

## ***Interactive comment on “Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of Lake Palcacocha, Peru” by Christian Huggel et al.***

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Contribution to the Peer Review of “Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of Lake Palcacocha, Peru” by Christian Huggel et al.

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### Summary

The submitted manuscript aims to evaluate the physical and socioeconomic drivers of glacial lake outburst flood (GLOF) risk from Lake Palcacocha, a moraine-dammed proglacial lake in the Peruvian Andes. Based on a review of climate science and glaciology literature, the paper finds that ‘the growth of lake Palcacocha has a clear anthropogenic signal’ and that this has significantly increased the GLOF hazard. The paper also considers socio-economic, institutional, governance-related, cultural and emotional drivers of GLOF risk, and the resultant implications for greenhouse gas emitters’ responsibility for compensatory payments in ongoing legal proceedings.

Our comments relate to the accuracy of (1) the authors’ assessment of the attribution of GLOF risk to anthropogenic greenhouse gas emissions, and (2) the framework developed for understanding the drivers of GLOF risk in a legal context.

#### 1. Accuracy of the GLOF hazard attribution

The authors note that (lines 191-203):

‘The only available quantitative glacier attribution study that also includes the tropical Andes concludes that globally more than two thirds of the 1991-2010 glacier mass loss is due to anthropogenic forcing, and for tropical regions finds that an anthropogenic signal in observed glacier mass loss of recent decades is detectable with high confidence (Marzeion et al., 2014). The anthropogenic signal is much stronger for the past 2-3 decades as compared to earlier time periods. . . . Lake growth was highest in the 1990s and 2000s (Fig. 3), coinciding with the period where glacier shrinkage can regionally be attributed to anthropogenic emissions with high confidence. We therefore conclude that growth of lake Palcacocha has a clear anthropogenic signal.’

We are concerned that this statement underestimates the role of human influence on the GLOF hazard from Lake Palcacocha. Regional warming of 0.75-1.5 °C has been attributed to anthropogenic influence (Allen et al., 2018, see fig. 1.3) and mountain

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glacier lengths act as lowpass filters of the climate they experience (Oerlemans, 2000; Roe, Baker and Herla, 2017) with multidecadal response times (Jóhannesson, Raymond and Waddington, 1989). This suggests that the expansion of Lake Palcacocha (and the resultant increase in GLOF hazard) is likely to have been attributable to human influence considerably prior to the period over which the authors indicate the presence of an anthropogenic signal.

Further to this, we are concerned the submitted manuscript misinterprets the findings of Marzeion et al., (2014). Taken at face value, the Marzeion et al. calculations would indicate that for low-latitude glaciers (shown in their supplementary material) anthropogenic influence on mass balance emerges only in the last three decades. However, (a) there would be a time lag of at least a decade between the emergence of human influence on mass balance and human influence on glacier lengths (Jóhannesson, Raymond and Waddington, 1989), (b) the glacier's length response to changes in mass balance is strongly influenced by the glacier topography and is therefore specific to the landscape on which the glacier lies, and (c) the results of Marzeion et al. (2014), if taken at face value, would indicate that mass balance was strongly negative throughout the 20th Century. Therefore, if they were an accurate representation of Palcaraju glacier's mass balance, significant glacial retreat would be expected throughout the historical period, rather than only emerging in recent decades as has been observed (as described by the Huggel et al. manuscript). Consequently, the concurrence between the period of time for which mass loss is most attributable to anthropogenic greenhouse gas emissions (according to Marzeion et al., 2014) and the period of most rapid expansion of Lake Palcacocha does not appear to be a solid foundation on which to make a statement of the role of human influence on the observed retreat of this glacier.

With respect to the effect of Lake Palcacocha's expansion on the GLOF hazard, the authors explain that (lines 210-213):

“Some of the factors [influencing GLOF magnitude and probability] (such as lake formation) are closely related to climate change while others can be associated to geologic

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or geotechnical conditions (e.g. dam stability), or are explicitly influenced by human intervention aiming at reducing the risk of GLOFs (e.g. lake freeboard determined by the height of the constructed drainage canal).”

Anthropogenically-driven glacial retreat has directly resulted in the formation of a large proglacial lake and is the primary and necessary cause of GLOF risk. Non-climatic factors mediate the impact of climate change on the GLOF hazard, but in our view the authors should state explicitly that these factors are less important causes of the present GLOF hazard. The need to implement adaptive measures to reduce GLOF risk is therefore the result of the expansion of Lake Palcacocha and the other factors identified by the authors are largely incidental and would have been inconsequential but for the impact of climate change on the glacier's retreat.

2. Accuracy of the framework for understanding risk, and its relevance for ongoing legal proceedings

The paper gives comparable weight to the physical and 'interacting socio-economic, institutional and cultural processes' which contribute to flood risk. The existence of these social influences on flood risk is not challenged here but this framing obscures the fact that present GLOF risk is a direct result of the anthropogenically-driven retreat of the glacier.

Huggel et al present 'risk (and associated loss and damage) [as] a multi-faceted construction' and argue that 'the question of causality can often not be fully solved, at least not in a quantitative way' and 'in contrast [to the physical GLOF risk causal chain] the current conditions of exposure and vulnerability of people and values in Huaraz to GLOF hazard can only be understood with a historical perspective of social, economic, political and cultural dynamics'. It is undoubtedly true that exposure and vulnerability play a crucial role in determining the ultimate risk, however, non-climatic factors, such as the decision of Spanish colonialists to select this location for the city of Huaraz in the 16th Century (etc) would not have mattered if not for climate change and thus are,

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in our view, legally irrelevant as far as the question of causality is concerned. Similarly, we believe that the possible failure of local government agencies to develop successful risk-reduction mechanisms is not relevant for understanding the primary cause of the present GLOF hazard and therefore need to implement costly adaptation measures. Climate change is a necessary cause of flood risk in this setting.

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