Response to reviewers
Manuscript for Hydrology and Earth System Sciences
Manuscript number: HESS-2015-188
Title: Sensitivity of water scarcity events to ENSO driven climate variability at the global scale
Authors: Veldkamp, T.I.E., Eisner, S., Wada, Y., Aerts, J.C.J.H., Ward, P.J.

General response

We thank the two reviewers and the editor for the time taken to review and process our manuscript. We are pleased that the reviewers find the work important as well as being of sufficient scientific quality and general interest to consider publication in HESS after revisions. The reviewers provided a number of suggestions to improve the manuscript. In response, we have made major revisions, clarifications, and/or additions to parts of the manuscript, as outlined in this document. Based on the reviewer's comments and the subsequent revisions, we feel that the manuscript has greatly improved. In the following sections, we respond to each of the reviewers' remarks or questions.

Reviewer #1:

R1. The paper presents an analysis of what were the effects of ENSO climate variability on global patterns of water availability and water scarcity. It appears that these relationships have not been studied before in such a comprehensive way, which makes the study a new and thorough contribution to the field. The authors address their research question based primarily on outputs from a global water model.

A1. We thank the reviewer for the positive and thorough comments and are pleased that he/she values the scientific relevance of our research. The reviewer provides several very useful comments/suggestions for revisions. We will address these in the revised manuscript, as per our responses to each comment below.

Major comments:

R2. In the Abstract and the Introduction it should be mentioned that it is well-known that ENSO affects patterns of precipitation and drought in many regions; the new idea here seems to be to relate it to water scarcity, which should be pointed out compared to the many existing climatological analysis. The findings could also be better linked to those studies in the Discussion (i.e. ENSO tends to decrease precipitation in specific regions: is that congruent with your analysis of subsequent effects on runoff and water scarcity). Part of this can now be found in section 3.1, which should be removed from the results but used as a general introduction to the topic.

A2. Indeed, we agree with reviewer #1 that this work provides an extension to earlier work devoted to evaluate the correlation between ENSO and precipitation and hydrological extremes. In the introduction of the original manuscript we already referred to a number of studies focused on the relation between drought and precipitation patterns and ENSO driven variability at the regional scale: Chiew et al., 1998; Kiem and Franks, 2001; Lü et al., 2011; Mosley, 2000; Moss et al., 1994; Piechota and Dracup, 1999; Räsänen and Kummu, 2013; Whetton et al., 1990. The references used to point out the state-of-the-art for the global scale discuss, however, mainly ENSO's impact on streamflow variability in general. Therefore we added three more references of studies that specifically focus on ENSO's impact on global and regional scale patterns of precipitation and droughts: Dai & Wigley, 2000; Ropelewski et al., 1987; and Vicente-Serrano et al., 2011 (see Revised MS with track changes: page 4, line 114-119). Moreover, we have made some amendments in the abstract to emphasise that our contribution builds further on the existing knowledge on ENSO's impact on precipitation and droughts (see Revised MS with track changes: page 2, line 46-47). Within the discussion section we have now discussed our results in the light of these existing studies, using- amongst others- the comparisons made in section 3.1 of the original manuscript (see Revised MS with track changes: page 15-16, line 545-561).

R3. The percentage of affected people etc. is often mentioned in the text, which makes it somewhat difficult to follow the key results/arguments. It would be very helpful to see a table which lists the main global numbers for the different cases.

A3. Indeed, the large amount of numbers presented in the manuscript make it somewhat difficult for readers to identify the key message. To accommodate this, we have added four tables (see Revised

MS with track changes: page 10 (l:338), page 11 (l:369), page 12 (l:411), page 14 (l:481)) to the result section that summarize per paragraph/topic discussed the main results. In doing so, we have deleted quite some numbers from the text and refer to the tables instead.

R4. Some sections should be shortened or removed, as the paper is long and as some information is provided several times. These include the following: 1.The introductory paragraph to section 2 (I suggest to just delete it). 2. The first paragraph of section 3.3 (delete). 3. The many figures and long results section: I suggest to focus the main paper on either water scarcity or water stress, as they differ only marginally and as it is a bit lengthy to read results and look at maps for both. The respective other indicator could then be entirely (text, figures) addressed in the Appendix, or it could simply be stated that the results would not differ much when choosing another indicator. Figures could also be rearranged to highlight key findings/maps: Fig. 1b could be moved to the appendix and Fig. A2a be shown here. Fig. A3 not needed at all, I think. 4. Section 3.3: needs to be shortened. 5. The final part of the Discussion (from line 10, "The results presented. . .") is wordy and could be shortened or substantiated with some literature references and/or more concrete examples.6. First paragraph of Conclusions: said several times, could be deleted.

A4. Many thanks for the suggestion. We agree with reviewer #1 that the manuscript could benefit from shortening. We have therefore completely revised the results section, made a selection in the figures to show, and shortened a number of the more technical aspects as follows:

- *We have shortened the text, referred more to existing literature, and removed repetitive parts in the introduction and methods section.*
- *We have condensed the results section, putting more emphasis on the main/important results of our analysis and shortened text where possible.*
- *Within the results section we now focus on the CTA indicator for water scarcity as the results found for the WCI are quite similar. If differences in results arise we mention it in the text.*
- *We have made a selection of the figures and removed 2 figures from the main body of text and 5 figures from the Supplementary information.*
- *We have added 4 tables to the results section that summarize the main results.*
- *We have shortened both the discussion and conclusions section, removed repetitive text, and highlighted the most important results and policy implications.*

<u>Technical comments:</u>

R5. Define "blue" and "green" water availability.
A5. We agree with reviewer #1 that we should have emphasized the differences between the blue, green and other types of water resources, and corresponding water scarcity interpretations more clearly. Therefore, we have clarified this in the revised manuscript (see Revised MS with track changes: page 6, line 204-208).

R6. Page 5468 line 2 and elsewhere: "found relationships": I think the term "found" can be removed, or reformulate "relationships found here".
A6. Agree, we have removed it in this specific case and reformulated it elsewhere.

R7. Section 2.1: Can water scarcity issues really be solved FPU-internally? I think this is just a crude assumption, not a fact.

A7. Yes, it is indeed an assumption that water scarcity issues could (ideally) be solved FPU-internally, made also in earlier research by Kummu et al. (2010). We are aware of the fact that this assumption only holds in an ideal situation (optimal infrastructure, management, governance), on which we have elaborated in section 2.4 of the revised manuscript (see Revised MS with track changes: page 7, line 234-239). Moreover, we have now stated more clearly in both section 2.2 and 2.4 that this is an assumption and not a fact (see Revised MS with track changes: page 5 (l:157-160), page 7 (l:234-236)).

R8. Section 2.3: A bit more info on how water consumption was calculated would be helpful.

A8. Thank you for pointing this out. We have made amendments in section 2.3 to clarify the calculation procedure for consumptive water use (see Revised MS with track changes: page 6, line 185-191). However, in order to keep section 2.3 concise we refer to Wada et al. (2011b, 2014b) for a complete description and discussion on the framework for the calculation of consumptive water demand.

R9. Section 2.4: Isn't 0.4 the conventional threshold for water stress (as opposed to 0.2)?

*A9. 0.4 is the conventional threshold for water stress when using the **withdrawal** to availability ratio. In this study we applied a **consumption** to availability ratio which uses consumptive water demands rather than withdrawals, and which takes into account water that has been recycled (industry) or not used (irrigation) and flows back into 'nature'. The threshold level for water stress using consumptive water demands is therefore conceived to be lower than the threshold level for water stress as estimated using withdrawals, 0.2 opposed to 0.4 respectively (Hoekstra et al., 2012; Wada et al., 2011a). The choice of a critical threshold level to assess water scarcity conditions is related to the minimum environmental flow requirements that apply for each basin (Pastor et al., 2014; Smakhtin et al., 2004). Richter et al. (2012) and Hoekstra et al. (2011) adopted a 'presumptive environmental flow standard' of 0.8 in order to avoid major changes in natural structure and ecosystem functions. This value of 0.8 coincides with 0.2 critical threshold level for water stress events which we used in our study. We acknowledge that this 0.8 is a general standard that does not hold for all basins (Pastor et al., 2014; Smakhtin et al., 2004). Although efforts have been put in the characterization of minimum environmental flow requirements per basin (Pastor et al., 2014; Smakhtin et al., 2004), their outcomes have not been taken up yet widely by water scarcity assessment studies.*

We clarified this in the revised manuscript (see Revised MS with track changes: page 7, line 214-230).

R10. Section 3.1: Clarify whether this section is about simulations with or without socioeconomic trends.

A10. As stated within the introductory paragraph of section 3, we assessed in section 3.1 and 3.2 the sensitivity of water availability, consumptive water use, and water scarcity conditions to ENSO driven climate variability under 'fixed' socioeconomic conditions (i.e. without socioeconomic trends). We did so because 'transient' socioeconomic conditions (including socioeconomic trends with respect to: population, GDP, growth in irrigated areas), and their impacts on consumptive water demand and water scarcity estimates, disguise the possible correlations with ENSO driven climate variability. In section 3.3, we included the socioeconomic trends to evaluate whether those areas with statistically *significant correlations to ENSO driven climate variability are actually affected by adverse water scarcity conditions, and how these shares change over time taking into account the socioeconomic trends. In the revised manuscript (section 3.1-3.3) we have put more emphasis on whether and where we used simulations with or without socioeconomic trends (see for example Revised MS with track changes: page 9 (l:306), page 10 (l:362-363), page 13 (l:449)).*

R11. Indicate what value of the correlation coefficient the 0.5 or 0.1 significance corresponds to.
A11. The values of $P < 0.01$ (water availability) and $P > 0.5$ (consumptive water use) refer to the field significance which is defined by Livezey & Chen (1982) as the "collective significance of a finite set of individual significance tests (local significance)".To evaluate the field significance, we estimated probability density functions of the number of cells showing a statistically significant correlation at a confidence level of 95% using the bootstrapped correlation results for each of the 3-monthly JMA SST correlation values as input. With a p-value of < 0.01 (water availability) we can reject the H_0 hypothesis that the results (a significant correlation found for a share of the global land area) are obtained by chance. With a P-value of >0.5 (consumptive water use) we cannot reject the H_0 hypothesis which indicates that chance plays a decisive role in the correlation results (thus non-significant correlations). To clarify this we have extended the explanation on field significance in the methods section of the revised manuscript (see Revised MS with track changes: page 8, line 258-267) as well as in the results section (see Revised MS with track changes: page 9, line 311-316).

R12. The 'threshold' coefficient seems to be relatively low, which could be considered in the discussion of the findings
A12. For both the correlation analysis and the field significance tests applied in our contribution we used a 95% confidence interval (or $p \leq 0.05$) as a measure of statistical significance. We noticed that we made a typo in section 3.1 and 3.2 of the original manuscript (where was stated that we used a 5% confidence interval). We have amended this in the revised version (see Revised MS with track changes: page 9 (l:310), page 11 (l:365)).

R13. Second paragraph of this section: from line 8 you discuss "Positive correlations" but to me it is not clear in what way these numbers differ from those presented in the preceding paragraph (what's the difference between the two).
A13. Within the first paragraph of section 3.1 we discuss the share of total land surface area with a significant correlation to ENSO driven climate variability (irrespectively whether it is a positive correlation or a negative one). Different regions respond, however, differently on ENSO driven climate variability. Yearly water resources availability is for example higher in South Africa and Australia under El Nino stages than under La Nina stages, whilst the opposite holds for California and some regions in the southern part of Latin America (Revised manuscript Fig. 1). This is reflected in the positive (i.e. more water available with the JMA SST index moving towards El Niño values) and negative (i.e. less water available with the JMA SST index moving towards El Niño values) correlation values found. To clarify this we have included in the revised manuscript a table that summarizes these different percentages (section 3.1, Table 2) (see Revised MS with track changes: page 10, line 338).

R14. Next page line 4: what's the "memory of the soil"?

A14. The memory of the soil, or soil moisture memory, refers to the ability of the soil to 'remember' anomalous wet or dry conditions long after these conditions occurred in the atmosphere or any other stage of the hydrological cycle (Seneviratne et al., 2006). We have clarified this in the text (see Revised MS with track changes: page 16, line 574-576). Since the irrigation water demand estimates are partly determined by the rates of crop evapotranspiration and the availability of green water (soil moisture/water in the unsaturated soil), the found variability in this parameter might be out of phase with the variability found in the atmospheric conditions (ENSO driven climate variability as assessed by the JMA SST anomaly index) which in turn explains the relative low significant correlation. Including, per region or soil characteristic area, the length/size of the soil memory as a time lag could potentially improve the correlation of consumptive (irrigation) water demand with ENSO driven climate variability. More research is, however, needed in order to be able to express this relation between the size of the soil memory and the time lag used within the ENSO correlation analysis.

R15. Section 3.2: define "significant anomalies" (line 20).
A15. The assessed anomalies comprise the differences between the median values of water scarcity conditions between El Niño (EN) and La Niña (LN) years, and the median values under all years. A bootstrapped version of the non-parametric Mann-Whitney U test (n = 1000, p = 0.05) was used to test the statistical differences in median values. We clarified this in section 3.2 (see Revised MS with track changes: page 12, line 403-405).

R16. Section 3.3 line 24: "significant correlations" with what, the absolute WCI value or the number of scarcity events?
A16. The significant correlations and its associated percentage (33.1%) as mentioned in this line refer to the share of land area for which its absolute WCI values is significantly correlated with the ENSO driven climate variability as measured with the JMA SST, expressed as percentage of the land area being at least once affected by water stress events. To summarize, 23.1% of the total land surface was affected at least once by water stress events. For one-third (33.1%) of this 23.1%, the land-area in case also showed a significant correlation of the absolute WCI values with ENSO driven climate variability, i.e. 7.6% (33.1% x 23.1%) of the total land surface area. We agree with reviewer #1 that this was not clear in the original manuscript. Moreover, we think that the numbers presented in this paragraph of the original manuscript distract from the main results/messages in this section. We have therefore decided to omit this paragraph in the revised manuscript.

R17. The Discussion should emphasize that the two water scarcity / stress metrics are rather simple, possibly masking regional ENSO effects on drought and water limitation.
A17. Agree, in the revised manuscript we have made some amendments to emphasize this point (see Revised MS with track changes: page 18, line 640-647).

R18. Second paragraph of Conclusions: do you mean global or regional "water scarcity conditions become more extreme. . ."?
A18. We meant here regional water scarcity conditions. We found significant correlations between water scarcity conditions and ENSO driven variability in FPUs covering >28.1% of the global land area and >31.4% of the total population in 2010. We have clarified this in the revised manuscript (see Revised MS with track changes: page 19, line 660).

Within this study we did not evaluate the sensitivity of global scale aggregates to ENSO driven climate variability. A global scale aggregate (or: mean) value for water scarcity conditions obscures the regional patterns in water scarcity conditions and therefore the impact of water scarcity events in terms of population and land area affected. Globally, there is enough water to cover human and environmental needs, it is merely the inability to cover water demands at a certain space and within a specific time period that causes water scarcity events to happen and which creates impacts on the ground. Assessing the sensitivity of global scale aggregates of population or land area affected to ENSO's variability neither provides a lot of information. Different regions show positive and negative correlations with ENSO's climate variability, this implies that effects weight out when aggregating these results to the global scale, which results in turn in non-significant correlations or anomalies. Ward et al. (2014) came across this issue, for example, when looking at the anomalies in flood risk at the globally aggregated and regional scale. Although a decision maker or aid/development agency might be interested in the global totals of population/land area affected by water scarcity events under a certain ENSO stage, we think that it is more informative (e.g. when thinking of predictability or putting a regional focus on adaptation or aid) to provide the insights at a regional scale.

R19. Fig. 1: What is SST_bestoff?

A19. SST_bestoff refers to the 3-monthly JMA SST period that showed the highest correlation with the observed variability in water resources availability, consumptive water use, and water scarcity conditions. In order to accommodate for regional differences in lag-times and peak of the ENSO signal, we assessed the sensitivity of water availability, consumptive water use, and water scarcity conditions to ENSO driven climate variability using four sets of 3-monthly mean JMA SST values: October – December, November – January, December – February, and January – March (see section 2.5). Figures 1, 2, and A.2, show for each FPU the correlation coefficient (if significant), using the 3-monthly JMA SST period with the highest correlation (JMA $SST_{bestoff}$). We clarified this in the figure captions.

R20. Fig. 2: Is this with or without socioeconomic change? But anyway, only water availability is responsive cf. Fig. 1.

A20. Figure 2 visualizes the sensitivity of the CTA-ratio to ENSO driven climate variability under fixed socioeconomic conditions (i.e. without socioeconomic trend), see also reviewer comment #9. We specified this in the figure caption. The variation in the WCI is indeed only driven by variations in water resources availability (as the socioeconomic term consists of population only). The CTA-ratio is, however, both influenced by variations in water resources availability and consumptive water use (see Fig. 1). This explains the slight differences in pattern between Fig. 1 & Fig. 2, and between Fig. 2 and A.2. In section 3.2 we discuss this with an example of Southeast Asia.

R21. Fig. 5: Can there be dots in areas with zero frequency? What does it mean "could be" significantly correlated?

A21. Dots, indicating the areas with a significant correlation of CTA-values to variation in JMA SST values, can indeed occur in areas with zero frequency of water scarcity events. CTA-values can be calculated for every FPU, whilst water scarcity events are said to occur only if the critical threshold values are being reached (WCI ≤ 1700; CTA-ratio ≥ 0.2). The fact that no water scarcity events occur in a certain FPU does not imply, however, that its CTA-value cannot correlate to ENSO driven climate variability. Especially those regions in which water scarcity events do not occur yet but for which the

CTA-values move rapidly towards the critical threshold value, can benefit of the presence of a significant correlation with ENSO driven climate variability. In order to focus on the main results/messages of this section we have decided, however, to omit this figure and corresponding paragraph in the revised manuscript.

R22. Fig. A9: "(a) shows. . ."?

A22. Thanks for pointing this out. Indeed, the caption with this figure was not correct. We have amended this (see Fig. A.4): "The figure shows the regional variation in developments of population (%) affected by either water scarcity events and/or ENSO driven climate variability over the period 1961-2010, as estimated with the WCI for water shortage conditions (compared to Fig. 5 in the revised manuscript that represent the result under the CTA-ratio). The figure shows per world region the growth in population living under water shortage events and/or living in areas sensitive to ENSO riven climate variability, relative to the growth in total global population (set at 100 in 1961). Y-axis ranges from 0 up to 400."

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Reviewer #2:

Many studies have already investigated of the climate impacts of ENSO, but the present study is the first that combines the occurrence of water scarcity with the influence of ENSO events. In this way the study provides some new insight in the relation of water scarcity and climate variability.

We thank the reviewer for his/her thorough and fruitful comments. We have made our best efforts to implement the very useful recommendations throughout the manuscript. Below, we address each of major and minor comments point-by-point.

<u>Major comments:</u>

R1. While the study is generally interesting, parts of the manuscript are somewhat lengthy and may be shortened. In this respect, the whole paper should be checked for redundant text. The whole manuscript comprises too many figures, with an appendix that has even more figures than the main text. As all figures are referred and discussed in the text, it is quite difficult to judge which figures are the important ones. Some of the appendix figures are likely dispensable, e.g. A2 or A3. I suggest determining which figures are essential for the study, and then remove those figures that are not important. Pease avoid showing all figures that you made during the study!

A1. We agree with reviewer #2 that shortening and removing the redundant text and figures could improve the manuscript. We have therefore condensed the results section, removed redundant text and figures, and made amendments to other sections as follows:

- *In the introduction and methods section we have removed repetitive parts and redundant text and referred more to existing literature.*
- *We have completely revised the results section, putting more emphasis on the main/important results of our analysis and shortened text where possible.*
- *Within the results section we now focus on the CTA indicator for water scarcity as the results found for the WCI are quite similar. If differences in results arise we mention it in the text.*
- *We have removed redundant figures: 2 figures from the main body of text and 5 figures from the supplementary information.*
- *We have added 4 tables to the results section that summarize the main results.*
- *We have shortened both the discussion and conclusions section, removed repetitive text, and highlighted the most important results and policy implications.*

R2. Sect. 3.1 discusses results of the study mixed with results from literature so that it remains unclear what is the new contribution to science by the authors in this section.

A2. Agree, within the revised manuscript we have split our contribution from the results presented by earlier research. A portion of this reference to earlier research has been transferred to the introduction and used as a general introduction (see also review comment 1 from reviewer #1) whilst other parts have been moved to the discussion section in order to place our results in the context of previous research (see Revised MS with track changes: page 15-16, line 545-578).

R3. Sect. 3.3 comprises a lot of number crunching. I suggest putting all number in a summarizing table and discuss only those numbers explicitly in the text that are important. For all other numbers the new table should be sufficient. Further it seems sufficient to concentrate on discussing one of the indices, e.g., CTA. If you then write about numbers and it may be sufficient to write the WCI number only in brackets if you think the information is necessary in the text. In addition, some of the percentages given refer to the total land area, some of them only to a specific land area (e.g. p. 5481 – line 2), which is sometimes confusing. Providing both percentage in the table would be helpful. In summary, I suggest some revisions to be conducted before the paper may be accepted for publication.

A3. Thank you for pointing this out. Indeed, the main messages/results of our research are somewhat obscured by the large amount of numbers presented throughout the results section. To accommodate for this, we have added four tables to the result section that summarize per section the main results (see Revised MS with track changes: page 10 (l:338), page 11 (l:369), page 12 (l:411), page 14 (l:481)). Moreover, we have completely revised the results section, putting more emphasis on the key messages, deleting quite some numbers from the text and referring to the tables instead, and removing redundant text. We focus only on the CTA indicator for water scarcity in the revised results section as the results for the WCI are quite similar. In case of differences in results between the two indicators we mention it in the text.

Technical comments:

R4. p. 5466 – line 6 … climate change. However, …
A4. Amended.

R5. p. 5467 – line 16 I assume that the term "blue water" is not familiar to everyone so that it needs to be properly defined.
A5. Agree, in the revised manuscript we explain the term blue water in the introduction as 'the water available in rivers and lakes' (see Revised MS with track changes: page 3 (l:93-94)) whilst we put more emphasis on the differences between the blue, green and other types of water resources, and their corresponding water scarcity interpretations in section 2.4 (see Revised MS with track changes: page 6 (l:204-208)).

R6. p. 5475 – line 6-14 Very long sentence that makes it difficult to follow. I suggest separating into several sentences to improve readability.
A6. Amended.

R7. p. 5478 – line 5-7 It is written: " …whereas it might be more appropriate for consumptive water use to assess its correlation either using monthly time-scales or yearly maxima." Can't this be checked?
A7. If the research was entitled to the sensitivity of consumptive (irrigation) water use to ENSO driven climate variability only, we could have done so indeed. However, estimating the correlation between consumptive (irrigation) water use and ENSO driven variability at a monthly time-scale or using monthly maxima requires an extensive analysis on potential time lags between the observed ENSO conditions and the variability in consumptive irrigation water demand, amongst other because of issues related to the soil moisture memory and differences in crop growth rates, rates of evapotranspiration, and water demands (see also Comment 11, Reviewer #1). Since we used

consumptive water demands mainly as input for our water scarcity metrics, we were especially interested in the yearly totals whilst a detailed analysis on yearly maxima or monthly values was out of the scope of this research.

R8. p. 5478 – line 20-24 Sentence is difficult to read. Please rewrite!
A8. Amended, moreover we have added a table in the revised manuscript to summarize all the numbers presented (see Revised MS with track changes: page 11 (l:369)).

R9. p. 5479 – line 13 It is written: " … we did not find any FPUs with (in)significant correlations for water availability, … I don't understand. Does this mean that you don't find any correlation at all? If so then write it directly.
A9. We meant here that for all FPUs for which water resources availability can be significantly correlated with ENSO driven climate variability we also found a significant correlation in water shortage conditions with ENSO driven variability. We have clarified this in the revised manuscript (see Revised MS with track changes: page 11 (l:394-396))

R10. p. 5480 – line 25-26 It is written: "… we found correlations … …for one-third (33.1%) of the land area susceptible to water stress events (blue dots)." Does mean 33% of the total land area, or 33% of the susceptible land area? Please clarify in the text!
*A10. We meant here 33% of the susceptible land area, thus 7.6% (33.1% * 23.1%) of the total land area. We agree that this was not clear in the original manuscript. Moreover, we think that the numbers presented in this specific paragraph obscured the key messages in this section. We have therefore decided to omit this paragraph in the revised manuscript.*

R11. p. 5481 – line 10-11 What is a factor difference? A factor is multiplicative, a difference is additive. I don't understand.
A11. We meant here that the share of population (41.1%) affected by water scarcity events is a factor 2.9 higher than the share of land area (13.9%) affected by water scarcity events. We agree with the reviewer that this was not clear in the original manuscript. Therefore, we have amended this throughout the results section, whilst we summarized our main results in accompanying tables (see for example Revised MS with track changes: page 13 (l:466))

R12. p. 5481 – line 13-18 This sentence is difficult to read and seems to only duplicate the caption of figure 6. Please avoid duplicating figure captions in the main text!
A12. Amended.

R13. p. 5483 – line 22 … that all individual GHMs …
A13. Amended.

R14. p. 5484 – line 1 … areas sensitive to …
A14. Amended.

R15. p. 5484 – line 14 Due to clustering effects ….
A15. *Amended.*

R16. p. 5485 – line 27 It is written: " …. of ENSO lacks (…). Here, some words seem to be missing after '… lacks'.
A16. *Amended.*

R17. p. 5486 – line 4 … value remain stationary ….
A17. Amended.

R18. p. 5486 – line 16 … modulate the ENSO …
A18. Amended.

R19. p. 5487 – line 5 … presented here, are …
A19. *Amended.*

R20. p. 5488 – line 3-5 Sentences "…water resources availability and consumptive water use to ENSO driven climate variability." And "We found that both water resources availability and water scarcity conditions can be significantly correlated with ENSO driven climate variability…" are redundant. Please merge appropriately.
A20. Amended.

R21. p. 5499 – Figure 1 Panel titles are too small. Also, it would make more sense to show FPUs in Fig. 1 as FPUs are used in Fig.2.
A21. Agree, in the revised manuscript we now show FPUs in Fig. 1. Moreover, we have changed the font size of the panel titles.

R22. p. 5507 – Figure 9 The black colour is difficult to separate from the grey one (Water Gap/Ensemble mean ENSO). It seems that the middle panels are the only panels that include the red and the orange line, but actually I cannot distinguish both lines. If they are the same one of those lines may be obsolete
A22. We agree with the fact that the black colour is difficult to separate from the grey ones. In the revised version we have therefore changed its colour to yellow. We understand that this figure requires some more explanation. The colours black (in the revised manuscript yellow), orange, and red are each only used twice in the different sub-figures representing the ensemble-mean values whilst the grey lines (dotted, dashed, and continuous) represent the individual GHMs in every sub-figure. Sub-figures I and IV show, the modelling spread in population 'sensitive to ENSO driven variability' (grey lines) relative to the ensemble-mean result for this topic (black line, now yellow). Sub-figures II and V show, the modelling spread in population 'affected by water scarcity' (grey lines) relative to the ensemble-mean result for this topic (orange line). Sub-figures III and VI show, finally, the modelling spread in population 'affected by water scarcity & sensitive to ENSO driven variability' (grey lines) relative to the ensemble-mean result for this topic (red line). In order to make this clear we revised the caption for this figure.

Title Page

Title: Sensitivity of water scarcity events to ENSO driven climate variability at the global scale

Submitted to: Hydrology and Earth System Sciences

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T.I.E.V., J.C.J.H.A., and P.J.W. designed research; T.I.E.V., S.E. and Y.W. prepared datasets; T.I.E.V. analyzed data; and T.I.E.V., S.E., Y.W., J.C.J.H.A., and P.J.W. wrote the paper.

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Abstract

Globally, freshwater shortage is one of the most important risks for society. Changing hydro-climatic and socioeconomic conditions have aggravated water scarcity over the past decades. A wide range of studies show that water scarcity will intensify in the future, as a result of both increased consumptive water use and, in some regions, climate change ~~However~~. Although it is well-known that ENSO affects patterns of precipitation and drought at global and regional scales, less attention has been paid yet to the impacts of climate variability on water scarcity conditions, despite its importance for adaptation planning. Therefore, we present the first global scale sensitivity assessment of water scarcity ~~and water availability~~ to El Niño-Southern Oscillation (ENSO), the most dominant signal of climate variability.

We show that over the time period 1961-2010, both water availability and water scarcity conditions are significantly correlated with ENSO~~-~~ driven climate variability over a large proportion of the global land~~-~~ area (>28.1%); an area inhabited by more than 31.4% of the global population. We also found, however, that climate variability alone is often not enough to trigger the actual incidence of water scarcity events. The sensitivity of a region to water scarcity events, expressed in terms of land~~-~~ area or population ~~impacted~~exposed, is determined by both hydro-climatic and socioeconomic conditions. Currently, the population actually impacted by water scarcity events consists of 39.6% (~~water stress~~CTA: Consumption to Availability ratio) and 41.1% (~~water shortage~~WCI: Water Crowding index) of the global population whilst only 11.4% (~~water stress~~CTA) and 15.9% (~~water shortage~~WCI) of the global population is at the same time living in areas sensitive to ENSO driven climate variability. These results are contrasted however by differences in found growth rates under changing socioeconomic conditions, which are relatively high in regions ~~affected by~~exposed to water scarcity events.

Given the correlations found between ENSO and ~~both~~ water availability and ~~water~~ scarcity conditions, and the relative developments of water scarcity impacts under changing socioeconomic conditions, we suggest that there is potential for ENSO-based adaptation and risk reduction which could be facilitated by more research on this emerging topic.

Keywords

ENSO, climate variability, hydroclimatology, water scarcity, water resources availability, global hydrology

1. Introduction

Over the past decades, changing hydro-climatic and socioeconomic conditions have led to increased regional and global water scarcity problems (Alcamo et al., 1997; Kummu et al., 2010; van Beek et al., 2011; van Vliet et al., 2013; Veldkamp et al., 2015; ~~Vorosmarty~~Vörösmarty et al., 2000; Wada et al., 2011a). Freshwater shortage is recognized as one of the most important global risks, not only in terms of likelihood but also with respect to its impacts, with societal and economic consequences that result from the inability to meet water demands (Hanemann, 2006; Howell, 2013; Rijsberman, 2006; Young, 2005). In the near future, projected changes in human water use and population growth – in combination with climate change - are expected to aggravate water scarcity conditions and their associated impacts on society (Alcamo et al., 2007; Haddeland et al., 2014; Kiguchi et al., ~~2014~~2015; Lehner et al., 2006; Prudhomme et al., 2014; Schewe et al., 2014; Sperna Weiland et al., 2012; Stahl, 2001; van Vliet et al., 2013; Wada et al., 2014a).

Whilst a wide range of studies have assessed the role of long-term climate change and changing ~~socio-economic~~socioeconomic conditions on past and future global blue water availability and water scarcity events, the impact of inter-annual climate variability is less well understood (Kummu et al., 2014; Lundqvist & Falkenmark, 2010; Rijsberman, 2006; Veldkamp et al., 2015). Taking into account the impact of climate variability relative to longer-term changes in either the ~~socio-economic~~socioeconomic or climatic conditions is, however, important as these factors of change may amplify or offset each other at the regional scale (Hulme et al., 1999; McPhaden et al., 2006; Murphy et al., 2010; Veldkamp et al., 2015). Correct information on current and future water scarcity conditions and thorough knowledge on the relative contribution of its driving forces, such as inter-annual variability, help water managers and decisions makers in the design and prioritization of adaptation strategies for coping with water scarcity.

To address this issue, we assess in this paper the sensitivity of blue water resources availability~~,~~ (i.e. the water available in rivers and lakes), consumptive water use, and blue water scarcity events to climate variability driven by El Niño-Southern Oscillation (ENSO) at the global scale over the time period 1961-2010. Moreover, we evaluated whether those areas with ~~found~~a statistically significant correlations have been ~~affected by~~exposed to blue water scarcity events; if there is a spatial clustering in terms of population or land~~-~~area ~~affected by~~exposed to blue water scarcity events and/or population living in areas sensitive to ENSO driven climate variability, and whether this spatial clustering has changed over time given the ~~socio-economic~~socioeconomic developments. Within this contribution we investigate the impact of ENSO as it is the most dominant signal of inter-annual climate variability (McPhaden et al., 2006). Also, since ENSO can be predictable with reasonable skill up to several seasons in advance (Cheng et al., 2011; Ludescher et al., 2014), this can provide useful information for adaptation management to account for inter-annual variability in blue water resources and blue water scarcity estimates, enabling the prioritization of adaptation efforts in the most affected regions ahead of those extreme events (Bouma et al., 1997; Cheng et al., 2011; Dilley & Heyman, 1995; Ludescher et al., 2013; Ward et al., 2014a,b; Zebiak et al., 2014).

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ENSO is the result of a coupled climate variability system in which ocean dynamics and sea level pressure interact with atmospheric convection and winds (ocean-atmosphere feedback mechanisms). El Niño is the oceanic component, whereby waters over the eastern equatorial Pacific Ocean reach anomalously high temperatures. This eastern Pacific Ocean surface is relatively cool under neutral conditions, while it reaches anomalously low temperatures during La Niña conditions. The Southern Oscillation is the atmospheric component, represented by the east-west shifts in the tropical atmospheric circulation between the Indian and West Pacific Oceans and the East Pacific Ocean (Kiladis & Diaz, 1989; Parker et al., 2007; Rosenzweig & Hillel, 2008; Wallace & Hobbs, 2006; Wang et al., 2004). ENSO is well-known for its impacts on ~~both average river flows~~precipitation and hydrological extremes (~~peak~~such as drought and ~~low flows~~flooding) at local and regional scales (e.g. Chiew et al., 1998; Kiem & Franks, 2001; Lü et al., 2011; Mosley, 2000; Moss et al., 1994; Piechota & Dracup, 1999; Räsänen & Kummu, 2013; Whetton et al., 1990~~).~~; Zhang et al., 2015). Several studies have also examined ENSO's impact at the global scale (Chiew & McMahon, 2002; Dai & Wigley, 2000; Dettinger et al., 2000; Dettinger & Diaz, 2000; Labat, 2010; Ropelewski & Halpert., 1987; Sheffield et al., 2008; Vicente-Serrano et al., 2011; Ward et al., 2010; Ward et al., 2014a~~) with~~). Though, only a limited number of studies ~~assessing~~assessed the societal impacts (e.g. in terms of population affected, GDP loss, or with respect to human health) of hydrological extremes under the different ENSO stages at the global scale (Bouma et al., 1997; Dilley & Heyman, 1995; Kovats et al., 2003; Rosenzweig & Hillel, 2008; Ward et al., 2014b). To the best of our knowledge, none of these studies have executed a global-scale assessment ~~of~~to the sensitivity of water ~~resources~~ scarcity events to ENSO driven climate variability, combining therein both the availability~~,~~ and consumptive ~~water use patterns, and~~ demand for water resources as well as the exposure to adverse water ~~scarcity events to ENSO.~~scarce conditions.

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2. Methods

~~In short, we carried out this assessment through the following steps: (1) used daily discharge and runoff time-series (0.5º x 0.5º) from an ensemble of three global hydrological models (WaterGAP, PCR-GLOBWB, and STREAM) (Section 2.1); (2) combined time-series of water availability, consumptive water use and population to calculate water scarcity conditions for the period 1961-2010 (Section 2.2 – 2.4); (3) identified statistical relationships between water availability, consumptive water use and water scarcity conditions, and indices of ENSO (Section 2.5.1); and (4) evaluated whether the areas with significant correlations with ENSO are actually affected by water scarcity events, how the impacts (population and land area affected) are clustered, and how the impacts have changed through time. Modelling uncertainty was evaluated by comparing the results from the ensemble mean time-series with the outcomes of the individual global hydrological models (section 2.6).The following paragraphs describe our methods in detail.~~

2.1 Ensemble mean monthly runoff and discharge

We simulated global gridded daily discharge and runoff over the period 1960-2010 at a resolution of 0.5º x 0.5º using three global hydrological models: PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2014b), STREAM (Aerts et al., 1999; Ward et al., 2007) and WaterGAP (~~Muller~~Müller Schmied et al., 2014), forced with WATCH Forcing Data - ERA Interim (WFDEI) daily precipitation and temperature data (0.5ºx0.5º) (Weedon et al., 2014) for the period 1979-2010 and WATCH forcing data ERA40 (WFD) for the period 1960-1978 (Weedon et al., 2011). In order to compensate for offsets in long-term radiation fluxes between the two datasets, as found by Müller Schmied et al. (2014), WFD down-welling shortwave and longwave radiation were adjusted for use in WaterGAP to WFDEI long-term means following the approach of Haddeland et al. (2012). Daily values were aggregated to time-series of monthly discharge and runoff. Using global hydrological models gives us the advantage of a global coverage whereas the portfolio of observed datasets (water availability and consumptive water use) is bounded by its biased regional distribution (Hannah et al., 2011; Ward et al., 2010; Ward et al., 2014a). However, we are aware of the caveats using these types of models to estimate water availability as all large-scale hydrological models have their own strengths and shortcomings (Gudmundsson et al., 2012; Nazemi & Wheater, ~~2014a, 2014b~~2015a, b). Therefore, we constructed ensemble-mean time-series of both monthly discharge and runoff capturing the three global hydrological models. The results of the individual modelling efforts were used to evaluate the modelling agreement (Section 2.4 and 3.5).

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2.2 Calculating water availability

Water availability is expressed in this paper as the sum of monthly runoff per ~~grid-cell and~~ Food Producing Unit (FPU). FPUs represent a hybrid between river basins and economic regions ~~within~~for which it is generally assumed that water scarcity issues can be solved internally (Cai & Rosegrant, 2002; de Fraiture, 2007; Kummu et al., 2010; Rosegrant et al., 2002). We used here an updated version of the FPUs used by Kummu et al (2010), which consists of 436 FPUs, excluding small island FPUs. For ~~grid-cells or~~ FPUs located within one of the world's larger river basins we redistributed runoff in order to avoid local over- or under-estimations in water availability. Runoff was redistributed across the ~~grid-cells~~FPUs within these larger river basins, proportionally to the discharge distribution of that large river basin (Gerten et al., 2011; Schewe et al., 2014):

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$$\mathrm{WA_i} = \frac{\mathrm{R_b} * \mathrm{Q_i}}{\sum \mathrm{Q_i}}, \qquad \textbf{Eq. 1}$$

whereby WA_i is the monthly water availability within ~~grid-cell~~FPU i, R_b is the total monthly runoff within large river-basin b, Q_i is the monthly discharge in ~~grid-cell~~FPU i, and $\sum Q_i$ is the sum of the monthly discharge over all cells within large river-basin b.

Subsequently, we calculated the annual water availability by aggregating the simulated ensemble-mean monthly water availability time-series using hydrological years~~, both at the grid-cell and FPU level.~~. The use of hydrological years is necessary in this assessment as ENSO tends to develop to its fullest strength during the period December – February, which intersects with the standard calendar year boundaries (Ward et al., 2014a, b). Hydrological years are referred to by the year in which they end, e.g. hydrological year 1961 refers here to the period October 1960 – September 1961. Within this study we follow Ward et al (2014a) and distinguish two hydrological years on the basis of long-term monthly maximum water availability per river basin: October – September (standard) and July – June (for river basins that have their long-term monthly maximum water availability in September, October or November). The river basin delineation used here was derived from the WATCH project (Döll & Lehner, 2002) and is equal to the river basin delineation that is used as the input for the FPU classification used within this study. We used the hydrological years setting determined at grid-level, using the WATCH river-basins, as input for the distinction between hydrological years at FPU scale. If an FPU consisted of more than one river basin we based the choice of hydrological year on the month (with long-term maximum water availability) with the highest prevalence within this FPU~~. Fig. A.1 shows for both the grid-cell level and FPU-scale the hydrological year distinction as used within this study.~~ (see Fig. A.1).

2.3 Calculating consumptive water use

~~Time-series of monthly consumptive~~Monthly gridded water ~~use~~consumption (0.5º x 0.5º) ~~were~~was estimated for the sectors~~:~~ livestock, irrigation, industry and domestic within PCR-GLOBWB~~, being forced with~~ using daily WFD-EI precipitation and temperature data in combination with yearly information on: livestock densities; the extent of irrigated areas; desalinated water use; non-renewable groundwater abstractions; and past socioeconomic developments, namely GDP, energy and electricity production, household consumption, and population growth (Wada et al., 2011b, 2014b~~;~~). For a complete description and extensive discussion of the methodological steps taken to compose these monthly consumptive water use time-series, we refer to Wada et al~~.,~~. (2011b, 2014b). Time-series of desalinated water use and non-renewable ground water abstractions were subtracted from the total consumptive water use estimates as they lower the need for blue water. Subsequently we aggregated gridded monthly consumptive water use into yearly totals per FPU ($WC_{i,yr}$), following the hydrological years. Since the resulting 'transient' consumptive water use estimates are partially driven by changing ~~socio-economic~~socioeconomic conditions (population, GDP, and growth in irrigated areas) and therefore disguise any possible correlations with ENSO driven climate variability, we repeated the steps above whilst we fixed the ~~socio-economic~~socioeconomic parameters at 1961 levels (following the ~~hydro-~~hydrological year naming convention). These 'fixed' consumptive water use estimates were used to evaluate the sensitivity to ENSO driven climate variability (Section 3.1 and 3.2) whereas the 'transient' water consumption time-series were used to evaluate the development of water scarcity conditions under changing ~~socio-economic~~socioeconomic conditions (Section 3.3).

2.4 Calculating water scarcity conditions

Blue water scarcity refers to the imbalance between blue water availability (i.e. water in rivers, lakes and aquifers) and the needs for water over a specific time period and for a certain region (Falkenmark, 2013). Although water scarcity could also relate to the green (water in the unsaturated soil), white (part of rainfall that feeds directly back into the atmosphere), and deep blue (fossil ground water) water sources (Savenije, 2000), we focus here on blue water scarcity (hereafter: water scarcity) only. Within this study we applied two complementary indicators to express water scarcity conditions per FPU: the Water Crowding Index (WCI) for population-driven water shortage and the Consumption-to-Availability ratio (CTA-ratio) for demand-driven water stress (Brown & Matlock, 2011; Rijsberman, 2006). The WCI quantifies the yearly water availability per capita (Falkenmark, ~~1986~~1989, 2007, 2013), whereby water ~~requirements~~demands are based on household, agricultural, industrial, energy and environmental water consumption (Rijsberman, 2006). Like previous studies (e.g. Alcamo et al., 2007; Arnell, 2003;

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Kummu et al., 2010), we used 1700 m^3/capita per year as the threshold level to evaluate water shortage events. The CTA-ratio evaluates the ratio between ~~water consumed and water availability in a specific region and is the most used indicator for water stress assessments (e.g. used in Wada et al. 2011a; Hoekstra et al. 2012; Kiguchi et al. 2014; Vorosmarty et al. 2000; Oki & Kanae 2006; Falkenmark 2013a;). In line with earlier studies (Hoekstra et al., 2012; Kiguchi et al., 2014; Veldkamp et al., 2015; Wada et al., 2011a), a threshold level of 0.2 was used here to indicate water stress events.~~consumptive water used and water availability in a specific region and is a derivative from the Withdrawal-to-Availability (Raskin et al., 1997). Usually, a region is said to experience water stress events when water withdrawals comprises ≥40% of the available water resources, whilst moderate water stress conditions occur if 20% ≥ WTA ≤ 40% (Raskin et al., 1997). These values are widely quoted and applied in previous research contributions, e.g. by Alcamo et al. (2003, 2007), Arnell et al. (1999), Cosgrove & Rijsberman (2000), Hanasaki et al. (2013), Kiguchi et al. (2015), Kundzewich et al. (2007), Oki et al. (2001, 2006), Vörösmarty et al. (2000). Hoekstra et al. (2012) and Wada et al. (2011a) applied this WTA-ratio in an adapted form, using blue water footprints and potential consumptive water use estimates respectively to assess water stress conditions: the CTA-ratio. This approach accounts for the share of water that has been recycled (industry) or not used (irrigation) and which flows back into the natural system. The threshold level for water stress using these consumptive water demands is therefore conceived to be lower than the threshold level for water stress as estimated using withdrawals. Following Hoekstra (2011, 2012), Richter et al. (2012), and Wada et al. (2011a), we applied a threshold level of 0.2 to indicate water stress events. Equations 2 and 3 show the use of the WCI ($WCI_{i,yr}$) and the CTA-ratio ($CTA_{i,yr}$), respectively:

$$\mathrm{WCI}_{i,yr} = \frac{\mathrm{WA}_{i,yr}}{\mathrm{P}_{i,yr}} \qquad \text{(water shortage event if } \mathrm{WCI}_{i,yr} \leq 1700\text{)}\,, \qquad \text{Eq. 2}$$

$$\mathrm{CTA}_{i,yr} = \frac{\mathrm{WC}_{i,yr}}{\mathrm{WA}_{i,yr}} \qquad \text{(water stress event if } \mathrm{CTA}_{i,yr} \geq 0.2\text{)}\,, \qquad \text{Eq. 3}$$

whereby $WA_{i,yr}$ is the water available per spatial unit i and hydrological year yr, $P_{i,yr}$ is the population, and $WC_{i,yr}$ is consumptive water use. Water scarcity conditions were assessed here at the FPU-scale. The FPU scale is seen as an appropriate spatial scale to study water scarcity conditions as it is generally assumed that lower-scale water scarcity issues can be overcome by the reallocation of water demand and supply within this spatial unit (Kummu et al., 2010). However, one should keep in mind that, due to the assumption of full exchange possibilities –both from an infrastructural and water management perspective- and its relative large spatial scale, analysis executed at the FPU-scale may disguise lower-scale water scarcity issues (Kummu et al., 2010; Wada et al., 2011a).

The population data used for the calculation of the WCI (Eq. 2) were adopted from Wada et al. (2011a, b), who derived yearly gridded population maps (0.5º x 0.5º) from yearly country-scale FAOSTAT data in combination with decadal gridded global population maps (Klein Goldewijk & van Drecht, 2006). We aggregated these gridded population maps to FPU-scale for use in this study. In line with the hydrological year naming convention, population estimates were used for the year in which the hydrological year ends, e.g. for hydrological year 1961 we used population estimates of 1961 as input for the WCI and to calculate water scarcity impacts.

2.5 Sensitivity of water availability, consumptive water use, and water scarcity conditions to ENSO ~~driven climate variability~~

~~At the grid-cell level, we~~We examined the relationship respectively between water availability, consumptive water use, and water ~~consumption~~scarcity conditions, and ENSO driven climate variability by means of their correlation with the Japan Meteorological Agency's (JMA) Sea Surface Temperature (SST) anomaly index (~~http://coaps.fsu.edu/jma, ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/).~~http://coaps.fsu.edu/jma.html). We used here three-monthly mean values of the JMA SST over the periods October-December, November-January, December-February, and January-March, as El Niño and La Niña expressions are strongest in these months (Dettinger & Diaz, 2000). Following Ward et al. (2014b), we examined the correlation between WA_{ann}, WC_{ann}, CTA_{ann}, and ~~WC_{ann},~~WCI_{ann}, and the 3-monthly mean JMA SST ~~value~~values (OND, NDJ, DJF, JFM), using Spearman's rank correlation coefficient ~~Rho. Significance~~. Statistical significance was assessed by means of regular bootstrapping (n = 1000, p ~~=~~≤ 0.05) while field significance, i.e. the joint statistical significance of multiple individual significance tests (Livezey & Chen, 1982; Wilks, 2006), for each of the 3-monthly JMA SST correlation values was tested using the binomial distribution (Livezey & Chen, 1982). ~~Subsequently, we assessed at the scale of FPUs the relationship between water scarcity conditions, and ENSO driven climate variability. Again, the three-monthly mean values of the JMA SST over the periods October-December, November-January, December-February, and January-March were used to calculate Spearman's Rho correlation coefficients, while we tested significance using regular bootstrapping (n = 1000, p = 0.05). Moreover~~With field significance testing we counted the number of individual tests with a significant result and assessed the probability of yielding this result by chance given its statistical distribution (Livezey & Chen, 1982; Wilks, 2006). Subsequently, we examined the percentage anomalies in the median values of water scarcity conditions between El Niño (EN) and La Niña (LN) years, compared to the median values under all years. To distinguish between El Niño, La Niña and neutral years we used the classification of ENSO years from the Center for Ocean-Atmospheric Prediction Studies based on the JMA SST values ~~(http://coaps.fsu.edu/jma.shtml).~~. Years are assigned as El Niño or La Niña years when their 5-month moving average JMA SST index values are ~~(-)~~(+/-)0.5 °C or greater (El Niño)/ smaller (La Niña) for at least six consecutive months (including October-December). Reference to the different ENSO years was adjusted to be consistent with the naming convention used for the hydrological years (Table 1). We used a bootstrapped version of the non-parametric Mann-Whitney U test (n = 1000, p ~~=~~≤ 0.05) to test the statistical differences in median values.

[Table 1 approximately here]

The critical threshold-values put in place for the WCI and the CTA-ratio (here: 1700 and 0.2 respectively) determine whether water scarcity conditions adversely affect population or society. Per FPU we therefore evaluated which ~~percentage~~proportion of land-area ~~in~~, for which ~~there is a~~we found a significant correlation between ENSO and water scarcity conditions, ~~are~~is also ~~affected by~~exposed to water scarcity events~~; and~~, and how population is clustered in these areas compared to the general pattern of population density~~; and~~. Moreover we assessed how these numbers

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Formatted: Font color: Black, Pattern: Clear (White) changed through time given the changing ~~socio-economic~~socioeconomic conditions, relative to developments in: (1) the population and land-area sensitive to ENSO driven climate variability but not ~~affected by~~exposed to water scarcity events; (2) the population and land-area ~~affected by~~exposed to water scarcity events, in areas that lack a significant correlation with ENSO driven climate variability; and to (3) the total population growth.

2.6 Evaluating modelling uncertainty

A cross-model validation was executed in order to evaluate the modelling uncertainty whereby we compared the results from the ensemble-mean with the outcomes of the individual global hydrological models. We examined the agreement among the different modelling results and the ensemble-mean when looking at: (1) the sensitivity of water availability and water scarcity conditions to ENSO driven climate variability; and (2) the impacts of water scarcity events and relation to ENSO driven climate variability under changing ~~socio-economic~~socioeconomic conditions.

3 Results

~~In this section, we first demonstrate how water availability and consumptive water use correlate with ENSO driven climate variability at the grid-cell level, keeping the socio-economic conditions fixed at 1961 levels (section 3.1). Subsequently, we show how sensitive water scarcity conditions are to ENSO driven climate variability (section 3.2). Finally, we evaluate whether those areas with statistically significant correlations are actually affected by adverse water scarcity conditions, and discuss how these shares change over time under socio-economic developments.~~

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3.1 Sensitivity of water availability and consumptive water use to ENSO ~~driven climate variability~~

Significant correlations of water availability to variations in JMA SST were found across ~~24~~37.1% of the global land surface (excluding Greenland and Antarctica~~). For consumptive water use,~~) whilst we found ~~3.1% of the land surface to be~~for consumptive water use (simulated under fixed socioeconomic conditions at 1961 levels), significantly ~~correlated with yearly variations in JMA SST.~~correlations covering 8.3% of the total land area (Fig. 1 and Table 2). Using the 3-monthly JMA SST period with the highest correlation, Fig. 1 shows for both water availability and consumptive water use its correlation coefficient with the inter-annual variation in the 3-monthly average JMA SST values~~ at the grid-cell level.~~. Only those correlations which reach statistical significance at a ~~5~~95% confidence interval are shown here. Field significance, the collective 'global' significance of the total of individual 'local' hypothesis tests (Livezey & Chen, 1982; Wilks, 2006), was tested for the individual 3-month correlation results and found to be highly significant when looking at water availability ($p < 0.01$) but insignificant when considering consumptive water use ($p > 0.5$). ~~In figure A.2 (Appendix) we present the results at FPU scale, and in figure A.3 we show the results for all FPUs (irrespective of statistical significance). At this scale of FPUs, we found percentage of total land area with significant correlations of 37.1% for water availability and 8.3% for consumption water use.~~

~~*[Figure 1 approximately here]*~~

~~Regions well known for their correlation of hydrological extremes with ENSO variability (both peak discharges and low flows) also have a statistically significant correlation between ENSO and annual total water resources availability. When comparing our results to previous studies (e.g. Dettinger and Diaz, 2000; Ward et al.,2010, 2014a), we find corresponding significant correlations in the regions mid-west North-America, the Caribbean, Latin America, Southern Africa, South-East and Central Asia and the Pacific. Moreover, the sign of the correlations found within four large river basins in Latin America and Africa, (Amazon Congo, Paraná, and Nile) is supported by earlier estimates of Amarasekera et al. (1997) who assessed the correlation between ENSO and the natural variability in the flow of tropical rivers. Significant correlations as shown for other regions were also found in case studies focusing on Northern America (e.g. Clark II et al., 2014; Schmidt et al., 2001), South-east Asia (e.g. Lü et al., 2011; Räsänen & Kummu, 2013), Southern Africa (e.g. Meque & Abiodun, 2014; Richard et al., 2001), and Australia (e.g. Chiew et al., 2011; Dutta et al., 2006).~~ Positive correlations, i.e. more water available with the JMA SST index moving towards El Niño values, were found for 13.2% of the global land surface, while negative correlations were found in FPUs covering 23.9% of the global land surface. When looking at consumptive water use we found positive significant correlations for only 1.0%, and negative correlations for 7.3% of the global land surface.

[Figure 1 approximately here]

~~8.5% (13.2%) of the global land surface, as measured at the grid-cell (FPU) level, while negative correlations were found in basins covering 15.6% (23.9%) of the global land surface.~~ ***[Table 2 approximately here]***

~~The spatial variation in sign of the found correlation is in line with the results of Ward et al. (2014a), who found that annual flood and mean discharge values intensify under La Niña and decline when moving towards El Niño phases globally in more areas than the other way around. When looking at consumptive water use we found positive significant correlations for only 0.6% (1.0%), and negative correlations for 2.5% (7.3%) of the global land surface (Fig. 1.A). In line with earlier research (e.g. Meza et al., 2004; Islam & Gan, 2015) we would have expected to find more areas with a significant correlation between consumptive water use and ENSO driven climate variability. A number of explanations could be given for the absence of significant correlations patterns in this study: 1) the consumptive water use estimates used in this study are calculated by means of multiple socio-economic and hydro-climatic proxies and variables, such as extent of irrigated areas, number of livestock, GDP, (long-term mean) monthly temperatures, and precipitation estimates, and should be interpreted as potential consumptive water use; 2) of these variables only irrigation water use could be linked directly to ENSO driven climate variability by means of its temperature and precipitation input variables. 'Fixed' consumption numbers in other sectors might attenuate therefore the variability found within the irrigation sector; 3) climate-driven variations in irrigation water demands are the result of changes in crop evapotranspiration and changes in green water availability, which do not have a univocal relation with ENSO driven climate variability at all times, but are partly determined by the month-specific cropping calendar and antecedent conditions, such as the memory of the soil; and 4) yearly totals of consumptive~~

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~~water use were applied in this study to assess its sensitivity to ENSO driven climate variability whereas it might be more appropriate for consumptive water use to assess its correlation either using monthly time scales or yearly maxima.~~

3. 2 Sensitivity of water scarcity conditions to ENSO ~~driven climate variability~~

Subsequently, we assessed how sensitive water scarcity conditions~~, measured at the FPU scale,~~ (simulated under fixed socioeconomic conditions at 1961 levels) are to ENSO driven climate variability. Significant correlations to variations in JMA SST were found for 28.1% and 37.9% of the global land surface~~ area~~ when using the CTA-ratio (water stress) and WCI (water shortage) respectively, while being tested under a ~~5~~95% confidence interval~~.~~ (Table 3). Due to the clustering of population and consumptive water use we found even higher percentages when looking at the population living in these areas, 31.4% and 38.7% of the global population in 2010 for the CTA-ratio and WCI respectively.

[Table 3 approximately here]

Fig. 2 shows the areas with a significant positive (red) or negative (blue) correlation of water stress conditions (CTA-ratio) with the variation in JMA SST values, using the 3-monthly JMA SST period with the highest correlation (JMA $SST_{bestoff}$). Correlation results found for water shortage conditions, as defined by the WCI, ~~are shown in Fig. A.4. This figure shows~~show a similar pattern~~, and in line with the correlations~~ as for ~~the annual~~ water ~~availability estimates~~stress and are given in Fig. A.2. For both metrics, we found that, for ~~the~~a majority of the land~~-~~ area with a significant correlation to ENSO driven climate variability, water scarcity conditions ~~(both CTA-ratio and WCI)~~ become more severe when the JMA SST index moves towards El Niño values~~, for 16.8% and 23.9% of the land surface area for water stress and water shortage, respectively.~~ (Table 3).

[Figure 2 approximately here]

The regional variation in sensitivity of water scarcity conditions to ENSO driven variability (Fig. 2 and Fig. A.~~4~~2) is clearly driven by the spatial distribution of water availability correlations as the general patterns are similar to those found in Fig. 1. The unequal clustering of water availability and consumptive water use leads, however, in some regions to a strengthening or weakening of the correlation signal, for example when comparing the regional variation in sensitivity results for water stress within the Amazon basin or in Southern Africa (Fig. 2) with the regional variation in correlation results for water availability ~~as found~~ in those areas (Fig. ~~A.2.~~1). For a selection of FPUs, we found significant correlations for both water availability and consumptive water use, while they lack significant correlations when considering water stress conditions, and vice versa. In Southeast Asia~~ (Fig. 3),~~, for example, we observed significant correlations between ENSO and water availability and consumptive water use~~,~~

(Fig. 1), but no significant correlations between ENSO and water stress~~.~~ (Fig 2). One explanation for this observation could be that if both water availability and consumptive water use increase or decrease with more or less the same strength under changing JMA SST values, the net effect on the CTA-ratio could be insignificant since the ratio between both variables remains equal. ~~When using the WCI, we did not find any~~All FPUs ~~with (in)~~that show a significant ~~correlations for~~correlation between water resources availability~~,~~ and ~~vice versa for~~ ENSO driven climate variability show as well a significant correlation with ENSO driven variability when looking at the water shortage conditions~~.~~ (Fig. A.2). This ~~could~~can be explained by the fact that the WCI is only driven by changes in water availability and population growth, of which the latter factor was fixed in this analysis. ~~Moreover, for all the FPUs with a significant correlation of water availability with varying JMA SST values, none of them lacks a correlation for the WCI due to the absence of population in this area (which would result in continuously infinite scarcity values when applying the WCI).~~

~~[Figure 3 approximately here]~~

~~Significant anomalies (p =~~Subsequently, we assessed the percentage anomalies in the median values of water scarcity conditions between El Niño (EN) and La Niña (LN) years, compared to the median values under all years. Significant anomalies ($p \leq 0.05$, tested by regular bootstrapping n = 1000) in water scarcity conditions under El Niño and La Niña years, compared to all years, were found for 12.8% and 14.8% of the global land~~-~~area using the CTA-ratio and the WCI respectively~~, see Fig. A.5 and Fig. A.6 in~~ (Table 4). Strongest signals anomaly signals were found during the ~~Appendix. These numbers could be split into 3.4% showing significant anomalies under El Niño years, 12.8% under~~ La Niña ~~years, and 3.4% under~~ phase for both ~~ENSO phases for~~ water stress ~~conditions (Fig. A.5), and 6.9% (El Niño phase), 9.5% (La Niña phase), and 1.6% (both EN and LN phase) for water~~ and shortage conditions ~~(Figure A.6).~~.

[Table 4 approximately here]

Not all regions with a significant anomaly under El Niño years show (significant) anomalies in the opposite direction during La Niña years. For example, Fig. ~~4~~3 visualizes the asymmetry in the anomalies found during the El Niño and La Niña phase for Latin America. Moreover, areas with significant correlations with the JMA SST index do not always show significant anomalies when looking at the different ENSO phases. This ~~could~~can be explained by the fact that only those years for which the 5-month moving average JMA SST index values are (-)0.5 °C or greater (El Niño)/ smaller (La Niña) for at least six consecutive months (including October-December) are assigned as El Niño or La Niña years (see Section 2.5). Using this ENSO year definition thus disguises all variability in JMA SST values that falls just below the threshold set, variation that can have a significant effect on water scarcity conditions however. ~~Therefore we continue our analysis with the correlations found for the JMA SST index values.~~

[Figure ~~4~~3 approximately here]

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3.3 Sensitivity of water scarcity events to ENSO ~~driven climate variability~~ under changing socioeconomic conditions

~~Whether those areas with significant correlations are actually in water scarcity requires a certain combination of water availability and consumptive water use (CTA-ratio) or population density (WCI). If water scarcity conditions do not approach the critical threshold levels for water scarcity, no critical water scarcity situation emerges. Although inter-annual variation in water availability determines for a large share the size and significance of variability in water scarcity conditions, it is thus only in combination with the 'right' socio-economic conditions that it can be decisive considering the actual incidence of water scarcity events (Veldkamp et al., 2015).~~

~~Fig. 5 shows per FPU the frequency of water stress events (CTA ≥ 0.2). Over the period 1961-2010, 23.1% of the total land surface was affected by water stress events, varying from being affected only once up to permanently being under influence of adverse water scarcity conditions. At the same time, we found significant correlations to variations in JMA SST values for one third (33.1%) of the land area susceptible to water stress events (blue dots). The global results found under the WCI (WCI ≤ 1700) are roughly similar, although the spatial distribution of affected land varies significantly due to the unequal clustering of population and consumptive water use (Fig. A.7). Using the WCI, up to 23.1% of the total land surface area has been affected by water shortage events at least once over the period 1961-2010 whilst 44.2% of this selected land area shows variations in water shortage conditions that could be significantly correlated to ENSO driven climate variability (blue dots). Percentages of population affected by water scarcity events are globally a factor 2.8 higher than the share of land area affected when using the CTA-ratio, with 39.6% of the global population being affected by water scarcity events in 2006-2010 respectively (using 5-year averaged values), compared to 13.9% of the global land area. Similar results were found under the WCI, 41.1% of the global population was affected by water scarcity events in 2006-2010 (using 5-year averaged values), compared to 13.9% of the total land area which is equal to a factor difference of 2.9.~~

~~[Figure 5 approximately here]~~

Due to the socioeconomic developments over the period 1961-2010 water scarcity conditions and their associated impacts intensified, both in absolute and relative sense~~. Figure 6 shows for the CTA-ratio (water stress) these increases in population and land area affected (red + orange fill) under changing socioeconomic conditions over the period 1961-2010 and at the global scale, relative to the total population and land area (dashed lines, set at 100 in 1961), and the development in population and land areas with a significant correlation to ENSO driven climate variability (grey + red fill). Similar graphs for the WCI (water shortage) are shown in Fig. A.8.~~ (Fig. 4 and Table 5). From 1961 to 2010, using 5-year averaged values, the total global population increased ~~with a factor 2.1 (~~from 2.97 ~~billion~~ to 6.25 billion~~)~~.. At the same time, we found ~~increases in~~that the global population ~~affected by water scarcity events. When using the CTA-ratio we found a factor difference of 5.5 (from 0.45 billion~~exposed to ~~2.47 billion), for the WCI we found increases of a factor 6.6 (from 0.39 billion to 2.57 billion). In relative sense, the population affected by~~ water scarcity events increased from ~~13.2% and 15.3% up to 41.1% and 39.6%, when looking at the WCI and CTA-ratio respectively. Unequal growth rates and the spatial clustering of population and consumptive~~

~~water use impact water scarcity events and its consequences given the fact that the share of land area affected by water scarcity events only doubled (factor: 2.2) over this same period for the CTA ratio, while it increased with a factor 4.7 when looking at the WCI.~~

~~Although the share of~~ 0.45 billion to 2.47 billion. The global population sensitive to ENSO driven climate variability increased with a factor 2.~~3 (WCI) to 2.~~4 ~~(CTA ratio) at~~over the same time period whilst its proportion to the global ~~level, it~~total population remained rather ~~equal over time when considered relative to the growth in total population, with relative growth factors of 1.1 using both the CTA ratio (from 28.7% to 31.3%) and the WCI (from 34.1% to 38.7%).~~unchanged (Table 5). The population sensitive to ENSO variability and living in areas ~~affected by~~exposed to water scarcity events currently represent only a minority of the global population~~, 15.9% for the WCI and~~ (11.4~~% when using the CTA ratio. However, these~~%). These results are, however, contrasted with relative high growth factors~~, 3.5 and 1.7 for the CTA ratio, and 6.9 and 3.3 for the WCI, representing the absolute and relative (with respect to the total population growth) increases over time respectively~~ (Table 5). The impact the spatial clustering of population and consumptive water use, and their unequal growth rates, on water scarcity events is shown by the fact that the share of land-area exposed to water scarcity events only doubled over this same period for the CTA-ratio (Fig. 4), from 7.4% up to 16.5% of the global land surface . The results found under for water shortage (WCI ≤ 1700) are roughly similar at the global scale (Fig. A.3, Table A.1) and therefore not discussed individually in this section.

[Figure ~~6~~4 approximately here]

[Table 5 approximately here]

Regional variations in the population ~~affected by~~exposed to water stress and/or being sensitive to ENSO driven climate variability under changing socioeconomic conditions, are visualized in Fig. ~~7~~5. Although these regional figures do not lend themselves to a similar growth factor analysis such as executed on the global numbers in Fig. ~~6~~4, we can distinguish by means of visual inspection different characteristic region-types. The first group of regions (Latin America Australia & the Pacific, the Caribbean, and Middle & Southern Africa) experiences significant correlations with ENSO variability for a relative large share of its land~~-~~-area and population (≥ 25% of the total population in 2010) whilst exposure to water scarcity ~~impacts are~~events is low (< 25% of the total population ~~affected~~ in 2010). The second group of regions shows both a relatively low sensitivity to ENSO driven climate variability (< 25% of the total population in 2010) and low exposure to water scarcity ~~impacts~~events (< 25% of the total population in 2010), e.g. Northern America and Western Europe. For the third group of regions (the Middle East, India, Southeast Asia, and West & Central Asia) we find significant water scarcity ~~impacts~~exposure (≥ 25% of the total population in 2010) but no or relative low sensitivity to ENSO variability (< 25% of the total population in 2010). Finally, the fourth group of regions shows relatively high exposure to water scarcity ~~impacts in terms of population affected~~events (≥ 25% of the total population in 2010) and abundant sensitivity to ENSO driven climate variability (≥ 25% of the total population in 2010), e.g. China and Northern Africa. Comparing these observations with the regional figures found for water shortage events (Fig. A.~~9~~4), assessed by means of the WCI, we found different results for the regions West & Central Asia (relative high sensitivity to ENSO variability & relative low water scarcity ~~impacts~~exposure), and Middle & Southern Africa, the Middle East and Southeast Asia (both experiencing relative high sensitivity to ENSO variability & high exposure to water scarcity ~~impacts~~events). Using both water scarcity metrics (i.e. CTA-ratio and WCI) in combination with the observed growth rates in population and population ~~affected by~~exposed to water scarcity events enables us to identify those regions where adaptation measures such as ENSO-based forecasting have the largest (future) potential in coping with and possibly reducing the adverse impacts of water scarcity events: the Caribbean, Latin America, Western & Central Asia, Middle & Southern Africa, Northern Africa, the Middle East, China, Southeast Asia and Australia & the Pacific.

[Figure ~~7~~5 approximately here]

3.4 Cross-model validation

The cross-model validation exercise, in which we compared the outcomes of the individual global hydrological models with their ensemble mean results, ~~shows~~reveals that our findings considering the sensitivity of water availability, consumptive water ~~consumption~~use, and water scarcity conditions to ENSO driven climate variability are robust to the use of different hydrological models. ~~When looking at~~ We found that for 22.8% of the ~~percentage~~global land~~-~~area ~~that shows~~(61.4% of the total land area with a significant correlation ~~between water availability and variations in JMA SST (~~under the ensemble-mean)~~**Fig.** 8) we find for 35.9% of this selected area that~~ all~~ the~~ individual GHMs show a significant correlation to variations in JMA SST in the same direction as the correlation results found under the ensemble-means~~ whilst the~~. Correlations found ~~correlations~~ under the ensemble-mean are supported by at least ~~two~~one global hydrological models for ~~72.3%~~one-third (36.8%) of ~~this~~the global land surface (Fig. 6), equal to 99.2% of the land area that shows a significant correlation to the ensemble-mean.

[Figure ~~8~~6 approximately here]

A comparison of the individual modelling results with the ensemble-mean in terms of the estimated population ~~affected by~~exposed to water scarcity events and/or living in areas sensitivity to ENSO driven climate variability ~~reveals~~shows the ~~size of inter-model deviations~~modelling spread at the global scale with respect to estimated impacts and their developments over time (Fig. ~~9~~7). Looking at the 2010 values, we find the smallest percentage difference between models in the estimates of the population ~~affected by~~exposed to water scarcity events (+17.2% CTA-ratio, +21.8% WCI), and the largest variations when looking at the population both ~~affected by~~being exposed to water scarcity events and living in areas sensitive to ENSO driven climate variability (+68.9% CTA-ratio, +54.2% WCI). Percentage deviations ~~are~~were found to be smaller when ~~considering~~ looking at the land~~-~~area ~~affected rather than the population affected~~exposed (Fig. A.10). As shown in Fig. ~~9~~7 and Fig. A.~~10~~5, the inter-model comparison reveals that the impact estimates of the ensemble-mean are conservative when comparing them with the

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individual modelling results, especially when looking at the population or land~~-~~-area sensitive to ENSO variability and/or being ~~affected by~~exposed to water scarcity events.

[Figure ~~9~~7 approximately here]

4. Discussion

Within this study we found that both water resources availability and water scarcity conditions can be significantly correlated with ENSO driven climate variability as measured with the JMA SST index for a relative large share of the global land~~-~~-area. Due to ~~the~~ clustering effects we found even larger ~~shares~~proportions when looking at the population living in these areas.

Regions well-known for their correlation of precipitation and hydrological extremes with ENSO variability (Dai & Wigley, 2000; Dettinger and Diaz, 2000; Ropelewski & Halpert., 1987; Vicente-Serrano et al., 2011; Ward et al.,2010, 2014a) also showed a statistically significant correlation between ENSO and annual total water resources availability or water scarcity conditions. This makes sense as precipitation deficits feed droughts, which possibly results in water scarcity events if consumptive demands outweigh the available water resources. On the other hand precipitation surpluses might result in increased water levels, floods, and increased flood risk but at the same time decreased water scarcity conditions. When comparing our results on water resources availability to these previous studies, we find corresponding significant correlations in the regions mid-west North-America, the Caribbean, Latin America, Southern Africa, South-East and Central Asia and the Pacific. Moreover, the sign of the correlations found within four large river basins in Latin America and Africa, (Amazon Congo, Paraná, and Nile) is supported by earlier estimates of Amarasekera et al. (1997) who assessed the correlation between ENSO and the natural variability in the flow of tropical rivers. Significant correlations as shown for other regions were also found in case studies focusing on Northern America (e.g. Clark II et al., 2014; Schmidt et al., 2001), South-east Asia (e.g. Lü et al., 2011; Räsänen & Kummu, 2013), Southern Africa (e.g. Meque & Abiodun, 2014; Richard et al., 2001), and Australia (e.g. Chiew et al., 2011; Dutta et al., 2006). The spatial variation in sign of the found correlation is in line with the results of Ward et al. (2014a), who found that annual flood and mean discharge values intensify under La Niña and decline when moving towards El Niño phases globally in more areas than the other way around.

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In line with earlier research (e.g. Meza et al., 2005; Islam & Gan, 2015) we would have expected to find more areas with a significant correlation between consumptive water use and ENSO driven climate variability. A number of explanations could be given for the absence of significant correlations patterns in this study: 1) the consumptive water use estimates used in this study are calculated by means of multiple socioeconomic and hydro-climatic proxies and variables, such as extent of irrigated areas, number of livestock, GDP, (long-term mean) monthly temperatures, and precipitation estimates, and should be interpreted as potential consumptive water use; 2) of these variables only irrigation water use could be linked directly to ENSO driven climate variability by means of its temperature and precipitation input variables. 'Fixed' consumption numbers in other sectors might attenuate therefore the variability found within the irrigation sector; 3) climate-driven variations in irrigation water demands are the result of changes in crop evapotranspiration and changes in green water availability, which do not have a univocal relation with ENSO driven climate variability at all times, but are partly determined by the month-specific cropping calendar and antecedent conditions, such as the memory of the soil (i.e. the ability of the soil to 'remember' anomalous wet or dry conditions long after these conditions occurred in the atmosphere or any other stage of the hydrological cycle (Seneviratne et al., 2006); and 4) yearly totals of consumptive water use were applied in this study to assess its sensitivity to ENSO driven climate variability whereas it might be more appropriate for consumptive water use to assess its correlation either using monthly time-scales or yearly maxima.

The analysis presented in this study ~~also reveals, however,~~revealed that inter-annual variability itself, such as the ENSO driven climate variability, is often not enough to cause water scarcity events to actually occur. We found that it is a combination of multiple hydro-climatic factors, such as the mean water resources availability and its inter-annual variability around the mean, together with the prevalent ~~socio-economic~~socioeconomic conditions, that determines the susceptibility of a region to water scarcity events, a finding earlier suggested by Veldkamp et al. (2015) and Wada et al. (2011a), and its implications being discussed in Hall & Borgomeo (2013). The actual impact of water scarcity events depends, moreover, not only on the number of people ~~affected~~exposed or the severity of a water scarcity event itself, but on how sensitive this population is to water scarcity conditions, whether and how efficiently governments can deal with water scarcity problems, and how many (financial and infrastructural) resources are available to cope with these water scarce conditions (Grey & Sadoff, 2007; Hall & Borgomeo, 2013).

Given the substantial share of land~~-~~ area, and the even higher rates of population, for which water resources availability and water scarcity conditions show significant correlations with ENSO driven climate variability there is a large potential for ENSO based adaptation and risk reduction to cope with water scarcity events and ~~its~~their associated impacts. The relative importance of ENSO driven climate variability in the year-to-year-variability as found in this study could assist water managers and decisions makers in the design of adaptation strategies, such as in optimizing the use of existing reservoir facilities in Australia (Sharma, 2000). Moreover, the potential predictability of ENSO with lead times up to several months, may help in the prioritization of (ex-ante) efforts in disaster risk reduction, such as pre-stocking foods and disaster relief goods or crop insurance systems based on ENSO indices (Coughlan de Perez et al., ~~2014a, b~~2014, 2015; Dilley, 2000; Suarez et al., 2008). Potential added value of adaptation measures targeting on the impacts of inter-annual variability is high, as it is especially this variability that people find difficult to cope with (Smit & Pilifosova, 2003). In this paper we looked, however, at naturalized flows, no reservoirs or inter-basin transfers were taken into account yet. Future research should therefore, first evaluate whether (virtual) water trading and water storage mechanisms are effective in reducing water scarcity conditions and whether management could be optimized using ENSO-forecasting parameters and at what costs.

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To get more insight in the expected correlation between ENSO, and water resources and scarcity conditions under longer-term climate change and ~~socio-economic~~socioeconomic developments, future research could use extreme JMA SST values as a test case in combination with the correlation values found to extrapolate the water resources and scarcity conditions under extreme events. Recent research showed that these extreme ENSO events may become more recurrent in the future (Cai et al., 2014; IPCC, 2013; Power et al., 2013~~), the~~). The uncertainty among the different climate models is, however, large and ~~any~~at the same time there is no agreement yet on the attribution of long-term climate change to increases in the sensitivity and frequency of ENSO events ~~lacks~~ (Van Oldenborgh et al., 2005; Paeth et al., 2008; Guilyardi et al. 2009). Considering a continuous increase in population growth and water scarcity impacts in the future, hotspots could be appointed that have to deal with water scarcity events and~~/or~~ are sensitive to ENSO driven variability at the same time. One should take into account, however, that we assumed in this study that the found correlations between water availability, consumptive water use, and water scarcity conditions, and the JMA SST index value ~~remains~~remain stationary over time. In reality, the strength of correlations between hydrological parameters and ENSO can change over time (Ward et al., 2014a). Further research is therefore needed to assess whether, how much, and in which direction these observed correlation values change under the combination of changing climatic conditions and historic and future ~~socio-economic~~socioeconomic developments.

~~The results presented in this study underpin the need for more research on the topic of ENSO and water scarcity, for example regarding the variability in consumptive water use and its correlations with ENSO driven variability, but also considering the potential economic impacts of water scarcity events.~~ Moreover, ENSO is part of an ocean-atmospheric climate variability system that constitutes of many more sub-regional systems and local circulation patterns (e.g. Indian Monsoon and European weather systems) which modulate the ENSO signal. ~~New~~Future research should look into the sensitivity of water resources availability and scarcity conditions to combinations of these systems.

~~Finally, future research should focus in the following directions to improve/extend the analysis carried out in this study. In this paper we looked at naturalized flows, no reservoirs or inter basin transfers were taking into account. Future research should evaluate whether water trading and water storage mechanisms are effective in reducing water scarcity conditions and whether management could be optimized using ENSO forecasting parameters: e.g. ex-ante storage or release of water to counterbalance the impacts of ENSO variability or the incorporation of ENSO variability in water transfer mechanisms, and finally at what costs? Moreover, no management decisions with respect to water saving measures have been taken into account. This could lead to substantial overestimations of the water scarcity conditions as presented in this study. Variability in water demand as observed within this study is based on physical parameters, whilst in reality well-organized societies can react to emerging water scarcity conditions, thereby diminishing their adverse impacts. In other less well organized regions, we might underestimate water scarcity impacts, as ill-management might prohibit a full and optimal exploitation of the available water resources in space and time, as assumed in this study.~~ Global assessment studies, such as the one presented ~~in this study~~here, are well able to identify the impact of ENSO on global-scale patterns ~~in~~of water scarcity ~~conditions and~~

~~sensitivity to ENSO driven climate variability~~. These types of studies are therefore well-suited for a first-order problem definition or for the large-scale prioritization of adaptation efforts~~, such as making a first distinction in regions were ENSO forecasting might be beneficial.~~. When interpreting these assessments one should keep in mind, however, that these studies should always be complemented with local or regional scale analyses to assess the actual level of water scarcity 'on the ground', their (economic) consequences, and regional or local scale potential for ENSO forecasting as adaptation strategy to cope with water scarcity events.

5. Conclusions

~~In~~Within this ~~paper~~contribution, we executed the first global~~-~~-scale sensitivity assessment of blue water ~~resources~~ availability, consumptive water use, and water scarcity ~~events~~ to ENSO driven climate variability~~ over the time period 1961-2010. An ensemble mean of three global hydrological models was used to estimate per FPU the yearly water resources availability and water scarcity conditions, considering both water shortage and stress. Correlations between ENSO, and water resources, water consumption and water scarcity conditions were determined using the JMA SST indices and ENSO phase determination whilst the sensitivity of water scarcity events to ENSO driven climate variability was assessed applying critical threshold values for both water shortage and stress. Finally, the sensitivity of water scarcity events to ENSO driven climate variability under changing socioeconomic conditions was evaluated opening the discussion on their implications for ENSO based adaptation and risk reduction.~~

. Throughout this paper we have shown that regional water scarcity conditions become more extreme under El Niño and La Niña phases ~~due to the sensitivity of water resources availability and consumptive water use to ENSO driven climate variability. We found that both water resources availability and water scarcity conditions can be significantly correlated with ENSO driven climate variability as measured with the JMA SST index for~~covering a relative large proportion (>~~–~~28.1%) of the global land~~-~~-area. Due to the spatial clustering of population and consumptive water use we found even larger shares (>31.4% of the total population in 2010) when looking at the population living in these areas~~.~~ being sensitive to ENSO driven climate variability. The ~~sensitivity~~exposure of a region to water scarcity events~~, expressed in terms of land area or population impacted,~~ is determined by both hydro-climatic and socioeconomic conditions. ~~The results~~Results on ~~the impacts of~~exposure to water scarcity events ~~presented~~, found in this study~~ provided~~, provide mixed signals. We found that the population that is currently ~~affected by~~exposed to water scarcity events consists of less than half of the global population (CTA-ratio: 39.6~~% and~~%, WCI: 41.1~~% for water stress and water shortage events respectively),~~%), whilst the population sensitive to ENSO variability and living in areas ~~affected by~~exposed to water scarcity events represent only a minority of the global population~~,~~ (CTA-ratio: 11.4~~% and~~%, WCI: 15.9~~% for the water stress and shortage respectively.~~%). These results are, however, contrasted by relative differences in growth rates under changing socioeconomic conditions, which are higher in regions ~~affected by~~exposed to water scarcity events than in regions that do not experience any water scarcity.

Given the ~~found~~ correlations ~~of~~found in this study for water availability and water scarcity conditions with ENSO driven climate variability, and seen the developments in the population and land~~-~~ area ~~affected by~~exposed to water scarcity events and/or being sensitive to ENSO driven variability under changing socioeconomic conditions, we found that there is large potential for ENSO based adaptation and risk reduction~~ to cope with water scarcity and its associated impacts.~~. The observed regional variations could thereby accommodate in a first-cut prioritization ~~of the implementation of~~for such adaptation strategies. Moreover, the results presented in this study show that there is both potential and need for more research on the issue of ENSO and water scarcity with emerging topics related to the economic impacts of water scarcity; the assessment of consumptive water use and its temporal variability; the combined impact of large scale oscillation systems on water resources and water scarcity conditions; and the transferability of global scale insights to local-scale implications and decisions.

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Tables

Table 1~~:~~. Hydrological years that fall under the El Niño and La Niña phase. Other years are classified as ENSO neutral.

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ENSO phase	Hydrological year
El Niño	1964,1966,1970, 1973, 1977,1983,1987,1988,1992,1998, 2003, 2007, 2010
La Niña	1965,1968,1971,1972,1974,1975,1976,1989,1999,2000,2008

Table 2. Percentage of the global land area for which (a) water resources availability and (b) consumptive water use show a significant (positive/negative) correlation with ENSO driven climate variability (as assessed with the JMA SST anomaly index).

	Significant correlation	Sign. positive correlation	Sign. negative correlation
Water Availability	37.1 %	13.2 %	23.9 %
Consumptive water use	8.3 %	1.0 %	7.3 %

Table 3. Percentage of the global land area for which water scarcity conditions show a significant (positive/negative) correlation with ENSO driven climate variability (as assessed with the JMA SST anomaly index). Water scarcity conditions were assessed by means of the CTA-ratio for water stress and WCI-ratio for water shortage.

	Significant correlation	Sign. positive correlation	Sign. negative correlation
Consumption to Availability Ratio (CTA-ratio)	28.1 %	16.8 %	11.3 %
Water Crowding Index (WCI)	37.9 %	23.9 %	14.0 %

Table 4. Percentage of the global land area for which FPUs show significant anomalies in the median values of water scarcity conditions between the El Niño (EN) and La Niña (LN) phase, compared to the median values under all years. Water scarcity conditions were assessed by means of the CTA-ratio for water stress and WCI-ratio for water shortage.

	Significant Anomaly	Sign. Anomaly – El Nino Phase	Sign. Anomaly – La Nina Phase
Consumption to Availability Ratio (CTA-ratio)	12.8 %	3.4 %	12.8 %
Water Crowding Index WCI)	14.8 %	6.9 %	9.5 %

Table 5. Development of (a) the global total population, (b) the global population exposed to water scarcity events (CTA-ratio), (c) the global population living in areas sensitive to ENSO driven climate variability, and (d) the global population being exposed to water scarcity events (CTA-ratio) & living in areas sensitive to ENSO driven climate variability, between 1961 and 2010 using 5-year averaged values. Numbers between brackets show the values expressed in percentage of the total population. Growth factors represent both the absolute increases as well as the relative increases over time.

	Total Population	Population exposed to water scarcity events(CTA >0.2)	Population sensitive to ENSO driven climate-variability	Population sensitive to ENSO driven climate-variability & exposed towater scarcity events (CTA >0.2)
1961-1965	2.97 billion	0.45 billion (15.3%)	0.85 billion (28.7%)	0.2 billion (6.8%)
2006-2010	6.25 billion	2.48 billion (39.6%)	1.96 billion (31.3%)	0.71 billion (11.4%)
Growth factor	2.1	5.5 (2.6)	2.3 (0.4)	3.5 (1.5)

Table A. 1. Development of (a) the global total population, (b) the global population exposed to water scarcity events (WCI), (c) the global population living in areas sensitive to ENSO driven climate variability, and (d) the global population being

exposed to water scarcity events (WCI) & living in areas sensitive to ENSO driven climate variability, between 1961 and 2010 using 5-year averaged values. Numbers between brackets show the values expressed in percentage of the total population. Growth factors represent both the absolute increases as well as the relative increases over time.

	Total Population	Population exposed to water scarcity events(WCI≤1700)	Population sensitive to ENSO driven climate-variability	Population sensitive to ENSO driven climate-variability & exposed towater scarcity events (WCI≤1700)
1961-1965	2.97 billion	0.39 billion (13.2%	1.01 billion (34.1%)	0.14 billion (4.8%)
2006-2010	6.25 billion	2.57 billion (41.1%)	2.41 billion (38.6%)	0.99 billion (15.9%)
Growth factor	2.1	6.6 (3.1)	2.4 (0.4)	6.9 (2.9)

Figures

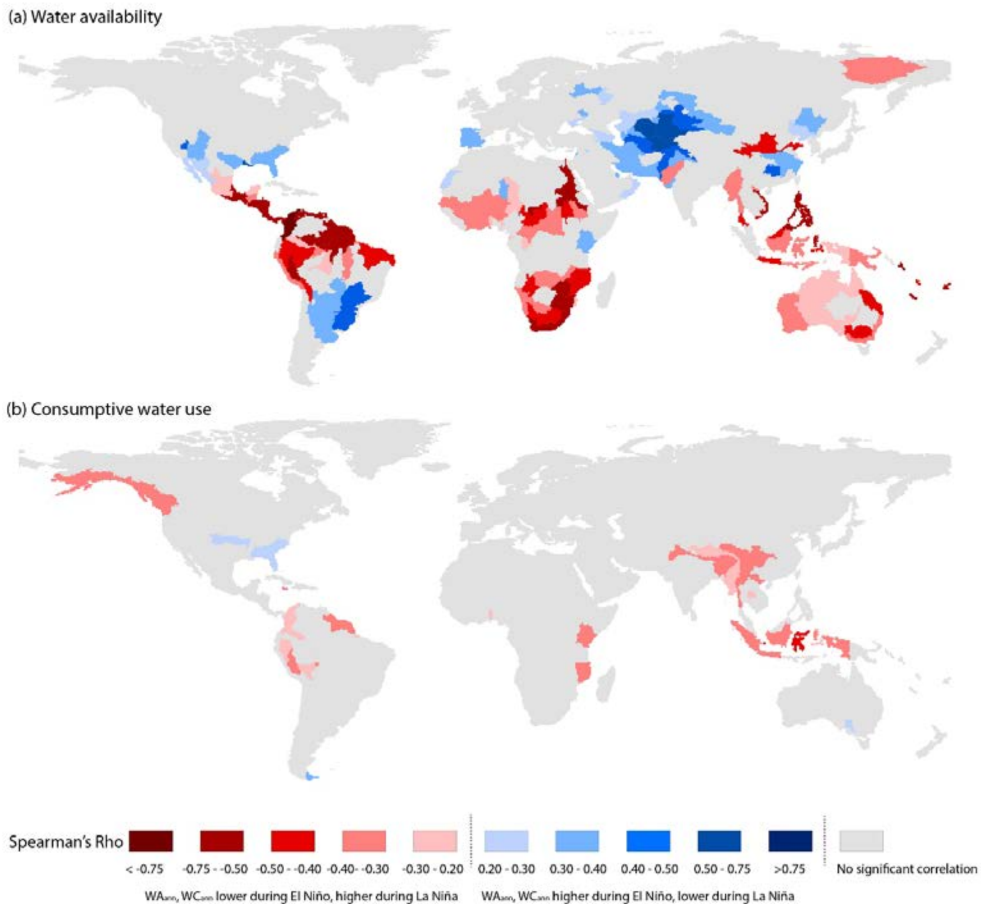

Figure 1. Correlation (Spearman's Rho) of yearly (a) water availability and (b) consumptive water use values, as assessed under fixed socioeconomic conditions, to variations in JMA SST using the 3-monthly period with the highest correlation (JMA $SST_{bestoff}$). Significance was tested by means of regular bootstrapping ($n = 1000$, $p \leq 0.05$) and the correlation is only shown for those areas which reach significance. Positive correlations indicate increases in annual water availability and consumption with the JMA $SST_{bestoff}$ index moving towards El Niño values. Negative correlations indicate decreases in annual water availability with the JMA $SST_{bestoff}$ index moving towards El Niño values.

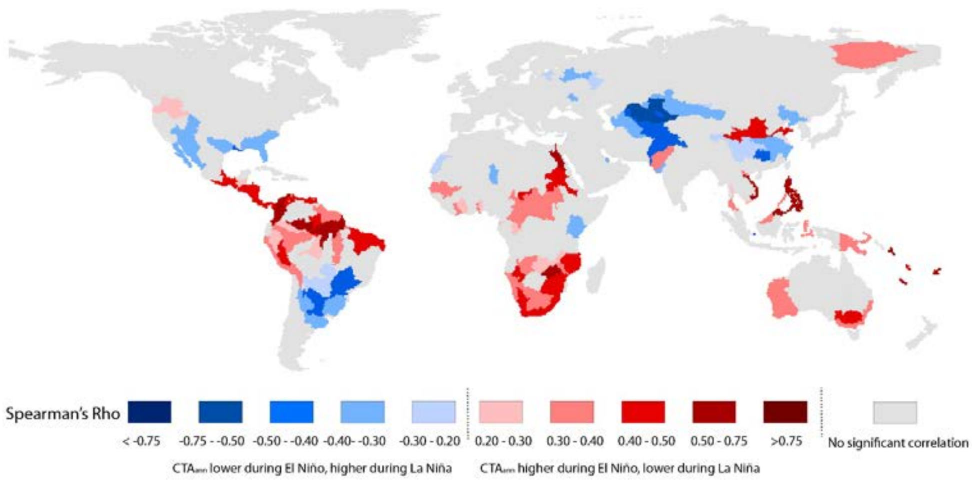

Figure 2. Correlation (Spearman's Rho) of yearly water scarcity conditions (CTA-ratio), as assessed under fixed socioeconomic conditions, to variations in JMA SST using the 3-monthly period with the highest correlation (JMA $SST_{bestoff}$). Significance was tested by regular bootstrapping ($n = 1000$, $p \leq 0.05$) and the correlation is only shown for those areas with significant correlations. Positive correlations indicate increases in CTA-ratio values (more severe water scarcity conditions) with the JMA $SST_{bestoff}$ index moving towards El Niño values. Negative correlations indicate decreases in CTA-ratio values (less severe water scarcity conditions) with the JMA $SST_{bestoff}$ index moving towards El Niño values.

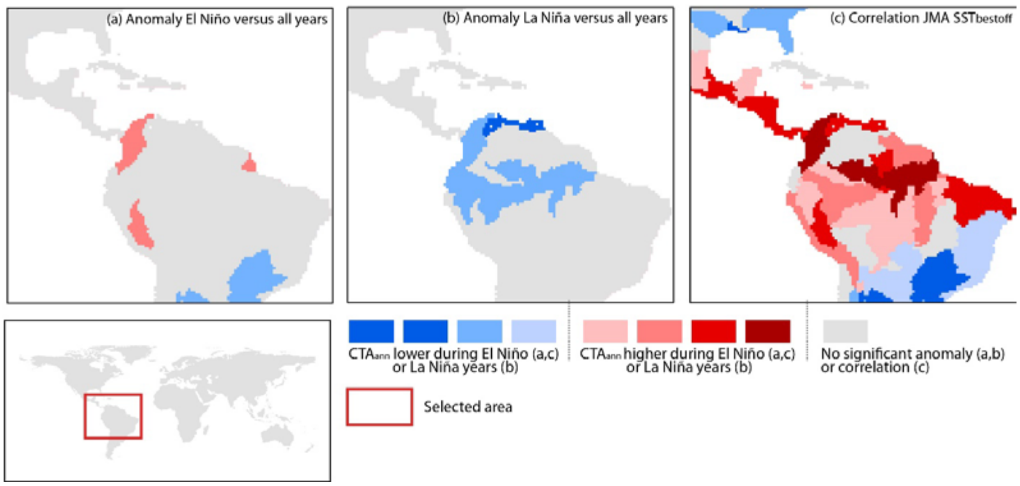

Figure 3. Comparison of results found when studying the: (a) anomaly in water scarcity conditions (CTA-ratio) between El Niño and all years; (b) anomaly in water scarcity conditions (CTA-ratio) between La Niña and all years; and (c) the sensitivity of water scarcity conditions (CTA-ratio) to ENSO driven climate variability measured by means of the JMA $SST_{bestoff.}$ Red colors indicate more severe scarcity conditions under El Niño phases (a,c) or La Niña phases (b). Blue colors indicate less severe scarcity conditions under El Niño phases (a,c) or La Niña phases (b).

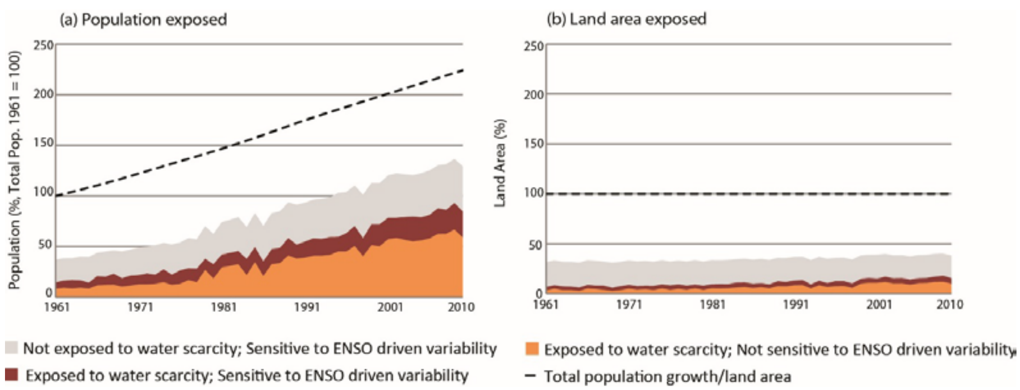

Figure 4. Development of population and land-area exposed to water scarcity events and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as estimated with the CTA-ratio. Figure 4.A shows the growth in population living under water scarce conditions and/or living in areas sensitive to ENSO driven climate variability relative to the total growth in global population (set at 100 in 1961). Figure 4.B shows the increase in land-area exposed to either water scarcity events and/or ENSO driven climate variability relative to the total global land-area (100).

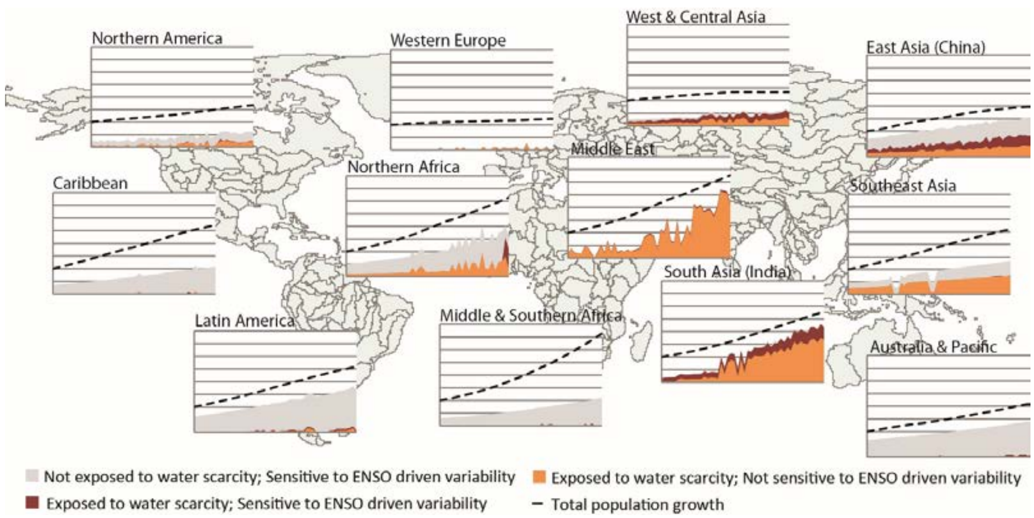

Figure 5. Regional variation in developments of population (%) exposed to water scarcity events and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as estimated with the CTA-ratio. The figure shows per world region the growth in population living under water scarcity conditions and/or living in areas sensitive to ENSO driven climate variability, relative to the total growth in global population (set at 100 in 1961). Y-axis (% population) ranges from 0 up to 400.

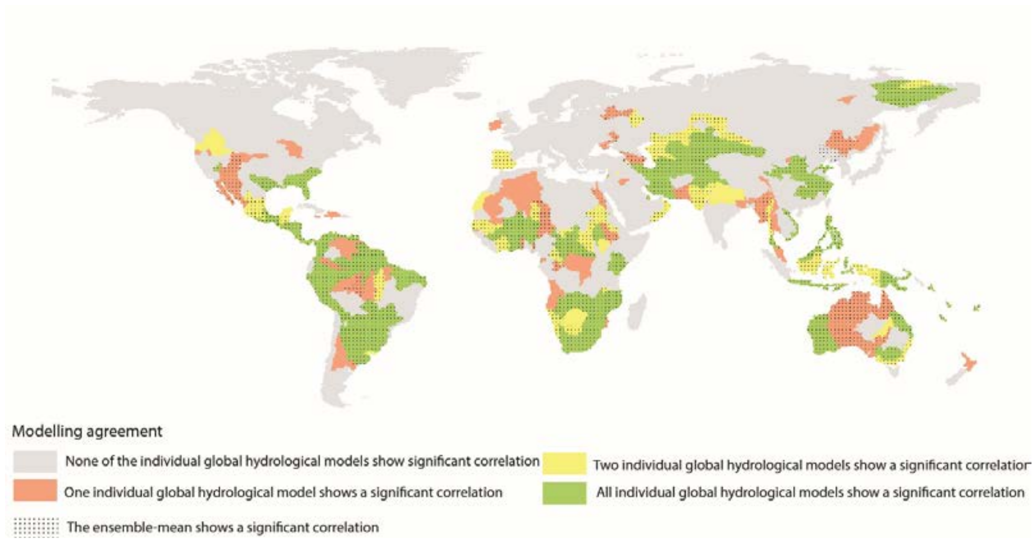

Figure 6. Modelling agreement in observed significant sensitivity of water availability to variation in JMA SST.

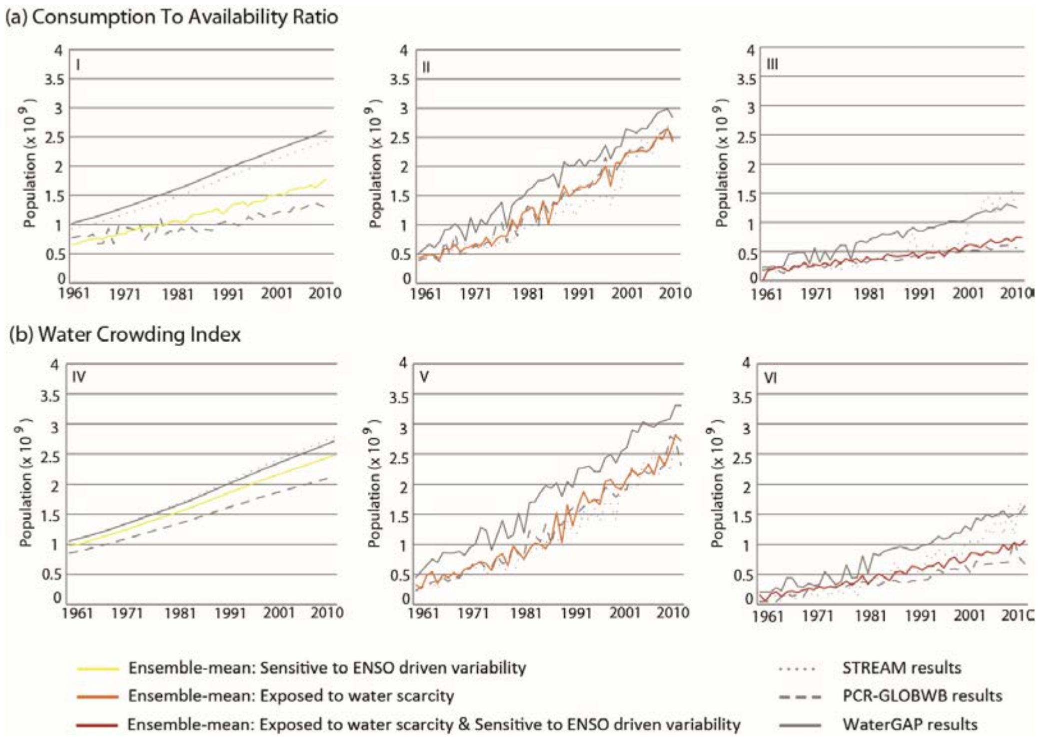

Figure 7. Development of the population and land-area exposed to water scarcity events (CTA-ratio) and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as assessed by the individual global hydrological models (STREAM, PCR-GLOBWB, and WaterGAP) and the ensemble-mean. Fig. I and IV show the development in population sensitive to ENSO driven climate variability as estimated under the ensemble-mean (yellow) and individual GHMs (grey). Fig. II and V present the increase in population exposed to water scarcity events for the ensemble-mean (orange) and individuals GHMs (grey). Fig. III and VI visualize the amount of people being exposed to water scarcity events while at the same time living in areas with a significant correlation to ENSO driven climate variability for the ensemble-mean (red) and individual GHMs (red).

Appendix A: Supplementary Figures

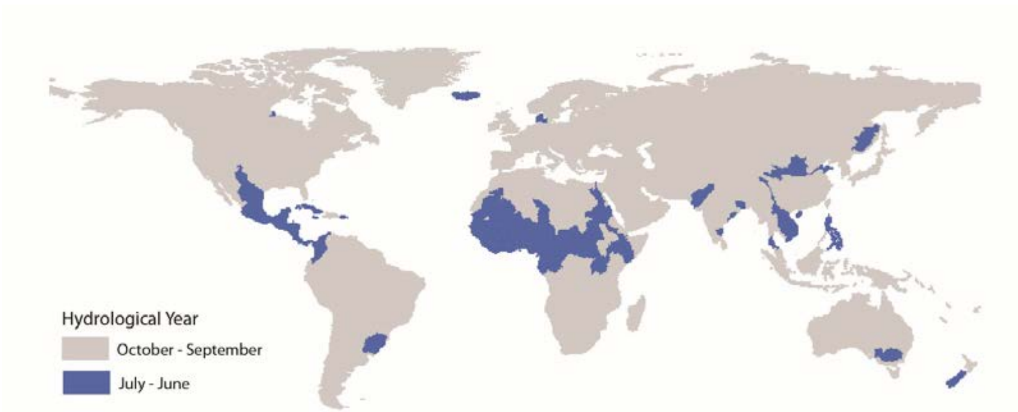

Fig. A 1. Hydrological years used in this study.

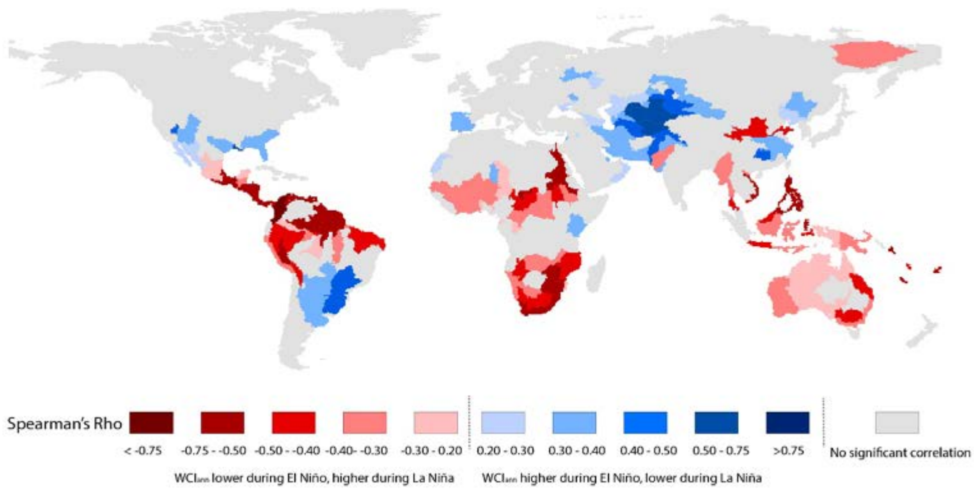

Fig. A 2. Correlation (Spearman's Rho) of yearly water scarcity conditions (WCI), as assessed under fixed socioeconomic conditions, to variations in JMA SST using the 3-monthly period with the highest correlation (JMA $SST_{bestoff}$). Significance was tested by regular bootstrapping (n = 1000, $p \leq 0.05$) and the correlation is only shown for those areas with significant correlations. Positive correlations indicate increases in WCI values (less severe water scarcity conditions) with the JMA $SST_{bestoff}$ index moving towards El Niño values. Negative correlations indicate decreases in WCI values (more severe water scarcity conditions) with the JMA $SST_{bestoff}$ index moving towards El Niño values.

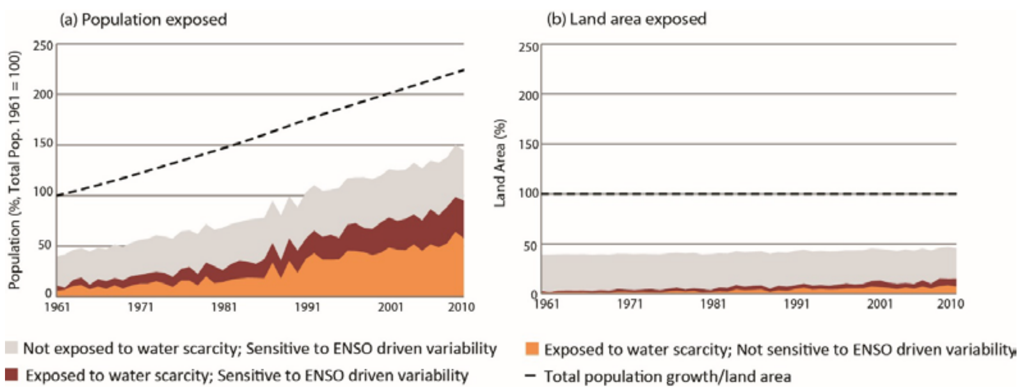

Fig. A 3. Development of population and land-area exposed to water scarcity events and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as estimated with the WCI. Figure A.3.A shows the growth in population living under water scarce conditions and/or living in areas sensitive to ENSO driven climate variability relative to the total growth in global population (set at 100 in 1961). Figure A.3.B shows the increase in land-area exposed to either water scarcity events and/or ENSO driven climate variability relative to the total global land-area (100).

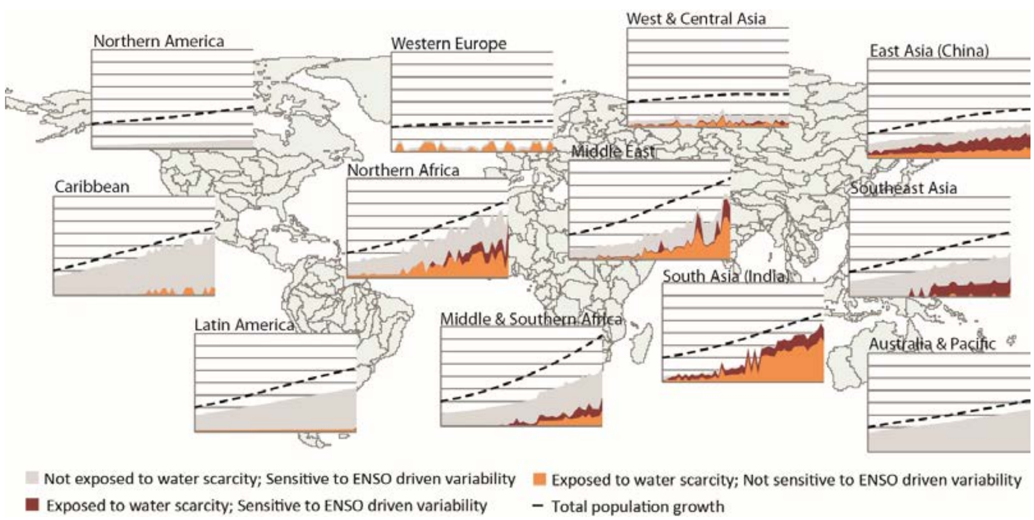

Fig. A 4. Regional variation in developments of population (%) exposed to water scarcity events and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as estimated with the WCI. The figure shows per world region the growth in population living under water scarcity conditions and/or living in areas sensitive to ENSO driven climate variability, relative to the total growth in global population (set at 100 in 1961). Y-axis (% population) ranges from 0 up to 400

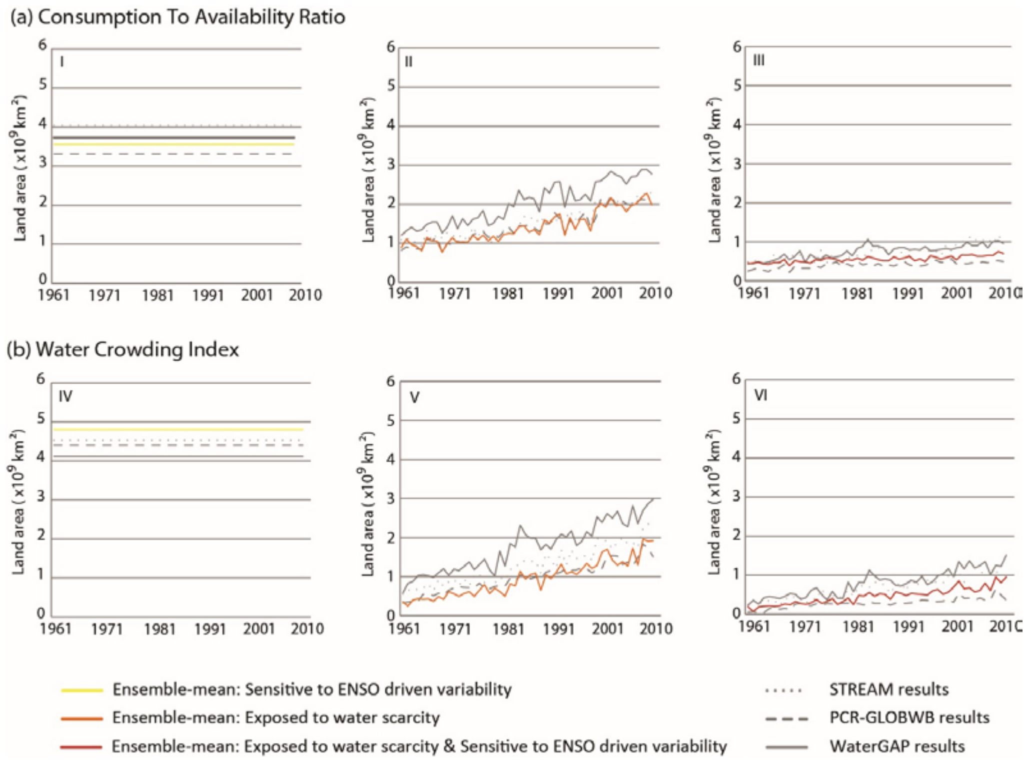

Fig. A 5. Development of the population and land-area exposed to water scarcity events (WCI) and/or being sensitive to ENSO driven climate variability over the period 1961-2010, as assessed by the individual global hydrological models (STREAM, PCR-GLOBWB, and WaterGAP) and the ensemble-mean. Fig. I and IV show the development in population sensitive to ENSO driven climate variability as estimated under the ensemble-mean (yellow) and individual GHMs (grey). Fig. II and V present the increase in population exposed to water scarcity events for the ensemble-mean (orange) and individuals GHMs (grey). Fig. III and VI visualize the amount of people being exposed to water scarcity events while at the same time living in areas with a significant correlation to ENSO driven climate variability for the ensemble-mean (red) and individual GHMs (red).