Responses to the comments from Anonymous Referee #2

We are very grateful to the reviewer for the positive and careful review. The thoughtful comments have helped improve the manuscript. The reviewer's comments are italicized and marked in blue, and our responses immediately follow.

In this manuscript, the authors analyze the impact of global warming of 1.5 and 2 degCon hydrological drought in the Wudinghe watershed. This catchment is a semi-arid region in Central China. The authors show that precipitation is slightly increasing in the future leading to a decrease in drought frequency. However, the authors argue that increased variability is leading to more extreme droughts. The manuscript is overall well written and organized, but lacks some important details (for example, validation of the hydrologic model, downscaling of meteorological forcing from monthly to 6-hourly values). The authors use temperature increases based on local temperature instead of global ones, which is a mistake. They should substitute it by global temperature (see further arguments below). The calculation of the employed streamflow index leads to the fact that this one is very dry during the baseline period. This seems odd because the baseline should be neither dry nor wet. The authors need to double check these. Given this assessment, this paper is a welcome contribution to HESS that enriches ourknowledge about the consequences of global warming. However, the paper requires substantial improvements. During the preparation of their revised manuscript, I recommend the authors to also include a 3 degC global warming threshold. After all, it will be a miracle if mankind will manage to limit global warming to 2 degC. It is much morelikely that we will reach 3 degC within the 21st century. Including this threshold would improve the appeal of the paper.

Response: Thanks for your careful review and detailed advices. We have now clarified the details on validation and downscaling method, revised the results by using global temperature as warming threshold, re-calculated streamflow index with a consistent baseline period, and added results for the 3 degC global warming threshold. Please see our responses below for details.

Please find my further comments below:

Major Comments

Section 2: Why are their two correction methods for past and future periods? The authors should mention the differences between those. Which downscaling method is used to obtain 6-hourly forcings. Is CLM-GBHM really only driven by precipitation and temperature? I would have expected that radiation, pressure an humidity are also required. The temporal downscaling might be crucial because future projections often include more heavy precipitation events. Is this preserved by the 6-hourly downscaling procedure?

Response to R2C1: Thanks for the comments. There was actually only one correction method (Li et al., 2010) used in this study. However, this method treated the historical and future series differently. The method assumed the same cumulative density functions for both simulated and observed data during historical period, while this was not the case for future period, for which the equidistant quantile matching adjustment was applied to the final results. After bias correction at monthly scale, new daily precipitation series were generated based on the ratio of new and old monthly mean results, and daily temperature data were based on the difference between new and old monthly means. The same method was applied to generate 6-hourly data from daily time series based on CRUNCEP 6-hourly climate dataset (https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/atm/datm7/) during 1959-2005. Other input climate forcing variables used by CLM-GBHM (i.e., incident solar radiation, air pressure, specific humidity and wind speed) were taken from CRUNCEP data. Historical (1961-2005, 45 years) variables were directly taken from corresponding years, and future (2006-2099, 94 years) variables were generated by looping the CRUNCEP data twice. Except for the correction at monthly time scale, other characteristics (e.g., heavy precipitation) were preserved the same as the GCMs', no matter for historical simulation or future projection. We have revised this part as follows:

"All CMIP5 simulations were bias corrected before being used as land surface model input. After interpolating CMIP5 simulations and China Meteorological Administration (CMA) station observations to the same resolution (0.05 degree in this study), a modified correction method (Li et al., 2010) based on widely-used quantile mapping (Wood et al., 2002; Yuan et al., 2015) was applied to CMIP5/ALL historical and CMIP5/RCPs future simulations to fit their cumulative density functions to observed ones based on monthly mean values. Bias-corrected daily precipitation and temperature were then further temporally downscaled to a 6-hours interval based on their intraday distribution from CRUNCEP (https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/atm/datm7/) 6-hourly dataset for driving land surface hydrological model. Other 6-hourly climate forcings, i.e. incident solar radiation, air pressure, specific humidity and wind speed, were directly taken from CRUNCEP data."

Section 3.1: Sheng et al. 2017 only presented an evaluation of CLM-GBHM for a historical period with observation based forcing. It is unclear if CLM-GBHM will also give a reasonable behavior if forced with GCM output. The authors should present a validation following the strategy of Samaniego et al. 2018 (Figure S5).

Response to R2C2: Thanks for the advice. We have now validated the GCM driven model performance during historical period by comparing simulated monthly standardized streamflow index (SSI) with offline simulations, as follows:

"These historical changes could be captured by hydro-climate model simulations to some extent, although both the warming and drying trends were underestimated (Table 2). Ensemble monthly SSI series from GCM driven model simulations were also compared to offline results (CRUNCEP driven) during historical period, resulting in a correlative coefficient of 0.47 (p<0.01)."

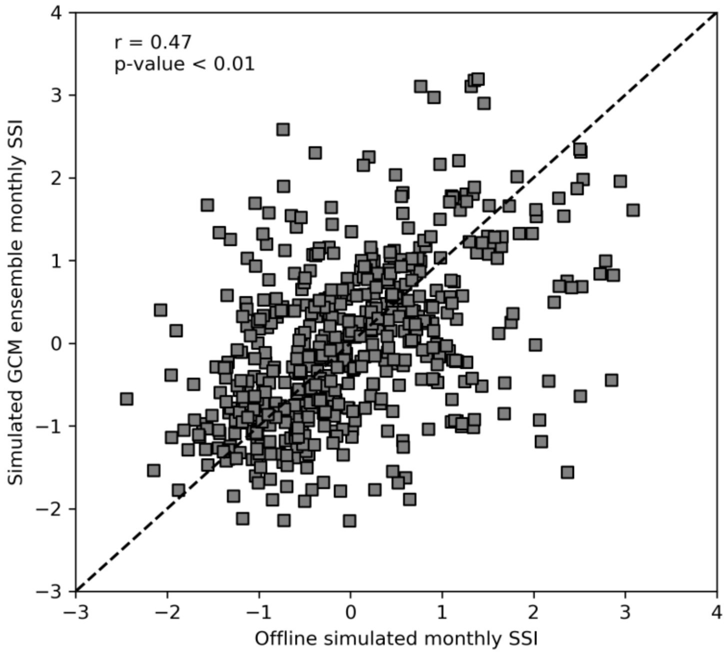

Figure R1: Comparison of historical monthly SSI between GCM driven simulations and offline simulations.

Section 3.2: It is not clear which temperature dataset is used for the calculation. According to the abstract starting at l. 22ff an results at l. 225ff, the temperature is referring only to that of the Wudinghe catchment, but this is not valid. Temperature increases are always referring to those periods when global temperature is reaching a threshold. Climate change is a global phenomena. We are interested on the effects in the Wudinghe catchment when global temperature increase reaches 1.5 or 2 degC. This also allows to compare the results of this study to that of others.

Response to R2C3: Thanks for your kind advice. We have now revised the manuscript followed your advice by using global warming thresholds of 1.5, 2 and 3 degC as follows:

"Here, "1.5 ℃ warming level" referred to a global temperature increase of 0.89 (=1.5-0.61) ℃ compared to the baseline. Similarly, "2 ℃ warming level" referred to an increase of 1.39 (=2-0.61) ℃, and "3 ℃ warming level" referred to an increase of 2.39 (=3-0.61) ℃ compared to the baseline, respectively."

"As listed in Table 3, crossing years for most GCM/RCP combinations reaching 1.5 ℃ warming level are before 2032 except for GFDL-ESM2M and MRI-CGCM3. Model ensemble years for different RCP scenarios have small differences, and total ensemble year for all GCMs and RCPs is 2025, indicating that 1.5 ℃ warming level would be reached within 2015-2034. As for the 2 and 3 ℃ warming level, the total ensemble year is 2042 and 2070, respectively. There are large differences in crossing year between different GCMs, ranging between 2016 to 2075 for 1.5 °C, 2030 to 2076 for 2 °C, and 2051-2086 for 3 °C. Generally, three global warming thresholds would be reached first under RCP8.5 and last under RCP6.0 scenario. All GCMs will not reach 3 °C warming level under RCP2.6, while under other RCP scenarios this temperature increase would probably be reached around 2073 or even as early as 2050s."

Section 3.3: As the probability distribution are fitted for the historical values, it is important to mention that this resembles an approach of no adaptation. Using adaptation and no adaptation can have a large impact on estimated drought characteristics (Samaniego et al. 2018).

Response to R2C4: Thanks for your advice. It is true that big differences exist with/without climate adaptation strategies. We have specified at the end of Section 3.3 as follows:

"As future SSI values were all calculated based on historical values, it is important to mention that drought analysis here represented those without adaptation (Samaniego et al., 2018)."

Section 3.4: It is not clear to me which time series are analysed for the uncertainty contribution. The authors should expand their explanation.

Response to R2C5: Thanks for the advices. Our objective is to separate future projections ($X_{m,s,t}$) into three parts: reference value (i_m), smooth fit ($x_{m,s,t}$) and residual ($e_{m,s,t}$) during future period (2006-2099). However, the reference value i_m is unknown and extra work is needed to calculate it. So, we fit the baseline period (1986-2005) to remove residual in history and get the reference value i_m. We have revised the corresponding parts as follows to make it clear:

"In order to separate internal variability from other two factors with long-term trends, a 4th order polynomial was selected to fit specific time series: the fitting was first carried out during baseline period (1986-2005) to obtain an average i_m as a reference value, and then during future period (2006-2099) to obtain a smooth fit $x_{m,s,t}$. Future projections ($X_{m,s,t}$) were then separated into three parts: reference value (i_m), smooth fit ($x_{m,s,t}$) and residual ($e_{m,s,t}$), …"

Section 4.2: I do not know why the authors calculate the median year among all models when a threshold is calculated, especcially since this value is depending to a large extent on the RCP considered. It would be more informing to report the range of earliest and latest period when a threshold is crossed. It will happen somewhere around this period.

Response to R2C6: Thanks for the comments. Here we use the median year to represent the ensemble mean status reaching the specific thresholds, and also for separating uncertainties in the Discussion Section. We have now added the ranges of the earliest and latest crossing years reaching each threshold in Table 3, which are 2025 (2016~2075) for 1.5 degC, 2042 (2030~2076) for 2 degC, and 2070 (2051~2086) for 3 degC.

Section 4.3: L. 259ff. It would be interesting to include drought area. It is very interesting that the drought frequency is 10.2 events per 20 years and the duration is 6.4months. This implies that there is drought 27that there should be a drought according to the definition. This is also in line with Figure 7, which shows that SSI during the baseline period is less then -0.2, although it should be zero. Taking the values from Figure 6a, the values for 1.5 and 2 degC warming result in droughts that occur 20authors need to double check why the values are so unrealistic for the baseline. This is crucial because the main conclusions are based on these numbers. It seems like the baseline period has been significantly dry within the historical record. The authors should include the standard deviations for the individual characteristics in Figure 6 and show the results for individual GCMs instead of RCPs because the uncertainty is larger for the former.

Response to R2C7: Thanks for the comments and advices. In this paper, we focus on hydrological drought events and streamflow extremes which are only meaningful near river channels, no spatial pattern as well as drought area could be extracted. We would like to consider drought area when studying on other drought events in future works, e.g. meteorological drought or agricultural drought.

For the second comment, we used the historical period (1961-2005) instead of baseline period (1986-2005) to get the historical SSI distribution, which leads to the phenomenon that "the baseline period has been significantly dry within the historical record". We have now followed the reviewer's suggestion, and revised it to get the correct results based on the baseline SSI distribution as follows:

"Figure 6 shows the characteristics of hydrological droughts during baseline period and the periods reaching all warming levels. The number of hydrological drought events averaged among all RCP scenarios and climate models is 7.0 in the baseline period, and it drops to 6.2 (-11% relative to baseline, the same below) at 1.5 ℃ warming level, 5.2 (-26%) at 2 ℃ warming level and 5.4 (-23%) at 3 ℃ warming level (Figure 6a). However, hydrological drought duration increases from 5.0 months at baseline to 6.5 (+30%), 5.9 (+18%) and 6.0 months (+20%) at 1.5, 2 and 3 ℃ warming levels, respectively. Drought severity increases dramatically from 1.9 at baseline to 5.4 (+184%) at 1.5 ℃ warming level, and then drops to 4.1 (+116%) at 2 ℃ warming level and rebounds to 5.4 (+184%) at 3 ℃ warming level (Figure 6a). These results indicate that although precipitation and runoff increase, the Wudinghe watershed would suffer from more severe hydrological events in the near future at 1.5 ℃ warming level. The severity could be alleviated in time periods reaching 2 ℃ warming level, with more precipitation occurring over the watershed.

The analysis on individual scenarios suggests a similar conclusion (Figures 6b-6e).

Drought amount and severity increase generally when radiative forcing increases. The least changes in drought severity are found under RCP4.5 scenario while the most changes are under RCP6.0 scenario. Higher thresholds could lead to more moderate drought events under low emission scenarios (RCP2.6/4.5) because of more precipitation in near and middle future, while high emissions (RCP6.0/8.5) would increase the risk of hydrological drought over the Wudinghe watershed significantly."

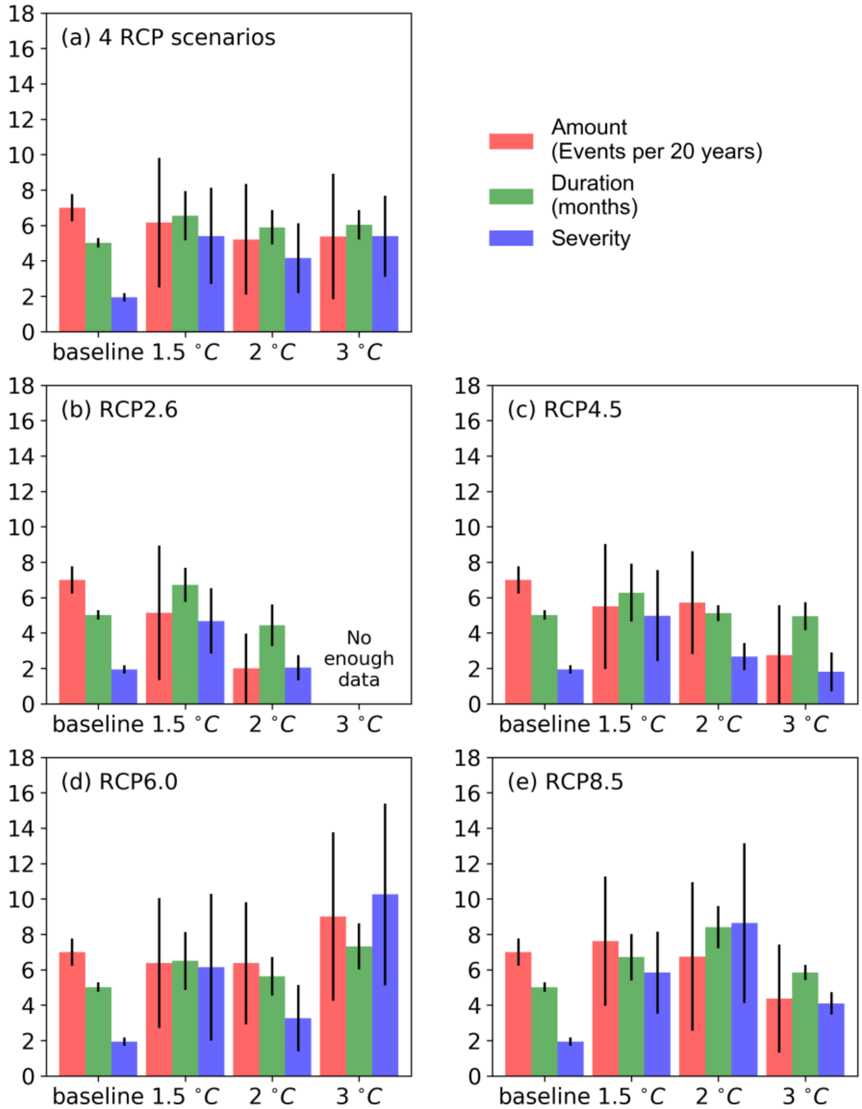

Figure 6: Comparison of the characteristics (amount (number of drought events per 20 years), duration (months) and severity) averaged among climate models and RCP scenarios for hydrological drought events during the baseline period (1986-2005) and the periods reaching 1.5, 2 and 3 ℃ warming levels. Black lines indicate 5%-95% confidence intervals.

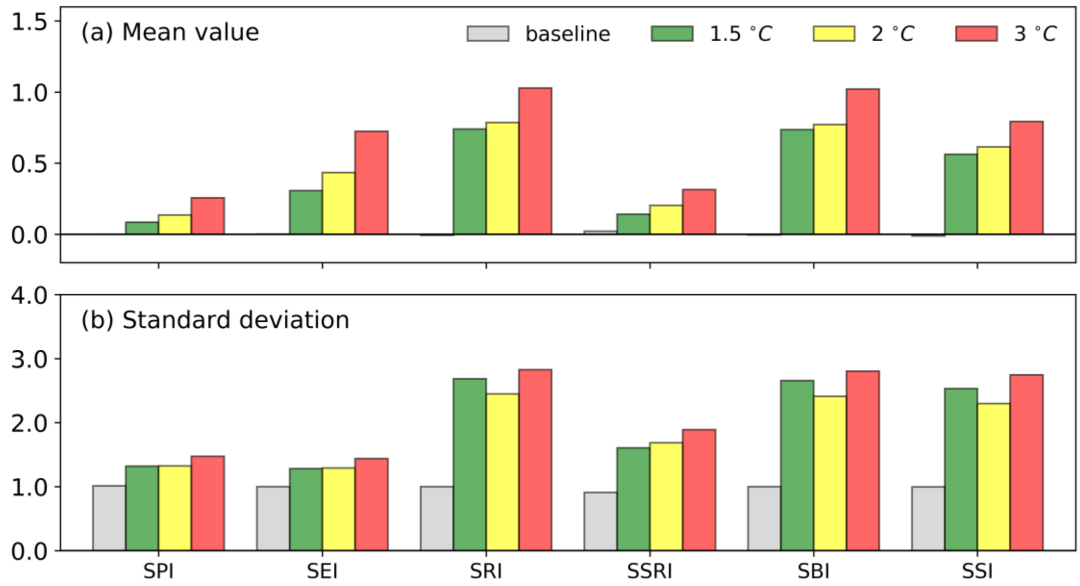

Figure 7. Comparison of (a) mean values and (b) standard deviations for hydrological indices averaged among climate models and RCP scenarios during the baseline period (1986-2005) and the periods reaching 1.5, 2 and 3 ℃ warming levels. SPI, SEI, SRI, SSRI, SBI, SSI represent standardized indices of precipitation, evapotranspiration, runoff, surface runoff, baseflow (subsurface runoff) and streamflow, respectively.

Section 5: The authors argue that high mean values and higher variability lead to more extreme droughts (l. 296ff). I am wondering whether this actually is the case. As the number of events is decreasing from the baseline to the future periods, it could simply be that the modest drought events are not occurring anymore during future periods and only the extreme ones still occur. The authors should check whether the most extreme events during the baseline and future periods show the same characteristics as all events.

Response to R2C8: Thanks for your advices. We have compared the 10% driest drought events, as showed in Figure R2. Compared to Figure 6 (representing 20% driest events), it’s true that the most extreme events during the baseline and future periods are not the same, with more frequent and severe extreme events occur in the future.

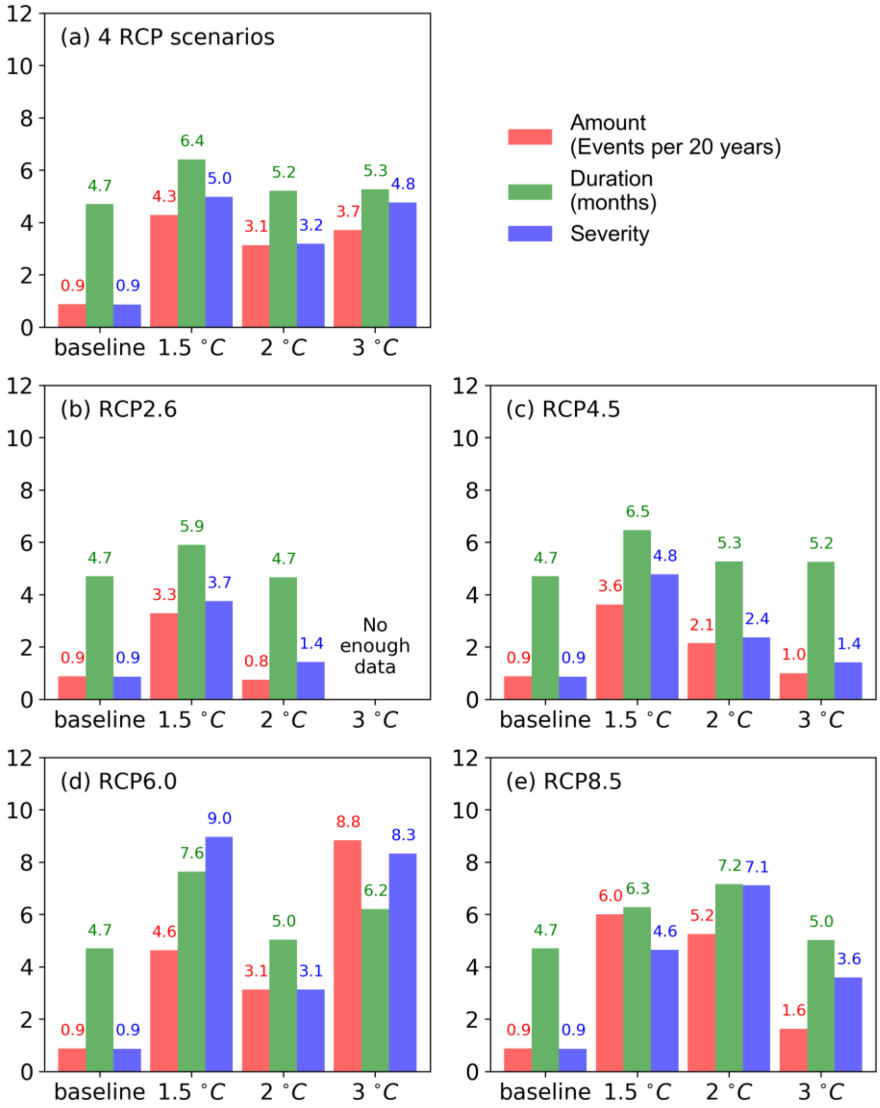

Figure R2: Same as Figure 6, but for SSI<-1.3 representing a dry condition with a probability of 10%.

We have modified the corresponding part as follows:

"Figure 7 shows that mean values increase as temperature increases for all standardized hydrological indices, showing a wetter hydroclimate in the near future with more precipitation, evapotranspiration, runoff and streamflow (Figure 7a). However, variabilities for the standardized indices in the future are higher than those during baseline period, indicating larger fluctuations and higher chance for extreme droughts/floods at both warming levels (Figure 7b). Actually for extreme drought events (with a SSI < -1.3, representing a dry condition with a probability of 10%), the ensemble mean amount of drought events are 4.3, 3.1 and 3.7 at 1.5, 2 and 3 ℃ warming levels, which are much more than the baseline period with 0.9 (not shown)."

L. 300ff.: The uncertainty contribution is not fitting to the analysis because it is based on a continuous time axis. It should be stratified for those periods identified by the *time-sampling approach for each GCM/RCP combination. The authors should mention the recent work by Marx et al. (2018) that showed that uncertainty contribution by hydrologic model can be as high as that of the GCM. The former is not included here.*

Response to R2C9: Thanks for the comments and advices. It's true that this method is based on a continuous time series, and here we simply used it on drought frequency analysis. For future studies, uncertainty in hydrological model should also be considered. We have revised the discussion as follows:

"Besides, previous studies (Marx et al., 2018; Samaniego et al., 2018) have showed that uncertainties contributed from hydrological and land surface models can be comparable to that from GCMs, indicating the importance of introducing multiple land surface models into the analyzing frame of uncertainty separation, and the significance of exploring more suitable methods in further studies."

L. 330ff.: I do not think that the different warming rates are an issue because the are effectively removed by the time-sampling approach. Regarding the regions, naturally warming rates are varying in space, but only one region is considered here. Again, local temperature increase have to replaced by global ones.

Response to R2C10: Thanks for the advices. We have revised the manuscript to analyze drought events based on global warming thresholds. For this part, what we would like to mention is that temperature increases vary a lot for different regions. For a typical period when global warming reaches 1.5 degC, the local warming would be over 2 degC, which increase the local drought crisis and suggest that more climate adaptation strategies should be taken.

Figures 3 and 6: There is a contradiction in the use of drought frequency in these two figures. The magnitude of values does not match.

Response to R2C11: Thanks for your advice. We have changed the legend in Figure 6 by replacing "frequency" with "amount".

References

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