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Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise

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The contribution to sea-level rise from mountain glaciers and ice caps has grown over the past decades. They are expected to remain an important component of eustatic sea-level rise for at least another century[1,2], despite indications of accelerated wastage of the ice sheets[3–5]. However, it is difficult to project the future contribution of these small-scale glaciers to sea-level rise on a global scale. Here, we project their volume changes due to melt in response to transient, spatially differentiated twenty-first century projections of temperature and precipitation from ten global climate models. We conduct the simulations directly on the more than 120,000 glaciers now available in the World Glacier Inventory[6], and upscale the changes to 19 regions that contain all mountain glaciers and ice caps in the world (excluding the Greenland and Antarctic ice sheets). According to our multi-model mean, sea-level rise from glacier wastage by 2100 will amount to 0.124 ± 0.037 m, with the largest contribution from glaciers in Arctic Canada, Alaska and Antarctica. Total glacier volume will be reduced by 21 ± 6%, but some regions are projected to lose up to 75% of their present ice volume. Ice losses on such a scale may have substantial impacts on regional hydrology and water availability[7].

Mountain glaciers and ice caps include only a minor fraction of all water on Earth bound in glacier ice (<1%) compared with the Antarctic and Greenland ice sheets (>99%), but their retreat has dominated the eustatic sea-level contribution in the past century[1,8]. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change[9] (IPCC) projects twenty-first-century global sea-level rise due to wastage of mountain glaciers and ice caps to range between 0.07 and 0.17 m for different initial ice volume estimates and emission scenarios. This corresponds roughly to one-third of total predicted sea-level rise. The IPCC's approach allows for changes in glacier area, but glacier hypsometry is not modelled explicitly and hence for any warming scenario glaciers would melt away completely rather than approach a new equilibrium at higher altitudes. Ref. 10 developed a geometric volume model that allows glaciers to reach a new equilibrium and used a statistical grid-based approach to calculate the global glacier volume changes. They project a sea-level rise until the end of the twenty-first century of 0.046 m and 0.051 m using temperatures from two global climate models (GCMs) forced by the A1B emission scenario[11]. However, ref. 10 excluded the mountain glaciers and ice caps in Greenland and Antarctica (that is, those ice masses that are physically disconnected from the ice sheets), which comprise 32% of the total volume of all mountain glaciers and ice caps on Earth[12]. The IPCC (ref. 9) projections include these ice masses in an *ad hoc* manner by adding arbitrarily 20% to the projections of the glaciers outside Greenland and Antarctica. Another study[1] found accelerating rates of mass loss from available glacier mass balance data between 1995 and 2005.

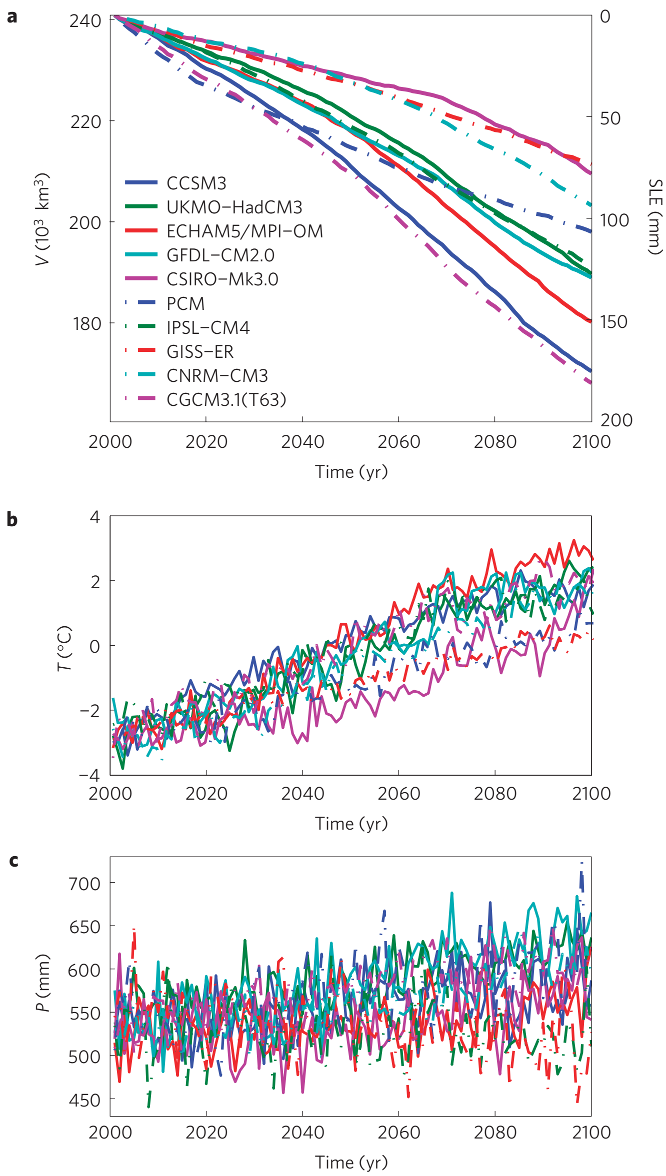

Figure 1 | Glacier volume evolutions in response to GCM projections. **a**–**c**, Projected volume, *V*, of all mountain glaciers and ice caps and corresponding SLE of the volume change for 2001–2100 (**a**), projections of annual mean temperature (**b**) and precipitation (**c**) from ten GCMs, where the values are averaged over all of the grid cells containing mountain glaciers and ice caps from the World Glacier Inventory (WGI-XF).

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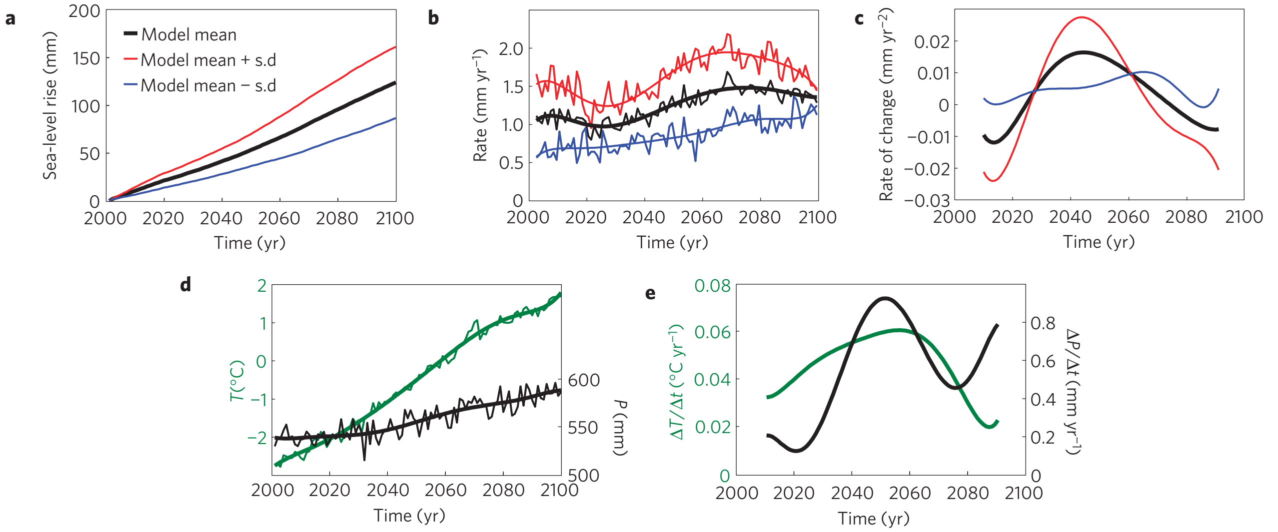

Figure 2 | Model projections for 2001–2100. a–e, Contribution of glacier wastage to sea-level rise, expressed in SLE (**a**), rate of sea-level rise including polynomial fit (**b**) and its rate of change (**c**), multi-model mean of annual temperature and precipitation projections (Fig. 1) including polynomial fit (**d**), and their annual rates of change (**e**). The black line in **a–c** denotes the model mean from 10 GCMs, red is the model mean + standard deviation and blue is the model mean − standard deviation. As the polynomial fit is not well constrained at the edges, the results for the first and last ten years in **c** and **e** are not shown.

Assuming this acceleration to remain constant over the twenty-first century, the projected total sea-level rise from all mountain glaciers and ice caps on Earth by 2100 is 0.240 ± 0.128 m (ref. 1), much larger than the one suggested by the IPCC (ref. 9) and especially by ref. 10. Assuming no acceleration, the projected sea-level rise drops to 0.104 ± 0.025 m (ref. 1), which is still considerably larger than the one in ref. 10. This indicates large discrepancies among the few available twenty-first century projections of mass loss by mountain glaciers and ice caps on a global scale (Supplementary Table S1). In addition, none of these estimates includes the effects of changing precipitation or provides regionally differentiated projections.

Here we project volume changes of all mountain glaciers and ice caps on Earth, spatially resolved for 19 glacierized regions, in response to twenty-first-century temperature and precipitation projections from ten GCMs (Supplementary Table S2) that were included in the IPCC report[9]. First we calibrate an elevation-dependent surface mass balance model with available mass balance observations worldwide (see the Methods section). Specifically, we use observed seasonal mass balance profiles[13–15] from 36 glaciers (Supplementary Table S3), and area-averaged mass balance estimates for 41 glacier regions[14] compiled from more than 300 glaciers with available observations between 1961 and 2004 (Supplementary Table S4). The latter are used as reference values for the initialization of our model, that is, to obtain initial mass balances for our future projections (Supplementary Methods). The model is forced by gridded climate data: monthly near-surface air temperature data from ERA-40 reanalysis[16] and a precipitation climatology[17] (see the Methods section). For the set of 36 glaciers with observed seasonal mass balance profiles we carry out multiple regressions between the calibrated model parameters and variables from the gridded climate data. The result is a set of transfer functions that allow us to assign parameter values to any glacier in the world on the basis of its climatic setting (Supplementary Table S5). The model is then applied to each individual mountain glacier and ice cap (with area ≥0.01 km^2) available in the recently updated and extended World Glacier Inventory[6] (WGI-XF), in total 120,229 mountain glaciers and 2,638 ice caps, henceforth referred to as WGI-XF glaciers. The total area of these glaciers covers roughly 40% of the global mountain glacier and ice cap area (317,724 km^2 out of 741,448 km^2, ref. 12).

To quantify future volume changes, we run the calibrated mass balance model for all WGI-XF glaciers with downscaled monthly twenty-first-century temperature and precipitation from ten GCMs, based on the widely used mid-range greenhouse emission scenario A1B (see the Methods section). As glaciers lose mass owing to temperature increase, they retreat and hence their hypsometry changes. We use volume–area–length scaling[18,19] to account for these changes and their feedbacks to glacier mass balance (for example, area-averaged mass loss may slow down as the glacier retreats from low-lying, high-ablation altitudes), allowing receding glaciers to approach a new equilibrium in a warming climate.

We present our volume projections for 19 glacierized regions (Supplementary Fig. S1), each containing a subset of WGI-XF glaciers. For nine of these regions the glacier inventory (WGI-XF) is incomplete, with the largest inventory gaps in Antarctica, Greenland and North America[12]. In these nine regions, we upscale the future volume changes with a scaling relation between the regional ice volume change and regional glacierized area (see the Methods section). The initial ice volumes for all 19 regions are taken from a recent study[12] where the global mountain glacier and ice cap volume was found to be 0.60 ± 0.07 m sea-level equivalent (SLE).

All projections for the twenty-first century show substantial mountain glacier and ice cap volume losses (Fig. 1a). However, results are highly sensitive to the choice of the forcing GCM. Volume losses range from 12 to 30%, corresponding to 0.07–0.18 m SLE. All ten GCMs unanimously project an increase in annual mean temperatures averaged over all grid cells containing WGI-XF glaciers (3.1–6.6 K), and the annual precipitation increases for most but not all GCMs (8% precipitation decrease to 21% increase) (Fig. 1b,c).

To compare our results with those of ref. 10, we exclude the mountain glaciers and ice caps in Greenland and Antarctica. For the GCM run common to both studies (GFDL-CM2.0), we arrive at a much higher projection for the twenty-first-century sea-level rise (0.096 m SLE) than ref. 10 (0.046 m SLE). This is probably due to the larger temperature sensitivity of our model owing to differences in model design and calibration as well as differences in model initialization. Whereas we initialize the model for each of the 41 glacier regions[14] individually (Supplementary Methods,

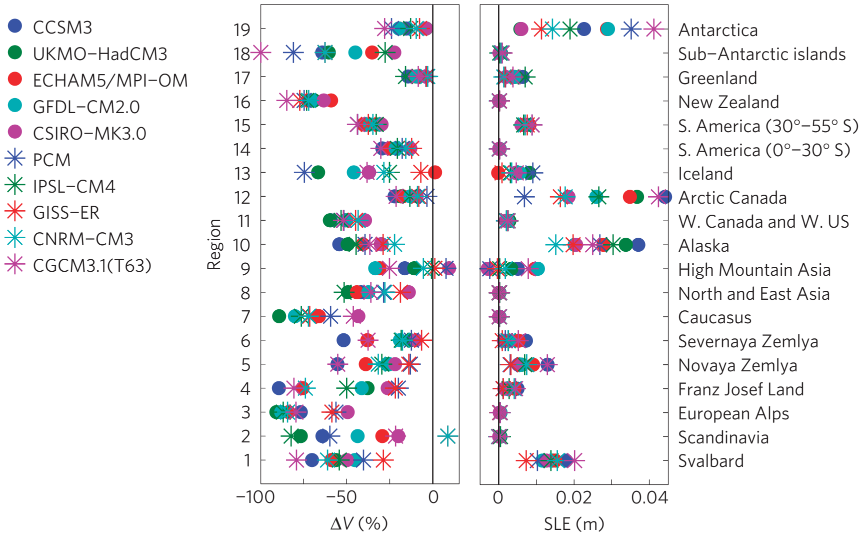

Figure 3 | Regional twenty-first-century glacier volume change. Volume change, ΔV, expressed in per cent from initial volume in year 2000 and in SLE. Results are presented for 19 regions based on temperature and precipitation projections from ten GCMs.

Table S4), ref. 10 used a globally uniform parameter adjustment as the final calibration step. Furthermore, our total initial volume for these glaciers (0.41 m SLE; ref. 12) is larger than in ref. 10 (0.241 m SLE). For all ten GCMs, the projected global volume loss for all glaciers outside Greenland and Antarctica ranges from 0.060 to 0.136 m SLE.

Assuming that future temperature and precipitation projections from all ten GCMs are equally credible, we calculate a multi-model mean for global volume loss by 2100 of 0.124 ± 0.037 m SLE, where the uncertainty range is ±1 standard deviation (Fig. 2a). According to the multi-model mean, the volume loss rate varies between 0.9 ± 0.4 mm SLE yr^{-1} and 1.6 ± 0.4 mm SLE yr^{-1} during the twenty-first century (Fig. 2b), and the volume loss acceleration peaks at 0.016 ± 0.010 mm SLE yr^{-2} in the 2040s (Fig. 2c). Multi-model means of annual temperature and precipitation (Fig. 2d), and their rates of change (Fig. 2e), depict the temperature as a dominant driver of our modelled glacier volume changes. Hence, the decline in the rate of temperature rise around 2060 is followed by a decline in the rate of volume loss. When averaged over 2002–2006, the projected volume loss rate of 1.1 ± 0.4 mm SLE yr^{-1} closely matches the estimated rates of recent mountain glacier and ice cap contribution to sea-level rise[1,2].

Volume change (as % of initial volumes) varies considerably among the 19 regions and among the GCMs (Fig. 3, Supplementary Table S6). The multi-model mean ranges between 8 and 75% volume loss, with the smallest values in Greenland (8 ± 4%) and High Mountain Asia (10 ± 16%), and the largest values in the European Alps (75 ± 15%) and New Zealand (72 ± 7%). Despite the large relative volume loss in the last two regions, their contribution to sea-level rise is negligible owing to the small total ice volume. The main contributors to global mountain glacier and ice cap shrinkage by 2100 are Arctic Canada (0.027 ± 0.012 mSLE), Alaska (0.026 ± 0.007 m SLE), Antarctica (0.021 ± 0.012 m SLE), Svalbard (0.014 ± 0.004 m SLE) and the Russian Arctic (Franz Josef Land, Novaya Zemlya and Severnaya Zemlya; 0.013 ± 0.003 m SLE). The largest scatter of volume projections among the ten GCMs is found in Scandinavia (from 83% volume loss to 9% volume gain by 2100), the sub-Antarctic islands (22–100% volume loss) and Franz Joseph Land (20–89% volume loss). This is mainly caused by high mass balance sensitivities to temperature and/or precipitation changes of these regions and by the large range in temperature and/or precipitation projections.

A major uncertainty in our estimates arises from the initialization of our model to previously reported spatially differentiated mass balance estimates[14]. According to the reported standard errors in the reference area-averaged mass balance estimates[14], we assume an error range of ±0.15 m yr^{-1} for each glacier region (equivalent to ±0.31 mm SLE yr^{-1} in globally averaged mass balance). Reinitializing the model with the lower bound estimates for each of the 41 glacier subregions, the projected multi-model mean for the twenty-first-century volume loss is 0.103 ± 0.037 m SLE. For the upper bound initialization, the projected volume loss is 0.142 ± 0.037 m SLE. We also quantify the uncertainties due to biases in the model input data, model calibration and scaling methods (Supplementary Methods, Figs S2, S3), and show that the errors lie within the range of ±0.04 m SLE for the global volume change by 2100. Further uncertainties are discussed in Supplementary Methods.

Our projected sea-level rise from glacier wastage is probably a lower bound because only the surface mass balance is modelled, neglecting any mass loss by iceberg calving of marine-terminating glaciers. Studies on marine-terminating ice caps[20,21] have shown that calving may account for roughly 30–40% of total mass loss, and hence constitutes a significant contributor to mass loss, especially in polar environments where many glaciers terminate in the sea. However, owing to the scarcity of estimates and the complexity in modelling iceberg calving, this component to mass loss is still neglected in global-scale mass balance modelling of mountain glaciers and ice caps[9,10,22,23].

Our range of projected twenty-first-century volume loss forced by ten GCMs and the A1B emission scenario is similar to the IPCC (ref. 9) range based on an ensemble of GCMs. In addition, our spatially differentiated projections reveal the main regional contributors to sea-level rise as well as the regions most vulnerable to glacier wastage. Many of these glacierized regions are still facing large uncertainties in the climate projections due to the choice of GCM. On a global scale, less than half of the mountain glacier and ice cap volume will have disappeared by the end of the twenty-first century. Therefore, glaciers other than the ice sheets will continue to be an important contributor to sea-level rise and watershed hydrology, if warming continues beyond 2100 as is expected[9].

Methods

For each WGI-XF glacier, monthly melt (in metres water equivalent) is calculated through a degree-day model that differentiates between degree-day factors for snow and for ice (Supplementary Methods). Monthly snow accumulation is obtained from a threshold temperature that differentiates between snow and rain. Refreezing is parameterized as a function of annual mean air temperature[24]. Mass balance calculations are carried out for 20 m elevation bands.

We tune the model parameters to yield maximum agreement between (1) times series of modelled and observed area-averaged winter and summer mass balance, and (2) series of modelled and observed winter and summer mass balance along glacier elevation, averaged over the period of observations. The tuning is carried out for each individual glacier in the subset of 36 glaciers. Modelled area-averaged mass balances, B (in kg m^{-2}), are converted into SLE by:

$$\mathrm{SLE} = -\frac{BS}{\rho S_{\mathrm{ocean}}}$$

where S is the glacierized area, ρ is the density of water and S_{ocean} is the area of the ocean (362×10^{12} m^2).

The area–altitude distribution of each WGI-XF glacier is approximated from the available data in WGI-XF (ref. 6) on surface area, length and glacier elevation range (minimum and maximum elevation) following the approach of ref. 10: for mountain glaciers, the area–altitude distribution is approximated with a linearly increasing function from the terminus to the mean altitude and a linearly decreasing function above (Supplementary Fig. S4). This approximation relies on the argument that observed area–altitude distributions tend to have a maximum near the mean altitude where the mass flux of ice is greatest. The distribution for ice caps, assuming perfect plasticity, is approximated by a parabolic shape with a circular base[25] (Supplementary Fig. S4). If the elevations are not reported in the WGI, we derive these from the 30-arc-sec (1-km) gridded, quality-controlled digital elevation model of the Global Land One-kilometre Base Elevation (GLOBE) project[26]. The elevations from GLOBE are extracted by finding maximum and minimum elevations within the range of $1/48^\circ$ ($\sim$2.5 km) from a glacier. The sensitivity of our volume projections to the biases in these data is tested and shown to lie within the error range of ± 0.04 m SLE for the global volume change by 2100 (Supplementary Methods).

As GCMs are unable to represent the local subgrid-scale features and dynamics, this leads to biases in the climate variables over the local glacier scale. Following a statistical downscaling approach[27], we shift the future monthly temperature time series for each GCM grid cell containing WGI-XF glaciers by the average bias for each month between the GCM and ERA-40 temperatures over the period 1980–1999. Annual precipitation in the GCM is scaled with a correction factor between precipitation climatology[17] and GCM mean precipitation over 1980–1999.

After deriving the volume projections for all WGI-XF glaciers we upscale the projections for nine glacierized regions with an incomplete glacier inventory. We assume that in each of these regions the ratio of volume change of all WGI-XF glaciers and the total volume change is equal to the ratio of the area of all WGI-XG glaciers and total initial glacierized area. This upscaling relation serves as a good first-order approximation, as tested on the ten regions with complete glacier inventories (Supplementary Methods, Fig. S3).

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Author contributions

V.R. led the development of this study, prepared all data sets and carried out all calculations. R.H. initiated the study and contributed to the development of the methodology, discussion of results and the writing of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to V.R.