Extended scenarios for glacier melt due to anthropogenic forcing

T. M. L. Wigley[1] and S. C. B. Raper[2]

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[1] The IPCC Third Assessment Report (TAR) developed a formula for the global meltwater contribution to sea level rise from Glaciers and Small Ice Caps (GSICs) that is applicable out to 2100. We show that, if applied to times beyond 2100 (as is necessary to assess sea level rise for concentration-stabilization scenarios), the formula imposes an unrealistic upper bound on GSIC melt. A modification is introduced that allows the formula to be extended beyond 2100 with asymptotic melt equal to the initially available ice volume (V_0). The modification has a negligible effect on the original TAR formulation out to 2100 and provides support for the IPCC method over this time period. We examine the sensitivity of GSIC melt to uncertainties in V_0 and mass balance sensitivity, and give results for a range of CO_2 concentration stabilization cases. Approximately 73–94% of GSIC ice is lost by 2400. **Citation:** Wigley, T. M. L., and S. C. B. Raper (2005), Extended scenarios for glacier melt due to anthropogenic forcing, *Geophys. Res. Lett.*, *32*, L05704, doi:10.1029/2004GL021238.

1. Introduction

[2] The sea level rise chapter [*Church et al.*, 2001] in the IPCC Third Assessment Report (TAR) presents an algorithm for calculating GSIC melt based on the work of *Gregory and Oerlemans* [1998] and *Van der Wal and Wild* [2001]. GSIC melt (the category excludes glaciers on the margins of Greenland or the Antarctic Peninsula) is calculated in two steps. First, a melt value is calculated assuming that the total ice area remains constant. The corresponding sea level rise is denoted g_u. This is then corrected to allow for the fact that, as melting occurs, the area of ice must decrease, so the mass balance sensitivity must decrease. The corrected sea level rise is denoted g_s. Melt model parameters were determined for a range of coupled atmosphere/ocean GCMs.

[3] In the TAR, a simple climate model (MAGICC) was used to calculate global-mean temperature projections out to 2100 for a range of emissions scenarios [*Cubasch et al.*, 2001] (for MAGICC details see *Raper et al.* [2001] and *Wigley and Raper* [2001, 2002]). These projections were then used to drive the TAR ice-melt algorithms, the results of which, along with oceanic thermal expansion projections, were used to extend the range of sea level projections.

[1] National Center for Atmospheric Research, Boulder, Colorado, USA.
[2] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

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[4] As incorporated into the MAGICC model, the TAR formula for sea level rise from GSIC melt (relative to an unspecified GSIC steady-state point) is

$$g_u(t) = g_u(1990) + \int_{1990}^{t} [\alpha(0.15 + T(t'))]dt' \quad (1)$$

$$g_s(t) = g_u(0.934 - 0.01165\ g_u) \quad (2)$$

where α is a global mass balance sensitivity (i.e., sea-level-equivalent melt rate per unit global-mean warming) defined by $d^2g_u/dtdT$ and assumed to be a constant, and T is global-mean temperature change from the late 19th century. The 0.15 accounts for changes between the GSIC steady-state point and the late 19th century [*Zuo and Oerlemans*, 1997].

[5] This method was only meant to be applied out to 2100, and it gives unrealistic results if carried too far beyond 2100. The reason is that, with the quadratic correction factor, g_s must have an upper bound. This occurs when $dg_s/dg_u = 0$ (i.e., $g_u = 40.1$ cm) at which point $g_s = 18.7$ cm. The available amount of GSIC ice that could melt is almost certainly greater than this (we use a range of values from 30 cm to 50 cm below, based on *Church et al.* [2001]). In any event, interpreting this upper bound as the available amount of GSIC ice would be inappropriate because the available amount of ice should be an independent input, not an artifact of an empirical correction for area changes.

[6] For all credible future scenarios out to 2100, g_u never approaches 40.1 cm, so the upper bound for g_s is never reached, and the TAR method can be applied with impunity. For stabilization scenarios, however, which may extend well beyond 2100, the TAR method can lead to unsatisfactory results, so some alternative must be developed.

2. An Extended TAR Formula

[7] In devising an extension to the TAR formula, we begin by considering the area correction. Rather than modifying the TAR's empirical correction formula, we incorporate the reason for this correction directly by making the global mass balance sensitivity a function of the GSIC area (A). For consistency, we must define a new mass balance sensitivity (β) relative to g_s rather than g_u, i.e., $\beta(t) = d^2g_s/dtdT$. If A_0 is the initial GSIC area and β_0 is the initial sensitivity, then $\beta(t) = \beta_0(A/A_0)$. For individual glaciers or ice caps, standard area-volume scaling would allow this to be expressed in terms of volume changes. If we assume that a similar scaling can be applied to the global total, then the time-varying sensitivity is given by

$$\beta = \beta_0(V/V_0)^n = \beta_0((V_0 - g_s)/V_0)^n; \quad \beta_0 = \beta_{1990}[V_0/(V_0 - g_s(1990))]^n \quad (3)$$

where V is GSIC volume (in sea-level equivalent) and β_{1990} is the g_s sensitivity in 1990. The exponent 'n' has the value 0.74 for glaciers up to 200 km^2 in area and 0.82 for ice caps [see, e.g., *Chen and Ohmura*, 1990; *Meier and Bahr*, 1996; *Raper et al.*, 1996; *Bahr et al.*, 1997]. We use 0.82 here for two reasons: first, because the results out to 2100 are insensitive to 'n' (as becomes clear below); and, second, because, for times beyond 2100, ice caps account for a larger fraction of the total remaining ice volume. Larger values of 'n' lead to less rapid melt.

[8] In terms of g_s, and incorporating the area correction directly into the formulation, the equivalent of equation (1) is

$$g_s(t) = g_s(1990) + \int_{1990}^{t} [\beta_0(0.15 + T(t'))((V_0 - g_s)/V_0)^n]dt' \tag{4}$$

where α has been replaced by β, and β has been expressed in terms of g_s using equation (3).

[9] Equation (4) may be rewritten as a simple first-order differential equation, viz.

$$dg_s/dt = \beta_0(0.15 + T(t))(1 - g_s/V_0)^n \tag{5}$$

which can easily be integrated numerically.

[10] First, however, to obtain insight into this new formulation we consider a simplified case where n = 1 (we retain n = 0.82 in the full calculations). Equation (5) can then be written as

$$dg_s/dt + g_s f(t) = V_0 f(t) \tag{6}$$

where

$$f(t) = \beta_0(0.15 + T(t))/V_0 \tag{7}$$

The general solution is

$$g_s(t) = g_s(1990)\exp(-Z) + V_0\exp(-Z) \cdot \left\{ \int [f(t')\exp(Z)]dt' - 1 \right\} \tag{8}$$

where

$$Z(t) = \int [f(t')]dt' \tag{9}$$

Although an analytic solution can be obtained for temperature increasing linearly with time (in terms of the Error function) the result is messy and it is sufficient to consider the case where temperature remains constant at the 1990 level. Using T(1990) = 0.65°C [*Jones and Moberg*, 2003], equation (8) becomes

$$g_s(t) = g_s(1990)\exp(-0.8\,\beta_0\,t/V_0) + V_0\{1 - \exp(-0.8\,\beta_0\,t/V_0)\} \tag{10}$$

This is a physically satisfying result since it involves the total initial GSIC ice volume (V_0) directly. For short times ($t \ll 860$ years; see below) the melt is independent of V_0 (and, hence, the scaling exponent 'n'), justifying the TAR formulation. Uncertainties in g_s accrue initially through uncertainties in the initial (or 1990) sensitivity. For long times, melt uncertainties reflect uncertainties in both the global mass balance sensitivity and the total available GSIC volume (see below), so results at this limit are also insensitive to 'n'.

[11] Let us now compare this new result with the TAR formula for short times, where 'short' is defined by $t \ll V_0/(0.8\beta_0)$ (i.e., using β_0 = 0.058 cm/yr-°C, see Appendix A, and V_0 = 40 cm; and remembering that the 0.8 term has units of °C, $t \ll 860$ years). The new result, equation (10), becomes

$$\begin{aligned} g_s(t) &= g_s(1990)(1 - 0.8\,\beta_0\,t/V_0) + 0.8\,\beta_0\,t \\ &= g_s(1990) + 0.8\,\beta_{1990}\,t \end{aligned} \tag{11}$$

using $\beta_0 = \beta_{1990}\,V_0/(V_0 - g_s(1990))$ (equation (3) with n = 1). The implied constant melt rate is, of course, only valid for short times.

[12] In comparison, the TAR formula for zero warming beyond 1990 and short times reduces to

$$g_s(t) = g_s(1990) + 0.8\,\alpha\,t(0.934 - 0.0233\,g_u(1990)) \tag{12}$$

Equations (11) and (12) are identical when one realizes that

$$\begin{aligned} \beta_{1990} &= [dg_s/dT]_{t=1990} = [dg_s/dg_u]_{t=1990}(dg_u/dT) \\ &= (0.934 - 0.0233\,g_u(1990))\,\alpha \end{aligned} \tag{13}$$

The new result therefore satisfies the following *a priori* desirable conditions: it is identical to the TAR formula for short times (and very similar, therefore, throughout the 21st century); it does not suffer from the artificial melt maximum arising from the quadratic area correction factor; the melt tends asymptotically to the initially-available ice volume; and the new area correction method is based on a physical, albeit very simple, model.

[13] Furthermore, the agreement between the old and new results for the 21st century (see also below) has two implications. First, it shows that the empirical area correction used in the TAR is closely equivalent to assuming that the global mass balance sensitivity is linearly dependent on the remaining area of GSIC ice. Second, since the TAR relationship is based on results from more sophisticated ice modeling, the match between the present and the TAR results endorses the validity of the sensitivity-area-volume relationship that we have assumed.

[14] We now return to the more general solution of equation (5), with n = 0.82. Figure 1 compares the new results with the TAR results. In both cases the GSIC formulation has been embedded in the MAGICC climate model so ice melt is driven by the same time-dependent temperature changes. For the new formulation an initial ice volume (V_0) of 40 cm has been assumed. (Table 11.3 in the TAR gives a value of 50 cm that includes GSICs on the margins of Greenland and the Antarctic Peninsula. The latter account for about 20% of the GSIC area.) The g_u sensitivity (α), which, with V_0, determines the initial g_s sensitivity (β_{1990} or β_0) is the same in both cases (viz. the mean of the seven individual model results used in the TAR). As an illustrative forcing scenario we have used

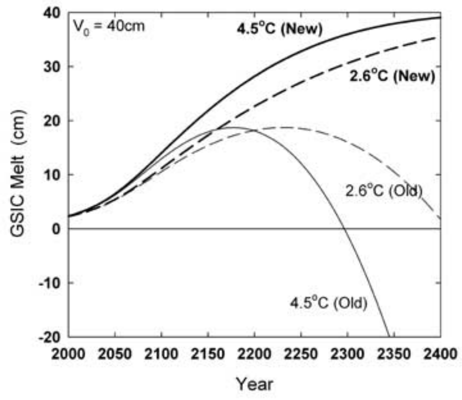

Figure 1. Glacier and Small Ice Cap (GSIC) melt (from steady state) comparing results using the IPCC TAR formulation (labeled 'Old') with results for the present method ('New'). Results shown are for CO_2 stabilization at 550 ppm using two different values of the climate sensitivity ($\Delta T2x$ = 2.6°C and 4.5°C). The initial GSIC ice volume is assumed to be 40 cm sea level equivalent.

the WRE550 concentration profile for CO_2 [*Wigley et al.*, 1996], with, for other gases, median SRES emissions [*Nakićenović and Swart*, 2000] out to 2100 then constant emissions thereafter. We use central estimates for all climate model parameters as given by *Wigley and Raper* [2001], except for the climate sensitivity, and run the simulations out to 2400. Results are shown for two different climate sensitivities, $\Delta T2x$ = 2.6°C and 4.5°C.

[15] A number of things are evident in Figure 1. First, out to 2100, there is very close agreement between the TAR results and those for the new method. Second, the artificial maximum melt that occurs as a result of the TAR quadratic area-correction method is illustrated. It should be noted, however, that this maximum occurs well after 2100. Both of these points support the acceptability of the TAR method at least out to 2100. Third, in the high climate sensitivity case using the new method, the total ice melt is 39 cm in 2400, indicating that, under the assumed scenario, almost all the GSIC ice has melted by this time.

3. Assessment of Uncertainties

[16] Uncertainties can easily be quantified using the new method. In the TAR, the 2-sigma melt range is given as approximately ±40% of the melt. In the present formulation, this is equivalent to imposing similar (±40%) error bounds on the initial g_s sensitivity. As noted above, this source of uncertainty will dominate initially. In addition, there are uncertainties arising from uncertainties in V_0. Based on figures given in the TAR (and noting that GSIC here, and in the TAR, does not include glaciers that are on the margins of Greenland or the Antarctic Peninsula), the 2-sigma uncertainty range for V_0 is about 40 ± 10 cm. While the range, 30 cm to 50 cm, is consistent with initial volume estimates used in previous IPCC reports it should be noted that our purpose here is to assess sensitivities to V_0 rather than provide a definitive quantification of the uncertainty range. Six extreme cases will be considered: high and low β_0; high and low V_0; high β_0 combined with high V_0; and low β_0 combined with low V_0; (see Figure 2).

[17] Figure 2 shows that initial uncertainties arise solely from uncertainties in the global mass balance sensitivity. It is not until well beyond 2100 that initial ice volume uncertainties become (increasingly with time) important, justifying the neglect of initial ice volume as a parameter in the TAR formulation. By 2400, both sensitivity and initial ice volume uncertainties contribute significantly to overall uncertainty.

4. Stabilization Projections

[18] We now consider three stabilization cases. For simplicity, only CO_2 concentration is assumed to stabilize, at 350 ppm, 550 ppm and 750 ppm (following the WRE profiles). As with Figure 1, for non-CO_2 gases we use median SRES emissions out to 2100 with constant emissions thereafter. As a consequence, radiative forcing continues to increase after CO_2 is stabilized (stabilization dates are shown by the short vertical lines in Figure 3). These forcing increases, however, are relatively small, arising from the slow approach to steady state concentrations for long-lived gases like N_2O, CF_4 and SF_6. The continued increases in global-mean warming (see Figure 3) are due, in large part, to thermal inertia of the climate system.

[19] Figure 3 shows both global-mean temperature changes (top panel) and projected GSIC melt (lower panel) for the three cases. The results are shown only for central estimates of the various model parameters (which include a climate sensitivity of $\Delta T2x$ = 2.6°C).

[20] The most striking result from Figure 3 is the much lower relative sensitivity of GSIC melt to future atmospheric composition changes compared with global-mean temperature. This is in part due to the constraint of a fixed

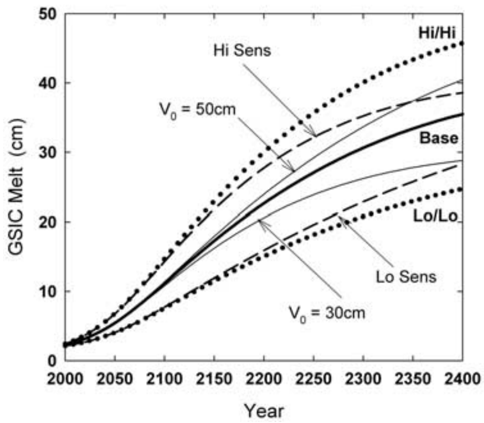

Figure 2. Sensitivity of GSIC melt to uncertainties in: V_0, the initial GSIC ice volume (thin full lines); and the global mass balance sensitivity (dashed lines; Hi Sens and Lo Sens are 1.4x and 0.6x the central sensitivity value). The Base case (central bold line) has V_0 = 40 cm sea level equivalent, and the high and low V_0 cases have V_0 = 30 cm and 50 cm. Hi/Hi and Lo/Lo (outer dotted lines) combine the V_0 and mass balance sensitivity extremes. Results are for CO_2 stabilization at 550 ppm and use a climate sensitivity of $\Delta T2x$ = 2.6°C.

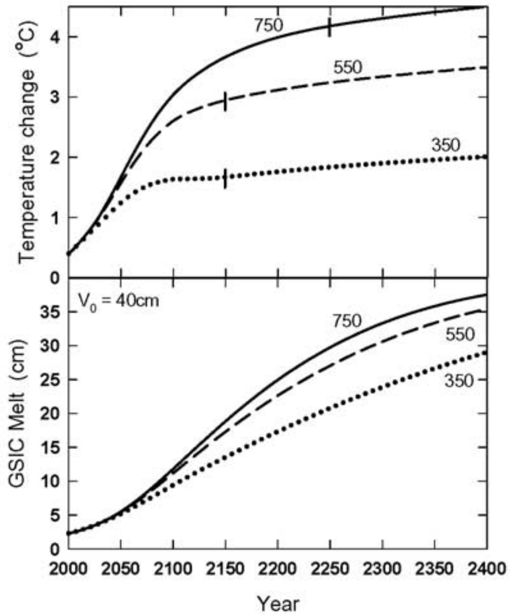

Figure 3. Projected changes in global-mean temperature from the late 19th Century (upper panel) and GSIC melt from an initial steady state (lower panel) for three CO_2 stabilization cases. CO_2 concentrations follow the WRE 350 (dotted lines), 550 (dashed lines) and 750 (full lines) profiles, and non-CO_2 emissions follow the median of the SRES scenarios to 2100 and assume constant emissions thereafter. Central model parameters are used including a climate sensitivity of $\Delta T2x = 2.6°C$ and an initial GSIC ice volume of 40 cm. Short vertical lines in the upper (temperature) panel show the years at which CO_2 concentrations stabilize: 2150 for WRE 350 and 550, and 2250 for WRE750.

amount of available ice, which prescribes an upper bound for ice melt. However, the separation of the GSIC melt cases is small relative to global-mean temperature even in 2100, when the GSIC melt results are virtually independent of the available ice volume. Insensitivity to the forcing scenario here is a result of the long relaxation time for global GSIC melt identified above in equation (10).

5. Conclusions

[21] A simple extension of the TAR GSIC melt model has been introduced in which the global mass balance sensitivity is a simple function of the remaining GSIC ice volume. This avoids the need for an empirical area correction factor while reproducing TAR model results with high accuracy out to 2100. The extension introduces the initial GSIC ice volume (V_0) as an additional parameter, and allows the model to be run beyond 2100. To 2100, melt uncertainties are due almost entirely to mass balance sensitivity uncertainties. Beyond this, V_0 uncertainties become increasingly important; by 2400 both sources of uncertainty are equally important. Three CO_2 stabilization cases were considered. Asymptotic (2400) global-mean temperature changes range from 2.0°C to 4.5°C for stabilization levels of 350 ppm to 750 ppm and a climate sensitivity of $\Delta T2x = 2.6°C$. The constraint of a finite available ice volume means that the range of GSIC melt values is much less, at most −24% to +10% relative to the 550 ppm stabilization case (maximum percentage differences occur around 2200). By 2400, even for CO_2 stabilization at 350 ppm, 73% of the available ice has melted (up to 94% for stabilization at 750 ppm).

[22] A final caveat is in order. One of the implications of the present model is that, even if temperatures remained constant at today's level, all of the GSIC ice would eventually melt. (Actually, total melting would take an infinite time, but 99% of the ice would melt in 1000–2000 years.) Given the altitudinal distribution of GSIC ice, this is unlikely to be realistic. For any given asymptotic warming, one would expect only a fraction of the available ice to melt [see, e.g., *Wigley and Raper*, 1995] – although defining what this fraction is presents a challenge. The long time scale that characterizes GSIC melt (of order 800 years) does, however, give us some confidence in applying the model at least out to 2400.

Appendix A: Key Numerical Values

[23] The simulations use average values from the seven AOGCMs listed in Table 11.17 of *Church et al.* [2001]. The primary values are the g_u sensitivity, $\alpha = 0.0625$ cm/yr-°C, and the 1990 value of g_u, $g_u(1990) = 2.14$ cm. From equation (2) we have $g_s(1990) = 1.945$ cm, from equation (13) $\beta_{1990} = 0.0553$ cm/yr-°C, and from equation (3) (using $V_0 = 40$ cm and $n = 0.82$) $\beta_0 = 0.0577$ cm/yr-°C.

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S. C. B. Raper, Alfred Wegener Institute for Polar and Marine Research, D-27515 Bremerhaven, Germany.
T. M. L. Wigley, National Center for Atmospheric Research, Boulder, CO 80307, USA. (wigley@ucar.edu)