak during JASO, consistent with the seasonal distribution of TC frequency 330 shown in Fig 1. Instead of gaining moisture from the southern boundary and losing moisture from 33 the eastern boundary like the mean-flow moisture fluxes, the direction of TC moisture fluxes is 332 opposite. That is, TC moisture flux causes a net import at the eastern boundary and a net export at 333 the southern boundary. 334

To understand this difference in moisture transport between the mean flow and TCs, case studies 335 for different types of TCs are carried out. Figure 6 shows the total TC moisture fluxes and their 336 divergence for two different TCs: a westward-moving TC (Tai-Kat) and a northward-moving TC 337 (Masta). In a single time step, the TC moisture flux shows a cyclonic circulation with predominant 338 convergence (not shown). As the TC moisture flux is summed along its trajectory (multiple time 339 steps) for either a westward-moving or a northward-moving TC, the cumulative TC moisture flux 340 is modified due to the partial overlap of the 5° circles around the TC on consecutive timesteps, i.e., 341 the front of a TC in its direction of travel at the *n*th time step is overlapped by the rear part of a TC at 342 the n + 1th time step. Due to the cyclonic flow around the TC, the direction of the wind (and hence 343 the moisture transport) reverses, such that the cumulative TC moisture flux is weakened in the TC 344 area along the trajectory. Meanwhile, TC moisture fluxes at the edges of the TC area orthogonal 345 to the direction of propagation remain strong or even are strengthened, because the moisture flux 346 retains its sign as the TC propagates. As shown in Figure 6, there are strong forward fluxes (same 347 direction as the TC propagation direction) to the right of a TC, and strong rearward flux (opposite 348 direction to the TC propagation direction) to the left of a TC. This is the case for either westward-349 moving TCs or northward-moving TCs. As most westward-moving TCs appear to the south of 350 the EA landmass (between 15°-25°N, as shown in Figure 8), the south/southeast coast of China is 351 exposed to the easterly moisture flux prevailing to the right of these TCs. Therefore, TC moisture 352 fluxes enter the EA region from the eastern boundary during the active period (JASO). 353

A similar argument applies to the northward-moving TCs and moisture export from the southern boundary. With northward-moving TCs approaching the coast of EA, the northerly moisture flux to the left of the direction of propagation of these TCs has a large impact. Therefore, there is an export of moisture at the southern boundary during the TC active period. Note that the moisture export at the southern boundary is smaller than the moisture import at the eastern boundary. This

could be because the propagation direction of TCs and the direction of moisture flux are opposite 359 to each other at the southern boundary, which reduces the intensity of moisture flux. This could 360 also be because the moisture flux at the southern boundary is weaker than the moisture flux at the 361 eastern boundary due to drier air. The easterly moisture flux at the eastern boundary is imported 362 directly from the warm and humid ocean, but the northerly moisture flux at the southern boundary 363 is exported from the EA landmass. After weakening and drying as a result of the rough land 364 surface and the lack of moisture supply from the ocean, the TC intensity is reduced. For all these 365 reasons, only a fraction of moisture is exported at the southern boundary compared to the moisture 366 imported at the eastern boundary. 367

We also note that the export of moisture at the southern boundary disappears after August and 368 changes sign in September. This is due to changes in the background meridional specific humidity 369 gradient (Figure 7). The mean specific humidity field shows a reversed meridional gradient during 370 JJA (i.e., higher humidities in the subtropics than at the equator), and a normal meridional gradient 371 before and after JJA. The reversed specific humidity gradient is due to the strong mean moisture 372 flux convergence and high land surface temperature over the EA during the EASM. As shown in 373 Equation 2, the TC eddy moisture flux is composed of three terms $(\bar{\mathbf{v}} \cdot \mathbf{q}' + \mathbf{v}' \cdot \bar{\mathbf{q}} + \mathbf{v}' \cdot \mathbf{q}')$. Among 374 them, the second term (i.e., the mean specific humidity transported by TC eddies) dominates (not 375 shown). Therefore, when comparing the TC moisture flux in August and September, though the 376 TC eddies themselves are similar in structure, the TC moisture flux changes its sign due to the 377 reversed moisture meridional gradient. 378

Another interesting point is that, as shown in Figure 8, although September and October feature more westward-moving TCs (57 and 62 TCs, respectively), the TC moisture flux transport through the eastern boundary is smaller compared to that of August or July, which have 40 or 52 westwardmoving TCs, respectively. This is due to the seasonal shift of TC locations: any TC that contributes

to moisture flux on the eastern boundary needs to be located north of $16^{\circ}N$ between $100^{\circ}-121^{\circ}E$ 383 (the dotted line in Figure 8). In September, 54% of the westward-moving TCs appear to the north 38 of this line, and this proportion decreases to 24% in October. Although there are fewer total 385 westward-moving TCs in July and August, there are more westward-moving TCs north of 16°N (90% in July and 73% in August). The range and position of WNPSH shown in Figure 4 also 387 indicate changes in background circulation that contribute to this shift. In October, the WNPSH 388 locates at lower latitude and is elongated from the east of Philippine westward to reach the Indo-389 China Peninsula. The easterlies along the southern flank of the WNPSH favour more westward-390 moving TCs, and because of its low latitude, more TCs are located to the south of 16°N. 39

392 6. Conclusion and Discussion

This study was motivated by the need to quantify the contributions of TCs to the water budget 393 over the EA, especially over China. Previous studies in this field focus either on the drivers of 394 TC variability on temporal scales from intra-seasonal to decadal, or on the contribution of TCs to 395 rainfall. This study is therefore an attempt to bridge the gap between studies that investigate TC 396 variations and studies that focus only on the TC contribution to rainfall over the EA. This study 397 retains its focus on the climatological contributions of TCs atmospheric moisture transport, as well 398 as extreme and total rainfall. We found a distinct seasonal cycle and direction of moisture transport 399 by TCs when compared to the mean moisture transport associated with the EASM. 400

In this study, TC tracks over the WNP and EA were first identified by applying an objective feature tracking method to the ERA-Interim 6-hourly re-analysis (1979–2012). Compared with the observation dataset IBTrACS, the correspondence between these two data is 95-98% over the Western North Pacific and East Asia (Strachan et al. 2013; Roberts et al. 2015). According to TC tracks, TCs over the WNP and EA are separated into two groups according to propagation direction: the westward and northward-moving TCs. The TC seasonal frequency histograms from 1979–2012 show that JASO is the active season for both groups of TCs, accounting for 58% of the overall number over the WNP and EA.

Consistent with the seasonal cycle in TC numbers, during JASO, TC rainfall has the largest contribution over the EA coast, with an averaged contribution between 10–30% of the total rainfall. TC rainfall reaches as far north as 45°N in September for the northward-moving TCs and has its maximum impact over the Indochina peninsula for the westward-moving TCs in October. TC rainfall contribution is largest over the tropical islands, i.e., Taiwan, the Philippines and Hainan island, with contributions as high as 50% of the total rainfall.

TC rainfall contributions to the extreme daily rainfall (above the 95th percentile) are investigated in terms of occurrence and amount. The contribution of TCs to the occurrence of extreme daily rainfall is around 50% over the EA coast. This contribution is higher (60–70%) over tropical islands. The TC contribution to the extreme rainfall amount is higher in percentage than the contribution to the extreme rainfall occurrence over some regions, e.g., the Anhui Province of China along the Yangtze River Valley. This indicates that TC-related extreme rainfall over these regions is heavier than extreme rainfall unrelated to TCs.

⁴²² Due to different seasonal cycles, moisture transport associated with TCs is another important ⁴²³ source for the water budget of the EA, although its magnitude is smaller than the mean-flow ⁴²⁴ moisture transport associated with the climatological EASM. The mean-flow moisture transport ⁴²⁵ reaches a maximum during JJA and features a moisture convergence band (the Mei-Yu front) ⁴²⁶ marching north in July and gradually withdrawing to the south in the following months. The ⁴²⁷ TC moisture transport reaches a maximum during JASO; it is an important moisture supplier ⁴²⁸ especially after the EASM withdraws. The pathways of moisture flux transported by the mean flow and TCs also show different patterns. For the mean flow, moisture is imported from the south and exported to the east with its maximum during the EASM season (JJA). For TCs, moisture is imported from the east and exported to the south during the TC active season (JASO). This different pattern of TC moisture transport is closely related to TC propagation directions, changes in the mean meridional humidity gradient and the shift of TC positions with large-scale background flow during the season.

The diagnostics conducted in the study have been repeated with the IBTrACS data and show 435 similar results. Quantitative differences, however, are found. The TC moisture fluxes via both 436 boundaries (as defined in Figure 5) are larger by using the IBTrACS data. It is about 20% larger 437 for the TC moisture influx via the eastern boundary during the TC peak season. The difference 438 in the net TC moisture flux is less than 10% due to the larger TC moisture efflux via the southern 439 boundary during the TC peak season. And, the sign change of TC moisture flux in September 440 on the southern boundary is delayed to October while using the IBTrACS tracks. Nevertheless, 441 results from both TC tracks support the same conclusions. 442

A major aim of this study was to identify and quantify the contribution of TCs to rainfall and 443 the water budget over the EA, especially China. However, simulating rainfall over the EA remains 444 a challenge for state-of-the-art general circulation models (GCMs) (Sperber et al. 2013; Song and 445 Zhuo 2014). As TCs make an important contribution to the rainfall and water budget over the EA, 446 it is essential that models represent accurately not only the characteristics of TCs themselves, but 447 also their impacts on the large-scale atmospheric environment. The TC feature tracking method 448 used in this study offers an opportunity to compare TC activity in model simulations to reanalysis 449 data using an identical method. It will be valuable to assess model simulations using the analysis 450 techniques developed this study, especially for sensitivity tests with a single model (e.g., tests of 451 horizontal resolution or of atmosphere-ocean feedbacks). Roberts et al. (2015) (and references 452

therein) showed that model resolution is crucial for a realistic simulation of TC behaviour and variability, and higher resolution GCMs are increasingly able to capture TC intensity and the largescale environmental conditions that contribute to tropical cyclogenesis. To further understand the water budget over this region, contributions from other components need to be quantified. This will also help to identify deficits in model simulations and improve the skill of climate prediction and weather forecasting over this region.

Acknowledgments. The authors thank Kevin Hodges for discussions and comments, especially
on the feature checking methodology; the authors appreciate discussions with Malcolm Roberts.
This work and its contributors were supported by the UK-China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part
of the Newton Fund. NPK was also funded by a UK Natural Environment Research Council
Independent Research Fellowship (NE/L010976/1).

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