Impact of Changes in CO_2 Concentration on the Rate of Extreme Precipitation Events in the Planet Simulator

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Abstract. Extreme precipitation events are a major consequence of recent global warming. It is therefore important to quantify the change in extreme events in regard to a rising global CO_2 concentration. We use precipitation data from a climate model of intermediate complexity, the Planet Simulator, in order to count the number of extreme events for simulations with varying CO_2 concentrations. The analysis shows an increase in extreme precipitation events for higher CO_2 concentrations. Moreover, the rate of change is just slightly higher for a planet with Pre-Industrial ice sheet configuration than for one with Last Glacial Maximum ice sheets. The influence of different ice configurations is dominated by the influence of increasing CO_2 concentration. Limitations of the simulations are a used mixed ocean layer model and a resolution of the standard "T21". Further studies could include a general ocean circulation model and higher resolutions.

1 Introduction

As people in e.g. Europe know from their daily lives, precipitation is not equally distributed over the days of a year, but is often concentrated on individual days, where some of these days have extraordinary large precipitation. Such events certainly affect human life, e.g. in context of agriculture, floods, water supply, or just the daily plans of citizens. This work investigates how the rate of such extreme events changes under a change of CO_2 in the atmosphere.

For the purpose of this work, an extreme precipitation event is defined as a day of extraordinary large precipitation. Note that other events could also be seen as extreme precipitation events, e.g. droughts. With this definition, we want to find out if an increase of CO_2 leads to a higher rate of extreme precipitation events. The investigation is performed for a planet with Pre-Industrial (PI) ice constellation, as well as for a planet with an ice constellation of the Last Glacial Maximum (LGM). In more detail, the Last Glacial Maximum means a time ca. 21,000 years BP, when ice sheets covered North America and Northern Europe.

2 Data

The used data originates from different runs of the Planet Simulator (PlaSim), which is a climate model of intermediate complexity that was developed at the Meteorological Institute of the University of Hamburg (Fraedrich et al., 2005a, b, c). It consists substantially of an atmospheric global circulation model, together with a simple mixed ocean layer model and dynamic sea ice, vegetation and landscape. In all simulations, PlaSim's cold bias was corrected via tuning of certain parameters based on Lyu et al. (2018). For the LGM simulations, the used land-sea mask, topography and ice sheet data is from Tarasov and Andres (personal communication). Six simulations are used, which are listed in Table 1: For the PI and the LGM configuration each, three simulations with different CO_2 concentrations are used in order to test how the planet's event rate changes under different CO_2 concentrations.

Since we only want to compare the effects of different CO_2 concentrations and ice configurations, orbital parameters are kept constant at the PI-orbital configuration (eccentricity = 0.0167, obliquity = 23.44°, MVELP = 102.7°, see Lunkeit et al.) across all simulations. The simulations ran for 30 to 50 years and our data is from the last ten years when they had reached equilibrium. As spatial resolution of PlaSim the standard "T21" is used, which means a grid consisting of 32×64 cells (latitude-longitude grid). PlaSim simulations provide daily resolved precipitation data for each grid cell.

Table 1. Details of the experiments analyzed in this project, all output data can be also found on Moodle.

Experiment	Group	Experiment description	Variables	Data Source
1.2	HotterThan TheEarth	ice-PI, orbit-PI, 185/280/560ppm	pr	`fluffy/home/hotter/PlaSim_0318 /plasim_output/...`
5.2	Die Einfallslosen	ice-LGM, orbit-PI, 185ppm	pr	`fluffy/home/einfallslose/PlaSim_0318 /plasim_output/exp52_iO_o1_c185`
6.2	Zettel	ice-LGM, orbit-PI, 280ppm	pr	`fang/home/zettel/Plasim_0318 /plasim_output/exp62_i0_o1_c280`
9.2	tutors	ice-LGM, orbit-PI, 560ppm	pr	`fang/home/hagridshut/PlaSim_0318 /plasim_output/exp92_i0_o1_c560/`

3 Methods

In order to identify extreme events, a local threshold for every grid cell is computed and any daily precipitation exceeding this threshold is considered as an extreme event. Such an approach is also used in literature for investigation of extreme events (Katz and Brown, 1992).

In the following, the threshold of one simulation is defined as the mean in the individual simulation, plus the standard deviation of the PI simulation with the lowest CO_2 concentration (185ppm) multiplied by a constant factor $c = 5$:

$$\text{Threshold} = \text{Mean} + c \cdot \text{Std}_{PI,185ppm} \tag{1}$$

The method is visualized in Figure 1 by picking one grid cell and its local threshold. In this manner, the absolute number of events per year is computed throughout all grid cells for each simulation.

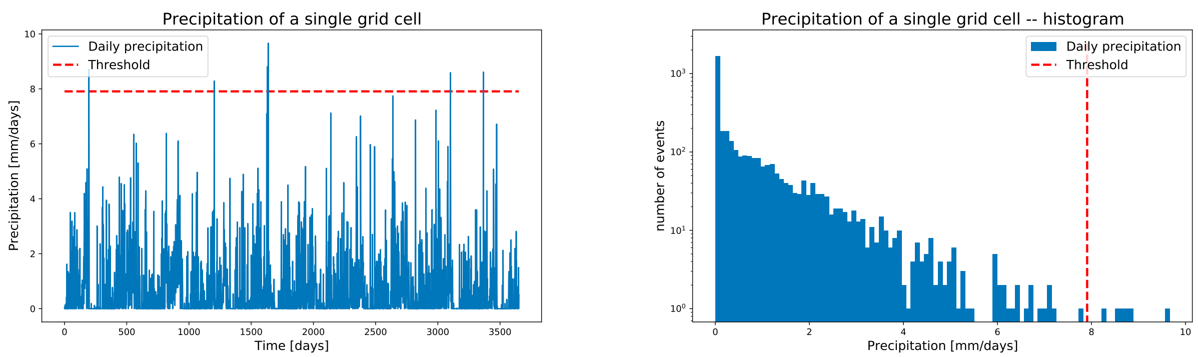

Figure 1. Illustration of how extreme precipitation events are counted by defining a local threshold ($\text{Mean} + 5 \cdot \text{Std}_{PI,185ppm}$), exemplarily shown for one grid cell (at 53°N and 11°E, for the LGM ice 185ppm simulation). *Left:* time series plot. *Right:* histogram plot.

We choose the same standard deviation value of the PI-ice 185ppm configuration for the threshold of all simulations. Hence, the number of events with a large deviation from the mean is comparable between simulations. We choose a factor of $c = 5$, so that the threshold is high enough to count only a few outstanding days, but low enough that not all days are excluded. The definite value of the factor is of course changeable, depending on one's understanding of "extraordinary large precipitation".

But the value is not crucial, since the investigation is rather about changes and differences in the number of events, than about the absolute values. This is just important to be kept in mind, when absolute values are shown.

4 Results

The resulting rate of events around the globe is shown in Figure 2, exemplarily for the LGM-ice 560ppm simulation. There are regions with a relatively high amount of extreme events, such as North-Eastern Europe, parts of the Indian Ocean and in and around Antarctica, but also regions with very few extreme events, like the equator or the Sahara desert. Some band-like structures around certain latitudes can also be observed. (For the other simulations see Fig. B2 in the Appendix).

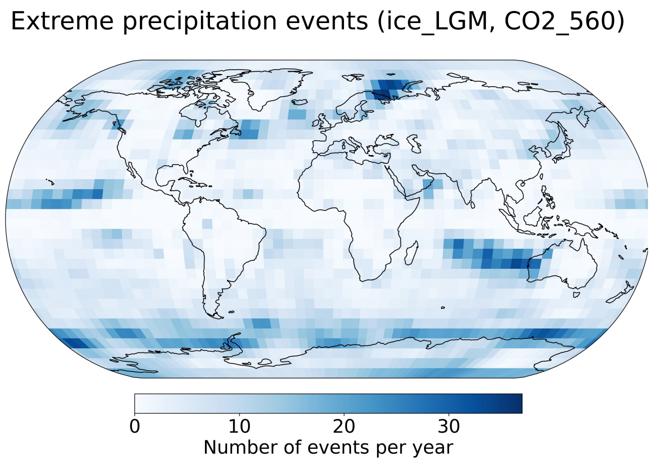

Figure 2. Number of extreme precipitation events per year, averaged over the last ten years of the simulation. (For LGM ice configuration at a CO_2 concentration of 560ppm.)

In order to investigate the local change in the rate of events with increasing CO_2 concentration, the difference between the total number of events for the highest and lowest CO_2 concentration are shown in the Fig. 3. (The differences between 560ppm-280ppm and 280ppm-185ppm can be seen in Fig. B1 in the Appendix.)

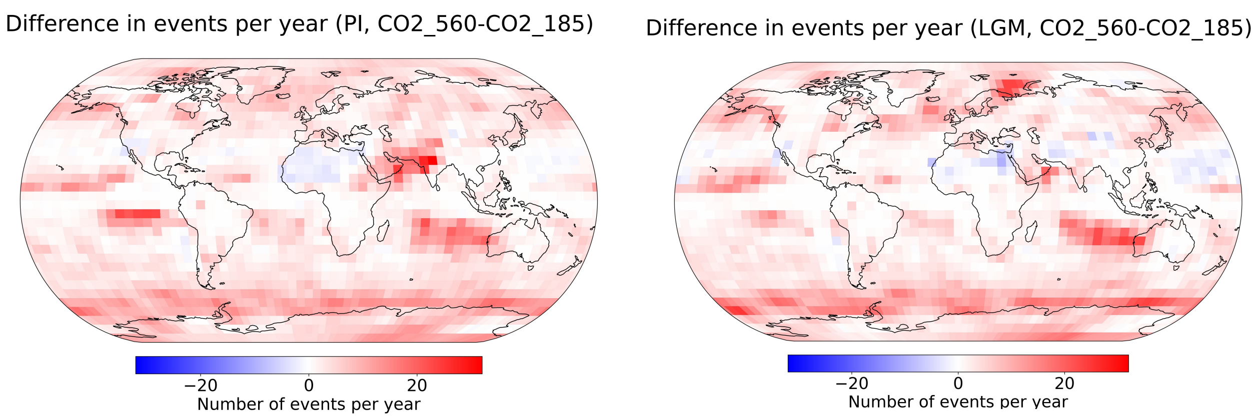

Figure 3. Differences in the mean amount of extreme events per year, between CO_2 levels of 560ppm and 185ppm. (Left: PI ice configuration, right: LGM ice configuration).

In both configurations there is an overall increase in extreme events for rising CO_2 levels, and the regional distributions also look very similar. In some regions, there is a minor decrease in precipitation extremes, for example in the Sahara, in Southern California and parts of the Himalayas.

By computing the (surface area weighted) global mean of extreme precipitation events for the last ten years of the simulations, the rate of change for both ice sheet configurations can be quantified. This is shown in Figure 4:

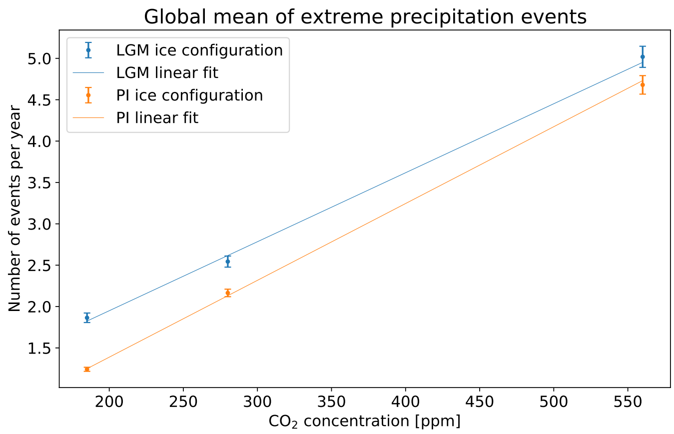

Figure 4. Area-weighted global mean number of extreme precipitation events per grid cell per year.

The rising trends in Figure 4 match the increase seen in the global plots. The increase follows nearly a linear trend: 0.83 ± 0.05 additional events per 100ppm CO_2 increase (per grid cell) in the LGM ice configuration and 0.93 ± 0.03 for PI ice. So the rise is slightly stronger for the PI ice configuration compared to the LGM ice, but there are still more events in the LGM ice configuration overall. Furthermore, the increase of extreme precipitation event rates with increase of CO_2 dominates against the differences between the ice sheet configurations.

Additionally, the zonal means are shown in Figure 5 for all simulations.

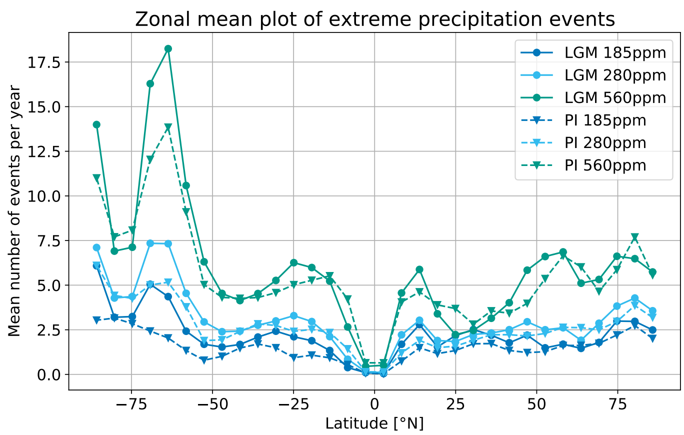

Figure 5. Zonal mean number of extreme precipitation events per year.

The zonal plot shows almost no extreme events at the equator and increasing numbers further away from the equator, with the highest peak at around 64°S. The trends in terms of peak and trough positions are in general similar for LGM and PI. But interestingly, the LGM numbers are generally higher than the PI numbers in the Southern Hemisphere, while there is no clear trend in the Northern Hemisphere. In other words, most of the offset seen in figure 4 seems to come from differences in the Southern Hemisphere.

5 Discussion and Conclusion

As a result of this work with the Planet Simulator, it was seen that an increase in CO_2 concentration in general leads to an increase of extreme precipitation events around the world, with local specialities. Additionally, the influence of CO_2 is dominant against the influence of a change in ice sheet constellation between LGM and PI.

Main differences between the PI and LGM ice configuration are the prescribed, glacier covered areas in Northern Europe and North America. Some stronger effects can be observed regionally in those areas (Fig. 3). Surprisingly, a main increase in extreme events for both ice configurations can be observed in the Southern Hemisphere (Fig. 5), particularly in the coast and sea region around Antarctica where typically sea ice cover is located. This points towards a link between local sea ice and precipitation extremes. Additionally, it seems that a change in glacial cover in the Northern Hemisphere affects the climate globally, since the change of the ice sheet configuration affects the extreme event rate elsewhere, e.g. near the Arabian Coast and India. In the region of India and the Arabic coast are special rain schemes present, due to the Monsoon. Those might be notably influenced by the CO_2 and ice sheet changes and could be investigated further. Other increases of event rates are located in the area of the Indian Ocean and the eastern Pacific, while there are a few places with a decrease of event rates, especially in the area of the Sahara. The latter ones might be candidates for an analysis of droughts.

One thing that stands out in all regional and zonal plots (Fig. 2, 3, 5) is that there are few to none extreme events counted directly around the equator. The main reason for this is that this area regularly experiences heavy precipitation with strong variability. While in other regions single events of large precipitation are clearly outstanding (as shown in Fig. 1), they are not outstanding in the equator region since there are too many of them. As a consequence, those days are not 5 times the standard deviation higher than the mean and not counted. So it could be argued that our method is more suited to regions with infrequent precipitation extremes than to regions that regularly experience heavy precipitation.

In further investigation could be tested how stable the performed analysis is under different thresholds. The height of the chosen threshold factor defines which events are considered: E.g. with a factor of 5 mainly extreme outliers are investigated, while a lower factor would rather investigate the variability of precipitation. Complementary to our approach, the group "Schenk" investigated how the actual amount of precipitation and the standard deviation of the precipitation change with CO_2. Their analysis considers different setups than ours and monthly data, but they found an increase of standard deviation in similar areas where we found increasing event rates (e.g. an increase around Antarctica and India/Indian Ocean and a decrease in the Sahara). Interestingly, they find most increase of standard deviation at the equator, which matches our thoughts about the equator. If we reduced the threshold factor to 1, our findings would probably approach theirs. In general, it seems to be the case that absolute amount of precipitation, its standard deviation and the extreme event rate are fairly coupled. This could be a topic for further analysis.

Additionally, as a further approach, a threshold for an extreme event could be defined based on a dangerous amount of precipitation. E.g., based on amounts of precipitation, under which local flooding occurs or when noticeable damage to crops takes place. For that, a higher resolution of the simulation would be interesting and important, and research into local backgrounds necessary.

References

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Appendix A: Code and Data Availability

A python script including the algorithm for counting the number of extreme events as well as the code for creating all figures can be found on GitLab. Locations of the used data sets are listed in Table 1.

Appendix B: Additional Figures

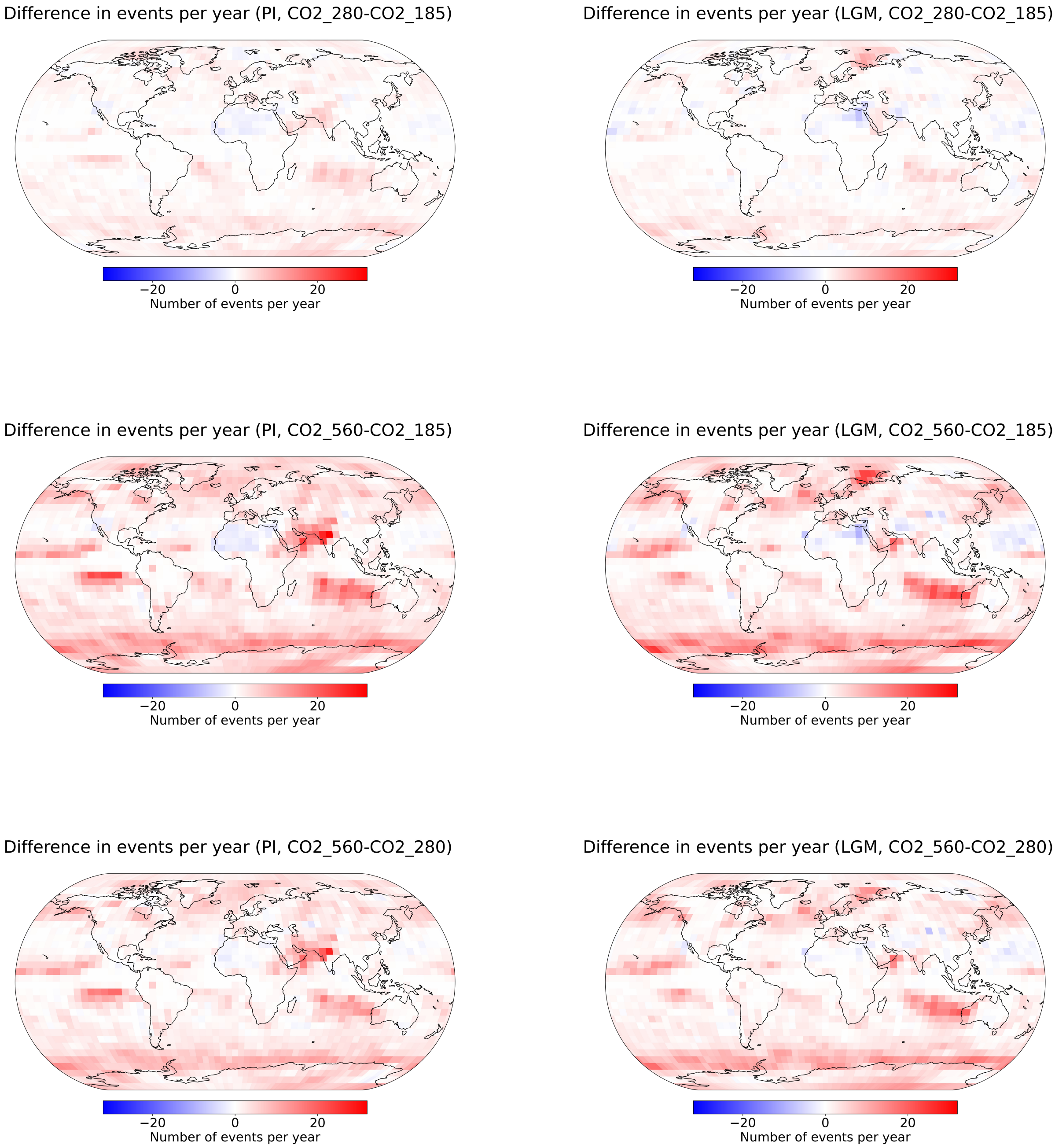

Figure B1. Differences in the mean amount of extreme events per year, between simulations with different CO_2 levels. (Left: PI ice configurations, right: LGM ice configurations).

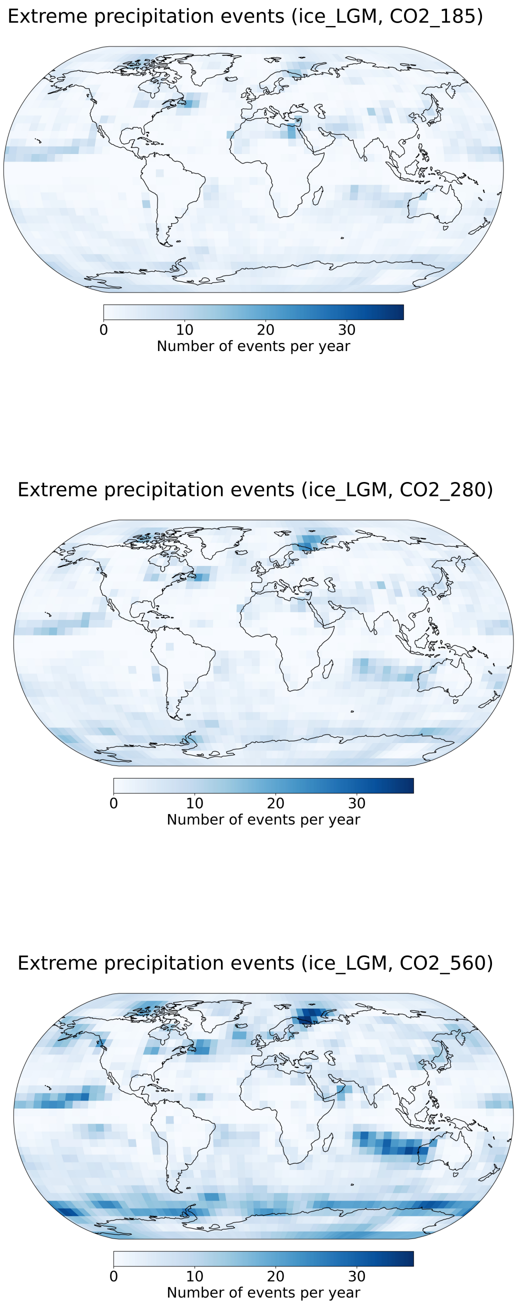

Figure B2. Number of extreme precipitation events per year, regional distribution for LGM (left) and PI (right) ice configuration at different CO_2 levels

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