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Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution

Regine Hock,[1,2] Mattias de Woul,[3] Valentina Radić,[1,4] and Mark Dyurgerov[3,5]

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[1] The Intergovernmental Panel on Climate Change (IPCC) estimates that the sum of all contributions to sea-level rise for the period 1961–2004 was 1.1 ± 0.5 mm a^{-1}, leaving 0.7 ± 0.7 of the 1.8 ± 0.5 mm a^{-1} observed sea-level rise unexplained. Here, we compute the global surface mass balance of all mountain glaciers and ice caps (MG&IC), and find that part of this much-discussed gap can be attributed to a larger contribution than previously assumed from mass loss of MG&IC, especially those around the Antarctic Peninsula. We estimate global surface mass loss of all MG&IC as 0.79 ± 0.34 mm a^{-1} sea-level equivalent (SLE) compared to IPCC's 0.50 ± 0.18 mm a^{-1}. The Antarctic MG&IC contributed 28% of the global estimate due to exceptional warming around the Antarctic Peninsula and high sensitivities to temperature similar to those we find in Iceland, Patagonia and Alaska. **Citation:** Hock, R., M. de Woul, V. Radić, and M. Dyurgerov (2009), Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution, *Geophys. Res. Lett.*, *36*, L07501, doi:10.1029/2008GL037020.

1. Introduction

[2] Sea-level rise is dominated by ocean thermal expansion and mass losses from glaciers [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007; *Domingues et al.*, 2008]. Mass losses from MG&IC have been major and accelerating contributors to rising sea-level and are expected to dominate eustatic sea-level rise, exceeding the contributions from the Antarctic and Greenland ice sheets for at least another century [*Meier et al.*, 2007]. However, global mass balance estimates of these glaciers are scarce [*Kaser et al.*, 2006]. The *IPCC* [2007] estimate for 1961–2004 is based on extrapolation of only about 300 mostly short and unevenly distributed surface mass balance records [*Kaser et al.*, 2006] covering less than 2% of the total glacier area. Since Greenland and Antarctica are almost void of in-situ surface mass balance data for MG&IC, these glaciers tend to be excluded in global analyses [*Raper and Braithwaite*, 2006; *Cogley*, 2005]. In the absence of observations, IPCC's regional estimate of Antarctica's MG&IC is based on only two rough estimates, assuming the regional specific mass balance to be equal either to the global average [*Ohmura*, 2004] or the average of the glaciers of the Canadian High Arctic [*Dyurgerov and Meier*, 2005]. We argue that these assumptions are improbable and lead to substantial underestimation of mass loss in this area. Hence, there is an urgent need for better methods to quantify mass changes from MG&IC especially in data sparse regions.

[3] Here, we implement a grid-based modelling approach to estimate changes in surface mass balance on a global scale including regions where measurements are lacking. We use a gridded global glacier data set, reanalysis temperature and precipitation trends, and modelled glacier mass balance temperature and precipitation sensitivities, the latter defined as the changes in mass balance in response to a given instant temperature/precipitation change [*de Woul and Hock*, 2005]. We choose the period 1961–2004 to allow direct comparison to IPCC estimates. We do not consider shorter periods, as have some previous studies [*IPCC*, 2007; *Meier et al.*, 2007; *Kaser et al.*, 2006], since our method relies on temperature and precipitation trends, and these tend to become unreliable for shorter than multi-decadal time scales due to large interannual variability. Global glacier surface mass balances are computed on a regular 1 × 1° global grid and converted into sea-level equivalent (SLE, defined as minus specific mass balance multiplied by glacier area divided by global ocean area), thus assuming all glacier mass loss directly contributing to sea-level. We incorporate all MG&IC including those around the ice sheets in Greenland and Antarctica (Figure 1a), but we exclude the ice sheets.

2. Methods

[4] Global SLE (mm a^{-1}) for the period 1961–2004 is computed by:

$$SLE = -\frac{1}{NA_{ocean}}\sum_{i=1}^{I}A_i\sum_{n=1}^{N}\left(\Delta b_{i,n}+b_{i,0}\right) \tag{1}$$

where N is number of years (44 years; 1961–2004), A_{ocean} is the area of the ocean (362 × 10^6 km^2), I is number of glacierized grid cells and A_i is glacierized area in grid cell i. $\Delta b_{i,n}$ is the change in surface mass balance (m w.e. a^{-1}) for any year n with respect to the reference mass balance $b_{i,0}$ at $t = t_0$ caused by changes in air temperature and precipitation. Here $b_{i,0}$ is the surface mass balance at $t = t_0$ (m w.e. a^{-1}) and corresponds to the balance that would occur during $t > t_0$ in an unchanging climate. Limited data [*Cogley*, 2005; *Dyurgerov and Meier*, 2005; *Kaser et al.*, 2006; *Cogley*, 2009] suggest that the global surface mass balance was negative during the years leading up to 1961 implying $b_0 < 0$.

[1]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2]Department of Earth Sciences, Uppsala University, Uppsala, Sweden.
[3]Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden.
[4]Now at Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada.
[5]Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA.

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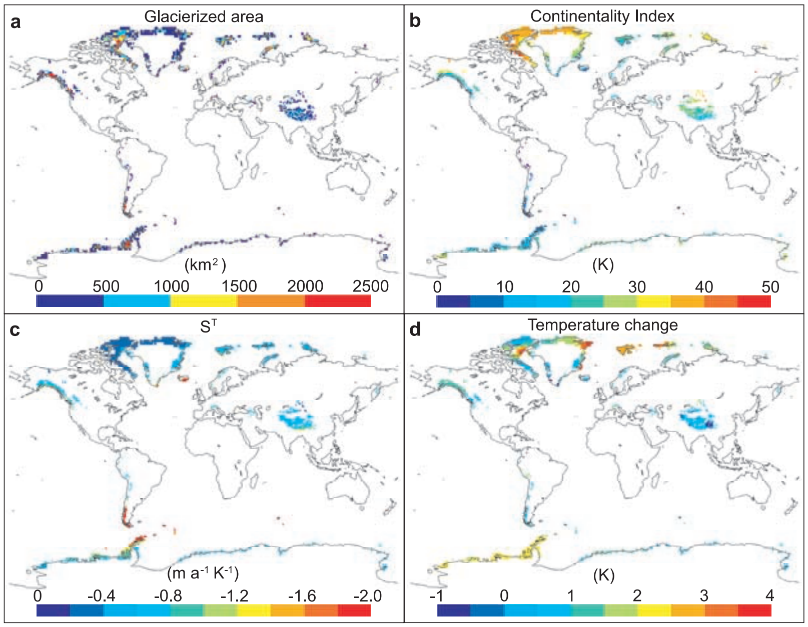

Figure 1. Input variables to global surface mass balance calculations. (a) Glacierized area of the $1 \times 1°$ grid (704 000 km^2, 1376 grid cells). Note that grid cells in Greenland and Antarctica may contain some portion of ice sheets, but these areas are not included here. (b) Continentality index defined as the temperature difference between the coldest and warmest month of the same year averaged over the ERA-40 period 1958 to 2001. (c) Modelled mass balance sensitivity, S^T (m a^{-1} K^{-1}), to a 1 K uniform warming. (d) Total annual mean temperature change between 1961 and 2004.

The calculations of *Kaser et al.* [2006] imply a global mass balance b_0 of about -0.2 ± 0.1 m w.e. a^{-1} corresponding to 0.30 ± 0.15 mm SLE a^{-1}. Since grid-based information on $b_{i,0}$ is not available we first compute global SLE assuming $b_{i,0} = 0$ and then add $b_0 = 0.30 \pm 0.15$ mm SLE a^{-1} to obtain our global estimate (equation (1)). For regional estimates we assume that the relative contribution of each grid cell to global estimates 1961–2004 is the same for $b_{i,0}$ and Δb_i.

[5] Here $\Delta b_{i,n}$ is computed for each grid cell i and year n from mass balance sensitivity to a uniform 1 K temperature increase, S^T, and to a 10% precipitation increase, S^P, temperature changes, ΔT, for each month, m, and annual precipitation changes in %, ΔP, with respect to year t_0:

$$\Delta b_{i,n} = S_i^T \sum_{m=1}^{12} \left(\Delta T_{i,n,m} SSC_{i,m} \right) + \frac{1}{10} S_i^P \Delta P_{i,n}. \qquad (2)$$

SSC is the seasonal sensitivity characteristic [*Oerlemans and Reichert*, 2000], i.e. the contribution of each month, m, to the annual sensitivity ($\sum_{m=1}^{12} SSC_{i,m} = 1$).

[6] Annual sensitivities are obtained from calibrating a temperature and precipitation driven mass balance model to 88 glaciers for which seasonal mass balances ≥5 years were available [*Dyurgerov and Meier*, 2005] (Figure S1).[1] The model relates summer balances to positive degree-day sums and winter balances to the sum of daily precipitation when temperatures are below freezing [*de Woul and Hock*, 2005] and is forced by daily data from the 0.5° resolution re-analysis data (ERA-40) by the European Centre for Medium-Range Forecasts which are available for mid-1957 to mid-2002 [*Simmons et al.*, 2004]. The mass balance model is perturbed by a hypothetical uniform 1 K temperature and 10% precipitation increase in order to obtain, for each glacier, mass balance sensitivities [*de Woul and Hock*, 2005]. There is an obvious relationship between mass balance sensitivity and a continentality index, *CI* (Figure S2), defined as the average difference between the coldest and warmest month of the year averaged over the ERA-40 period. Glaciers in maritime environments (low *CIs*) tend to be more sensitive to temperature increase than those in continental environments (high *CIs;* Figures 1b and 1c) in agreement with previous studies [*Oerlemans and Reichert*, 2000; *de Woul and Hock*, 2005]. We extrapolate mass balance sensitivities to all glacierized grid cells using the regression equations of Figure S2.

[7] Mass balances tend to be more sensitive to temperature changes in summer than in winter, and temperature changes are generally not uniformly distributed over the year. Therefore, we calculate the seasonal sensitivity characteristic (SSC) [*Oerlemans and Reichert*, 2000], i.e., the contribution of each month to total sensitivity, by running the model with each month perturbed individually by 1 K for all 88 glaciers. SSCs displayed characteristic shapes depending on continentality index and annual precipitation (Figure S3). While in continental climates the mass balance is sensitive to a 1 K temperature only during a few summer months, in maritime climate almost all months contribute to the total sensitivity. Based on visual inspection we identify seven distinct SSC classes constrained by ranges in continentality indices and annual precipitation. Each grid cell falls in one of these classes allowing SSCs to be extrapolated to the entire grid. Precipitation sensitivities

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL037020.

Table 1. Surface Mass Balance (in sea level equivalent, SLE, mm a^{-1}) 1961–2004 of All Mountain Glaciers and Ice Caps[a]

SLE^{excl}, mm a^{-1}	Area^{excl}, 10^3 km^2	SLE^{A+G}, mm a^{-1}	Area^{A+G}, 10^3 km^2	SLE^{incl}, mm a^{-1}	Area^{incl}, 10^3 km^2	Reference
0.51 ± 0.29 (65%)	518 ± 41 (74%)	0.28 ± 0.17[b] (35%)	186 ± 15 (26%)	0.79 ± 0.34 (100%)	704 ± 56 (100%)	This study
0.43 ± 0.15 (86%)	546 (70%)	0.07 ± 0.10 (14%)	239 (30%)	0.50 ± 0.18 (100%)	785 (100%)	*IPCC* [2007]

[a]excl is excluding and incl is including those in Greenland, *G*, and around Antarctica, *A*. The ice sheets are not considered. *IPCC* [2007] adopted the estimates by *Kaser et al.* [2006]. Note that in contrast to IPCC, our SLE error estimates are based on a full error analysis (see auxiliary material) and represent standard errors referring to 68% confidence limits (1 σ). The IPCC error estimates are intended to refer to 90% confidence intervals; however, errors are informal estimates computed simply from the standard deviation of three independent SLE estimates [*Kaser et al.*, 2006], and hence, IPCC's uncertainties are probably underestimated.

[b]Antarctica MG&IC alone (132 ± 11 × 10^3 km^2) contribute 0.22 ± 0.16 mm a^{-1} (28%). IPCC does not report separate estimates for Antarctica and Greenland MG&IC.

are interpolated as a function of mean annual precipitation (Figure S2).

[8] Temperature, ΔT, and precipitation changes, ΔP (equation (2)), are obtained from linear trend analyses (hence, assuming changes to be monotone) of suitable meteorological data derived principally from the ERA-40, and expressed for each year as anomalies from monthly mean temperatures and annual precipitation averaged over the baseline period 1961–1990, respectively (Figure 1d). Due to large discrepancies between ERA-40 temperature trends and observations, for Svalbard we used the 5° × 5° resolution temperature Climatic Research Unit CRUTEM2v data [*Jones and Moberg*, 2003] and for Alaska the temperature and precipitation trends obtained from 77 weather stations [*Arendt et al.*, 2009]. The ERA-40 data end in 2001 but trends were assumed unaltered until 2004. In Antarctica ERA-40 temperature trends tend to overestimate recent warming [*Simmons et al.*, 2004]. To correct for this bias we compute the monthly temperature trends during 1961–2004 from available long-term observational records (http://www.antarctica.ac.uk/met/gjma/). For each grid cell in Antarctica we replace the ERA-40 trend by the nearest observational trend in case the former exceeds the latter, and thus obtain trends in good agreement with previous studies [*Turner et al.*, 2005]. The trends in some grid cells in East Greenland and Arctic Canada (Figure 1d) are suspiciously high, but potential errors have negligible effect on the result since mass balance sensitivities are low in these areas. Changes in mean annual temperature and precipitation over the period 1961–2004, averaged over all glacierized grid cells, are +1.2°C (std. dev. σ = 0.7°C) and +19% (σ = 18%), respectively.

[9] Except for Greenland and Antarctica, we determine glacier area from the GGHYDRO 2.3 global hydrographic data set, which gives the percentage of glacierization in a 1 × 1° global grid [*Cogley*, 2003]. For Greenlandic MG&IC we resample the 0.05° longitude × 0.02° latitude glacier area data set by *Weng* [1995] to a 1 × 1° grid. Since grid-based data for Antarctica are not available, we make our own estimate for the spatial distribution of ice masses disconnected from the ice sheet (Figure 1a). Based on the Antarctic Digital Database by the Scientific Committee on Antarctic Research [*ADD Consortium*, 2000], the areas classified as "non-rock" of all islands around mainland Antarctica south of 60°S are assumed glacierized, and their areas were compiled to a 1 × 1° grid. We exclude the islands in the Ross and Ronne-Filchner ice shelves due to expected very cold climate conditions with almost no surface melt. Our methodology is not applicable where melting is negligible, and we aim to keep our estimate conservative. Although a first-order approximation, our data set provides the first grid-based data set of MG&IC in Antarctica thus advancing IPCC's MG&IC estimate which has neglected any spatial differentiation in this region.

3. Results

[10] Global surface mass balance sensitivity to a uniform 1 K temperature rise, derived as an unweighted mean over all grid cells, is −0.68 m a^{-1} K^{-1} (σ = 0.26 m a^{-1} K^{-1}). Modelled values for the 88 glaciers ranged from −0.20 m a^{-1} K^{-1} (Devon Ice Cap, Canada) to −2.93 m a^{-1} K^{-1} (Eyjabakkajökull, Vatnajökull, Iceland). Our approach allows us to compute a spatially distributed global pattern of mass balance sensitivities to temperature revealing highest sensitivities around the Antarctic Peninsula, in Iceland, Patagonia and southern Alaska (Figure 1c). Global mean sensitivity to a 10% precipitation increase is +0.11 m a^{-1} (σ = 0.08 m a^{-1}), compensating for only 16% of the effect of a 1 K warming and confirming the dominant role of temperature for glacier mass changes [*de Woul and Hock*, 2005; *IPCC*, 2007].

[11] Surface mass loss due to changes in temperature and precipitation for the period 1961–2004 was 0.49 ± 0.30 mm SLE a^{-1}, assuming the surface mass balance was zero at the start of the simulation ($b_{i,0}$ = 0 in equation (1)). Adding b_0 = 0.30 ± 0.15 mm SLE a^{-1} to Δb (equation (1)) yields our total SLE from MG&IC of 0.79 ± 0.34 mm a^{-1} for the period 1961–2004 (Table 1). This is considerably higher than the IPCC estimate (0.50 ± 0.18 mm a^{-1}) although our area estimate is smaller (~10%). This suggests that previous assessments have underestimated the total contribution of glacier melt to sea-level rise although we note that our revised and the IPCC's estimates overlap within error bounds. Note that uncertainties are not directly comparable. In contrast to *IPCC* [2007], we perform a full error analysis based on error propagation (see auxiliary material, Figure S4, and Table S1).

[12] The strength of our grid-based approach is that it allows us to analyse the global distribution of SLE from MG&IC (Figure 2). Antarctica and Greenland MG&IC contributed 0.28 ± 0.17 mm SLE a^{-1}(35%) of global SLE from MG&IC which is considerably more than the 0.07 ± 0.10 mm a^{-1} (14%) reported in IPCC despite their larger area estimate (Table 1). The contribution of Antarctic MG&IC alone is 0.22 ± 0.16 mm a^{-1} (28% to the global total) originating almost entirely from the Antarctic peninsula and surroundings, while the East Antarctica contribution is roughly zero, due to relatively little warming or even cooling (Figure 1d) and low mass balance sensitivities (Figure 1c). Although direct surface mass balance data are

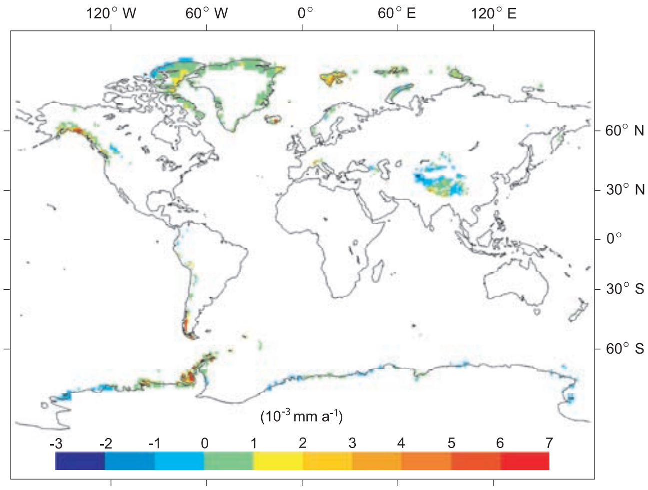

Figure 2. Modelled surface mass balance from all glacierized grid cells 1961–2004 (10^{-3} mm SLE a^{-1}).

very sparse for this period, observations of exceptional rates of temperature increase [*Vaughan et al.*, 2001; *Turner et al.*, 2005; *Steig et al.*, 2009], retreating glacier fronts [*Cook et al.*, 2005], increase in melting area [*Tedesco et al.*, 2007], and rapid disintegration of ice shelves on the Antarctic Peninsula [*Vaughan et al.*, 2001] provide circumstantial support for our alternative estimate. Both the mass balance sensitivities to temperature (Figure 1c) and the temperature increases (Figure 1d) around the Antarctic Peninsula are far above global average. This combined with large area (Figure 1a) is expected to yield large mass losses, and suggests a high likelihood of considerable future sea-level rise contribution from this region if current climate conditions persist. Consistent with previous work [*Arendt et al.*, 2002; *Rignot et al.*, 2003], other large contributors (Figure 2) are Alaska (17%), South America (south of 30°S, 13%), and Arctic Canada (12%), the latter due to large glacierized area (21% of global), and the former two regions due to large areas (Figure 1a) combined with large temperature sensitivities (Figure 1c).

4. Discussion of Uncertainties

[13] Our estimates are subject to uncertainties due to simplifications in the model, and errors in the climate, mass balance and area data sets. ERA-40 data have many shortcomings, although a significant improvement occurred after 1978 when more satellite data were incorporated [*Bromwich and Fogt*, 2004]. Nevertheless linear trends for 1958–2001 for the northern hemisphere are generally less positive in ERA-40 than in the observational Climatic Research Unit CRU data [*Simmons et al.*, 2004] providing confidence that our larger SLE estimates compared to IPCC do not stem from overestimation of temperature trends. However, in some regions, e.g. Antarctica, ERA-40 trends are substantially overestimated exceeding observed trends by up to a factor two [*Simmons et al.*, 2004], and we constrained the trends by other observational data. ERA-40 precipitation trends have received far less scrutiny in terms of validation, but errors affect our results to a far lesser degree due to the dominance of air temperature as driver for recent MG&IC surface mass balance changes [*IPCC*, 2007]. Our approach assumes constant area, and hence neglects any mass balance feedback due to glacier retreat and thinning, but the available data indicate that cumulative area changes were less than the uncertainty (8%) of our area estimates (Table S1) justifying neglect of this effect.

[14] We consider only surface mass balances, neglecting any additional dynamic mass losses by iceberg calving, thus underestimating total mass loss in grid cells where calving occurs. Studies on Arctic sea-terminating ice caps [*Burgess et al.*, 2005] have indicated that calving may account for roughly 30–40% of total mass loss, but estimates are scarce, highly uncertain and vary regionally and in time. A study of differences between direct and geodetic mass balances worldwide [*Cogley*, 2009], the latter implying better allowance for calving, indicates calving contributions to total mass losses that are consistent with *Burgess et al.* [2005]. Conversely, part of surface melt water will re-freeze when percolating into cold firn (internal accumulation), leading to overestimation of total mass loss. As a rough first-order estimate, we conducted a separate trial of our model in which we approximated internal accumulation using a widely used expression for superimposed ice [*Woodward et al.*, 1997] and obtained a global SLE estimate which was 16% lower. However, the relative contribution of Antarctic MG&IC remained high (30%). Although potentially large sources of error in the total contribution of glaciers to sea-level rise, both calving and internal accumulation are still in their infancy of being assessed and modelled properly, in particular on a global scale. In fact, IPCC simply assumes these opposing processes to cancel each other, and hence our global SLE estimate which only includes surface mass balance is directly comparable to IPCC's MG&IC estimate.

5. Conclusions

[15] Although our model does not capture all processes driving the currently observed glacier mass changes, it provides a considerable advance in assessing global scale surface mass balance of MG&IC compared to IPCC's approach which relies on interpolation of relatively few in-situ surface mass balance records, and hence performs poorly in regions without measurements. Surface melting is important as it may trigger further dynamic losses through acceleration of glacier flow due to lubrication of basal ice or thinning and retreat of tidewater margins [*Pritchard and Vaughan*, 2007]. Our results highlight the role of the MG&IC around the Antarctic Peninsula where climate is distinctly different from the cold conditions of the ice sheet, and large mass balance sensitivities to temperature, exceptional warming and large area combine to yield large potential for glacier mass loss. We emphasize a strong need for improved glacier inventory and in-situ mass balance data from this region especially in light of strongly accelerated global mass loss from MG&IC during the last decade [*IPCC*, 2007; *Kaser et al.*, 2006]. This combined with improved methods to estimate internal accumulation and dynamic mass losses is essential to arrive at firmer estimates of the cryospheric component of sea-level rise.

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M. de Woul and M. Dyurgerov, Department of Physical Geography and Quaternary Geology, Stockholm University, SE-10691 Stockholm, Sweden.

R. Hock, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA. (regine.hock@gi.alaska.edu)

V. Radić, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada.