<Author's response>

Journal: HESS

Title: Evaluation of impact of climate change and anthropogenic change on regional hydrology.

Author(s): S. Chang et al.

MS No.: hess-2018-91

MS Type: Research article

Referee #3

We appreciate the thoughtful comments from the reviewers, which have helped us to improve the original manuscript. We explain in detail how we responded to the reviewer's comments, with line numbers referring to the revised manuscript unless otherwise noted.

General comments:

The authors have presented an evaluation of the relative sensitivity of a water system in western Florida to a variety of forcings: precip/temp (via GCMs), evapotranspiration calculation method, and human water use scenario. They find that the system is relatively insensitive to ET calculation method, as well as to water use scenario. The authors conclude that the system is most sensitive to GCM projection. The quality of writing is good, and the results figures are professional. However, I have methodological concerns with the work, as well as concerns with the presentation of results. I am not sure that the concerns can be addressed in a straightforward re-write, but maybe they can. Most importantly, I think that the authors need to: 1) better justify the claim that RCP doesn't particularly matter; 2) use a physically-based ET calculation method (and not a temperature based method like Hargreaves); 3) present model calibration/validation for the hydrologic model and the groundwater model, as well as the human water system model; 4) show where the water use scenarios come from and why the authors feel justified in not changing land use. If the authors were able to do all of these things, I would re-review, but if they cannot, I think it would be best not to publish the work in HESS.

Response: We address each of these concerns in the response to comments below.

Index		Comments
1	Referee review	Line 45: the authors note that the GCMs have biases that prevent accurate reproduction of historical hydrological conditions, but do not address those biases. The bias correction and downscaling methods mentioned do not correct for problems with the large-scale synoptic forcing that results in the failure of GCMs to reproduce natural variability (e.g., precipitation timing, variance, low frequency oscillatory behavior), and therefore are not particularly useful for use in driving hydrologic models. They are especially poor at the precipitation extremes (flood and drought). I cannot agree that a climate change analysis should be driven with downscaled, bias-corrected GCM output.

	Author's response	We agree with the reviewer that GCMs are not particularly good at large-scale synoptic forcing that produce natural variability (e.g., precipitation timing, variance, low frequency oscillatory behavior) We also agree that bias correction and downscaling methods cannot these correct problems, and will not produce climate events that are significantly outside the range of those that occurred during the historic period used for bias correction. Nevertheless previous research has shown that they are able to simulate broad features of the climate system and are useful for characterizing plausible projections of possible futures (Kundzewicz et al, 2008, 2009) and have been used in many studies to investigate hydrologic response to climate projections. The BCSA method used in this paper was developed by Hwang & Graham (2013). Hwang & Graham (2013) showed that BCSA performed better than BCCA, BCSD, or SDBC in reproducing the mean, variance and spatial correlation structure of daily precipitation over the state of Florida. Hwang and Graham (2014) showed that BCSA showed better performance than BCSD or SDBC in predicting retrospective streamflow and groundwater levels streamflow in the Tampa Bay Region when using the same INTB model used in this study. In particular Hwang and Graham (2014) showed that, when driven by GCMs downscaled using the BCSA method, the INTB model not only reproduced the mean and variance of daily streamflows but also accurately reproduced frequencies of extreme high and extreme low retrospective streamflows as well as 7Q2 and 7Q10 retrospective streamflows in the Tampa Bay region." The introduction of the paper was modified to include the following: "Although these bias correction and downscaling methods do not correct problems with large scale synoptic forcing, and are not particularly good at reproducing extreme floods or drought in retrospective period, previous research has shown that they are able to simulate broad features of the climate system and are useful for characterizing plausible projections of possible futures (Kundzewicz et al, 2008, 2009). Furthermore, previous work has shown that hydrologic models driven by bias-corrected downscaled retrospective GCM output adequately reproduce retrospective high stream flows (e.g. 7Q2 and 7Q10, as well as the long term mean and standard deviation of monthly flows (Hwang and Graham, 2014)." Section 2.4 of the paper was modified to include the following: "Hwang & Graham (2014) showed that BCSA showed better performance than other statistical downscaling methods (i.e .BCSD (Maurer et al, 2012) or SDBC (Abatzoglou & Brown, 2012)) in reproducing spatiotemporal statistics of both precipitation and daily streamflow in the Tampa Bay region. In particular, the INTB model, when driven by GCMs downscaled using the BCSA method, accurately reproduced frequencies of extreme high and extreme low retrospective streamflows as well as 7Q2 and 7Q10 retrospective streamflows in the Tampa Bay region." In addition the description of the BCSA method in Section 2.4 was improved.

2	Referee review	Line 150: only RCP 8.5 was used because previous work showed choice of RCP to be less important than choice of GCM or ET estimation method. And yet you found choice of ET estimation method to be essentially unimportant here. I am suspicious of this claim. RCP 8.5 has very much more ET potential than does RCP 2.6. I would like to see it demonstrated that the difference between those two scenarios is insignificant for hydrology. That has not been my experience.
	Author's response	Chang et al. (2016) evaluated projected changes in P – ET_0 over the continental USA using nine GCMs, ten ET_0 estimation methods, and three RCP scenarios. They showed that the first order sensitivity of water deficit projections (P-ET_0) over the Southeast USA were much higher to choice of GCM and ET_0 estimation method than to choice of RCP. First order sensitivities of water deficit projections to RCP scenarios were negligible (<0.01) for the 2030-2060 time period, and averaged 0.2 for the 2070-2100 time period. Therefore for computational efficiency, and to conservatively evaluate the influence of the most extreme carbon dioxide forcing on the hydrologic projections, only the RCP 8.5 scenario data was utilized for the future analyses in this study. It should be noted that a low first-order sensitivity does not imply that the choice of RCP does not have an important influence on hydrologic response. As Chang et al., (2016) indicate it merely implies that the choice of RCP was relatively unimportant as GCM or ET_0 method. Similarly, in this manuscript we show that the choice of ET estimation method is relatively less important than the choice of GCM or water use scenario in the manuscript, but again this does not mean that the choice of ET estimation method does not affect the results. We agree that RCP 8.5 scenario will produce higher reference ET (or potential ET) than RCP 2.6 does and will produce a different hydrologic response. By focusing on RCP 8.5 we conservatively evaluate the influence of the most extreme carbon dioxide forcing on the hydrologic projections The use of only RCP 8.5 is now better justified in section 2.3.
3	Referee review	Line 107: you use HSPF and Modflow in something called IHM, but don't show calibration validation. Calibration/validation is essential for this work. How does the combined tool do with low flow versus high flow? What can you really know about groundwater contribution? A number of statistics are given in this paper (lines 155-160) about actual evapotranspiration over the historical period, but how is this really known? You know precip, and you know streamflow, but you don't know either groundwater infiltration or evapotranspiration, so you're just guessing at which portion is which, aren't you? I'd like to see your confidence in these numbers better justified.
	Author's response	The IHM model for the Tampa Bay region (the INTB) was calibrated and validated for the years 1989-2006 by Tampa Bay Water. The results of the calibration, validation, parametric uncertainty analysis, sensitivity tests, water balance over the calibration/validation period can be found in Geurink & Basso (2013). We agree that actual evapotranspiration and groundwater recharge are difficult to measure. However the USGS operates an evapotranspiration estimation network

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<tr><td></td><td></td><td>over Florida (https://fl.water.usgs.gov/projects/sumner_floridaet/index.html).
This work
1) Measured actual ET from representative land covers in Florida using eddy covariances systems
2) Developed predictive models to estimate ET from environmental variables such as depth to water, season, and net radiation
3) Provided 2-km gridded satellite-based estimates of potential and reference ET on a daily time scale for the entire State for the years 1995 through 2010 which can be accessed at https://fl.water.usgs.gov/et/

The reference used to drive and actual evapotranspiration predicted by the INTB model were checked against the USGS results. The accuracy of the groundwater recharge estimate cannot be assessed directly, but confidence in the mass balance of the model is reflected in the calibration and validation statistics presented in Geurink and Basso (2013).</td></tr>
<tr><td>4</td><td>Referee review</td><td>Line 140: why is NLDAS-2 a good choice for bias-correction? What are the accuracy/biases of NLDAS-2?</td></tr>
<tr><td></td><td>Author’s response</td><td>Before choosing NLDAS-2 as a reference data, we compared the performance of NLDAS-2 over Tampa Bay region to the historical observations of the weather stations used to calibrate and validate the INTB model . We concluded that the performance of NLDAS-2 over Tampa Bay region was not perfect but adequate for our purposes. . Some examples of the performance of NLDAS-2 over Tampa Bay region.

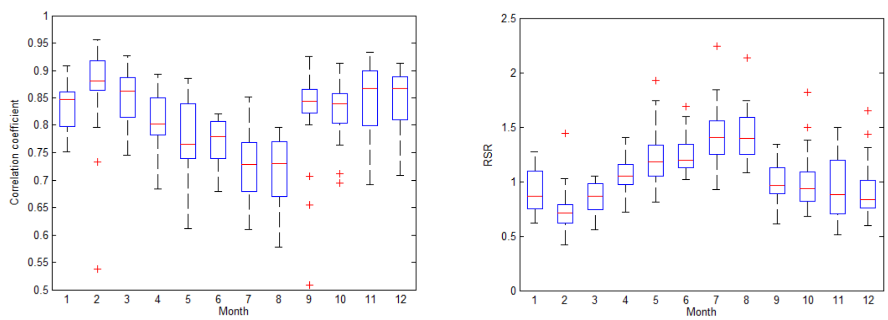

Figure 1. Correlation coefficient and RSR between NLDAS-2 and historical observations (precipitation) by daily comparison (1982-2011).

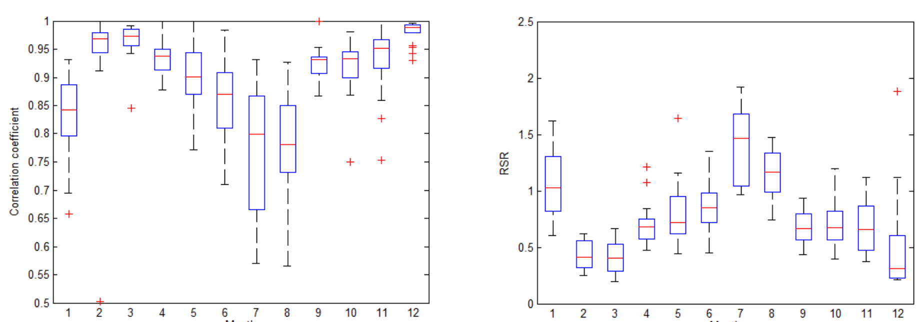

Figure 2. Correlation coefficient and RSR between NLDAS-2 and historical observations (precipitation) by monthly comparison (1982-2011).</td></tr>
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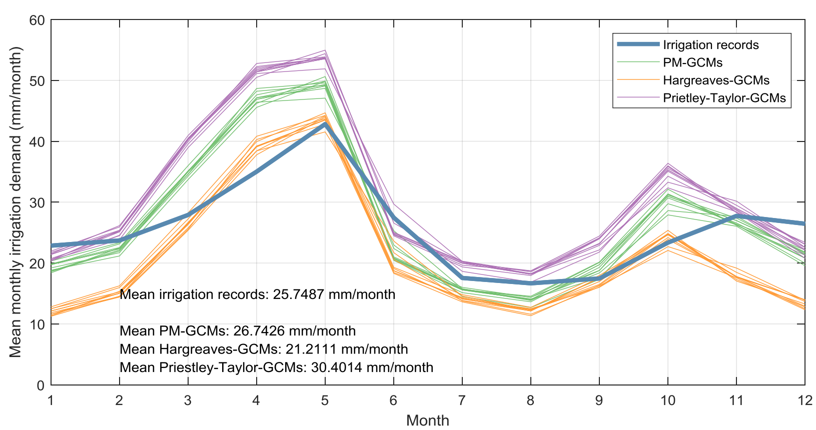
		The NLDAS-2 is gridded data that derived from the analysis fields of the NCEP North America Regional Reanalysis. The details of NLDAS-2 validation can be found in the link (https://ldas.gsfc.nasa.gov/nldas/NLDAS2valid.php). One of the reasons we choose NLDAS-2 as a reference data is NLDAS-2 provides all climatic variables needed to estimate Penman-Monteith evapotranspiration. Section 2.4 of the revised manuscript now includes a more detailed justification of the use of NLDAS-2" "NLDAS-2 was selected for bias correction because it includes all the parameters needed to estimate Penman-Monteith reference evapotranspiration. Comparison of the gridded NLDAS-2 data to the precipitation and temperature observations from the weather stations used to calibrate the INTB model showed that the NLDAS-2 data reproduced observed long term monthly means values with biases that ranged from 4 to 12 mm for daily precipitation and 1 to 2°C for daily temperature. Correlations among daily values ranged from 0.75 to 0.87 for rainfall and 0.75 to 0.98 for temperature."
5	Referee review	Line 147: Your historical period is only 24 years. Are you confident that that is long enough to capture variability properly?
	Author's response	While 24 years of historical data likely does not capture all the multidecadal variability of climate and hydrology that occur in the study region, retrospective and future climates are typically analyzed over 30 year time periods. However NLDAS-2 provides climatic data from 1979 to present but we found several data error issues in 1979-1981, so we used 1982-2005 for the retrospective period (In CMIP5 GCMs, the retrospective period ends in 2005).
6	Referee review	Line 200: Please provide calibration/validation results for the AFSIRS model. Is AFSIRS using Penman-Monteith for evapotranspiration? Can Hargreaves really substitute?
	Author's response	We used the AFSIRS model to estimate agricultural irrigation demands based on retrospective GCM data. Retrospective GCM data do not reproduce actual daily historical climate sequences so we do not have calibrated/validated results for the AFSIRS for the retrospective GCMs. However the mean monthly irrigation demand over the retrospective period can be compared to the mean monthly irrigation demand estimates used to calibrate and validate the INTB model. 

		Figure 3. Average monthly estimate historic irrigation and irrigation demand simulated by AFSIRS model in the INTB model domain. Figure 3 shows the mean monthly irrigation demand over the INTB model domain. The Blue line is the historical time series of irrigation used in the calibrated INTB model. The orange, green and purple lines are average monthly irrigation estimated by AFSIRS using the Hargreaves, Penman Monteith and Priestly Taylor ET_0 estimated from the retrospective GCMs. While none of the ET estimation methods reproduce the estimated historic data perfectly, all reproduce the seasonal trends quite well. Some of the deviations from the estimated historical data are likely due to the fact that the AFSIRS model does not include water demand for bed preparation, irrigation system maintenance, freeze protection, or crop cooling requirement, only crop water demand in the root zone Since our analysis is focused on changes in future demand, not reproducing observed historical data precisely, we believe the use of the AFSIRS model to estimate climate driven agricultural water demand. We added the following sentence at the end of section 2.6: "It should be noted that the AFSIRS model does not predict water demand for bed preparation, freeze protection, crop cooling requirements, or maintenance of irrigation systems. Thus the irrigation demand estimated for the retrospective period only includes crop water demand for evapotranspiration."
7	Referee review	Line 243: what does item (7) in this list mean?
	Author's response	In response to comments from all three reviewers we have significantly revised the justification and explanation of the future water use scenarios, and added an analysis of each one's ability to meet future water demand and maintain or improve compliance with current water resource regulations. In short, the future scenarios were developed based on discussions with Tampa Bay Water staff, projected increases in public water demand (*Tampa Bay Water Water Demand Management Plan Final Report*, 2013), projected changes in agricultural land use and agricultural irrigation demand (*Florida Statewide Agricultural Irrigation Demand Estimated Agricultural Water Demand, 2015-2040.,* 2017), potential agricultural adaption behaviors, and potential changes in groundwater regulations. The range of scenarios was designed to explore the largest range in possible future water uses that were consistent with these sources of information. In the early 2000s Tampa Bay Water was permitted by the South Florida Water Management District (SWFWMD) to pump 158 MGD groundwater to meet public water supplies. However at that time local groundwater overdraft was adversely affecting wetlands and lakes in the area and leading to salt water intrusion. Thus in 2002 the permitted groundwater pumping capacity was reduced to 121 MGD in 2002 and further reduced to 90 MGD in 2008. Scenario 7 referred to by the reviewer assumes that these groundwater pumping restrictions are relaxed and the CWF are permitted to operate at 130 MGD. The full improved justification and explanation of the future water use scenarios is included in Section 2.7 of the revised manuscript. The full analysis of the

		scenarios' ability to meet future water demand is included in Section 3.6 of the revised manuscript.
8	Referee review	Line 247: why is irrigation assumed to be 85% efficient? That seems to me to be an important sensitivity.
	Author's response	In the INTB model region, drip and spray irrigation are used (Geurink & Basso, 2013). In general these types of irrigation have 85-95% efficiencies (Irmak et al., 2011; Jacobs & Dukes, 2007). We added the references in section 2.6 of the revised paper: "Groundwater pumping for irrigation assumed 85% irrigation efficiency based on Irmak et al. (2011) and Jacobs & Dukes (2007),"
9	Referee review	Line 289: the only 2 equations presented are poorly described and confusing. Please put in terms of this study. It is not clear how the results are useful and interpretable. Is it a sensitivity in long-term average hydrology? A sensitivity in conditionality? What are the conditional relationships shown in (2)? Very difficult to make sense of how these relationships are applied in the results tables.
	Author's response	We used variance-based sensitivity analysis to evaluate the first order sensitivity of long-term changes in mean seasonal streamflow and groundwater level to the choice of GCM, ET_0 estimation method, and human water use scenario. Section 2.8 was revised to better explain how the variance based sensitivity analysis was performed in this study. The revised explanation is included below: "Using the variance-based GSA method the variance-based first order effect is expressed as: $$V_{X_i}\left(E_{X_{\sim i}}(Y \mid X_i)\right)$$ Where V is the scalar model output (i.e., change in mean monthly streamflow or groundwater level), and X_i are the factors causing variation in the model output (i.e. choice of GCM, ET_0 method, water use scenario). The expectation operator $E_{X_{\sim i}}(Y \mid X_i)$ indicates that the mean of Y is taken over all possible values of X except X_i (i.e., $X_{\sim i}$) while keeping X_i fixed. The variance, V_{X_i} , is then taken of this quantity over all possible values of X_i . The first-order sensitivity coefficient is $$S_i = \frac{V_{X_i}\left(E_{X_{\sim i}}(Y \mid X)\right)}{V(Y)}$$ where $V(Y)$ the total variance of Y over all X_i. S_i is a normalized index varying between 0 and 1, because $V_{X_i}\left(E_{X_{\sim i}}(Y \mid X_i)\right)$ varies between 0 and $V(Y)$ according to the identity (Mood et al., 1974): $$V_{X_i}\left(E_{X_{\sim i}}(Y \mid X_i)\right) + E_{X_i}\left(V_{X_{\sim i}}(Y \mid X_i)\right) = V(Y)$$ The first-order sensitivities of future changes in mean seasonal streamflow and groundwater level to the choice of GCM, ET_0 estimation method, and water use scenario were calculated over the full ensemble of 8 GCMs, 3 ET0 methods and 8

		water use scenarios (192 samples) for each future period in order to evaluate the relative contributions of each of these factors on the variation among projections of future changes."
10	Referee review	Line 331: Only Hargreaves was used. This is hugely problematic. Temperature-based evapotranspiration methods are empirical in nature, and have very high sensitivity to temperature that causes them to "overestimate ET in a way that is greatly at variance with the fundamental principle of conservation of energy at the land surface" (Lofgren and Rouhana (2016) "Physically Plausible Methods for Projecting Changes in Great Lakes Water Levels under Climate Change Scenarios", Journal of Hydrometeorolgy, 17, 2209-2223). You cannot perform a climate change assessment with pumped up temp values using a temp-only evapotranspiration calculation.
	Author's response	We agree that exploring the impacts of choice of ET_0 estimation methods when predicting climate change impacts on hydrologic systems is important. In an earlier paper (Chang et al.; 2016) we showed that projected changes in P – ET_0 were sensitive to both the choice of GCM and the choice of ET_0 method, and that for the Southeast USA the choice of GCM and ET_0 method had approximately equal influence on changes in future P – ET_0 throughout most of the year. However, several of the ET_0 methods used by Chang et al (2016) were found to produce unreasonably high or low historic ET_0 estimates for the study region using retrospective and observation data. Therefore in this study we used three of the ten ET_0 estimation methods that are widely used in the Southeast USA, produced retrospective predictions that were consistent with observations, and showed a range of wet to fairly dry projections of future P-ET_0 (Chang et al, 2016). These methods include a temperature-based method (Hargreaves; Hargreaves and Allen, 2003), a radiation-based method (Priestley-Taylor; Allen et al., 1998), and a combination method (Penman-Monteith; Allen et al., 1998). It should be noted that Chang et al (2016) showed that Hargreaves actually projected on average wetter future P-ET_0 conditions in the study area, and Penman-Monteith and Preistley-Taylor projected on average drier future P-ET_0 conditions in the study area. In this paper we showed that for these three ET_0 methods future changes in streamflow and groundwater level were relatively insensitive to the choice of ET_0 estimation method. We point out in the revised paper that these results do not indicate that the choice of reference ET estimation method does not affect the change in streamflow or groundwater, only that the choice of reference ET estimation method is less influential than the choice of GCM or choice of human water use scenario. For simplicity in the original paper we showed the relatively insensitivity of ET_0 method using variance based sensitivity analysis, and then proceeded to do the remainder of the analyses only for Hargreaves method, which was the method Tampa Bay Model used to calibrate the INTB model. To address the reviewer's concerns in the revised paper we retained analysis of the 3 ET_0 methods in the analysis of projections of future changes in streamflow (section 3.2), future changes in groundwater availability (section 3.3), future changes in surface water available for public water supply (section 3.4) and future changes in compliance with groundwater regulations (section 3.5). However for brevity, in the new

		scenario discovery analysis of ability to meet future water demand (section 3.6), only the scenarios using the Hargreaves ET_0 method, the method used to calibrate the INTB model, are shown. Results using the other two methods give similar results. Sections 2.5, and 3.2-3.5 were revised to reflect the changes described above.
11	Referee review	Line 474: I don't think the results "clearly show" this. Much hand-waving is done.
	Author's response	We appreciate the reviewer's comment and have carefully edited the manuscript to discuss differences among projections due to GCM, ET method or water use scenario rather than discussion drivers of future uncertainty. For example in Section 3.4 (which previously included line 474) the revised paper reads: "These results underscore the fact that differences in projections of future availability of water from these rivers for public supply are driven more strongly by differences climate models than differences in future human water use scenarios. Furthermore manipulating groundwater use to change the amount of available surface water has a very small effect for a given climate. "
12	Referee review	Figure 2: I'm not sure that boxplots are the best way to show this. There are trends that get obscured, aren't there?
	Author's response	We have edited Figure 2 for better understanding.
13	Referee review	Figure 3: Where are the historical baselines on these CDF's? How well does each GCM perform relative to the historical? Even after BCSD, probably big misses in retrospective relative to historical observed.
	Author's response	After BCSA (please note that we did not use BCSD), GCMs reproduced historical CDFs relatively well.

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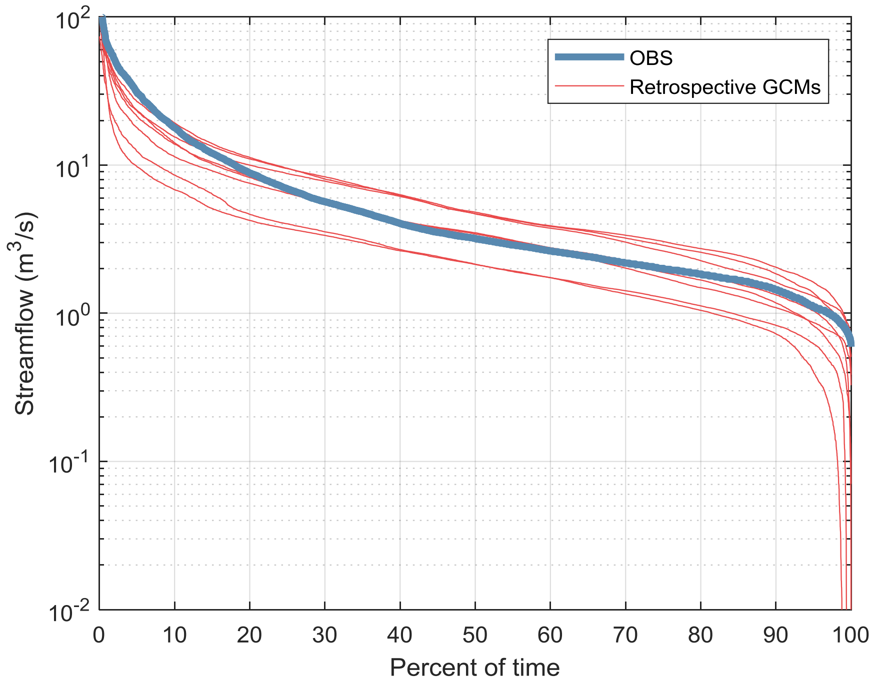
<td>

Figure 4. CDFs of Hillsborough river streamflow (observation and retrospective GCMs).

However in the revised manuscript we eliminated the presentation and discussion of streamflow and groundwater CDFs because they were difficult to interpret and we do not think they are necessary to support the primary conclusions of this study.</td>
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<td rowspan="2">14</td>
<td>Referee review</td>
<td>For sensitivity analysis, the ranges matter, don’t they? So how were the ranges of change in pumping, ag, etc., determined? Local expert elicitation? Where do these projections/expectations come from?</td>
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<td>Author’s response</td>
<td>In response to comments from all three reviewers we have significantly revised the justification and explanation of the future water use scenarios and added an analysis of each one’s ability to meet future water demand and maintain or improve compliance with current water resource regulations. In short, the future scenarios were based on discussions with Tampa Bay Water staff, projected increases in public water demand (Tampa Bay Water Water Demand Management Plan Final Report, 2013), projected changes in agricultural land use and agricultural irrigation demand (Florida Statewide Agricultural Irrigation Demand Estimated Agricultural Water Demand, 2015-2040., 2017), potential agricultural adaption behaviors, and potential changes in groundwater regulations.

To more clearly separate the impact of human water use versus climate change on the hydrologic system, three extreme groundwater use reduction scenarios were developed. As discussed in the revised manuscript, and shown in the new Figure 6, climate scenarios that project that future precipitation will be approximately equal to retrospective rainfall can only meet both 2045 public water demand and maintain existing compliance with groundwater level regulations for these extreme scenarios that completely eliminate groundwater pumping for public water supply purposes.</td>
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</table>

		In addition scenarios that increased groundwater pumping were also examined. In the most extreme of these scenarios pumping from the Tampa Bay Water's consolidated wellfields (CWFs) was increased from the current permitted 90 MGD to 130 MGD, which is less than the 158 MGD that was permitted in the early 2000s. Figure 6 shows that only the 2 wettest future climates projected by the GCMs used in this study can meet both projected public water supply demands and maintain or improve compliance with current ground water regulations if CWF pumping is increased to 130 MGD. The full improved justification and explanation of the future water use scenarios is included in Section 2.7 of the revised manuscript. The full analysis of the scenarios' ability to meet future water demand is included in Section 3.6 of the revised manuscript.
15	Referee review	Difficult to parse whether this paper is talking about changes in long term means or changes in variability. Where is the discussion of changes in variability/extremes? Hugely important for how much water will actually infiltrate versus evaporate. Changes in timing/duration/intensity/frequency of precipitation. And was surface storage modeled for its effect on evaporation and long-term infiltration? I didn't see that.
	Author's response	The INTB model runs on a 15 minute time step to more accurately predict the distribution of evapotranspiration, surface runoff, groundwater, particularly in response to extreme events. However in this paper we focused on the impact of changes in long-term mean streamflow and mean groundwater level to understand future water availability for public supply. Tampa Bay Water's current water supply system is composed of 3 sources: desalination (25MGD), groundwater pumping (90 MGD) and surface water supply that includes a 15.5 billion gallon reservoir. As we describe in the revised paper Tampa Bay Water operates surface-water pumps on the Hillsborough and Alafia rivers to meet public water demand. The volume of flow permitted for extraction varies daily based on maintaining sufficient in-stream flows and spring flows to protect aquatic ecosystem. In addition, groundwater pumping for water supply from Tampa Bay Water's consolidated well fields is regulated to maintain groundwater levels that promote environmental protection of lakes and wetlands near wellfields. The highest demand for water in the Tampa Bay Region comes in May at the end of the dry season when surface water flows and groundwater levels are low. Tampa Bay Water satisfies demand by adjusting its expensive but seasonally independent desalinization, inexpensive groundwater, and intermediate cost surface water supplies on a weekly basis based on hydrologic conditions relative to environmental regulations and available reservoir storage. We analyzed the change in surface water available for extraction on an annual basis assuming that there would be sufficient future storage in the system and sufficient flexibility in source rotation to use all available water regardless of differences in real-time supply and demand. This storage could include an additional surface reservoir (that would be indeed be subject to surface evaporation) or aquifer storage and recovery which is used in Florida as a lower cost storage system that does not have the same evaporative losses.

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