A SLIPPERY SLOPE: HOW MUCH GLOBAL WARMING CONSTITUTES "DANGEROUS ANTHROPOGENIC INTERFERENCE"?

An Editorial Essay

In a recent article (Hansen, 2004) I included a photograph taken by Roger Braithwaite with a rushing stream pouring into a hole in the Greenland ice sheet. The photo relates to my contention that disintegration of ice sheets is a wet, potentially rapid, process, and consequent sea level rise sets a low limit on the global warming that can be tolerated without risking dangerous anthropogenic interference with climate.

I asked glaciologist Jay Zwally if I would be crucified for a caption such as: "On a slippery slope to Hell, a stream of snowmelt cascades down a moulin on the Greenland ice sheet. The moulin, a near-vertical shaft worn in the ice by surface water, carries water to the base of the ice sheet. There the water is a lubricating fluid that speeds motion and disintegration of the ice sheet. Ice sheet growth is a slow dry process, inherently limited by the snowfall rate, but disintegration is a wet process, spurred by positive feedbacks, and once well underway it can be explosively rapid."

Zwally replied "Well, you have been crucified before, and March is the right time of year for that, but I would delete 'to Hell' and 'explosively"'. I thought immediately of the fellow who went over Niagara Falls without a barrel. Would not he consider that a joy ride, compared to slipping on the banks of the rushing melt-water stream, clawing desperately in the freezing water before being hurtled down the moulin more than a kilometer, and eventually being crushed by the giant grinding glacier? "A slippery slope to Hell" did not seem like an exaggeration.

On the other hand, I was using "slippery slope" mainly as a metaphor for the danger posed by global warming. So I changed "Hell" to "disaster."

What about "explosively"? Consider the situation during past ice sheet disintegrations. In melt-water pulse 1A, about 14,000 years ago, sea level rose about 20 m in approximately 400 years (Kienast et al., 2003). That is an *average* of 1 m of sea level rise every 20 years. The nature of glacier disintegration required for delivery of that much water from the ice sheets to the ocean would be spectacular (5 cm of sea level, the mean annual change, is about 15,000 cubic kilometers of water). "Explosively" would be an apt description, if future ice sheet disintegration were to occur at a substantial fraction of the melt-water pulse 1A rate.

Are we on a slippery slope now? Can human-made global warming cause ice sheet melting measured in meters of sea level rise, not centimeters, and can this occur in centuries, not millennia? Can the very inertia of the ice sheets, which protects us from rapid sea level change now, become our *bête noire* as portions of

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the ice sheet begin to accelerate, making it practically impossible to avoid disaster for coastal regions?

Ice sheet modeling: is something wrong with this picture? IPCC (2001) estimates sea level rise of between 9 and 88 cm in 110 years, for scenarios that include rapid, probably unrealistic, growth of climate forcings. This calculated sea level rise is due mainly to thermal expansion of ocean water, and secondarily to melting alpine glaciers, with the Greenland and Antarctic ice sheets calculated as being close to mass balance. For the heavily studied IS92a scenario, with 715 ppm of CO_2 in 2100, as well as large increases of CH_4, O_3 and black carbon (BC), the central estimate of sea level rise is 40–45 cm, with 30 cm from thermal expansion of ocean water, 10–15 cm from alpine glaciers, and practically no net change of the Greenland and Antarctic ice volume. More recent simulations with a high-resolution (T106) global climate model (Wild et al., 2003) result in both the Greenland and Antarctic ice sheets *growing* at a rate equivalent to *sea level fall* of 12 cm per century when doubled CO_2 (beyond today's level) is reached. These results, I argue, understate the potential for significant ice sheet disintegration.

Zwally et al. (2002) have shown empirically that ice sheet flow on Greenland speeds up in response to meltwater delivered to the ice sheet base via moulins. Parizek and Alley (in press) parameterize this melt-water basal lubrication in their two-dimensional ice sheet model, concluding that Greenland is likely to make a greater contribution to sea level rise than previously believed. However, their calculated sea level rise is still modest. For example, a scenario with CO_2 doubling by 2100 reduces the Greenland ice sheet volume less than 1% by 2100, yielding an 0.6–6.6 cm contribution to sea level rise, with the range depending upon uncertain model parameters.

Such a contribution to sea level rise seems almost innocuous. However, I suggest that the calculations do not yet fully and realistically incorporate important processes that will accelerate ice sheet disintegration.

Energy balance and feedbacks. The Earth is now out of energy balance by close to $+1$ W/m^2, i.e., with that much more energy absorbed from sunlight than the energy emitted to space as thermal radiation (Hansen, 2004). This large growing planetary energy imbalance has no known precedent, greatly exceeding the global mean energy imbalance associated with changes of the Earth's orbital elements that paced the natural building and decay of ice sheets.

The planetary energy imbalance is due mainly to rapid growth of greenhouse gases, especially CO_2 and CH_4, and the thermal inertia of the ocean. CO_2 and CH_4 amounts today are far outside the ranges that existed for hundreds of thousands of years (Figure 1). Although prehuman climate changes were paced by changes of the Earth's orbit, the climate change mechanisms functioned by altering atmospheric composition and surface properties. Humans now control the Earth's atmospheric composition and surface properties. The impact of the changing atmosphere and surface on the Earth's energy balance can be calculated with global climate models and verified with measurements of ocean heat storage (Levitus et al., 2000).