improve upon previous estimates by accounting for feedback between the land, ocean, and atmosphere, and highlight the importance of the land-hydrological cycle and its interactions with climate when assigning contributions to changes in sea level.

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Recent increases in extreme rainfall during typhoons in Taiwan

Role of global warming questionable

Taiwan, which is situated in one of the main paths of western North Pacific tropical cyclones (TCs), has experienced a series of TCs with an extraordinary amount of rainfall since the late 1990s. As of 2015, 11 of the top 15 typhoons based on total rainfall since hourly rainfall observations began in 1960 have occurred in the 21st century. The most extreme case was the record-breaking Typhoon Morakot in 2009. This eventcaused considerable economic losses and casualties and became the first natural disaster in Taiwan to trigger the resignation of the Premier. Some scientists have warned that because of anthropogenic global warming, this large increasing trend in extreme rainfall will continue into the future with dire consequences,as has been widely reported in the media.

The assertion that global warming will cause a dramatic increase in rainfall in Taiwan is based on the fact that as the temperature rises, the capacity of water vapor in the air expands. The thermodynamic law governing this relationship predicts that for every 1 °C of warming, the water vapor capacity increases by 7%. Therefore, the probability and amount of extreme rainfall will increase, and dynamic storm processes can further increase these effects through feedback mechanisms.

A team of researchers from the National Taiwan University (NTU) Department of Atmospheric Sciences led by Professor Hung-Chi Kuo and including doctoral students Yi-Ting Yang (now a postdoctoral researcher) and Li-Huang Hsu collaborated with Distinguished Professor Chih-Pei Chang (visiting from the U.S. Naval Postgraduate School) to tackle this problem. They found that while the increase in rainfall in recent decades is a manifestation of climate change, it would be a mistake to attribute the apparently large increasing trend of typhoon rainfall to anthropogenic global warming[1,2].

The research team usedhourly rainfall data averaged over 21 stations in Taiwan (Fig. 1a) and collected during the 91 typhoons that made landfall from 1960-2015. When all typhoons are considered together, the rainfall intensity exhibitsa large increasing trend over the period. To look for the possible cause of this trend, they separated the typhoons according to the track type of each storm, as defined by the Central Weather Bureau, and focused on the three leading track types that directly cross Taiwan:the Northern type (N, Fig. 1b), Central type (C, Fig. 1c), and Southern type (S, Fig. 1d). The average separation between adjacent track types is approximately 110 km, which is about half of the length of the Central Mountain Range (CMR) shown in Fig. 1a.

An important factor that affects the amount of typhoon rainfall is the terrain effect of the

CMR, which occurs when the southwesterly flow of the typhoon circulation encounters the western slope of high mountains. This wind-terrain interaction is a major reason why Taiwan typhoons often produce heavy rainfall that causes more damage than that caused by strong winds. Figure 1e shows three examples of low-level typhoon circulation, one for each track type. Here,it is clear that the three track types give rise to different degrees of wind-terrain interactions on the western slope of the CMR. The terrain effect is strongest for the N type and weakest for the S type; hence, the northern track storms should produce more rainfall than the central track storms, which produce more rainfall than the southern track storms. When the research team analyzed the rainfall intensity, they found that this indeed was the case when the typhoon center approaches Taiwan from the east before landing and after the typhoon makes landfall when its center is over land.

However, after the typhoon center exits Taiwan and moves into the Taiwan Strait, the C type storms have approximately the same rainfall intensity as N type storms, both of which are significantly larger than S type storms. This can be explained by another major factor associated with heavy typhoon rainfall. The typhoon season in Taiwan overlaps significantly with the Southwest monsoon season (June – September), during which strong monsoon wind surges often compound the wind-terrain interactions to the southwest of Taiwan and produce enhanced moisture convergence and heavy rainfall, especially after a typhoon exits Taiwan.In this final phase of the life history of a Taiwan typhoon, the wind-monsoon interaction is largest for C type storms (shown in Fig. 1e, where the red arrow indicates the monsoon flow). Notably, this interaction is larger than that associated with N type storms because N type storms are further to the north and away from the South China Sea. Thus, the C type rainfall intensity is more enhanced, resulting in the two types of storms having similar high rainfall intensities. However, although S type centers interact strongly with the Southwest monsoon after exiting land, they have diminished terrain interaction with the CMR; thus, their rainfall intensity over Taiwan is the lowest.

When the three track types are examined separately, the large increasing trend in rainfall intensity in past decades is much less clear. Taiwan has experienced a large increasing trend in typhoon rainfall fortwo reasons. First, N type storms have moved more slowly across Taiwan and therefore produced more rainfall because they remained over land longer on average. Second, more typhoons made landfall in Taiwan during in the 21st century than before, and the bulk of the increased frequency involved C type storms, which, along with the N type storms, produced higher amounts of rainfall than did S type storms. Therefore, the long duration of N type storms and the increased frequency of C type storms have caused the apparent increase in rainfall over Taiwan, In fact, the increasing trend in typhoon intensity is much smaller than that in total typhoon rainfall. This trend was most discernible during the final phase after a typhoon center exited Taiwan.

The next question involves determining why these changes in track type behavior have occurred. Here, it is useful to note that the distance between the different track types is on the order of 110 km, a mesoscale distance, and the largest increase in frequency occurs in C type events, with no bias toward the northern or southern tracks. Therefore, these changes cannot be attributed to the typhoon track changes proposed in some global warming studies, which occur on the order of 1000 km or larger. Moreover, the increase in typhoon frequency is clearly a local phenomenon because over the large western North Pacific basin, the frequency of TCs decreased over the study period. Additionally, the increase in the rainfall intensity during the over-land and exit phases of C type storms and the increase in the duration of N type storms appear both related to the strengthening of the Southwest monsoon in the early 21st century. This strengthening has increased wind-monsoon interactions and therefore rainfall when a storm exits Taiwan. In addition, these changes have slowed the westward movement of typhoons slightly because they oppose the easterly steering flow. The reduction in the steering flow is very small, but the effect becomes significant for N type storms due to the large wind-terrain interaction. This interaction produces large latent heating that is anchored to the terrain, which provides an important stationary forcing mechanism of N type storms and their movements[3].

The final question involves determining whether the strengthening of the southwest monsoon is a result of global warming. The answer is unlikely

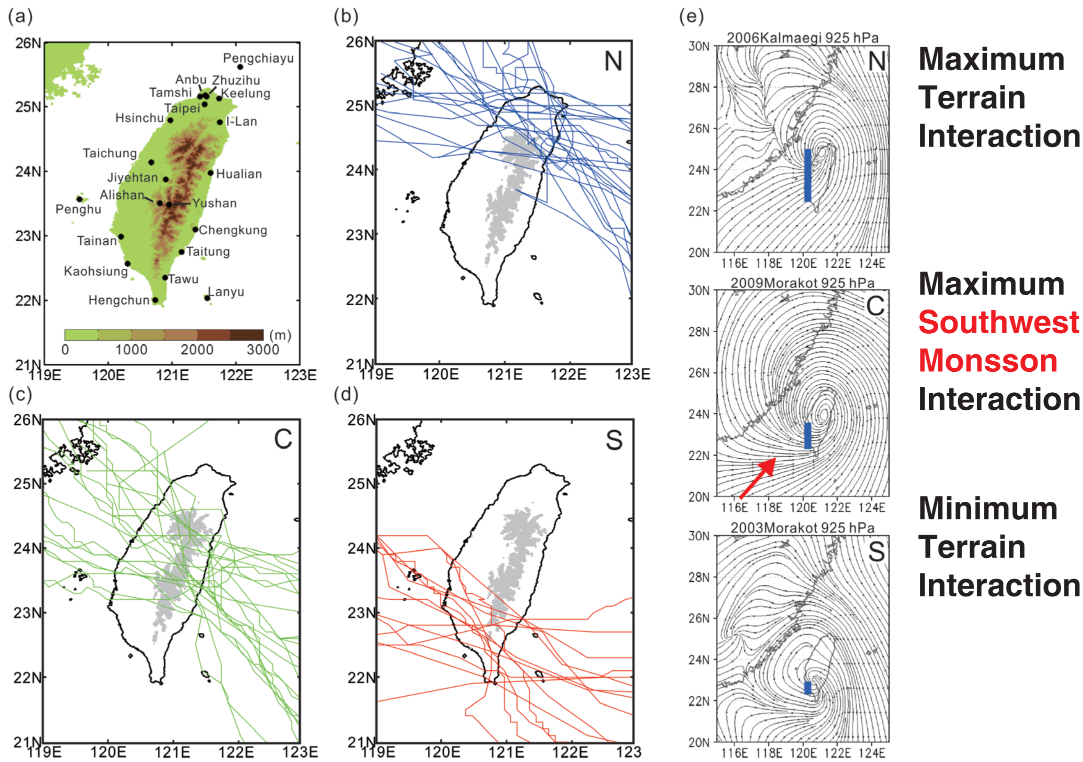

Figure 1. a) Taiwan topography and rainfall stations. b)-d) The northern (N), central (C) and southern type (S) tracks. e) Examples of 925 hPa streamlinesbased on the European Centre for Medium-Range Weather Forecasts - TOGA Global Advanced Analysisof the three track types.

for two important reasons. First, the increasing water vapor capacity with increasing temperature tends to reduce tropical circulation in global warming models, so the Southwest monsoon should be weaker, not stronger. Second, recent analyses[4] comparing the strengthening of the tropical monsoon to decadal-scale oscillations have indicated that the strengthening is better correlated with natural variability, such as Mega ENSO and the Atlantic Multidecadal Oscillation, and is poorly correlated with the north-south hemispheric differences that can serve as an anthropogenic global warming index. The NTU research team concludes that the apparent increasing trend in extreme rainfall in Taiwan caused by typhoon activity is likely the result of natural climate variability and anthropogenic global warming does not appear to play an important role.

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