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First estimate of the future global population at risk of flooding

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Abstract:

Flooding is one of the major risks anticipated to increase in association with anthropogenically induced climate change which is likely to intensify the global water cycle. Currently, 20 to 300 million people per year are affected by floods that threaten both social security and sustainable development. This study presents the first estimate of future populations at risk of flooding. Results indicate that in the case of 3°C warming from the average of 1980–1999, approximately 300 million people could be at risk even in years of relatively low flooding; this number corresponds to the number of people affected in a devastating flood year at present. If the temperature increase is greater than 3°C, the flood-affected population would likely be even larger. We suggest that approximately 2°C warming, rather than 3 °C warming, should be considered the critical level of temperature increase.

KEYWORDS critical level; flood; impact of climate change; millions at risk.

INTRODUCTION

Several previous studies have estimated the number of people who will live in regions of severe water scarcity in the 21st century (e.g., Alcamo *et al.*, 2003; Oki and Kanae, 2006). Such estimates are necessary for identifying and attempting to avoid dangerous levels of climate change. On the other hand, only one estimate (Kleinen and Petschel-Held, 2007) of the future, global flood-affected population was introduced in the latest Intergovernmental Panel on Climate Change (IPCC) report (4th Assessment Report: AR4). Kleinen and Petschel-Held (2007) estimated that “up to 20% of the world’s population are likely to be affected by increased flood hazard by the year 2080 in the course of global warming.”

However, there are a few caveats that cannot be overlooked in Kleinen and Petschel-Held’s (2007) study. First, only monthly surface runoff was used for future flood estimation where the river-routing process was not incorporated; this method is not sufficient for evaluating changes in flood risk. To obtain river discharge at a cell in a global gridded distributed model, the surface runoff derived from a climate model must be aggregated with time-delay over all cells upstream of the particular cell at which river discharge is being computed. This computation, called “river routing,” was neglected in that study. Second, judgment of whether future flood frequency is likely to increase was made at the river-basin level (e.g., Mississippi, Mekong), and the entire population of each basin was uniformly classified into either the affected or non-affected population category. Further, Kleinen and Petschel-Held (2007) did not use actual flood records for comparison or validation of the simulation. Thus, although their study was a valuable attempt, the estimate of 20% should not be used without noting these issues, particularly in publically distributed documents.

Given this background, we attempted to calculate the first estimate of the flood-affected population worldwide in the 21st century within the context of global warming. We recognize by ourselves that this study presents a relatively rough estimate; nevertheless we believe this result is worth to present for seeking our future.

CALCULATION OF FLOOD DISCHARGE

Global daily river discharge from 1901–2100 was computed on a global river model with 1-degree horizontal resolution by inputting surface runoff derived from a relatively high spatial resolution (approximately 1.1-degree) climate model; this was the highest-spatial-resolution ocean-atmosphere coupled model presented in the IPCC AR4. Details on the calculation of river discharge have been described by Hirabayashi *et al.* (2008). As the future climate scenario, we used the scenario “A1B” from the IPCC’s Special Report on Emissions Scenarios (SRES). Compared to the other SRES scenarios, A1B suggests moderate warming. Because of the availability of climate model outputs with high spatio-temporal resolution for flood calculation, only this model and scenario set was chosen.

The river discharge corresponding to 100-year flood was calculated from the time series of simulated river discharge in the 20th century at the same resolution as described above, and *the value was fixed throughout the assessment for the 21th century*. Thus, the occurrence probability of a “100-year flood” (calculated using data for the 20th century) generally becomes much larger than 1/100 in the 21st century, as also described in detail by Hirabayashi *et al.* (2008). The same calculation procedure was applied for other flood probabilities (e.g., 50-year flood). Here, river discharge of the so-called X-

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year flood is defined as river discharge that has a probability of being exceeded in any given year of 1/X. If X = 100, then 1/X is 0.01. The successful validation of simulated X-year flood was described in Hirabayashi *et al.* (2008).

CALCULATION OF THE AFFECTED POPULATION

Actual flood-affected population and simulated flood-affected population

The time series of the actual flood-affected population since the 1990s was taken from the International Emergency Disasters Database (EMDAT; http://www.emdat.be), and is shown in Figure 1 as a blue solid line. Because the number of deaths, amount of economic damage and other statistics stored in EMDAT can be affected by many complicated and geographically and historically varying conditions, we examined the affected population, which seems to be a more robust index for climate change assessments, as the target of estimation in this study. The actual flood-affected population recorded for the 1980s is several times smaller than that for the 1990s. We assumed that the smaller population in the 1980s reflected less information being delivered to data centers at that time. Thus, our analysis focused on the 1990s and later. Please note that the future projections described later rely on the statistics from 1990s in EMDAT which may still contain underestimation because of less information delivery.

The flood-affected population derived from climate model outputs was computed for each year, at first, by summing the population in cells where the maximum flood-return period in a particular year exceeded 100 years. Population data used in this study is a gridded product by Bengtsson *et al.* (2006). Then, the same was carried out for the return period of 50 years. Both the results are shown as black lines in Figure 1. Computed

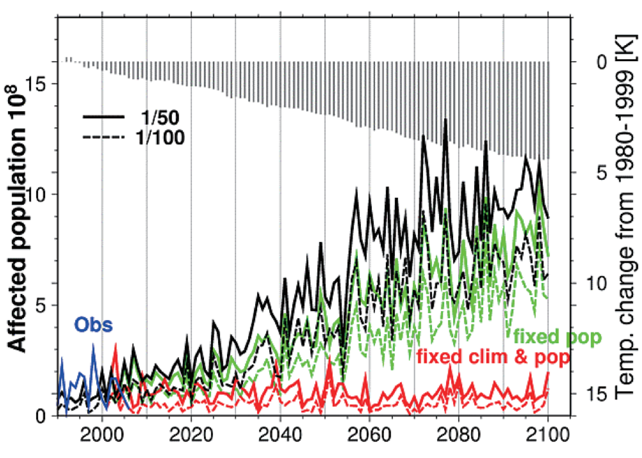

Figure 1. The actual flood-affected population in the past record (blue line) and the flood-affected population derived from climate model outputs with temporally changing population (black lines). Red lines show the flood-affected population derived from climate model outputs in 1901–2000 (= 100-year difference in the horizontal axis) with the population fixed at the value recorded in year 2000. Green lines show the flood-affected population derived from climate model outputs in 2001–2100 with the population fixed at the year 2000 value. The change in global mean surface air temperature (from the average of 1980–1999 as in the IPCC AR4) is also shown upside down.

population with uncertainty ranging from that of 50-year floods to that of 100-year floods is called hereafter as the flood-affected population by 1/50~1/100 floods. This uncertainty range is equal to the range between the black solid line and the black dotted line in Figure 1. The corresponding magnitude of floods with uncertainty range is hereafter called as 1/50~1/100 floods. There is potential for a future extended study that employs the calculation of flood-affected population dependent on the magnitude of flood at each cell. However, because of the lack of enough data for doing it, and thereby in order to avoid incorporating additional unknown parameters, this study applies the simple threshold method as described above.

Note that the year 1998 in the climate model, for example, cannot be intrinsically compared with actual year 1998 because observed sea surface temperature is not prescribed in a climate model in which the ocean and atmosphere are interactively coupled. Thus, Figure 1 should be examined not in terms of the exact values for each year, but rather in terms of the lowest and highest values, the variability range, and the trend of the time series for comparison.

The figure shows similarity between the actual affected population (blue line) and the affected population derived from climate model outputs (black line) in the period of 1990–2006. It indicates that the overlap of simulated 1/50~1/100 floods and population data provides a plausible measure of the flood-affected population. However, some peaks in the historical record (blue line), with values around 300 million, are not fully reproduced in the time series of the affected population derived from climate model outputs (black line) in 1990–2006. The time series of the actual flood-affected population varies from 20 to 300 million annually, while the time series of the flood-affected population derived from climate model outputs is relatively smooth in 1990–2006. The next subsection further examines this issue.

Potential sources of errors and uncertainty in the simulated flood-affected population

Because of the chaotic nature of the earth's climate system, actual climate variations and hence the population actually affected by flooding in 1990–2006 can be considered as a set of limited samples extracted from a huge number of samples. A single climate simulation for 1990–2006 may not have captured the actual variations of climate in 1990–2006. Therefore, the flood-affected population was calculated with a fixed population representing the year 2000 population and with variable climate model outputs in 1901 to 2000 (red lines in Figure 1). Here, we assumed that anthropogenically induced climate change was negligible in the 20th century. The variability range of the red lines in Figure 1 (also shown at the left in Figure 2 as vertical bars) again shows that the overlap of simulated 1/50~1/100 floods and population data provides an acceptable measure of the flood-affected population.

Nevertheless, climate model-based high peaks shown in the red lines are seemingly less frequent, like as in the black lines for 1990–2006, than high peaks of the actual affected population shown in the blue line. There are a few potential explanations for the incomplete representation of the affected population by this measure, especially for the less-frequent high peaks.

First, certain regions are more vulnerable to flood. Further, the occurrence and magnitude of flood disaster depends on numerous social factors, such as land use and infrastructure development, in addition to hydrological extremes. However, as the inclusion of various complicated factors would greatly lengthen the data

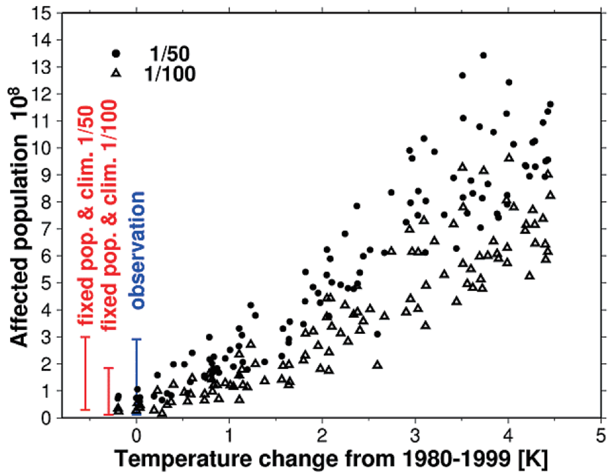

Figure 2. The flood-affected population and the change in global mean surface air temperature in the 21st century. For reference, the variability range of the actual flood-affected population in the past and the variability range of the flood-affected population with climate model outputs in 1901–2000 and with the population fixed at the year 2000 value are also shown at the left.

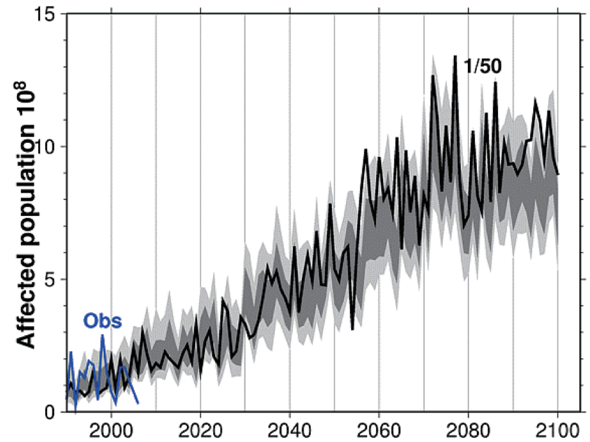

Figure 3. The actual flood-affected population in the past record (blue line), the flood-affected population derived from climate model outputs (solid black line, 1/50 floods only), and the output of a Monte Carlo simulation (shading). Details of the Monte Carlo simulation are described in the text. Dark shading indicates 95% of the Monte Carlo results. Light shading shows the top and bottom of the Monte Carlo results.

gathering and calculation processes, we adopted the simple globally uniform measure, so that we could accomplish the goal of assessing the impact of climate change on flood change. The uncertainty due to this first potential factor is partially accounted for by our use of 1/50 and 1/100 and the range between 1/50~1/100 in the analysis. Some regions may experience flooding disasters due to floods of less than 1/50 probability, but the major results and conclusion of this study are not affected by the selection of the upper criteria (=1/50). For example, the use of 1/40 in place of 1/50 does not change the conclusion. The same is applicable to the change in the selection of the lower criteria (=1/100).

Second, flooding disasters caused by tropical cyclones and associated storm surge are not necessarily represented in our analysis framework and thus remain a source of error. In a future extended study, these sources of errors and uncertainty should be better treated.

FUTURE PROJECTION

Taking the variability range of the population affected by 1/50~1/100 floods as a proxy, Figure 1 shows that the future flood-affected population is likely to increase gradually in the 21st century. While this increase is partly due to the total global population increase, the projected flood-affected population also increases even if the total global population is set at the value in year 2000 (green lines in Figure 1). In this particular model and scenario set, floods are predicted to become devastating around 2060 and beyond. We mean by devastating that even in those future years with relatively low flooding, more than 300 million people will be affected, a number that is similar to maximum numbers in the past actual record. The future potential maximum affected population may be several times larger than 300 million. The timing of "devastating" conditions roughly corresponds to a 3°C rise in global mean surface air temperature.

Previous studies (e.g., Allen and Ingram, 2002) have reported significantly positive correlations between global mean surface air temperature change and water cycle intensification; this relationship has apparently not depended greatly on model and scenario differences. Thus, our estimate of temperature change and the flood-affected population (Figure 2) should provide general values that can be applied to other models and scenarios. Visual and subjective inspection of Figure 2 suggests that an approximately 2°C increase of temperature should be considered the "critical level"; the effects of this rise in temperature do not reach the "de vastating" level of the 3°C increase, which would not be acceptable for global society. By the multi-model projections presented in the IPCC AR4, a 2°C increase roughly corresponds to 2060~2070 in the A2 scenario and 2060~2080 in the A1B scenario. The B1 scenario shows an approximately 2°C increase at the end of the 21st century. However, even with warming less than 2°C, increased flood risk is still likely to occur, as indicated in Figures 1 and 2. Countermeasures and plans must be developed to adapt this future risk.

Finally, we investigated the geographical concentration/scatter of the projected floods using a Monte Carlo simulation. The Monte Carlo simulation process was as follows. First, the number of cells with floods of 1/50 or larger was counted for each year. Second, the same number of cells was randomly selected for each year, and the sum of the population in those cells was calculated. This random procedure was repeated 1000 times for each year. The outputs of this Monte Carlo simulation can represent various hypothetical cases, such as cases in which floods mostly occur in highly populated areas, and cases in which floods mostly occur in less populated areas. The result of the Monte Carlo simulation is shown as shading in Figure 3. The interannual variability range of the black line (i.e., the variability range of the flood-affected population from climate model outputs) generally corresponds to the range of shading (indicating the Monte Carlo results) until approximately 2040. It appears that the interannual variability of affected people, and hence the interannual variability of the geographical distribution of flood occurrence, is random until approximately 2040. On the other hand, about after 2040, the variability range of the black line is located at the upper half of, or even beyond the range of, the Monte Carlo shading. This implies that the geographical distribution of flood occurrence in those years is likely to move away from random and to concentrate on highly populated areas. Eventually, as shown in Figure 6 of Hirabayashi *et al.* (2008), more frequent floods under climate change are likely to occur in Asia, Western Europe and tropical Africa and South America where population density is relatively high. This would represent a dire future for people worldwide as well as in those areas. In this aspect, warming greater than 3°C would present an even more dangerous scenario.

CONCLUSION

This study applied a simple proxy to a particular scenario and model set of future climate change. On the basis of the results, we suggest that approximately 2°C warming from the average of 1980–1999 should be considered the critical level. It is possible that human activities, if unchanged, may produce that 2°C warming 50–70 years from now.

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REFERENCES

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal* **48**(3): 317–337.

Allen MR, Ingram WJ. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**: 224–232.

Bengtsson M, Shen Y, Oki T. 2006. A SRES-based gridded global population dataset for 1990–2100. *Population and Environment* **28**: 113–131.

EMDAT. The OFDA/CRED international disaster database, University Catholic Louvain-Brussels, Belgium. http://www.emdat.be. [January, 2009]

Hirabayashi Y, Kanae S, Emori S, Oki T, Kimoto M. 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal* **53**(4): 754–772.

Kleinen T, Petschel-Held G. 2007. Integrated assessment of changes in flooding probabilities due to climate change. *Climatic Change* **81**: 283–312.

Oki T, Kanae S. 2006. Global hydrological cycles and world water resources. *Science* **313**: 1068–1072.