Sea-level rise from glaciers and ice caps: a lower bound

David B. Bahr[1], Mark Dyurgerov[2], Mark F. Meier[2]

[1]Department of Physics and Computational Science, Regis University, Denver, CO. dbahr@regis.edu

[2]Institute of Arctic and Alpine Research, UCB 450, University of Colorado at Boulder, Boulder, CO

Bahr, D. B., M. Dyurgerov, and M. F. Meier (2009), Sea-level rise from glaciers and ice caps: A lower bound, *Geophys. Res. Lett.*, 36, L03501, doi:10.1029/2008GL036309.

Abstract

One of the most easily measured dimensions of a glacier, the accumulation area, is linked to future changes in glacier volume and consequent changes in sea level. Currently observed accumulation areas are too small, forcing glaciers to lose 27% of their volume to attain equilibrium with current climate. As a result, at least 184 ± 33 mm of sea-level rise are necessitated by mass wastage of the world's mountain glaciers and ice caps even if the climate does not continue to warm. If the climate continues to warm along current trends, a minimum of 373 ± 21 mm of sea-level rise over the next 100 years is expected from glaciers and ice caps. When compared to recent estimates from all other sources, melt water from glaciers must be considered as a particularly important fraction of the total sea-level rise expected this century.

Introduction

A direct prediction of future sea level contributions is possible by scaling glacier volume to the easily measured standard of a glacier's health, the accumulation area ratio (AAR). Specific climatic and dynamic assumptions are not necessary, and as shown, the minimum possible contribution from glaciers and ice caps is substantial and a significant fraction of the most likely total of 0.8 meters from all sources over the next 100 years (Pfeffer et al., 2008). The link between climate and sea level is complicated by the ablation of ice which is difficult to measure in remote mountain environments (e.g., Meier, 1990; Ostrem and Brugman, 1991; Gregory and Oerlemans, 1998; Cogley 2005). As a result, many sea-level projections have had to justify particular climatological, hydrological, and/or dynamical models (e.g., Meier, 1990; Wigley and Raper, 1995; Zuo and Oerlemans, 1997; Gregory and Oerlemans, 1998; Raper and Braithwaite, 2006). More recent studies have used scaling analyses to link changes in glacier surface area to changes in ice volume (e.g., Raper et al., 2000; Raper and Braithwaite, 2006, Meier et al., 2007; Oerlemans et al., 2007; Radić et al., in press), but these approaches can be limited by a poorly constrained scaling constant and uncertainties when projecting future surface areas (Meier et al., 2005).

On average, a glacier in equilibrium will accumulate snow on its upper reaches and ablate snow and ice at its lower elevations. The AAR is the ratio of the accumulation area to the area of the entire glacier, with values for healthy glaciers ranging from approximately 0.4 to 0.8 (Meier and Post, 1962). Variations in the equilibrium AAR are caused by differences in glacier shapes and mass balance profiles, $(\boldsymbol{x})$, which give the net accumulation minus ablation of snow and ice at any position $\boldsymbol{x}$. The balance profile is a direct consequence of climate (precipitation and temperature) which can vary both regionally and locally due to orographic and other meteorological factors.

If we assign each glacier an equilibrium AAR_0 that indicates its value when the glacier's net balance is zero, then an $AAR < AAR_0$ indicates that the accumulation area has shrunk, the glacier is overextended, and the glacier must retreat to reach a new equilibrium with current climate. This hypothesized retreat involves the implicit but reasonable assumption that changes in the balance regime happen quickly relative to changes in the area of the glacier. Typical e-folding response times for glacier flow range from 10's to 1000's of years depending on the glacier's size (Bahr et al., 1998; Pfeffer et al., 1998; Jóhannesson et al., 1989), while a glacier's climate can change every year. Therefore, as the climate warms, a glacier's current AAR will not represent an equilibrium value. To reach an equilibrium with the current climate, the glacier will have to slowly change size until $AAR = AAR_0$. Note that in this case, the AAR is an observed medium term average, calculated over a period long enough to eliminate interannual variability but significantly shorter than the time scale of adjustment to equilibrium.

Long term mass balance data from 86 mountain glaciers and ice caps from around the world shows that the equilibrium AAR_0 differs for each glacier but averages 0.57 ± 0.01 (see Supplementary Data). The same data indicate that the average AAR from 1997-2006 is only 0.44 ± 0.02, suggesting that glaciers and ice caps around the world are out of equilibrium, as expected. The ratio $AAR / AAR_0 = \alpha_r$ gives a measure of the extent to which each glacier is out of equilibrium (Dyurgerov et al., submitted), and in this case $1 - \alpha_r = 0.23$ or approximately 23% out of equilibrium on average. The following analysis converts each glacier's α_r to a change in glacier volume. By summing over all glaciers this gives an estimate of sea-level rise.

Volume-AAR Scaling

Define the glacier's accumulation area as Sc and the glacier's total area as S. $AAR = Sc/S$ is the currently-observed average AAR. For the AAR to adjust back to equilibrium ($AAR = AAR_0$), the surface area must change because the current accumulation area Sc is dictated by climate. Therefore,

$$AAR_0 = \frac{Sc}{S + \Delta S}$$

where ΔS is the change in area necessary to reach equilibrium. Define p_s as the fractional change of the total area necessary to reach equilibrium. In other words $p_s = \Delta S / S$. Then

$$AAR_0 = \frac{Sc}{S + p_s S} = \frac{Sc}{(1 + p_s)S} = \frac{AAR}{1 + p_s}$$

Therefore,

$$1 + p_s = \frac{AAR}{AAR_0} = \alpha_r$$

To finish the derivation, recall that glacier volume V and surface area scale as a power law,

$$V = cS^{\gamma}$$

where data and theory both show that $\gamma = 1.36$ for glaciers and $\gamma = 1.25$ for ice caps (Bahr et al., 1997, Chen and Ohmura, 1990, Macheret et al., 1988). The constant of proportionality or scaling constant *c* will become irrelevant in a moment. Let p_v be the change in current volume that results from the change in surface area ΔS. In other words, $p_v = \Delta V / V$. Then

$$\begin{aligned} V + \Delta V &= c(S + \Delta S)^{\gamma} \\ V + p_v V &= c(S + p_s S)^{\gamma} \\ (1 + p_v)V &= c(1 + p_s)^{\gamma} S^{\gamma} \\ (1 + p_v) &= (1 + p_s)^{\gamma} \end{aligned}$$

Substituting α_r for $1 + p_s$,

$$1 + p_v = \alpha_r^{\gamma}$$

In other words, the fractional change in a glacier's volume, p_v, is given by the easily measured ratio of the currently-observed average AAR and the equilibrium AAR_0. Unlike some other scaling approaches, this derivation does not need the poorly constrained scaling constant c.

The AAR and Mass Balance Data

While accumulation areas can be measured remotely (e.g., satellite surveys) or with relatively short field seasons, mass balance data require time-consuming field work. As a result, only a few dozen glaciers around the world have adequate data for calculating α_r. From a collection of more than 128 glaciers and ice caps with balance data, only 86 have long-term AAR and mass balance records suitable for estimating AAR_0, which is derived from a regression of balance data with AAR data and finding the point at which the line intersects zero mass balance (for additional details, see Dyurgerov et al., submitted). For these 86 glaciers, the average AAR_0 is 0.57 ± 0.01, consistent with other data from 24,476 Eurasian glaciers and 5,422 European glaciers (exclusive of Russia) which have average AARs of 0.58 (Bahr, 1997).

Random yearly fluctuations in AARs and their measurements could introduce errors, so for each glacier we estimate AAR as the average AAR over some period. Among the subset of 86 glaciers and ice caps, some have AAR data that span decades, while others have only recent or intermittent data. The bulk of the measurements fall between 1960 and 2007, though many of the glaciers do not yet have values reported for 2007. Longer time periods incorporate significantly more data from a greater number of glaciers but dilute the climate signal which has changed most rapidly in the last 20 years. More recent and shorter time periods more accurately reflect the current climate but incorporate too few glaciers (e.g., only 17 glaciers and ice caps for 2003-2007). As a compromise, we have taken averages from 1997-2006 for 39 glaciers and 14 ice caps. This total of 53 glaciers and ice caps is a representative sample from around the world (see Supplementary Data).

Estimating Sea-Level Rise

For each glacier in the world, the change in volume necessary to reach equilibrium is given by $p_v V$ where V is the current glacier volume. In the following, we assume that p_v and V are independent quantities. In other words, we assume that the current volume of a glacier is not correlated with changes in volume that will be precipitated by the climate. Stated another way, today's glacier knows nothing about tomorrow's changes in climate. It follows that for any glacier, the expected (mean) change in volume between the current state and equilibrium state will be $E(p_v V) = E(p_v)\, E(V)$.

Summing over all N glaciers in the world, the total world-wide volume V_T of glacier ice (excluding ice sheets) is given by

$$V_T = \sum_N V = N E(V)$$

By the strong law of large numbers, replacing the sum by $N\,E(V)$ is valid for large values of N (cf. Ross, 1988, pg. 346). Although an exact count is impossible, N is sufficiently large at somewhere between 300,000 and 400,000 glaciers and small ice caps (Dyurgerov and Meier, 2005). The glaciers included in this count (the same ones used to estimate total ice volume below) are all mountain and sub-polar ice caps outside of the two major ice sheets, Greenland and Antarctica, but excludes the relatively small number of calving and other glaciers for which an AAR is not meaningful. Sea-level rise due to calving glaciers must be treated separately as discussed below. Glaciers on the periphery of Greenland and Antarctica are counted, including those near the West Antarctic ice sheet that have shown accelerated melting over the last decade, and all other individual Antarctic glaciers to 70° south. These peripheral glaciers are too small to be realistically included in the coarse grids used to model the larger ice sheets, and these lower-altitude glaciers, particularly near the West Antarctic, have a greater similarity to sub-polar systems (like Svalbard and the Canadian and Russian Arctic archipelagos) than to the colder ice sheets (Vaughn, 2006). The resulting total of 300,000 to 400,000 represents a substantial increase over previous estimates of 160,000 (Meier and Bahr, 1996), but an exact count is unimportant because the factor N will disappear shortly.

The total change in ice volume is given by

$$\Delta V_T = \sum_N p_v V = NE(p_v V) = NE(p_v)E(V) = E(p_v)V_T$$

The expected (mean) value of p_v can be calculated directly from AAR data (see Supplementary Data). For each glacier, we calculate α_r for that particular glacier's AAR_0. By scaling, this gives the fractional change in volume p_v for each glacier, as outlined above.

As long as the sample is representative of all glaciers, then the average p_v will give a representative mean value. Although the glaciers with long-term balance studies are strongly biased by size (we tend to study accessible glaciers of moderate to small size – e.g., Meier et al., 2007), the accumulation area ratios can vary widely for glaciers of any given size. In other words, the distribution of measured AARs is not likely to be affected by the size-related sampling bias, and statistics show no correlation between AARs and size for the glaciers used in this analysis (see Supplementary Data).

From the data, $E(p_v) = -0.27 \pm 0.05$ for glaciers and $E(p_v) = -0.26 \pm 0.08$ for ice caps. In other words, glaciers need to decrease in volume by 27% on average, and ice caps need to decrease by 26%. In water equivalent, the total volume of ice in the world's glaciers and ice caps (including those peripheral to Greenland and Antarctica) is estimated at $250 \pm 20 \text{ X } 10^3 \text{ km}^3$ and $132 \pm 60 \text{ X } 10^3 \text{ km}^3$ respectively (Dyurgerov and Meier, 2005; Meier et al., 2007). Therefore, a future equilibrium with the current climate implies a change in sea level of 89 ± 15 mm due to glaciers and 95 ± 29 mm due to ice caps. The total change in sea level is 184 ± 33 mm.

Discussion

A sea-level rise of 184 ± 33 mm is substantially larger than previous estimates that attribute 104 ± 25 mm to small glaciers and ice caps over the next 100 years when assuming no acceleration in ice loss (Meier et al., 2007). Our estimate places no bounds on time and only indicates the final outcome after all glaciers reach equilibrium. Therefore, it is possible that the additional ~80 mm represents sea-level rise that will occur after the 100 year time scale of previous estimates. However, with an e-folding response time that averages on decadal to century time scales for most glaciers, the bulk of the 184 mm of predicted rise is expected within this century.

The preceding analysis derives the changes in sea level to which we are committed by climate as it existed in 2006. Actual sea-level rise due to melting glaciers and ice caps will likely be much higher. Climate is not fixed and the rate of ice mass loss continues to accelerate. Furthermore, this analysis can only estimate the contribution of glaciers for which an AAR is well-defined. This represents the vast majority of glaciers, but large tidewater glaciers have truncated surface areas and anomalously high AARs caused by calving at the terminus. While relatively few in number, the dynamic instabilities of tidewater glaciers can contribute disproportionately large amounts of meltwater, estimated at roughly 94 mm through the year 2100 (Meier et al., 2007; Pfeffer et al., 2008).

If we assume that the current acceleration of warming and ice loss will continue unabated, then AARs will decrease and cause an additional contribution to sea level.

These future changes in AARs may be dramatic. In 1961, AARs averaged 0.54 for 475 glaciers in western North America (Meier and Post, 1962), close to the average equilibrium value of 0.57 noted above. In contrast, North American glaciers in the 1980's and 1990's had a mean AAR of 0.43 (Dyurgerov and Meier, 1997a) and the world-wide average from 1997 to 2006 in this data set (see Supplementary Data) is only 0.44. The large decrease in AARs indicates dramatic climate changes during the last 30 to 40 years (Dyurgerov and Meier, 1997b).

If a similar reduction of AARs occurs over the next 30 to 40 years, then we can reasonably expect the average AAR to drop linearly from roughly 0.54 in 1961 to 0.44 in 2007 to 0.31 by 2050. This is a conservative estimate – observations indicate a faster than linear decrease in global ice mass balance over the last 40 years (Kaser et al., 2006). Although the actual decrease in AAR may be faster than linear, this conservative estimate represents a 30% decrease from the current value. As a rough approximation, we can assume that the AAR of every glacier decreases by the same percentage, giving an estimate of the fractional volume change p_v for each glacier. In that case, the minimal sea-level rise from glaciers and ice caps will more than double to 373 ± 21 mm over the next 100 years.

The number of glaciers used in the calculation is limited primarily by those with long-term balance data. To expand this data set, numerical modeling of mass balance should play a key role (e.g., Oerlemans, 1993; Braithwaite and Zhang, 2000; Raper and Braithwaite, 2006). However, if the average AAR_0 is used as an approximation for all glaciers, then balance data is unnecessary. Applying the average value of 0.57 to the current data set, sea-level rise is estimated as 85 ± 17 mm from glaciers and 85 ± 35 mm from ice caps. The difference from the more precise calculation is only 4% for glaciers but 11% for ice caps. The total of 170 ± 39 mm differs by 8% or roughly 15 millimeters. In other words, using only the more easily measured AAR data, reasonable sea-level contributions can be approximated for glaciers, though some care should be exercised with ice caps.

Conclusions

A sea-level rise of 184 ± 33 mm is necessitated for the world's glaciers and ice caps to reach equilibrium with the climate as it existed in 2006. As such, this estimate is a lower bound, but one that is virtually guaranteed over the next century as the world's climate continues to warm. Actual meltwater contributions to sea-level rise could be substantially higher, driven by mass wastage from dynamically unstable tidewater glaciers and by the continued acceleration of ice loss. However, in the likely and conservative scenario that AARs continue to decrease at their current rate, sea level will rise by a minimum of 373 ± 21 mm over the next 100 years.

Minimal sea-level rise estimates can be updated annually as AAR data continues to be collected. To improve accuracy, these findings justify the energetic pursuit of additional AAR data, either by remote sensing (e.g., Raup, 2007) or field programs. However, even with increased accuracy, the amount of sea-level rise is unlikely to be revised downwards and will remain higher than many previous estimates of sea-level rise due to glaciers and ice caps (e.g., Meier et al., 2007). In part, the higher values reported here reflect the continued acceleration of ice loss and the more recent data used in this analysis. Our results also place no strict bounds on the time it takes to reach equilibrium and some fraction of the 184 mm rise may happen after the 100 year time scale of previous estimates; this seems unlikely, however, because the e-folding response time of glaciers strongly suggests that most of the predicted 184 mm sea-level rise will occur within the next 100 years. Previous estimates have also relied on predicted changes in glacier area that can be scaled to volume and meltwater production. Unlike AAR data which already contains a direct measure of this change in area, other methods of prediction introduce an additional layer of uncertainty. Numerical modeling, for example, is very difficult to apply globally due to scaling errors caused by numerical grids that can bisect ice masses (Meier et al., 2005). The AAR-volume scaling used in this analysis also eliminates potential errors introduced by the poorly constrained volume-area scaling constant central to many previous estimates.

References

Bahr, D. B. (1997), Width and length scaling of glaciers, *J. Glaciol.*, *43*(145), 557-562.

Bahr, D. B., Meier, M. F. and S. D. Peckham (1997), The physical basis of glacier volume-area scaling, *J. Geophys. Res.*, *102*(B9), 20355-20362.

Bahr, D. B., W. T. Pfeffer, C. Sassolas, and M. F. Meier (1998), Response time of glaciers as a function of size and mass balance: 1. Theory*, J. Geophys. Res.*, *103*, 9777-9782.

Braithwaite, R. J., and Y. Zhang (2000), Sensitivity of mass balances of five Swiss glaciers to temperature changes assessed by tuning a degree-day model, *J. Glaciol.*, *46*(152), 7-14.

Chen, J., and A. Ohmura (1990), Estimation of alpine glacier water resources and their change since the 1870's, *IAHS Publ. 193*, 127-135.

Cogley, J. G. (2005), Mass and energy balances of glaciers and ice sheets, in *Encyclopedia of Hydrological Sciences*, vol. 4, edited by M. G. Anderson, 2555-2573, John Wiley, Hoboken, New jersey.

Dyurgerov, M. B., and M. F. Meier (1997a), Mass balance of mountain and subpolar glaciers: a new global assessment for 1961-1990, *Arctic Alp. Res.*, *29*, 379-391.

Dyurgerov, M. B., and M. F. Meier (1997b), Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes, *Arctic Alp. Res.*, *29*, 392-402.

Dyurgerov, M. B., and M. F. Meier (2005), Glaciers and the Changing Earth System: a 2004 Snapshot, *Occasional Paper 58*, Institute of Arctic and Alpine Research, Univ. of Colorado, Boulder, Colorado. 117p. [http://instaar.colorado.edu/other/occ_papers.html]

Dyurgerov, M. B., M. F. Meier, and D. B. Bahr (submitted), Quantifying glacier area change: a committed contribution to sea level rise. (Available on request.)

Gregory, J. M., and J. Oerlemans (1998), Simulated future sea-level rise due to glacier melt based on regionally and seasonally resolved temperature changes, *Nature*, *391*, 474-476.

Jóhannesson, T., C. Raymond and E. Waddington (1989), Time-scale for adjustment of glaciers to changes in mass balance, *J. Glaciol.*, *35*(121), 355-369.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, *Geophys. Res. Lett.*, *33*, L19501, doi:10.1029/2006GL027511.

Macheret, Yu.Ya., P. A. Cherkasov, and L. I. Bobrova (1988), The thickness and volume of Dzhungarskiy Alatau glaciers from airborne radio echo-sounding data, *Mater. Glyatsiol. Issled.*, *62*, 59-70.

Meier, M. F. (1990), Reduced rise in sea level, *Nature*, *343*, 115.

Meier, M. F., and D. B. Bahr (1996), Counting Glaciers: Use of Scaling Methods to Estimate the Number and Size Distribution of the Glaciers of the World, *CRREL Special Reports, 96-27*, 89-94.

Meier, M. F., D. B. Bahr, M. B. Dyurgerov, and T. W. Pfeffer (2005), Comment on "The potential for sea level rise: New estimates from glacier and ice cap area and volume distribution," by Raper, S. C. B. and R. J. Braithwaite, *Geophys. Res. Lett.*, 32, L17501.

Meier, M. F., M. B. Dyurgerov, U. K. Rick, S. O'Neal, T. W. Pfeffer, R. S. Anderson, S. P. Anderson, and A. F. Glazovskiy (2007), Glaciers and ice caps to dominate sea level rise through 21st century, *Science*, *317*, 1064-1067.

Meier, M. F., and A. S. Post (1962), Recent variations in mass net budgets of glaciers in western North America, *IASH*, *58*, 63-77.

Oerlemans, J. (1993), Modeling of glacier mass balance, in *Ice in the Climate System*, W.R. Peltier (Ed). NATO ASI Series I, *12*, 101-116, Springer.

Oerlemans, J., M. Dyurgerov, and R. S. W. van de Wal (2007), Reconstructing the glacier contribution to sea-level rise back to 1850, *The Cryosphere*, *1*, 59-65.

Østrem, G., and M. Brugman (1991), *Glacier Mass-balance Measurements. A Manual for Field and Office Work*, NHRI Science Report No. 4, Ministry of Supply and Services, Canada, pp. 224.

Pfeffer, W. T., J. T. Harper, and S. O'Neel (2008) Kinematic constraints on glacier contributions to 21st-century sea-level rise, *Science*, *321*(5894), 1340-1343.

Pfeffer, W. T., C. Sassolas, D. B. Bahr, and M. F. Meier (1998), Response time of glaciers as a function of size and mass balance: 2. Numerical experiments, *J. Geophys. Res.*, *103*, 9783-9789.

Radić, R., R. Hock, J. Oerlemans (in press), Analysis of scaling methods in deriving future volume evolutions of valley glaciers, *J. Glaciol.*

Raper, S. C. B., O. Brown, and R. J. Braithwaite (2000), A geometric glacier model suitable for sea-level change calculations, *J. Glaciol.*, *46*(154), 357-368.

Raper, S. C. B. and R. J. Braithwaite (2006), Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature*, *439*, 311-313.

Raup, B., A. Kääb, J.K. Kargel, M. P. Bishop, G. Hamilton, E. Lee, F. Paul, F. Rau, D. Soltesz, S. J. S. Khalsa, M. Beedle, and C. Helm (2007), Remote sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) project. *Comp. and Geosci.*, *33*, 104-125.

Ross, S. (1988), *A First Course in Probability, 3rd Ed.,* Macmillan Publishing Company, New York, New York.

Vaughn, D. (2006), Recent trends in melting conditions on the Antarctic Peninsula and their implications for ice sheet mass balance and sea level. *Arct. Antarct. Alp. Res.*, 38, 147-152.

Wigley, T. M. L., and S. C. B. Raper (1995), An heuristic model for sea-level rise due to the melting of small glaciers, *Geophys. Res. Let.*, *22*, 2749-2752.

Zuo, Z., and J. Oerlemans (1997), Contribution of glacier melt to sea-level rise since AD 1865: a regionally differentiated calculation, *Climate Dyn.*, *13,* 835-845.

Supplemental Material

Online material includes spreadsheets of AAR and other data for all glaciers used in this analysis. The spreadsheets also include calculations of sea-level rise and standard errors. Additional details about the data and data compilation are also found in Dyurgerov et al. (submitted).