The comments of referee#2 are reproduced below in black. Our responses are in blue.

This is an interesting article. While I see the point (raised by an earlier reviewer and editor) that it does not generate much knowledge on the real (warming) world, I believe it neatly summarises and illustrates issues with climate damage function, with an original twist of argumentation. The current article could stimulate discussion on the merits, limitations, and validation of damage functions, which would be a valuable contribution to the scientific discourse around climate change.

I therefore think that the article should be published. However, there are some issues which require clarification, as listed below.

- Thank you for your positive comments on our work. Indeed, our main goal is not to generate knew knowledge on future climate change and its impacts but to question the relevance of (some) current damage functions.

Major Comments

Inconsistency: “known” cooling vs “unknown” warming scenario

An important line of argumentation seems to me that while we don’t know what a warming world looks like, we can form an idea about a cooling of similar magnitude by looking at the ice age data. However, in fact, the paper does not assume a full transition to an ice age (which would involve long-term equilibration of ice sheets etc) but a quick cooling, i.e. a scenario for which we have no data. The uncertainty may involve the question of snow accumulation, raised by an earlier interactive comment, and effects depending on it (e.g. circulation changes due to the albedo effect of the snow), but also changes in ocean circulations (how does the AMOC react to the cooling?). The fast cooling scenario may thus differ form an ice age in more respects than the presence or absence of ice caps.
So, is the damage in a fast cooling scenario just as speculative and difficult to assess than in a warming scenario?

There are in fact two types of uncertainty here, 1. what would the state of the climate system be like under fast cooling, 2., what would be the impacts for society?

In my view, there are two ways to deal with the first issue.

• Simply define that your cooling scenario is “an ice age except that ice sheets are not there yet”. You would have to explicitly acknowledge that this may not be the actual response of the Earth system to a cooling stimulus (such as rapid greenhouse gas depletion), but you could still analyse the potential (societal) impact of such a hypothetical climate.
• Or perform a model simulation (/team up with a modelling group) of a 4degree cooling in 100 years, either by dropping GHG concentrations or a reduction in solar irradiation.

I strongly encourage you to consider the second option.

Once you clarified your climate scenario, you can argue, as you do now, that the impact of society would be severe (with higher certainty than the severity of an equivalent warming?).

- Your comment is quite similar to the previous interactive comment of M. Verbitsky and we agree that we should clarify our climate change hypothesis: we assume a return to the last glacial maximum, except for the ice sheets. The hypothesis includes ecosystem changes, which were triggered not only by temperature and precipitation changes but also by lower CO2. Of course, this hypothesis implies some inconsistency, as the LGM climate takes into account the albedo and elevation impact of the ice sheets. We acknowledge that the response of the Earth system to a forcing that would lead to a 4°C cooling in 2100 would be different from the LGM (depending on the type of forcing) and therefore the LGM is not a perfect reverse analog of a future at +4°C. A short discussion on that issue will be added to the manuscript. Please also refer to the response to M. Verbitsky for the other modifications that would be implemented in our manuscript to clarify this issue.

Performing some ad hoc climate modelling to simulate a cooling of 4°C by 2100 would indeed allow avoiding the above mentioned issue. However, it would, in our view, raise at least two new issues:

1) Unrealistic forcing mechanism: As you mentioned, the forcing mechanism could be either a strong reduction in solar irradiation or a drop in GHG concentrations. But to reach -4°C, the decrease in solar irradiation would have to be much stronger than the natural changes currently reconstructed for the past millennia and a decrease of GHG would have to be even larger than for the LGM (since GHG drop alone during the LGM is not sufficient to simulate a full glacial climate, e.g. Kim, 2004.), which could not be reached within a century with natural mechanisms. Therefore, we would have to assume some anthropogenic factors, like massive atmospheric CO2 pumping and storage, which would be unrealistic. The last option would be a massive volcanic eruption, but it would have to last continuously for several decades, which would be a very questionable hypothesis.
2) Most importantly, the climate scenario would then rely on climate modelling only, with only one model, with all the associated uncertainties, especially concerning ecosystem changes. Therefore, confronting the climate projections with the damage projections would not be different from doing the same exercise in the case of a warming scenario (which of course remains a valid option to illustrate the inconsistency of climate damages projections). In our view, the main interest of using the LGM as a benchmark to test econometric models based on mean annual temperature is to have not only climate simulations but also various proxy data on the climate and ecosystem at that time.

This is why we decided to stick with the first proposed solution of clarifying our climate change hypothesis.

Asymmetry warming – cooling

The ice-age scenario obviously contains very severe impacts for human activities, many of which cannot be captured by looking at recent data, as the ice-age Earth might be a qualitatively different place from our current world.

However, this does not automatically imply that a warming of equal magnitude would have similarly huge impacts.

This does not invalidate your main argument, that (statistical) damage functions may well overlook major impacts of climate change which current data cannot capture, but I would like this asymmetry to be acknowledged explicitly. Even better, if possible, would be to include a brief discussion on whether it is plausible/impossible to know/implausible that warming has similarly strong impacts as cooling. For example, how does the area (or number of inhabitants, or value of infrastructure) threatened by sea level rise under 4 degree warming compare to the area (or number of people/ amount of wealth) threatened by snow under 4 degree cooling? Obviously, uncertainties are huge, but maybe something meaningful can still be said about the issue?

We agree that this point should be acknowledged explicitly.

When looking at some of the most dramatic climate projections for RCP8.5 at the end of the century, it seems rather plausible that warming would have similar strong impacts as a cooling of similar magnitude:

- On the one hand, at the LGM, large parts of North America and Europe would become rather unsuitable for large human populations and most modern economic activities. Currently 37 millions of people live in Canada and about 30 millions in northern Europe, where we can reasonably assume that only a small population could remain. Maintaining a total population of more than 700 millions of people in Europe despite the very cold temperature in winter and permafrost expansion is doubtful, even if the number of people that could still live there (probably mostly in southern Europe) remains speculative. Similarly, in India, data suggests that the north-western part of the continent experienced extreme desert conditions during the LGM (Ansari et al., 2007), which would probably have strong negative impact for its current 70 millions of inhabitants.
- On the other hand, the number of people currently living in areas which may be exposed to permanent inundations for a sea level rise of 1,46 m in 2100 was recently estimated to 340 millions (population growth and migration not taken into account, Kulp & Strauss 2019), a number that would be further increased for higher SLR values (SLR>2,4m has 5% probability according to Bamber et al., 2019). But the most alarming projections are maybe the ones concerning future heat stress: according to Mora et al. (2017), temperature and humidity conditions above potentially deadly threshold could occur nearly year-round in humid tropical areas, including some of the most densely populated areas, threatening hundreds millions of people. How people could adapt to such unprecedented climatic conditions remains an open question.

However, while we agree that from a physical point of view there is no a priori reason to postulate that warming and cooling of similar magnitude would have similar huge impacts, it should be noticed that this issue of symmetry between a warming and a cooling is implicitly assumed by the damage function itself: it was built on both negative or positive temperature anomalies. Therefore, by design, it cannot be assumed that such function would provide relevant damage estimates for a warming but not for a cooling (or the reverse).

A paragraph explaining the above points will be added in the general discussion.

Enumerative vs. data-driven damage function

You use two damage functions of the statistical kind and none of the enumerative kind. Is this a conscious choice, and could you please motivate it? For example, did you make this choice because statistical damage functions inherently include the (statistical) effect of both cooling and warming, whereas the enumerative ones primarily look at warming (e.g. they may include a term for heat stress on maize plants, but not for frost stress...)?

In particular, it seems to me that your argumentation shows that capturing climate damage exhaustively with a statistical approach is impossible, whereas an enumerative approach could work in principle (but maybe not in practice). Please clarify.

- Yes, this is a conscious choice, which will be justified briefly in section 2. As you pointed it out, enumerative damage functions are designed for a warming and we could not have applied them to a cooling. They may lead to implausible results as well (especially at a global scale), because some impacts are not accounted for or because the sectorial impacts are generalized based on evidence limited to a short time period or small spatial scale for instance. In that case, illustrating the disconnect with climate sciences would have required a different approach (e.g. questioning their assumptions, sector by sector, or providing damage estimates for impacts usually not taken into account, like extreme events).

- We consider that the enumerative approach could work in principle, providing that the potential cascading effects could be taken into account, but we doubt that this could actually be done at the global scale. Damage projections may be possible, to some extent, at region or country scale, but it remains a complex and challenging work and it is highly probable that high levels of uncertainties will remain, as very well pointed out in the article of Pezzey that you have indicated. A short paragraph will be added in the conclusion, to further discuss this point, including some of the issues raised by Pezzey (2017).

Minor Comments

• Line 253: “these regions would be about as suitable for humans as present day Arctic is”... Instead of this picturesque metaphor, I suggest to specify the conditions (how cold and dry? unsuitable for any form of present-day agriculture, forestry, even Sami-style animal husbandry?).

Please find below in red some additional information, which will be added to the text:

“In Europe, the mean annual temperature would decrease by 4-8°C in the Mediterranean region, by 8-12°C over the western, central and eastern regions and by more than 12°C over northern countries (Fig.2). For France for instance, whose current mean annual temperature is about 11°C, the temperature decrease would thus correspond to a shift to the current mean temperature of northern Finland. Over Western Europe, the mean temperature of the coldest month would decrease by 10-20°C (Ramstein et al., 2007) and mean annual precipitation would decrease by about 300 mm/year (Wu et al., 2007). Forests would be highly fragmented, replaced by steppe or tundra vegetation (Prentice et al., 2011). The southern limit of the permafrost would approximately reach 45°N, i.e. the latitude of Bordeaux (Vandenberghe et al., 2014). In such a context, maintaining European agriculture at its current state, among other human activities, would be a costly and technically highly demanding challenge. Energy needs for heating would tremendously increase, current infrastructures would be damaged by severe frost and it is doubtful that Europe could still sustain its current population on lands preserved from permanent snow accumulation. In Asia, similar problems would occur, with a decrease in mean annual temperature between 4 to 8°C over most Chinese regions for instance (Fig.1) The boreal forest would progressively vanish, replaced by steppe and tundra (Prentice et al.,2011). Permafrost would extend in the North-East and North China, up to Beijing, as well as in the west of the Sichuan (Zhao et al., 2014). As a result, rice cultivation in the northern province of Heilongjiang, currently >20.10^6 tons/year, i.e. about 10% of the national production (Clauss et al. (2016), would no longer be possible. Permafrost would not stretch out to the whole densely populated North China plains, but the cold and dry climate there would nonetheless prevent rice cultivation. The discharge of the Yangtze River at Nanjing would be less than half its present-day value (Cao et al., 2010), questioning current hydroelectricity production. In short, current livelihoods in these regions would no longer be sustainable and population would probably be much lower than today. ~~In short, these regions would be about as suitable for humans as present-day Arctic is.”~~

• Line 266ff: “Most places would become unsuitable for agriculture and water resources would largely decrease. Drier regions include ...India and Indonesia”.

Would drying be a severe concern in regions that are currently wet (like Indonesia and parts of India)? And even if rainfall decreases, could it not be that the reduction of evaporation due to cooling compensates the effect, leading to no severe increase in drought? Note that several regions, including the Mediterranean, and parts of South Africa, are threatened by drought under global warming (for example because of poleward expansion of the ITCZ system and hence the subtropical deserts). Of course, drought needn't be linear in global mean temperature, but possibly these regions would get less drought-prone under global cooling.

It is indeed important to take into account temperature, whose decrease could compensate for the precipitation decrease. Compilations of lake levels at the LGM indeed show that some were higher at the LGM whereas other where lower (McGee, 2020) and climate models show that drier places in terms of precipitation were not always drier in terms of hydrology (Scheff, 2017). This point, which has not been discussed in our manuscript, will be added in section 5.

Concerning Indonesia, you are right. Data for that region are rather sparse, and showing spatial variability: for Borneo for instance it seems that the vegetation cover was broadly similar during the Holocene and the LGM, suggesting that there was no pronounced dry season, whereas for Sumba, pollen data suggest enhanced aridity and water stress during the dry season (Dubois et al., 2014). Thus, it seems actually difficult to make hypotheses on the potential impact for human populations and the reference to Indonesia will either be suppressed or the uncertainties will be explained.

For India, data are also rather sparse. Analyses of a marine core in the Bay of Bengale suggest that fluvial discharge was reduced during the LGM, but the decrease is not quantified (Duplessy, 1982). Looking at simulation results, it seems that there was a decrease in P-E (Scheff, 2017) and a large decrease in runoff across monsoonal Asia, including India and south-east Asia (Li et al., 2013), suggesting that the decrease in temperature did not compensate for the decrease in precipitation. This could mean less flooding during the monsoon season, but also a decrease of water resources during the dry season, in areas where droughts are already a problem at present-day. Unfortunately, to our knowledge, there is no publication on the seasonality of runoff during the LGM. In regions already dry today, like the Pakistan or north western India, it seems that conditions were even more arid during the last glacial (Ansari & Vink, 2007). These references will be added in section 5.

• This reference could be interesting for the general discussion on damage functions: JCV Pezzey, "Why the social cost of carbon will always be disputed", https://onlinelibrary.wiley.com/doi/full/10.1002/wcc.558,

- Thanks for this reference, which will be added to the general discussion on damage functions. It nicely (and sometimes provokingly) summarizes the different issues, including for the statistical approach. It could also be cited in the conclusion, since it questions the very social/political utility of damage functions.

Technical Comments (typos etc)

• line 265: o fthe -> of the
• line 294: does not captures -> capture

• fig. 1: Islande -> Iceland

Additional references:

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Cao, G., Wang, J., Wang, L., & Li, Y. (2010). Characteristics and runoff volume of the Yangtze River paleo-valley at Nanjing reach in the Last Glacial Maximum. *Journal of Geographical Sciences*, *20*(3), 431-440.

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Scheff, J., Seager, R., Liu, H., & Coats, S. (2017). Are glacials dry? Consequences for paleoclimatology and for greenhouse warming. *Journal of Climate*, *30*(17), 6593-6609.