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Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004

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[1] Working with comprehensive collections of directly-measured data on the annual mass balance of glaciers other than the two ice sheets, we combine independent analyses to show that there is broad agreement on the evolution of global mass balance since 1960. Mass balance was slightly below zero around 1970 and has been growing more negative since then. Excluding peripheral ice bodies in Greenland and Antarctica, global average specific balance for 1961–1990 was -219 ± 112 kg m^{-2} a^{-1}, representing 0.33 ± 0.17 mm SLE (sea-level equivalent) a^{-1}. For 2001–2004, the figures are -510 ± 101 kg m^{-2} a^{-1} and 0.77 ± 0.15 mm SLE a^{-1}. Including the smaller Greenland and Antarctic glaciers, global total balance becomes 0.38 ± 0.19 mm SLE a^{-1} for 1961–1990 and 0.98 ± 0.19 mm SLE a^{-1} for 2001–2004. For 1991–2004 the glacier contribution, 0.77 ± 0.26 mm SLE a^{-1}, is 20–30% of a recent estimate of 3.2 ± 0.4 mm a^{-1} of total sea-level rise for 1993–2005. While our error estimates are not rigorous, we believe them to be liberal as far as they go, but we also discuss several unquantified biases of which any may prove to be significant.

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1. Introduction

[2] Because mass balance is a response to climate, observed glacier mass balances are independent tracers of global climatic change. When pooled, they also provide an essential estimate of a major contribution to changes in sea level, namely exchange of water between the terrestrial cryosphere and the ocean. A number of recent studies [e.g., *Rignot and Kanagaratnam*, 2006; *Zwally et al.*, 2005] have assessed the current mass balance of the two ice sheets. We therefore think it timely to provide a parallel, but unified, assessment for glaciers other than the ice sheets. Although there is a preponderance of negative values, disagreement persists between the estimates of ice-sheet mass balance. We show that this is not so for the other glaciers.

[3] Records of direct measurements of annual mass balance stretch back only to the mid 20th century, and only a few series cover the entire period since 1960. The main sources of data are the reports of the World Glacier Monitoring Service [e.g., *Haeberli et al.*, 2005], but we have added substantially to these sources by searching the literature, applying our own quality controls. Our datasets, containing annual mass-balance time series for more than 300 glaciers and believed to be almost complete, are the basis for three methodologically independent analyses which we combine to show that there is broad agreement on the evolution of global mass balance during the past half-century. We treat averages of the three analyses as "consensus estimates". (The consensus is only among the authors of this paper, but we are not aware of any analyses with which ours are inconsistent.) Differences between the analyses may well be significant and certainly point to a need for continued effort in the reduction of errors, but the consensus estimates leave little room for doubt that mass balance has become more negative since about 1970.

2. Analyses of Mass Balance

[4] Global estimates have been obtained by arithmetic averaging (series C05a: *Cogley* [2005]), area-weighting (DM05: *Dyurgerov and Meier* [2005]; O04: *Ohmura* [2004]), and polynomial spatial interpolation (C05i; *Cogley* [2005]). Each series has been updated to 2004 for the present report. Series C05a resembles closely the arithmetic-average series of the other two datasets. It appears here to illustrate the need to correct for the non-uniform spatial distribution of measurements. In the construction of DM05, single-glacier time series were assigned to 49 climatically homogeneous regions. In forming the regional averages, each time series was weighted by the area of its glacier. Then the regions, weighted by their glacierized surface areas, were assigned to 13 larger regions and finally to 6 large glacier systems. Several steps of area weighting were applied to avoid suggested biases towards smaller and temperate glaciers. *Ohmura* [2004] selected 141 glaciers from 18 regions, and averaged the annual balances of the selected glaciers to produce area-weighted regional averages. Global averages were calculated for years for which at least three regional averages were available. Regions without reliable annual averages, accounting for about one third of total glacierized area, were treated as having the same mass balance as the global average obtained without them. The C05i dataset is obtained by applying a spatial interpolation algorithm. At each glacierized cell in a 1° × 1° grid, a two-dimensional polynomial is fitted to the single-glacier observations, suitably weighted by their distance from the grid cell, and the resulting estimate of specific balance is multiplied by the glacierized area of the cell.

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[5] Our consensus estimate, labelled MB below, is the average of C05i, DM05 and O04 for 5-year spans (pentades).

3. Uncertainties

[6] Uncertainty of directly obtained annual surface mass balance of a single glacier is typically ±200 kg m^{-2} a^{-1} due to measurement and analysis errors [*Cogley*, 2005]. The main source of uncertainty is the natural horizontal variability of point mass balance, which is assumed to depend only on elevation.

[7] Direct measurements usually cover only the surface balance of the glacier. Internal accumulation is a cause for concern. This happens when surface meltwater percolates into cold firn or ice. It is difficult to measure or to model with confidence in the absence of subsurface temperature or density measurements. It is treated unevenly; some measurements correct for it in various ways, but most do not. When studied in detail, its magnitude is found to be 5–100% of annual net (surface plus internal) accumulation [e.g., *Rabus and Echelmeyer*, 1998]. The problem may be especially significant for sub-polar glaciers that are always below freezing in part.

[8] The calving of icebergs is a significant source of uncertainty. Calving is a dynamic process whose time scale can be quite different from the annual scale of surface mass balance, and it is difficult to match the two. In our datasets, all of the measurements from calving glaciers include the contribution of ice discharge to the total balance, but such glaciers are under-represented. Several studies suggest that at present calving glaciers have more negative mass balances than non-calving glaciers [e.g., *Glazovskiy and Macheret*, 2006; *O'Neel et al.*, 2005]. The bias due to under-sampling of dynamic processes of ice loss is therefore likely to be opposite to the internal-accumulation bias.

[9] Apart from its lack of historical depth, the principal temporal weakness of the global database is that the list of measured glaciers changes continually, with the number of measured glaciers fluctuating but seldom exceeding 100 in any one year. Among the more than 300 measured glaciers the commonest record length is one year, and many longer records have interruptions. These difficulties can be addressed by assuming that each annual measurement is a random sample of the average balance over whatever longer period is of interest. However, the variance of such a short sample is difficult to estimate satisfactorily, especially in the presence of a trend. The impact of the shifting population on spatial representativeness remains inadequately explored.

[10] The distance to which single-glacier measurements yield useful information about the annual balance of nearby glaciers is of the order of 600 km [e.g., *Cogley and Adams*, 1998]. This suggests that we can be moderately confident about estimates of regional mass balance when the region contains a moderate number of measured glaciers. For a region with few or no nearby measurements, however, there is in a statistical sense no better estimate than the global average with a suitably large uncertainty attached. Somewhat better estimates can plausibly be made by analogy with similar regions at different longitudes, or at the same latitude in the opposite hemisphere, but there is no reliable way to determine the error of such estimates. Among glacierized regions with very few measured glaciers Patagonia, Tibet, the Russian Arctic, Greenland and Antarctica may be singled out.

[11] Measurements by geodetic (e.g., altimetric, radar-interferometric and map-based) methods are mostly omitted from the present assessment, although DM05 includes some ad-hoc allowance for recent geodetic results from Alaska [*Arendt et al.*, 2002] and Patagonia [*Rignot et al.*, 2003]. Geodetic measurements typically cover variable spans of years to decades. It is difficult to assimilate them into an assessment based on annual direct measurements because they do not yield information about temporal variability. Patagonia is instructive because the geodetic measurements, covering over half of the ice in the region, suggest a regional mass balance of the order of -1000 kg m^{-2} a^{-1}, far more negative than the global average estimated from direct measurements alone.

[12] Because of the intensive fieldwork required, direct measurements are biased towards glaciers which are accessible and safe, which in effect means small and low-lying. There is some evidence [e.g., *Francou et al.*, 2005] that such glaciers have more negative balances, and also that temperate glaciers suffer greater losses in the current climate than less accessible and less well-represented polythermal and cold glaciers.

[13] We calculate the uncertainty in MB as $\sqrt{(2SE_{aa})^2+(2SD_{sc})^2}$, where SE_{aa} is the standard error of the arithmetic average C05a and SD_{sc} is the standard deviation of the spatially-corrected series C05i, DM05 and O04. A rigorous estimate is not within reach, but this confidence envelope allows for both natural variability, as measured by SE_{aa}, and uncertainty due to the non-representative sample, as measured by the dispersion SD_{sc} in a set of independent attempts at correction. It does not allow for the unquantified biases described above.

[14] There is further uncertainty due to the conversion from specific to total balance. The glacierized areas of several regions, such as Patagonia and Greenland, are known only approximately, and only C05i allows explicitly for this uncertainty. More significantly, only DM05 includes an explicit estimate of the extent of peripheral ice bodies in Antarctica, a difficulty which we address by upscaling. First, we calculate the global average specific balance b^{excl}, using the series $DM05^{excl}$ (that is, DM05 with its Greenland and Antarctic estimates excluded). To obtain the inclusive series b^{incl}, we multiply b^{excl} by the ratio $DM05/DM05^{excl}$. For the different pentades, this ratio ranges from 0.76 to 0.89 with an average of 0.80. The uncertainty in $DM05/DM05^{excl}$ will be small relative to the errors in b^{excl}, so we assume that the uncertainty in Greenland and Antarctic specific balance is equal to, not greater than, that in specific balance elsewhere.

[15] A bias with implications for both specific and total balances may arise from our ignorance about glaciers and ice caps in Antarctica. The DM05 estimate of their extent, 0.169 Mm^2, includes both northerly ice bodies which are beginning, under southward-propagating climatic warming [*Jacka et al.*, 2004], to suffer significant losses by melting, and southerly ice bodies, including some large ice rises, which probably are not. *Dyurgerov and Meier* [2005] estimate the regional balance of Antarctica as being equal to that of the Canadian High Arctic, the driest region at analogous

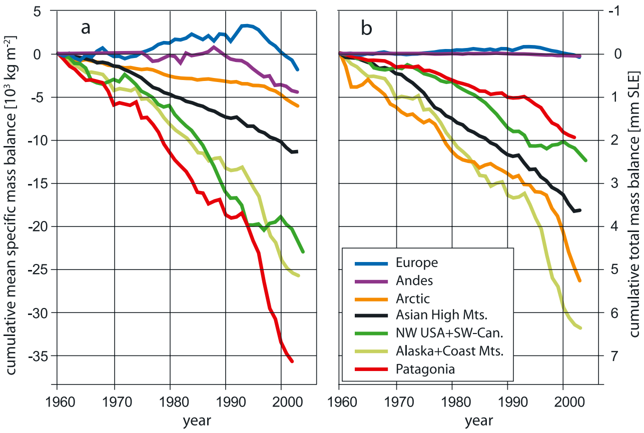

Figure 1. Cumulative (a) specific and (b) total mass balances of glaciers and ice caps, calculated for large regions [*Dyurgerov and Meier*, 2005]. Specific mass balances signalize the strength of the glacier response to climatic change in each region. Total mass balances indicate each region's contribution to sea level.

latitudes in the northern hemisphere. At present this is the only realistic way of addressing the bias.

[16] Although single-glacier balance estimates usually account for temporal changes of the glacier's area (that is, they are not "reference-surface balances" as defined by *Elsberg et al.* [2001]), little is known of regional changes in extents of glacierization. Observed rates range from $-0.03\%\ a^{-1}$ for the Russian Arctic (1952–2001; *Glazovskiy and Macheret* [2006]) to $-0.62\%\ a^{-1}$ for the Swiss Alps (1973–1999; *Paul et al.* [2004]). This will yield a growing overestimate of sea-level equivalent, because our unchanging estimates of total glacierized area are likely to be least inaccurate in the earlier part of the analysis period. Assuming, for illustration, that this bias was zero in 1961–1965, it would have reached −1% to −25% in 2001–2004 if the global rate were equal to that of the Russian Arctic or the Alps respectively. Considering the smaller sizes but lesser total extent of Alpine glaciers, the actual bias is probably nearer the smaller of the two rates.

4. Regional and Temporal Variations

[17] Analyses of large regions by *Dyurgerov and Meier* [2005] show strongest negative specific balances, and thus climatic-change signals, in Patagonia, NW USA + SW Canada, and Alaska until the early 1990s (Figure 1). Thereafter, rates became stronger in Patagonia and Alaska leaving NW USA + SW Canada third. Only Europe showed a mean value close to zero, reflecting the strong mass losses in the Alps being compensated by mass gains in maritime Scandinavia until the end of the 20th century. Values for Patagonia and Alaska are mainly derived from altimetric evaluations by *Arendt et al.* [2002] and *Rignot et al.* [2003], and authors of both papers note that the observed mass losses cannot be explained by surface mass balance only but also require increased dynamic discharge of ice. The latter, in turn, has possibly been triggered by previous negative surface mass balances of glaciers calving into tidewater as well as by increased meltwater production that enhances basal sliding. Also contributions from glaciers with periodic internal instabilities (surge type glaciers) must be considered [*Arendt et al.*, 2002; *Rignot et al.*, 2003]. Because of lack of suitable information, the mass loss of Patagonia has been extended in time in the same way as Alaskan mass balances [*Dyurgerov and Meier*, 2005].

[18] In Figure 2, we summarize the evolution of mass balance since 1960 in the form of pentadal averages. Detrended annual mass-balance time series seldom or never exhibit serial correlation. Averages over 5-year spans are thus less uncertain by a factor of $1/\sqrt{5}$.

[19] The confidence region of C05a is simply twice the standard error of the sample of unweighted single-glacier measurements. It shows that the sample variability of measured mass balances is highest before 1960. As indicated by the pentadal sample sizes at the top of Figure 2, very little weight should be placed on these early estimates. However, they suggest that global mass balance was negative, in circumstantial agreement with other evidence. We correct for spatial bias only after 1960, when up to 100 measured mass balances are available for each year. Before 1961, reliable estimates of the global evolution of mass balance will require modelling in terms of proxy variables such as changes in air temperature and glacier length.

[20] The three histories of spatially-corrected mass balance have similar shapes despite some offsets in magnitude. Since about 1970, mass loss rates have grown progressively more

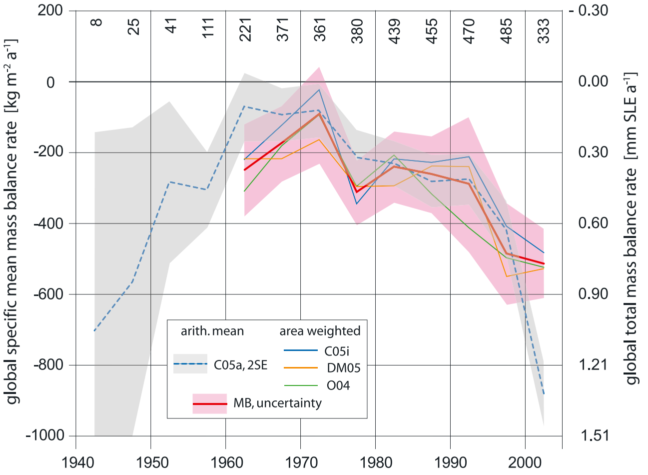

Figure 2. Pentadal average mass balance rates of the world's glaciers and ice caps, excluding Greenland and Antarctica, for the last half century. Specific mass balance (left axis) is converted to total balance and to sea-level equivalent (right axis) as described in Table 1. C05a: an arithmetic mean over all annual measurements within each pentade [*Cogley*, 2005]; the grey confidence envelope is twice the standard error of the C05a data, and the number of measurements is given at the top of the graph. C05i, DM05, O04: spatially-corrected series obtained as described in the text. MB: arithmetic mean of C05i, DM05 and O04; uncertainty (red shading) constructed as described in the text. The DM05 data, and thus the consensus estimate MB, are incomplete for the most recent pentade and likely include a positive bias because few data are yet available from Alaska/Patagonia, the most important sources of glacial runoff to the ocean.

Table 1. Global Average Mass Balance of Glaciers and Ice Caps for Different Periods[a]

	b^{excl}, kg m^{-2} a^{-1}	B^{excl}, Gt a^{-1}	SLE^{excl}, mm a^{-1}	b^{incl}, kg m^{-2} a^{-1}	B^{incl}, Gt a^{-1}	SLE^{incl}, mm a^{-1}
1961–2004	−283 ± 123	−155 ± 67	0.43 ± 0.19	−231 ± 101	−182 ± 78	0.50 ± 0.22
1961–1990	−219 ± 112	−120 ± 61	0.33 ± 0.17	−173 ± 89	−136 ± 70	0.38 ± 0.19
1991–2004	−420 ± 145	−230 ± 79	0.64 ± 0.22	−356 ± 121	−280 ± 95	0.77 ± 0.26
2001–2004	−510 ± 101	−278 ± 55	0.77 ± 0.15	−451 ± 89	−354 ± 70	0.98 ± 0.19

[a] Superscript *excl* and *incl* denote estimates excluding and including, respectively, glaciers and ice caps around the Greenland and West Antarctic ice sheets; the respective total ice surface areas are $A^{excl} = 546 \times 10^9$ m^2 and $A^{incl} = 785 \times 10^9$ m^2. b: specific mass balance; B: total balance, equal to $A \times b$; SLE: sea-level equivalent, equal to $-B/(\rho_w A_O)$, where $\rho_w = 1000$ kg m^{-3} and ocean area $A_O = 362 \times 10^{12}$ m^2. Year references are to the calendar year in which each northern-hemisphere balance year ends (in August or September depending on latitude).

negative (Table 1). During the climatic-normal period 1961–1990, glaciers and ice caps supplied about +0.35 mm SLE a^{-1} to the ocean, if we neglect those in Greenland and Antarctica (Table 1, "excl" columns). In the most recent (incomplete) pentade, 2001–2004, the rate is more than double this value. If we allow for Greenland and Antarctica (Table 1, "incl" columns), the rate is slightly higher, about +0.4 mm a^{-1}, for 1961–1990, while for 2001–2004 it is again more than double, at about +1.0 mm a^{-1}.

[21] The period 1991–2004 corresponds fairly closely to the span of satellite-borne altimetric monitoring of changes of sea level. For 1993–2005, *Mitchum* [2006] estimated the rate of sea-level rise as 3.2 ± 0.4 mm a^{-1}. Together with the 1.6 ± 0.3 mm a^{-1} estimate of *Willis et al.* [2004] for the thermosteric contribution during 1993–2003, and our estimate of 0.8 ± 0.3 mm a^{-1} (Table 1), this leaves a residual of 0.8 ± 0.6 mm a^{-1}. Note, however, that all of the errors contributing to the error of this residual are incomplete.

[22] Although we cannot date precisely the apparent inflection in the mass-balance curves (Figure 2), the three contributing analyses and MB are all least negative in 1971–1975. Their trends since that pentade are summarized in Table 2. All are similar and show unequivocally that the contribution of glaciers and ice caps to sea level rise has been increasing nearly steadily since 1971–1975.

[23] The arithmetic average C05a is strongly discordant during 2001–2004, due at least partly to the European heat wave of 2003. When European balances for 2003 are excluded, the pentadal arithmetic average increases from −874 to −755 kg m^{-2} a^{-1}. More broadly, the very negative northern mid-latitude balances for 2003 are offset by the high Arctic latitudes, where glacierization is extensive but balances are relatively few in number and only moderately negative. This discordance illustrates why it is critically important not just to maintain the existing observational network of benchmark glaciers, but where possible to extend its spatial coverage and to strengthen coordination.

[24] Over the last half century, both global mean winter accumulation and summer melting have increased steadily [*Dyurgerov and Meier*, 2005; *Ohmura*, 2004], and, at least in the northern hemisphere, winter accumulation and summer melting correlate positively, and the net balance negatively, with hemispheric air temperature [*Greene*, 2005]. *Dyurgerov and Dwyer* [2001] have analysed time series of 21 Northern Hemisphere glaciers and have found a rather uniform moderate increased mass turnover, qualitatively consistent with increased precipitation and low-altitude melting with warming. This general trend is also indicated by geodetic balance estimates from Alaska, the Canadian Arctic, and Patagonia, where substantial thinning of ablation areas and moderate thickening of accumulation areas were measured.

5. Discussion and Conclusions

[25] In presenting consensus estimates, we have in mind a loose analogy with the intercomparisons which have been so serviceable in improving the performance of general circulation models, and which have facilitated the development of ways of expressing for a broader audience the consensus among climate specialists [*IPCC*, 2001]. Accordingly the principal series (C05i, DM05, O04) are treated here as a small sample of methodologically independent but reasonable analytical outcomes. The raw measurements are correlated, but the sample average MB is probably the best consensus estimate of the evolution of mass balance. Given the present state of our understanding, we are unable to offer a rigorous estimate of uncertainty, but the envelope centred on the MB curve is objectively defined and, unquantified biases apart, we think that it is liberal.

[26] The biases relevant to estimates of specific balance are neglect of internal accumulation and under-representation of calving glaciers, both likely to be substantial but tending to cancel each other; the shifting-population effect, the significance of which is unknown; uneven and incomplete spatial coverage, which is addressed at least in part by each of our analyses; and over-representation of smaller and lower-lying glaciers, which may lead to overestimates of mass loss. The main bias affecting the conversion of specific balance to total balance and its sea-level equivalent is due to our inability to allow on the global scale for regional-scale shrinkage. The sum of these unquantified biases, which all require urgent attention, is at present a matter for debate.

[27] The decrease of mass balance from near zero around 1970 gives confidence that late 20th century glacier wastage is essentially a response to post-1970 global warming [*Greene*, 2005], reinforced by feedbacks among which the most important are probably the balance-altitude feedback (net melting lowers the glacier surface to warmer altitudes, increasing net loss) and the albedo feedback (more darker ice

Table 2. Trends in Pentadal Global Average Mass Balance, 1971–1975 to 2001–2004[a]

Analysis	*Trend*, kg m^{-2} a^{-2}	*Trend*, mm SLE a^{-2}
C05i	−10.7 ± 8.2	0.022 ± 0.014
DM05	−11.1 ± 7.4	0.023 ± 0.014
O04	−13.6 ± 4.2	0.027 ± 0.008
MB	−11.8 ± 5.8	0.024 ± 0.010

[a] Trends are fitted by linear regression to the data shown in Figure 2. Uncertainties are twice the standard error of the slope.

exposed at the surface promotes further melting). That the mass-balance curves do not decrease monotonically is presumably due to a combination of measurement and analysis error and possible real decadal variability.

[28] We will continue to work independently on analytical protocols, but a leading result of the work reported here is that all of these protocols, when applied to the available measurements, yield estimates which rule out the possibility that mass balance might at present be near to equilibrium. The analyses also require that the imbalance be growing more negative. In the terminology of the IPCC, we have very high confidence in these statements. In summary, the best consensus estimate is that glaciers and ice caps contributed about 0.35–0.40 mm SLE a^{-1} to sea-level rise during the climatic-normal period 1961–1990, and about 0.80–1.00 mm SLE a^{-1} during 2001–2004.

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