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Discussions

Interactive comment on "Climate-driven interannual variability of water scarcity in food production: a global analysis" *by* M. Kummu et al.

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We are grateful for the thoughtful and critical comments of the reviewer, which help us to improve the clarity and focus of the paper. We will take all the comments carefully into account when revising the paper, as specified below.

Prior to going to detailed responses we would like to, however, clarify the aim of our paper that was not fully understood. Our aim was not to analyse the actual historical evolvement of the green-blue water scarcity but to assess how present food production and related use of water resources is influenced by hydroclimatic variability. To cover this variability (and its potential changes as observed in the past), we used climatic records for the past decades. As the purpose of our paper is to assess the isolated

effect of climate variability on green-blue water scarcity, we had to keep other variables (e.g. population, land-use, diet and crop management) constant.

Our paper finds a certain difference in interannual water scarcity estimates and interannual variability in water scarcity due to hydroclimatic variability, which we hope is interesting enough to deserve publication due to the very important role of interannual variability in food production and underlying water resources (e.g. Haile, 2005; Tubiello et al., 2007; Zhang et al., 2010). The recent droughts in the US and in Australia, for example, have highlighted this importance. However, in most water scarcity studies average climate conditions are used and thus, the natural variability between years has been not taken into account.

From hydrological and climatological perspectives, 30 years of data are considered as an adequate time period, as it captures well the interannual climate variability (e.g. several ENSO cycles) and also possible long-term climatic trends. We thus selected for our climatological study period the most recent 30-yr period with available hydroclimatic forcing data for the model, being 1977-2006. This period thus represents the current climate conditions and interannual variability impacting on water resources used for food production.

Due to the absence of some of the required datasets (i.e. crop distribution, detailed irrigation data) for a more recent time period, we needed to use the year 2000 as a reference year for the water requirements related parameters and datasets (i.e. population, land cover, crop distribution, etc.).

We acknowledge that although we aimed to be clear on these issues throughout the paper, it might not fully reveal all the aspects specified above. We will pay special attention on this in the revised manuscript.

Reviewer's comment 1.1: Novelty. This paper claims (page 6944, line 13, and elsewhere) to analyze the interannual variability of global water scarcity for the first time. However, to my knowledge, other papers have done this, such as Wada et al 2011. In fact, the analysis by Wada et al 2011 is performed at the monthly time-scale for the past several decades and additionally incorporates changing water demand over time, thus making it more sophisticated than the constant treatment of population, land-use, diet (economic growth), and agricultural management in this paper.

Authors' response 1.1: We do acknowledge the critique towards the novelty of our paper. We had overlooked the Wada et al. (2011a) paper in terms of their excellent contribution on interannual variability in blue water stress and the evolution of its historical trend. We will add the contribution of that paper to the introduction and discussion parts of the revised manuscript, and refine the main novelty statement of our paper accordingly.

It is important, however, to differentiate interannual variability (the extent to which data points in a statistical distribution or data set diverge from the average value) from the historical evolvement (how this average value has changed over time). There are some papers analysing the historical evolvement of blue water scarcity (Kummu et al., 2010; Wada et al., 2011a) and others which analyse the intra-annual variability of water stress (Hanasaki et al., 2008; Wada et al., 2011b; Hoekstra et al., 2012).

After refined literature search, we did not find papers other than Wada et al. (2011a) which analyse in detail the global interannual variability in water scarcity. There are clear differentiations, and steps forward, in our study compared to former studies, on how variability has been analysed. These are listed and explained below, and they will also be made more explicit in the revision:

- While we analyse the green-blue water (GBW) scarcity, Wada et al. (2011a) analyse blue water stress. Both are important, but in terms of impact of water scarcity on food production, the GBW scarcity reveals much more information than only blue water stress. The reason is that green water contributes about 90% to agricultural water

consumption (Rost et al., 2008; Liu et al., 2009; Hoekstra and Mekonnen, 2012), such that a blue water analysis only captures scarcities related to irrigation (and domestic and industrial uses).

- Wada et al. (2011a) used the interannual variability to differentiate the anthropogenic and climatic component in the historical evolvement of blue water stress. They thus also a used fixed population and water use, for year 1960, to analyse the impact of climate variability. We use the population and land use for year 2000, i.e. significantly closer to the present situation. Thus, our analysis gives a more up-to-date picture of the impacts of climate variability on present water scarcity.

- Several studies state that the interannual climatic variability has increased in various parts of the globe. We assess whether this can be seen in GBW scarcity, as we compare the variability between two 30-yr time periods – while Wada et al. (2011a) used one 40-yr period.

- Instead of only assessing the impact of variability on water scarcity, we assess also the impact of it on the frequency of water scarcity.

- We also include an analysis of possible countermeasures on water scarcity and its variability.

We believe, therefore, that our paper is novel and includes new scientific information in various ways.

R1.2: Purpose. I do not understand the purpose of the paper, which is to determine whether a food production unit (FPU) is water scarce, based upon the ability of the FPU to be self-sufficient in terms of food production. This assumes that global food production would operate under a system of autarky, i.e. in the absence of any trade, even re-distribution within a single country. This assumption seems completely unrealistic, unwarranted, and even undesirable. To this point, calculations in the paper of global human population numbers subject to chronic water scarcity based upon this autarky assumption are mis-leading (section 3.3). People in these areas may not face water scarcity, due to the spatial separation between agricultural production and consumption. Similarly, domestic water demand is often given priority, even in areas with limited agricultural supplies. Rather than determining water scarcity based upon theoretical food self-sufficiency, it would make more sense to determine whether hydro-climatic conditions will enable theoretical yield values to be reached, such as on areas deemed "water scarce" by Foley et al 2011.

A1.2: We appreciate the critical comments on the purpose of our paper. There are, however, several issues that needs to be clarified regarding this purpose:

- Our approach does not assume that global food production would operate under absence of trade. We agree that this is neither realistic nor desirable, but a suitable working hypothesis for exploring climate- and water-driven quandaries of different countries or FPUs, and for exploring their dependency on trade or other (storage) options. In the absence of specific trade information, which is partly missing for the past and requires a study on its own, the self-sufficiency assumption is often made for explorative studies like this (Rockström et al., 2007; Fader et al., 2013). We think that this is important information, as security of domestic food supply for possible emergency situation is still important for many countries. At the same time, large part of the less developed countries do not have strong enough economies to enter global food markets and are thus mainly dependent on domestic food production. Globally more than 80% of the food (kcal-wise) is consumed in the country it is produced in (based on Food balance sheets; FAO, 2013b). We agree that the scope and limits of this analysis was stated a bit misleadingly in the paper, and the reasoning will be made more explicit in the revision.

- We agree that domestic water demand is often given priority over agricultural demand. However, global domestic water use represents only a small fraction of what is used for food production (324 km3 vs. 8,250 km3 when both green and blue water are taken

into account) (Hoekstra and Mekonnen, 2012). Therefore, we do think that it is crucially important to understand the green-blue water requirements for food production and how hydroclimatic variation impacts on that.

- One advantage of the GBW scarcity approach employed here is that it includes the availability of, and demand for, green water in food production, while most water scarcity indicators include only the blue water fraction.

- We acknowledge the suggestion of determining whether hydroclimatic conditions enable theoretical yield values to be reached. This is, however, a different research question and thus should be analysed in a study of its own.

R1.3: Methodology. If this paper quantifies the impact of hydro-climate variability on water availability and demand (3rd sentence abstract), then some demand factors must be incorporated into the analysis. These demand factors must then vary over time, since the major purpose of the paper is to obtain inter-annual water scarcity estimates. Constant population, land-use, diet, and crop management is too simplistic for an interannual analysis. Similarly, there are several empirical constants that simplify the analysis, but lead to questionable results. For example, fixing the fraction of caloric consumption to 80% vegetable and 20% meat and fixing water availability to 40% of the sum of runoff and water storage (page 6938, line 12).

A1.3: We are well aware of these limitations (see following explanations), and obviously we have not been clear enough regarding to the purpose of the study.

- The purpose of our paper is to assess the isolated effect of climate variability on green-blue water scarcity, as also recognised by the reviewer and as stated in various parts of the manuscript. Therefore, we had to keep other variables than climate (e.g. population, land-use, diet and crop management) constant. Otherwise we would get a mix of climatic and anthropogenic impacts, analysis of which would mean a comprehensive assessment of past food production and the hydrologic effects on it – though desirable, such a study would go way beyond the scope of this one, as clearly stated in the discussion part of our paper (p 6947, lines 19ff). Our paper finds a certain difference in interannual water scarcity estimates and interannual variability in water scarcity due to hydroclimatic variability, which we hope is interesting enough to deserve publication due to the very important role of interannual variability in food production and related blue and green water resources (e.g. Haile, 2005; Tubiello et al., 2007; Zhang et al., 2010).

- In addition, water scarcity studies mostly use 10-30 year average climate data, to avoid the impact of varying climate by e.g. ENSO cycles and extreme years. Here we wanted to understand how this variability in climate, that is normally evened out by using average climate conditions, would impact on the food production and associated water resources. We argue that this is very important, as recently the climate variability, and related extreme climate events, have reported to be increased in various parts of the globe (Coumou and Rahmstorf, 2012; IPCC, 2012).

- The demand factor in this study is the water requirements of producing the reference diet (i.e. agricultural water productivity). This requirement does vary over time (see variability in Figure 1C), as it is dependent on climate and therefore a central driver of water scarcity in space and time. One of the main aims of our study is to increase the global understanding on how the water requirements vary in response only to the climate within the 30-year study period.

- We do agree that the diet varies country-by-country. Our reference diet is, however, based on the WHO and FAO recommended production level required to eradicate hunger (WHO, 2003; FAO, 2013a) and thus, it is justified to use that same reference diet in each country (to assess whether they hypothetically would be able to produce that diet). The diet does, nevertheless, vary in the model on how (with which crops and livestock feed) each country might fulfil these requirements.

- The fixing of water availability to 40% of the sum of runoff and storage just applies for the blue water. Green water availability is calculated differently, as specified in the article. The threshold of blue water availability is taken from literature, i.e. should an area in question use more than 40% of their available blue water resources, the area is deemed to be under high blue water stress (Vörösmarty et al., 2000; Oki and Kanae, 2006; Falkenmark et al., 2007). We do agree that to use a global value of 40% is not the best approach, but work is only under progress to get better, spatially explicit, understanding of this limit (i.e. accessibility, environmental flow requirements, etc.).

Overall, we do think that our methodology fits very well to our aims in the paper. We will nevertheless improve the justification statements in the revised manuscript to be absolutely clear what methods are used and why, and we will expand the discussion of the methodology based on the comments of the reviewer.

R1.4: Additionally, it is not clear if groundwater is included as an explicit source of blue water. Groundwater is not mentioned on page 6937, lines 9-16, but is an important water source for agriculture. In LPJmL crop irrigation requirements are always assumed sufficient (implicitly assuming fossil groundwater is used), which over-estimates the water available for food production.

A1.4: Considering groundwater is of course a difficult thing. The model calculations include the renewable groundwater, and, as rightly stated by the reviewer, fossil groundwater (or water diverted from other locations) is implicitly assumed as well, should the other water resources be not sufficient. We will mention in the revision that this may lead to overestimations in some parts of the world.

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