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Reply to Comment on 'High-income does not protect against hurricane losses'

Tobias Geiger[1,4] 🔟 , **Katja Frieler**[1] and **Anders Levermann**[1,2,3]

1   Potsdam Institute for Climate Impact Research, Telegraphenberg A56, D-14473 Potsdam, Germany
2   LDEO, Columbia University, 61 Route 9 W, Palisades, NY 10964, United States of America
3   Institute of Physics, Potsdam University, Karl-Liebknecht-Str. 24/25, D-14476 Potsdam, Germany
4   Author to whom any correspondence should be addressed.

E-mail: geiger@pik-potsdam.de

Abstract

Recently a multitude of empirically derived damage models have been applied to project future tropical cyclone (TC) losses for the United States. In their study (Geiger *et al* 2016 *Environ. Res. Lett.* **11** 084012) compared two approaches that differ in the scaling of losses with socio-economic drivers: the commonly-used approach resulting in a sub-linear scaling of historical TC losses with a nation's affected gross domestic product (GDP), and the disentangled approach that shows a sub-linear increase with affected population and a super-linear scaling of relative losses with per capita income. Statistics cannot determine which approach is preferable but since process understanding demands that there is a dependence of the loss on both GDP per capita and population, an approach that accounts for both separately is preferable to one which assumes a specific relation between the two dependencies. In the accompanying comment, Rybski *et al* argued that there is no rigorous evidence to reach the conclusion that high-income does not protect against hurricane losses. Here we affirm that our conclusion is drawn correctly and reply to further remarks raised in the comment, highlighting the adequateness of our approach but also the potential for future extension of our research.

Recently, we applied various empirically derived damage models to project future TC losses for the United States [1]. In particular, we distinguished between two model types that differ with respect to their scaling of socio-economic drivers, i.e. using total affected GDP as a single predictor or separating the effect of affected population and average per capita GDP. Although statistics cannot determine which approach is preferable, we argue that in terms of process understanding there exists a dependence of the loss on both GDP per capita and population, such that an approach that accounts for both separately is preferable to one which assumes a specific relation between the two dependencies. Interestingly, we found that separating population and per capita GDP (i.e. income) results in a super-linear increase of TC losses with income, leading to the conclusion that high-income does not protect against hurricane losses.

Thereafter Rybski *et al* (hereafter RPK2017) argued that our conclusion needs to be revisited as it is based on one of the conflicting findings only. As correctly observed by RPK2017 both approaches only slightly differ with respect to their explanatory power. However, only one approach analyses the scaling of income with losses explicitly, while in the other approach income is only implicitly accounted for via total GDP. In this sense it is correct to say that 'high income does not protect against hurricane losses', as this super-linear scaling with rising income remains hidden if GDP is used as a single predictor, due to the very pronounced sub-linear scaling of losses with population. This finding has also been confirmed recently [2].

Generally, the availability of socio-economic data limits our analysis to a certain temporal period. In particular the TC-affected average income does not vary as strongly as e.g. TC-affected population between 1963 and 2012, as correctly observed by RPK2017, making it a worthwhile endeavor to explore potentially different functional scalings of socio-economic drivers with hurricane losses in future research. This point

directly links to the question raised by RPK2017 on how well can hurricane damage be predicted at all. The various drivers of TC damage are complex and have been controversially discussed in the literature, including subtle elements as the angle of landfall, the associated precipitation, and the storm's duration or gustiness [3]. Attempts to build models with higher certainty would consequently require many more predictors, most of which would be unavailable for future projections. On the more aggregate level, as in our approach, deviations remain quite large but smaller than in previous attempts [4, 5], where explained variances are smaller and uncertainty is usually not discussed. Moreover, we also did not aim to provide the best possible damage model but rather re-applied models that have been proposed in various contexts previously [2, 4–8], in a consistent setup. The fact that all analyzed models only slightly differ in the explained variance also illustrates that previous discussions about best model types, in particular with respect to wind-speed scaling, are misleading, and have overlooked the importance of the socio-economic component. In this respect, the currently missing propagation of model-uncertainties to projections, as argued by RPK2017, would not alter the main findings of our paper, i.e. the large divergence between both basic model types.

RPK2017 also raised a concern about the apparent discontinuity in GDP-by-state time series at 1997, introduced by the transition from SIC to NAICS industry definitions. While merging both series we encountered no significant changes in levels (for the overlapping year 1997) and trends in growth rates for total real GDP-by-state. We therefore see no reason that model performance may be obscured by the GDP data. As a side remark, the discontinuity, however, exists when looking at specific industries due to the reshuffling of the various contributing sectors.

Finally, RPK2017 pointed out that a recently reported power-law correlation between urban GDP and population [9] could be used to unite both basic model types. While providing an interesting insight we doubt that there exists a one-to-one correspondence between our analysis and [9], questioning the applicability of equation [6] from RPK2017. Where [9] relates a city's population to their urban economic activity, we determine exposed population and GDP

using hurricane wind-field extension. Our analysis does not distinguish between urban areas and rural regions and, due to large hurricane sizes, encompasses various forms of settlements.

In conclusion, our original paper has made an effort to ease comparability between various TC damage models and has shifted the emphasis to the socio-economic drivers, in particular the scaling of losses with income. However and in agreement with RPK2017, future research is needed to understand the origin of this scaling, to reduce model uncertainties and to improve the accuracy of future projections.

ORCID iDS

Tobias Geiger ⓘ https://orcid.org/0000-0002-8059-8270

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