Low Sea Level Rise Projections from Mountain Glaciers and Icecaps under Global Warming

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LETTERS

Low sea level rise projections from mountain glaciers and icecaps under global warming

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The mean sea level has been projected to rise in the 21st century as a result of global warming[1]. Such projections of sea level change depend on estimated future greenhouse emissions and on differing models, but model-average results from a mid-range scenario (A1B) suggests a 0.387-m rise by 2100 (refs 1, 2). The largest contributions to sea level rise are estimated to come from thermal expansion (0.288 m) and the melting of mountain glaciers and icecaps (0.106 m), with smaller inputs from Greenland (0.024 m) and Antarctica (−0.074 m)[1]. Here we apply a melt model[3] and a geometric volume model[4] to our lower estimate of ice volume[5–7] and assess the contribution of glaciers to sea level rise, excluding those in Greenland and Antarctica. We provide the first separate assessment of melt contributions from mountain glaciers and icecaps, as well as an improved treatment of volume shrinkage. We find that icecaps melt more slowly than mountain glaciers, whose area declines rapidly in the 21st century, making glaciers a limiting source for ice melt. Using two climate models, we project sea level rise due to melting of mountain glaciers and icecaps to be 0.046 and 0.051 m by 2100, about half that of previous projections[1,8].

The Intergovernmental Panel on Climate Change (IPCC) estimate[1,8] takes account of glacier shrinkage under climate warming, but their model uses a time-constant sensitivity for mass balance so that glaciers would melt away completely for any warming rather than approaching a new equilibrium. We apply a glacier mass balance model[3] to the total area of glaciers and icecaps[5], while taking account of changes in glacier area[4], but our model allows glaciers to approach equilibrium. Our model works on glacier areas within a regular 1° grid instead of irregular regions[8,9]. The global distribution of mountain glaciers and icecaps[10,11] that we use is shown in Fig. 1, but we note that the World Glacier Inventory[12] covers only part of the area. The major challenge for this project is to estimate the parameters that we need in areas not covered by the inventory data. Our glacier areas and volume[5] do not include mountain glaciers and icecaps around the Greenland and Antarctic ice sheets. We understand that they are nominally included in the 'Greenland' and 'Antarctic' sea level rise (SLR) contributions in ref. 1. Reference 8 uses the same areas as the 100 glacier regions of ref. 9, which clearly exclude Greenland and Antarctica, but assumes a larger ice volume, equivalent to a 0.5-m SLR[13] that is supposed to include glaciers and icecaps around the ice sheets[5–7]. The glacier areas and volume in ref. 8 are therefore inconsistent.

We apply our degree-day model[3] in regions where we can estimate the average equilibrium line altitude (ELA) from data in the glacier inventory, but we cannot do this for most parts of the world. Our solution is to run the mass balance model for seven regions with good glacier inventory data[12] and then to extrapolate results to the other regions. The seven regions (Axel Heiberg Island, Svalbard, northern Scandinavia, south Norway, the Alps, the Caucasus and New Zealand) cover a wide range of glacial and climatic conditions. We calculate mass balance profiles with the degree-day model for each grid cell within the seven regions and then approximate them with

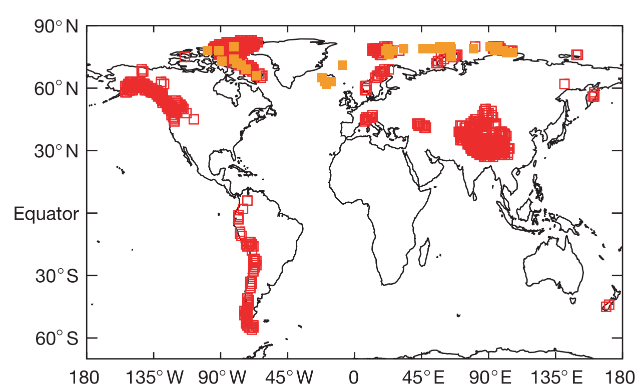

Figure 1 | Worldwide location of grid cells containing glaciers (red)[10] and individual icecaps (orange)[11].

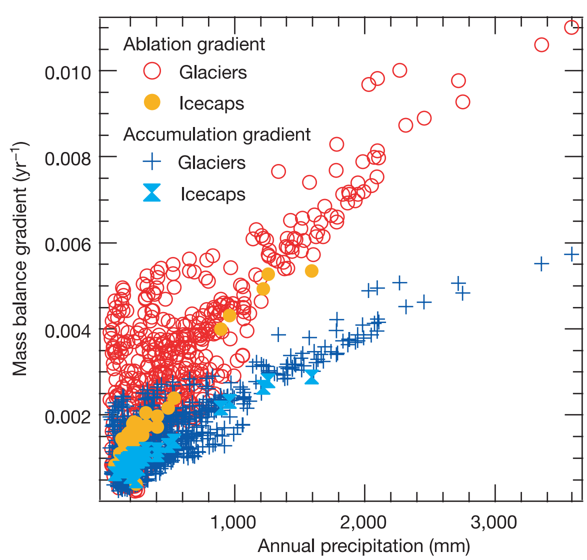

Figure 2 | Altitudinal gradients of mass balance in accumulation and ablation areas plotted against annual precipitation for all grid cells. The values are based on model results for seven regions in which the balance gradient in the accumulation area has correlations of 0.83 and 0.59 respectively with annual precipitation and summer temperature. The corresponding correlations for balance gradient in the ablation area are 0.83 and 0.63.

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two segments representing linear gradients of mass balance versus altitude in the accumulation and ablation areas respectively. We regress the resulting balance gradients on annual precipitation and summer temperature from a gridded climatology[14] and we apply the resulting multiple regression equation to all grid cells with glaciers (Fig. 1). There is an obvious association between balance gradients and annual precipitation (Fig. 2): lower balance gradients occur at higher latitudes with cold, dry climate where most icecaps are found. The few larger-gradient values are for the icecaps of Iceland with a relatively warm, wet climate.

We have already estimated[5–7] size distributions for area and volume of mountain glaciers in 1° latitude/longitude cells as well as area and volume estimates for 116 individual icecaps. Additionally, to run the geometric model[4], we need the altitude range (minimum to maximum altitude) and area–altitude distribution of the glaciers and icecaps. We estimate the altitudinal range of mountain glaciers from a roughness statistic[5] derived from high-resolution (30 s) topographic data[15] using a linear regression equation that we calibrate with data from the seven regions where altitude ranges are known. We then approximate the area–altitude distribution of mountain glaciers with a triangle defined by maximum, minimum and mean altitudes. Observed area–altitude distributions for mountain glaciers tend to have a maximum near to the mean altitude where the mass flux of ice is greatest. For an icecap, we assume a parabolic shape with a circular base[5,16]. This defines both the altitudinal range and the area–altitude distribution, for example, the area within each altitude band increases linearly with altitude up to the top of the icecap.

We calculate mass balance for individual grid squares with mountain glaciers and icecaps and area-weight these to give a global mass balance. We initially assume that the ELA for each mountain glacier or icecap has equal areas above and below, and we then adjust all ELAs to make the model balance fit the estimated global mass balance of $-0.130 \pm 0.033\,\mathrm{m\,yr^{-1}}$ for the 1961–1990 reference period[17]. We note that only a small ELA adjustment ($+18 \pm 17$ m) is needed, and this is within the uncertainty limits of observed ELA. This assumed global mass balance value defines the SLR for the reference period as $0.19\,\mathrm{mm\,yr^{-1}}$.

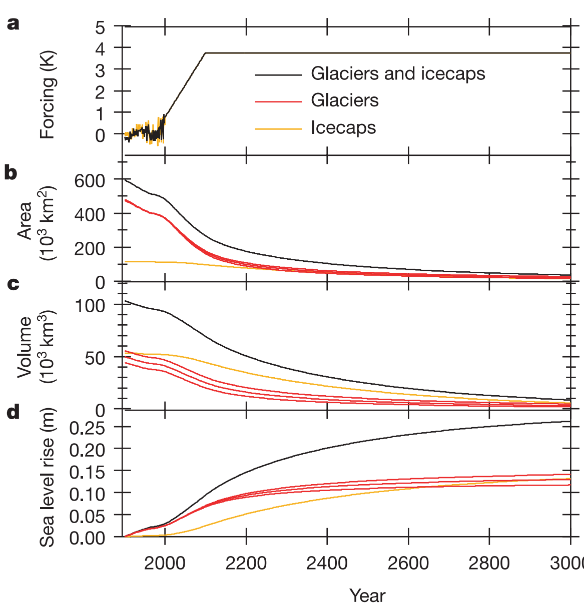

Figure 3 | Time evolution of mountain glacier and icecap metrics. Mountain glacier and icecap area (**b**), volume (**c**) and SLR contribution (**d**). The temperature forcing (**a**) for the 20th century is from climate data[14] and for the future is an idealized scenario. Results are shown for three reference period mountain glacier volumes (37×10^3, 43×10^3 and $49 \times 10^3\,\mathrm{km^3}$), but the corresponding total volumes and total SLR contributions are for the central value only. The total potential SLR is 0.26 m.

For comparison with earlier studies, we increase the temperature in the model by 1 K for all months to get a globally averaged mass balance sensitivity of $-0.35\,\mathrm{m\,yr^{-1}\,K^{-1}}$, which is slightly less than previous estimates of -0.39, 0.41 and $-0.37\,\mathrm{m\,yr^{-1}\,K^{-1}}$ (refs 9, 18 and 19, respectively). However, an estimated ±15% uncertainty in our mass balance gradients gives an uncertainty of $\pm 0.050\,\mathrm{m\,yr^{-1}\,K^{-1}}$ in our mass balance sensitivity, so our new result is not significantly lower than previous estimates. In this experiment, the highest SLR contributions come from individual grid cells in the Gulf of Alaska, Patagonia and Iceland, where we find large mass balance sensitivity to coincide with large ice areas. The large mass balance sensitivity is consistent with the recent high rates of ice loss in Alaska and Patagonia[20,21] if these regions recently experienced higher temperatures. To reproduce exactly the known glacier wastage region by region would require us to adjust the ELA in the reference period grid point by grid point. This could be the subject of further research. Here we adjust all ELAs uniformly to match the assumed global mean mass balance in the reference period as described above.

Several workers[1,3,8,9] conclude that the main climate variable controlling past and future global changes in mountain glaciers and icecaps is temperature change, with precipitation being of secondary importance. Reference 1 uses only temperature forcing in the form of anomalies and we do likewise, on the basis of the 1961–1990 reference period. We apply forcing annually by perturbing the ELA from its reference state for each grid cell by the temperature anomaly for each year divided by the lapse rate. (The temperature anomaly is the average over the four summer months in each hemisphere and the assumed lapse rate is $0.006\,\mathrm{K\,m^{-1}}$.) For each year, the procedure is to perturb the ELA from its reference state, calculate the change in volume from changes in mass balance, and then the resulting changes in total area and area–altitude distribution are calculated with the glacier geometric model[4].

In the next experiment, we use gridded temperature data (1° latitude by 1° longitude resolution) derived from observations[14] to assess mountain glacier and icecap changes over the 20th century, and we assume uniform warming for 1998–2100, followed by constant temperature to the end of the millennium. The results (Fig. 3) reflect the greater area but smaller volume of the mountain glaciers compared with the icecaps in the reference period[5]. During the 20th century, the areas and volumes for mountain glaciers decline much more than for the icecaps and contribute nearly all the SLR, while icecaps begin to make a significant SLR contribution in the 21st century. The decline in mountain glacier area and volume becomes a limiting factor in the glacier melt contribution to SLR during the

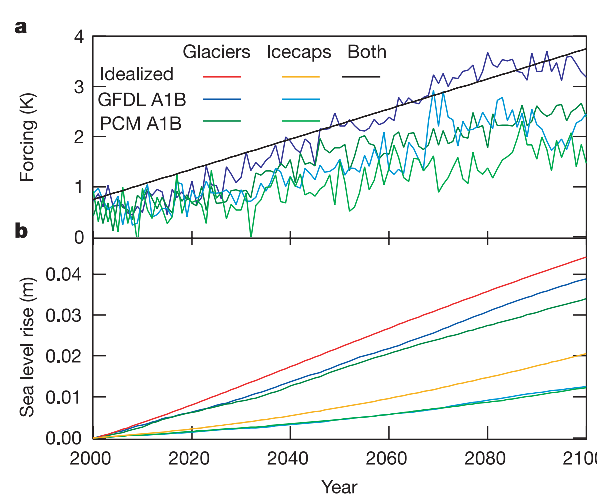

Figure 4 | Temperature forcing and SLR contribution for mountain glaciers and icecaps over the 21st century. The temperature forcing (**a**) is from two climate models using scenario A1B (ref. 2). The idealized scenario results are shown for comparison. The key in **a** also refers to the SLR contribution in **b**.

21st century. Even at the end of the millennium some ice survives, despite prolonged exposure to higher temperature.

We made further experiments to illustrate the glacier and icecap response to spatially differentiated forcing, using results from two climate models, the GFDL and the PCM[22,23]. The model simulations for GFDL_CM2_0_run1 and for NCAR_PCM1_run2 run through the 20th century, based on historical radiative forcing, followed by the 21st-century mid-range A1B scenario[2]. Figure 4a shows the 21st-century area-averaged mountain glacier and icecap temperature forcing from these two models; the idealized forcing is shown for comparison. The temperature response to radiative forcing of the GFDL model is greater than that of the PCM model, but both models show markedly greater warming over the mountain glacier regions compared with the icecap regions; there is a warming difference of about 1 K by 2100. These temperature differences are reflected in the SLR contributions in Fig. 4b. The main difference between the two projections is the greater mountain glacier melt using the GFDL model compared to PCM. By contrast, icecap melt over the 21st century is very similar for the two simulations.

We summarize here the SLR results for the 20th and 21st centuries (see also the Supplementary Information). On the basis of the observed climate, we estimate the mountain glacier and icecap contribution to SLR to be 0.028 m for the 20th century, which is similar to previous values[1]. The GFDL and PCM models give broadly similar SLR values (0.030 and 0.021 m) for the 20th century; for the A1B scenario the models give a much lower SLR for the 21st century (0.046 and 0.051 m) than previous estimates[1]. The dominant uncertainty for the 20th century is the uncertainty in area-weighted glacier mass balance for 1961–1990, but its relative importance drops very much in the 21st century compared to high negative mass balances under global warming. For the 21st century, the major uncertainty is the uncertainty in balance gradients, leading to differences in mass balance sensitivity.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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