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Climate Change and Sea Level Rise

A Review of the Scientific Evidence

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Abstract

Sea-level rise (SLR) due to climate change is a serious global threat: The scientific evidence is now overwhelming. The rate of global sea level rise was faster from 1993 to 2003, about 3.1 mm per year, as compared to the average rate of 1.8 mm per year from 1961 to 2003 (IPCC, 2007); and significantly higher than the average rate of 0.1 to 0.2 mm/yr increase recorded by geological data over the last 3,000 years. Anthropogenic warming and SLR will continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized. This paper reviews the scientific literature to date on climate change and sea level rise.

There appears to be a consensus across studies that global sea level is projected to rise during the 21st century at a greater rate than during the period 1961 to 2003 and unanimous agreement that SLR will not be geographically uniform. Ocean thermal expansion is projected to contribute significantly, and land ice will increasingly lose mass at an accelerated rate. But most controversial are the mass balance loss estimates of the Greenland and Antarctic Ice Sheets and what the yet un-quantified dynamic processes will imply in terms of SLR. Recent evidence on the vulnerability of Greenland and west Antarctic ice sheets to climate warming raises the alarming possibility of SLR by one meter or more by the end of the 21st century.

1 Introduction

Sea-level rise (SLR) due to climate change is a serious global threat: The scientific evidence is now overwhelming. The rate of global sea level rise was faster from 1993 to 2003, about 3.1 [2.4 to 3.8] mm per year, as compared to the average rate of 1.8 [1.3 to 2.3] mm per year from 1961 to 2003 (IPCC, 2007); and significantly higher than the average rate of 0.1 to 0.2 mm/yr increase recorded by geological data over the last 3,000 years.[1]

Even if greenhouse gas (GHG) emissions were stabilized in the near future, sea levels would continue to rise for many decades (IPCC, 2007). Until recently, studies of SLR typically predicted ranges within the 0-1 meter during the 21st century (Church et al., 2001). The IPCC AR4 report has projected a rise in sea level between 0.18 to 0.59 meters by the end of 21st century - across different emission scenarios. However, the models considered by the IPCC, 2007 did not include the full effect of changes in ice sheet flow, and IPCC projections have been criticized by many experts as being too conservative (Oppenheimer et al., 2008; Pfeffer et al., 2008; Solomon et al., 2008). New measurement information on the rates of deglaciation in Greenland and the West Antarctic suggest an alarming possibility that a threshold triggering many meters of sea level rise could be crossed well before the end of this century (Hansen et al., 2007; Helsen et al., 2008; Joughin et al., 2008; Kohler et al., 2007; Overpeck et al., 2006; Rignot, 2008; Van de Wall et al., 2008).[2]

SLR is a serious threat to countries with high concentrations of population and economic activity in coastal regions. The biophysical effects of SLR on coastal regions include: i) inundation, flood and storm damage; ii) wetland loss; iii) erosion; iv) saltwater intrusion v) coral bleaching (from higher sea water temperatures); vi) ocean productivity changes; and vii) species migration. Most of these impacts are broadly linear functions of sea level rise, although some processes such as wetland loss and change show a threshold response and are more strongly related to the rate of sea level rise, rather than the absolute change. These natural-system effects have a range of potential socio-economic impacts, including the following identified by McLean and Tsyban (2001): i) increased loss of property and coastal habitats, ii) increased flood risk and potential loss of life, iii) damage to coastal protection works and other infrastructure, iv) loss of renewable and subsistence resources, and v) loss of tourism, recreation, and transportation functions.

The impacts of SLR could be catastrophic for many developing countries. Recent World Bank estimates suggest that even a one-meter rise in sea level in coastal countries of the developing world would submerge 194,000 square kilometers of land area, and displace at least 56 million people (Dasgupta et al. 2007). The actual impacts, however, will depend on countries' ability to adapt to the potential impacts of SLR.

The impacts of climate change on sea level rise are complex. At play are the interactions between natural cycles and human activity, and a full assessment of the range of climate change consequences and probabilities involves a cascade of uncertainties in emissions, carbon cycle response, climate response, and impacts. In this paper we review the scientific literature on climate change and SLR to date.

In the next section we begin with a summary of the historical observations as noted by the IPCC in their latest report and in section 3, their predictions for the future. Section 4 then provides an overview of the latest research on SLR and serves as an update to the IPCC AR4 report. Section 5 provides an overview of some of the criticisms of the IPCC AR4 report and section 6 concludes the review.

2 Climate Change and SLR — Observations from the Past

(as summarized in the IPCC AR4 report)

The IPCC AR4 Report identifies several major factors that currently contribute to sea level change. These are:

- Ocean thermal expansion[3]
- Changes in glaciers and icecaps
- Glacial melt from the Greenland and Antarctica Ice Sheets
- A smaller contribution from snow on land and permafrost (changes in other[4] Cryospheric components which have marginal impacts).

Below we provide a brief description of the relative contribution of these factors to SLR as observed and modeled in the past. Table 1 summarizes these contributions and Appendix I provides a more detailed discussion of the sources of data and procedures commonly used to estimate these contributions to SLR.

Ocean thermal expansion

Instrumental records reveal that the world's oceans have warmed since 1955, accounting over this period for more than 80% of the changes in the energy content of the Earth's climate system. Records further reveal during the period 1961 to 2003, the 0 to 3000 m ocean layer has absorbed up to 14.1 × 1022 Joules, equivalent to an average heating rate of 0.2 Watts/m2 (per unit area of the Earth's surface). During 1993 to 2003, the corresponding rate of warming in the shallower 0 to 700 m ocean layer was higher, about 0.5 ± 0.18 W/m2. Hence, relative to 1961 to 2003, the period 1993 to 2003 had much higher rates of warming, especially in the upper 700 m of the global ocean.

Changes in glaciers and icecaps

During the 20th century, glaciers and ice caps have experienced widespread mass losses. These losses (excluding those around the ice sheets of Greenland and Antarctica) are estimated to have contributed 0.50 ± 0.18 mm/yr in sea level equivalent (SLE) between 1961 and 2003, and 0.77 ± 0.22 mm/yr between 1991 and 2003.

Glacial melt from Greenland and Antarctica

Whether the Greenland and Antarctic ice sheets have been growing or shrinking over time scales of longer than a decade is not well established from observations. Lack of agreement between techniques and the small number of estimates preclude assignment of best estimates or statistically rigorous error bounds for changes in ice sheet mass balances. However, acceleration of outlet glaciers draining from the interior has been observed in both the Greenland and Antarctic ice sheets.

According to the IPCC AR4, it is very likely (> 90% probability) that the Greenland Ice Sheet (GIS) shrunk from 1993 to 2003, with the thickening in central regions being more than offset by increased melting in coastal regions. An assessment of the data suggests a mass balance for the Greenland Ice Sheet of –50 to –100 Gigatons/year (a shrinkage contributing to rising global sea levels of 0.14 to 0.28 mm/yr) from 1993 to 2003, with even larger losses in 2005. The estimated range in mass balance for the GIS from 1961 to 2003 is between a growth of 25 Gt/yr and shrinkage of 60 Gt/yr (or –0.07 to +0.17 mm/yr SLE).[5]

There are even greater uncertainties for Antarctica Ice Sheet (AIS). Again according to the IPCC AR4 assessment of all the data yields an estimate for the overall AIS mass balance ranging from growth of 100 Gt/yr to shrinkage of 200 Gt/yr (or –0.27 to +0.56 mm/yr of SLE) from 1961 to 2003, and from +50 to –200 Gt/yr (or –0.14 to +0.55 mm/yr of SLE) from 1993 to 2003.

Snow on land

Snow cover has decreased in most regions, especially in spring. Satellite observations of the Northern Hemisphere snow cover from 1966 to 2005 show a decrease in every month except in November and December, with a stepwise drop of 5% in the annual mean in the late 1980s. In the Southern Hemisphere, the few long records or proxies mostly show either decreases or no changes in the past 40 years or more. Decreases in the snow pack have also been documented in several regions worldwide based upon annual time series of mountain snow water equivalent and snow depth.

Permafrost

Permafrost and seasonally frozen ground in most regions display large changes in recent decades. Temperature increases at the top of the permafrost layer of up to 3°C since the 1980s have been reported. Permafrost warming has also been observed with variable magnitudes in the Canadian Arctic, Siberia, the Tibetan Plateau and Europe. The permafrost base has been thawing at a rate ranging from 0.04 m/yr in Alaska to 0.02 m/yr on the Tibetan Plateau.

Summarizing each of these contributors in Table 1, the average rate of global mean SLR from 1961 to 2003, estimated from tide gauge data, is 1.8 ± 0.5 mm/yr. Thermal expansion's contribution to SLR over this period was 0.42 ± 0.12 mm/yr (about one-quarter of the total observed SLR), with significant decadal

Table 1. Contributions to SLR Based Upon Observations as Compared to Models Used in the IPCC AR4[6]

	Sea Level Rise (mm/year)					
	1961-2003			***1993-2003***		
Sources of SLR	*Observed*		*Modeled*	*Observed*		*Modeled*
Thermal expansion	0.42 ± 0.12		0.5 ± 0.2	1.6 ± 0.5		1.5 ± 0.7
Glaciers and ice caps	0.50 ± 0.18		0.5 ± 0.2	0.77 ± 0.22		0.5 ± 0.3
Greenland Ice Sheet		0.05 ± 0.12[a]			0.21± 0.07[a]	
Antarctic Ice Sheet		0.14 ± 0.41[a]			0.21± 0.35[a]	
Sum of individual climate contributions to SLR	1.1 ± 0.5		1.2 ± 0.5	2.8 ± 0.7		2.6 ± 0.8
Observed total SLR	1.8 ± 0.5 (tide gauges)			3.1 ± 0.7 (satellite altimeter)		
Difference (observed total minus the sum of observed climate contributions)	0.7 ± 0.7			0.3 ± 1.0		

Note: a – prescribed based upon observations.
Source: Table TS.3 (IPCC 2007).

variation, while the contribution from glaciers, ice caps and ice sheets was estimated to have been 0.7 ± 0.5 mm/yr (about less than half of the total). The sum of these estimated contributions is about 1.1 ± 0.5 mm/yr, which is less than the best estimate from the tide gauge observations (see Table 1).[7], [8]

More recent evidence using satellite altimetry[9] reveals a much higher response of SLR to climate change. The global average rate of sea level rise from 1993 to 2003 is 3.1 ± 0.7 mm/yr, which is close to the estimated total of 2.8 ± 0.7 mm/yr for the climate-related contributions due to thermal expansion (1.6 ± 0.5 mm/yr) and changes in land ice (1.2 ± 0.4 mm/yr). On average, thermal expansion and melting of ice each accounted for about half of the observed SLR during this period, although there is some uncertainty in the estimates.

3 Sea Level Rise — Predictions

(as summarized in IPCC AR4 report)

Global sea level is projected to rise during the 21st century at a greater rate than during 1961 to 2003. As in the past, there is unanimous agreement that sea level change in the future will not be geographically uniform.

However, quantitative projections of SLR have been a source of immense debate in the recent years, given the number of natural processes involved and the associated uncertainty of each systems reaction. The most important uncertainty relates to whether the discharge of ice from ice sheets will continue to increase as a consequence of accelerated ice flow, as observed in recent years. Limited understanding of ice flow dynamics prevents quantitative projections of discharge from ice sheets, and hence SLR with confidence. Despite these uncertainties, the IPCC does make the following overall observations about future SLR:

- Climate models are consistent with the ocean temperature observations and indicate that thermal expansion is expected to continue to contribute to sea level rise over the next 100 years. Since deep ocean temperatures change only slowly, thermal expansion would continue for many centuries even if atmospheric concentrations of greenhouse gases were stabilized;
- The retreat of glaciers and ice caps is expected to continue during the next 100 years and their contribution should decrease in subsequent centuries as this store of freshwater diminishes; and
- Although there is uncertainty about Antarctic Ice Sheet, melting of the Greenland Ice Sheet is projected to increase further in the recent future.

Ocean thermal expansion

Expected global average thermal expansion can be calculated directly from simulated changes in ocean temperature. Results are available from 17 Atmosphere-Ocean General Circulation Models (AOGCMs) for the 21st century for SRES scenarios A1B, A2 and B1, continuing from simulations of the 20th century (see Appendix 2 for an explanation of the different SRES scenarios). One ensemble member was used for each model and scenario.[10]

During the period 2000 to 2020, under scenario SRES A1B in the ensemble of AOGCMs, the rate of thermal expansion is 1.3 ± 0.7 mm/yr, and is not significantly different under A2 or B1. This rate is more than twice the observationally derived rate of 0.42 ± 0.12 mm /yr during 1961 to 2003. It is similar to the rate of 1.6 ± 0.5 mm/yr during 1993 to 2003.[11]

During the period 2080 to 2100, the rate of thermal expansion is projected to be 1.9 ± 1.0, 2.9 ± 1.4 and 3.8 ± 1.3 mm/yr under scenarios B1, A1B and A2 respectively in the AOGCM ensemble (the width of the range is affected by the different numbers of models under each scenario). The acceleration is caused by the increased climatic warming.

Glaciers and icecaps, Greenland ice sheet, Antarctic ice sheet, snow on land, and permafrost

Table 2 summarizes the current stock of ice, along with what this ice would represent in terms of sea level rise were it to completely melt.

Table 2. Area, Volume, and Sea Level Equivalent (SLE) of the other Major Contributory Factors to SLR
(Indicated are the annual minimum and maximum for snow, and the annual mean for the other components. The values for glaciers and ice caps denote the smallest and largest estimates excluding glaciers and ice caps surrounding Greenland and Antarctica)

	Area ***(10^6 km^2)***	***Ice volume*** ***(10^6 km^3)***	***Potential sea level rise*** ***(m)***[f]
Glaciers and Ice caps			
Smallest estimate [a]	0.51	0.05	0.15
Largest estimate [b]	0.54	0.13	0.37
Ice sheets	14.0	27.6	63.9
Greenland [c]	1.7	2.9	7.3
Antarctica [d]	12.3	24.7	56.6
Snow on Land (NH*)	1.9-45.2	0.0005-0.005	0.001-0.01
Permafrost (NH) [e]	22.8	0.011-0.037	0.03-0.10

Notes:
* Northern Hemisphere
a Ohmura (2004); glaciers and ice caps surrounding Greenland and Antarctica are excluded.
b Dyurgerov and Meier (2005); glaciers and ice caps surrounding Greenland and Antarctica are excluded.
c Bamber et al. (2001).
d Lythe et al. (2001).
e Zhang et al. (1999), excluding permafrost under ocean, ice sheets and glaciers.
f Assuming an oceanic area of 3.62 × 108 km2, an ice density of 917 kg m–3, a seawater density of 1,028 kg m–3, and seawater replacing grounded ice below sea level.

Source: Table 4.1, IPCC 2007.

Table 2 highlights the potential importance of ice sheets, glaciers and ice caps for the SLR in future. The present Antarctic and Greenland and ice sheets contain enough water to raise sea level by almost 57m, and 7m respectively; and melting of all glaciers and icecaps would raise sea level by 0.05m – 0.13m.

Projections of mass balance sensitivity of glaciers and icecaps

The acceleration of glacier loss over the next few decades is likely.

- Using monthly temperature changes simulated in glaciers and ice cap regions by 17 AOGCMs for scenarios A1B, A2 and B1, the global total surface mass balance sensitivity to global average temperature change for all glaciers and ice caps outside Greenland and Antarctica range between 0.61 ± 0.12 mm/yr/°C (SLE) and 0.49 ± 0.13 mm/yr/°C for various modeling techniques, subject to uncertainty in these areas (Zuo and Oerlemans, 1997; Oerlemans, 2001; and Oerlemans et al. 2006).
- For a seasonally uniform temperature rise, alternative studies have estimated that an increase of precipitation of 20 to 50% / °C will be required to balance ablation[12] increases for a sample of glaciers and ice caps (Oerlemans et al., 1998; Braithwaite et al., 2003; Would and Hock, 2006; Oerlemans et al. 2006). Although AOGCMs generally project larger than average precipitation changes in the northern mid- and high-latitude regions, the global average is 1 to 2% / °C, so ablation increases would be expected to dominate worldwide.
- The mean specific surface mass balance of a glacier or ice cap will change as volume is lost.[13] Omission of this effect leads to overestimates of ablation. In order to correct projections, a scaling relation between the area of a glacier and its volume was derived. Application of the scaling reduces the projections of the glaciers and ice caps contribution up to the mid-21st century by 25% and over the whole century by 40 to 50% with respect to fixed glacier and ice cap areas.
- Estimates suggest that in future decades Antarctic and Greenland glaciers and ice caps (not the ice sheets) will together contribute 10 to 20% to sea

level as part of the contribution of other glaciers and ice caps.

Hence, melt water from glaciers must be considered as an important contributor to the total sea level rise expected in this century.[14]

Greenland and Antarctica Ice Sheets

The average annual solid precipitation falling onto these ice sheets is equivalent to 6.5 mm of sea level this input being approximately balanced by loss from melting and calving (creation of icebergs) (IPCC, 2001). The balance of these processes is not the same for the two ice sheets, on account of their different climatic regimes. Antarctic temperatures are so low there is virtually no surface runoff; where the only reduction in size arises from ice discharge into the ocean and the formation of icebergs. Greenland, on the other hand, experiences summertime temperatures high enough to cause widespread melting (even in the interior), which accounts for half of the ice loss, with the remainder being the discharge of ice as icebergs or into small ice-shelves.

- In projections of surface mass balance changes for Greenland, ablation increase is important but uncertain, being particularly sensitive to temperature change around the margins. Climate models project less warming in these low-altitude regions than the Greenland average, and less warming in summer (when ablation occurs) than the annual average, but greater warming in Greenland than the global average (Church et al., 2001; Huybrechts et al., 2004; Chylek and Lohmann, 2005; Gregory and Huybrechts, 2006). In most studies, Greenland surface mass balance changes represent a net positive contribution to sea level in the 21st century because the ablation increase is larger than the precipitation increase.
- On the contrary, all studies for the 21st century considered by the IPCC AR4 project that Antarctic surface mass balance changes will contribute negatively to sea level, owing to increasing accumulation exceeding any ablation increase.
- For an average temperature change of 3°C over each ice sheet, a combination of four high-resolution AGCM simulations and 18 AR4 AOGCMs (Huybrechts et al., 2004; Gregory and Huybrechts, 2006) give surface mass balance changes of 0.3 ± 0.3 mm /yr for Greenland and –0.9 ± 0.5 mm/yr for Antarctica (SLE), that is, sensitivities of 0.11 ± 0.09 mm/yr/°C for Greenland and –0.29 ± 0.18 mm/yr/°C for Antarctica.[15]

Likelihood of abrupt changes

- Satellite and in situ measurement networks have demonstrated increasing melting and accelerated ice flow around the periphery of the Greenland Ice Sheet over the past 25 years. The few simulations of long-term ice sheet simulations suggest that the Greenland Ice Sheet will significantly decrease in volume and area over the coming centuries if a warmer climate is maintained (Gregory et al., 2004; Huybrechts et al., 2004; Ridley et al., 2005). A threshold of annual mean warming of 1.9°C to 4.6°C in Greenland has been estimated for the elimination of the Greenland Ice Sheet (Gregory and Huybrechts, 2006).
- Recent observations of accelerated ice streams in the Amundsen Sea sector of the WAIS, the rapidity of propagation of this signal upstream and the acceleration of glaciers that fed the Larsen B Ice Shelf after its collapse, have raised the concern of a collapse of the WAIS. It is possible that the presence of ice shelves tend to stabilize the ice sheet, at least regionally. Therefore, a weakening or collapse of ice shelves, caused by melting on the surface or by melting at the bottom by a warmer ocean, might contribute to a potential destabilization of the WAIS, which could proceed through the positive feedback of the grounding-line retreat. However, the present understanding is insufficient

for prediction of the possible speed or extent of such a collapse.

Projections of global SLR by IPCC AR4

The IPCC AR4 report projected increased global SLR between 0.18m and 0.59m across various emission scenarios over the next 100 years.[16] These projections, however, are calculated from projections of SLR due to thermal expansion, melting of glaciers-with the Greenland and Antarctic ice sheets calculated as being close to mass balance; and exclude rapid dynamical changes in ice flow. According to the IPCC AR4, present scientific understanding is insufficient for prediction of any rapid dynamical / abrupt changes in ice flow. In the next section provide an overview of the latest evidence alongside the IPCC AR4 conclusions.

4 Recent Evidence for the Greenland and Antarctic Ice Sheets

Since melting of polar ice sheets is the largest determinant of future SLR, and the present Greenland and Antarctic ice sheets contain enough water to raise sea level by almost 70 m (Table 2), even small changes in their volume would have a significant effect.

Table 3 below summarizes some of the mass balance estimates for each of the major ice sheets, several of which were also used in the IPCC AR4 assessment.

Greenland Ice Sheet

As noted earlier, Greenland's seasonal temperature variation causes widespread melting in the interior and through the discharge of icebergs and small ice-shelves. Tedesco's (2007) long-term results show that snowmelt extent has been increasing at a rate of ~40,000 km2 per year for the past 14 years. In addition, studies have found major short-term variations in ice discharge and mass loss from Greenland's major outlet glaciers.

Table 3. Mass balance (MB) of the East Antarctic (EAIS), West Antarctic (WAIS), Antarctic (AIS), and Greenland (GIS) Ice Sheets as Determined by a Range of Techniques and Studies (Not all studies surveyed all of the ice sheets, and the surveys were conducted over different periods within the time frame 1992 to 2006. For comparison, 360 Gt of ice is equivalent to 1 mm of eustatic sea level rise)

Study	*Survey period*	*Survey area 10^6 km^2 (%)*	*EAIS MB Gt/year*	*WAIS MB Gt/year*	*AIS MB Gt/year*	*GIS MB Gt/year*
Wingham et al., 1998 *	1992–1996	7.6 (54)	-1 ± 53	- 59 ± 50	- 60 ± 76	
+ Krabill et al., 2000 *	1993–1999	1.7 (12)				- 47
+ Rignot and Thomas, 2002 †	1995–2000	7.2 (51)	22 ± 23	-48 ± 14	-26 ± 37	
Davies and Li, 2004 *	1992–2002	8.5 (60)			42 ± 23	
+ Davies et al., 2005 *	1992–2003	7.1 (50)	45 ± 7			
+ Velicogna and Wahr, 2005 ‡	2002–2004	1.7 (12)				-75 ± 21
+ Zwally et al., 2005 *	1992–2002	11.1 (77)	16 ± 11	-47 ± 4	-31 ± 12	11 ± 3
+ Rignot and Kanagaratnam, 2006 †	1996 2000 2005	1.2 (9)				-83 ± 28 -127 ± 28 -205 ± 38
Velicogna and Wahr, 2006a ‡	2002–2005	12.4 (88)	0 ± 51	-136 ± 19	-139 ± 73	
+ Ramillien et al., 2006 ‡	2002–2005	14.1 (100)	67 ± 28	-107 ± 23	-129 ± 15	-169 ± 66
Wingham et al., 2006 *	1992–2003	8.5 (60)			27 ± 29	
+ Velicogna and Wahr, 2006b ‡	2002–2006	1.7 (12)				-227 ± 33
Chen et al., 2006 ‡	2002–2005	1.7 (12)				-219 ± 21
Luthcke et al., 2006 ‡	2003–2005	1.7 (12)				-101 ± 16
Stearns and Hamilton, 2007 #	2001–2006	1.0 (7)				-122 ± 30
Rignot, 2008 †	1974–2007	N/A		- 105 ± 27		
Rignot et al., 2008 †	1992–2006	134.0 (N/A)	- 4 ± 61	- 132 ± 60	- 60 ± 46	
Range			- 4 to 67	- 136 to –47	-139 to 42	-227 to 11

Notes:
N/A – not available
+ Studies included in the IPCC AR4 report
* Altimetry; † InSAR mass budget; ‡ Gravimetry; # Other method
Source: Adapted from Table 1 in Shepherd and Wingham, 2007.

Measurements by Howat et al. (2007) for two of Greenland's largest outlet glaciers: Kangerdlugssuaq and Helheim located on the central east coast indicate a doubling of the rate of mass loss in less than a year in 2004, and then a decrease in 2006 to near the previous rates. Despite this wide year-over-year variation the overall trend in the velocity structure of the GIS is clear – with a mass loss of about 100 Gt per year which is a considerable increase in the velocity structure from a near balance during the 1990s (Joughin et al., 2008; Kohler et al., 2007; Luthcke et al., 2006; Thomas et al., 2004; Van de Wal et al., 2008).

Antarctic Ice Sheet

Although low temperatures in Antarctica produce no surface runoff, recent satellite observations of ice discharge have challenged the notion that the ice sheet changes with eternal slowness. For example, using measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites, Velicogna and Wahr (2006a) determined that the Antarctic ice sheet mass decreased significantly, at a rate of 152 ± 80 km/yr of ice, equivalent to 0.4 ± 0.2 mm/yr of global SLR, during the period 2002-2005, with most of this loss from the WAIS. The EAIS exhibits the smallest range of variability among recent mass balance estimates (Table 3), however losses from the WAIS more than offset any growth occurring in the EAIS, leading to a net loss for the AIS as a whole. Thus most of the dynamic changes in the AIS are driven by losses in the WAIS.

Rignot (2006), with Advanced Land Observation System Phased-array Synthetic-Aperture Radar (ALOS PALSAR) data, has pointed out that pronounced regional warming in the Antarctic Peninsula has triggered an ice shelf collapse, and in turn leading to a 10-fold increase in glacier flow and rapid ice sheet retreat. In West Antarctica, the Pine Island Bay sector is draining far more ice into the ocean than is stored upstream from snow accumulation. This sector alone could raise sea levels by 1m and trigger widespread retreat of ice in West Antarctica.[17] Its neighboring Thwaites Glacier is widening and may double its width when the weakened eastern ice shelf breaks up. Widespread acceleration in this sector may be caused by glacier un-grounding from ice shelf melting by an ocean that has recently warmed by 0.3°C. In contrast, glaciers buffered from oceanic change by large ice shelves have only small contributions to sea level.[18]

At present, many glaciers in East Antarctica are close to a state of mass balance, but sectors grounded well below sea level, such as Cook Ice Shelf, Ninnis/Mertz, Frost and Totten glaciers, are thinning and losing mass. Hence, East Antarctica is not immune to changes.

Vaughan (2006) has noted that long-term records from meteorological stations on the Antarctic Peninsula show strong rising trends in the annual duration of melting conditions. In each case, the trend is statistically significant and represents a major increase in the potential for melting. For example, between 1950 and 2000 records from the Faraday/Vernadsky Station indicated a 74% increase in the number of positive degree-days. A simple parameterization of the likely effects of the warming on the rate of snow melt suggests an increase across the Antarctic Peninsula ice sheet from 28 ± 12 Gt/yr in 1950, to 54 ± 26 Gt/yr by 2000. Given a similar rate of warming over the next 50 years this may reach 100 ± 46 Gt/yr, a figure comparable to current loss estimates of the GIS.

Recently, Rignot et al. (2008) used satellite interferometric synthetic-aperture radar observations covering 85% of Antarctica's coastline to estimate the total mass flux into the ocean from 1992 to 2006. The mass fluxes from large drainage basin units were compared with interior snow accumulation calculated from a regional atmospheric climate model for 1980 to 2004. According to these estimates, in East Antarctica, small glacier losses in Wilkes Land and glacier gains at the mouths of the Filchner and Ross ice shelves combine to a near-zero loss of 4 ± 61 Gt/yr; but in West Antarctica, widespread losses along the

Bellingshausen and Amundsen seas increased the ice sheet loss by 59% in 10 years to reach 132 ± 60 Gt/yr in 2006. In the Peninsula, losses increased by 140% to reach 60 ± 46 Gt/yr in 2006.

Although it is difficult to predict the fraction of ablation that will become runoff, a calculation based on an established criterion for runoff indicates that the contribution from the Antarctic Peninsula, as a direct and immediate response to climate warming is significant, equivalent to (0.008–0.055) mm/yr of global sea level rise. Given future warming this could easily increase in the coming 50 years. This contribution due to increased runoff could be augmented by any dynamic imbalance in the glaciers draining the ice sheet. This finding appears to contradict the conclusions of previous assessments, including the IPCC, which considered the contribution of runoff from Antarctica to sea level rise would be insignificant.

5 Other Projections of SLR

In light of the recent evidence on the vulnerability of Greenland and West Antarctic Ice Sheets to climate warming, the conservative IPCC projections have been criticized by a number of researchers, even by other members within the IPCC (Solomon et al., 2008). Much of the debate surrounds the exclusion of dynamical changes in the ice sheets which tend to produce much larger impact estimates. According to the IPCC, until sufficient research evidence accumulates in this area, these uncertainties are too large to warrant inclusion in their predictions used for policy.

Hansen (2006, 2007) has been particularly vocal of the IPCC for its neglect of potential "ice sheet disintegration" in projections of SLR, which have remained relatively small until past few years. Due to the nonlinearity of the ice disintegration it is difficult to accurately predict the sea level change on a specific date, however the process is bounded by thresholds and once crossed, may trigger many meters of SLR well before the end of this century.

The largest uncertainties are with respect to the multiple feedbacks occurring on and under the ice sheets and in the nearby oceans that accelerate the process of ice sheet disintegration. For example, a key feedback of the ice sheets is the 'albedo flip' that occurs when snow and ice begin to melt. Snow-covered ice reflects most of the sunlight back to space however as warming causes increased melting on the surface, the darker wet ice absorbs much more solar energy. Most of the resulting melt water burrows through the ice sheet, lubricates its base, and speeds the discharge of icebergs to the ocean (Zwally et al., 2002). Satellite images of the Greenland ice sheet has revealed the appearance of large melt water pools on the ice surface in recent years (Moore, 2007). In a study which combined satellite-derived estimates of Arctic sea-ice age and thickness to produce a proxy ice thickness record for 1982 to the present, revealed a much-reduced extent of the oldest and thickest ice[19], leading to an enhanced risk of ice-albedo feedback in Arctic (Maslanik et al., 2007).[20]

Even with these dynamic uncertainties recent satellite observations point to accelerating trends in the rates of change among the contributors of SLR. Rahmstorf et al. (2007a) note that since 1990 the sea level has been rising faster than that projected by most climate models. Satellite data show a linear trend in SLR of 3.3mm/year over the period 1993-2006, whereas previous predictions by the IPCC (2001) projected a best estimate rise of less than 2mm/year.

An alternative to the IPCC AR4 SLR approach pioneered by Rahmstorf (2007b) estimates sea level rise indirectly from changes in global average near surface temperature, one of the more accurate variables in CGCMs. This semi-empirical technique estimates sea level rise based on changes in global average temperature and sea level between 1880 and the present. A proportionality constant of 3.4 mm/yr/ °C was computed from data on global SLR and global mean surface temperature for the 20th century. This proportionality constant applied to IPCC AR4 emission scenarios resulted in a projected SLR in 2100 of 0.5 to 1.4 meters above the 1990 level. Using a wider range of CGCM models, Horton et al. (2008)

update Rahmstorf's results and produce a broader range of sea level rise projections, especially at the higher end than outlined in the IPCC AR4. They predict sea level rise increases between 0.54 – 0.89m with a mean of 0.71m by 2100, however they admit that this does not include possible dynamic changes in the ice sheets.

Further support for the upper end of these results has been found by others using different techniques. For example, Pfeffer et al. (2008) explore kinematic scenarios of glacier contributions to sea level rise in the 21st century by setting 2m and 5m SLR targets and compare current loss rate evidence to see whether these objectives can be achieved. They find that a total SLR of about 2 meters by 2100 could occur under physically possible glaciological conditions but only if all variables are quickly accelerated to extremely high limits. More plausible but still accelerated conditions lead to total sea-level rise by 2100 of about 0.8m. They suggest that this estimate be a starting point for forecast refinements, but the range of 0.8 – 2.0m still remains a possibility with the inclusion of ice flow dynamics.

In the absence of our complete understanding of the processes that control ice sheet behavior and the shortage of observations characterizing how glaciers and ice sheets respond to changes in the climate, scientific inference can also be drawn from paleo-climatic changes. Paleo-climatic information indicates that the warming of the last half-century is unusual in, at least, the past 1300 years. The last time the Polar Regions were significantly warmer than the present for an extended period of time was about 125,000 years ago. Otto-Bliesner et al. (2007) used a global climate model, a dynamic ice sheet model, and paleo-climatic data to evaluate warming in the Northern Hemisphere and its impact on the Arctic ice fields during the Last Interglaciation (LIG, ~116,000 – 130,000 years ago). Their simulated climate matches paleo-climatic observations of past warming, and the combination of physically based climate and ice-sheet modeling with ice-core constraints indicates that the Greenland Ice Sheet and other circum-Arctic ice fields likely contributed 2.2 to 3.4 meters of sea-level rise during the LIG. Overpeck et al. (2006) using a similar method conclude that under a business-as-usual scenario, similar areas of Greenland could melt under the warmer environment, raising sea level by several meters by the end of the 21st century.

6 Conclusion

The IPCC AR4 report identifies several major factors that currently contribute to sea-level rise (SLR): 1) ocean thermal expansion, 2) changes in glaciers and icecaps, 3) glacial melt from the Greenland and Antarctica Ice Sheets, and 4) smaller contributions from terrestrial storage, snow on land and permafrost. Anthropogenic warming and SLR will continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized. There appears to be a consensus across studies that global sea level is projected to rise during the 21st century at a greater rate than during the period 1961 to 2003 and unanimous agreement that SLR will not be geographically uniform.[21] Ocean thermal expansion is projected to contribute significantly, and land ice will increasingly lose mass at an accelerated rate. But most controversial are the mass balance loss estimates of the Greenland and Antarctic Ice Sheets and what the yet un-quantified dynamic processes will imply in terms of SLR.

The IPCC AR4 report predicted increased global SLR between 0.18m and 0.59m across various emission scenarios over the next 100 years. However, this range has been cast in doubt by many experts as being too conservative and not adequately reflecting uncertainty (Oppenheimer et al., 2008; Pfeffer et al., 2008; Solomon et al., 2008). New data on rates of deglaciation in Greenland and Antarctica suggest greater significance for glacial melt, especially due to the uncertainty surrounding the dynamics of outlet glaciers (Helsen et al., 2008; Joughin et al., 2008; Kohler et al., 2007; Rignot, 2008; Van de Wall et al., 2008). Although there is continued evidence of ice sheet growth in the Eastern regions of Antarctica (Davis et al., 2005; Helsen et al., 2008; Ramillien et al., 2006; Rignot and Thomas, 2002; Velicogna and Wahr, 2006a; Zwally et al., 2005), when coupled with the measured losses in the West, and including Greenland, the evidence appears to point in the direction of increased SLR. The implications of these recent observations for sea-level rise could be dramatic: the Greenland and Antarctic ice sheets contain enough water to raise the sea level by almost 70m, so even small changes in their volume would have a significant effect. If the Greenland ice sheet were to melt completely, it would raise average sea level by approximately 7 meters.

Paleo-climatic information also indicates that the warmth of the last half-century is unusual in at-least the past 1300 years. The last time the Polar Regions were significantly warmer than at present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 - 6 meters of sea level rise (IPCC, 2007). As new research of the impacts of warming come in, we will be able to have more confidence in the ranges of impact, but current evidence leads to an alarming possibility that a threshold triggering many meters of sea level rise could be crossed well before the end of this century (Hansen, 2006; Overpeck et al., 2006).

Impacts of SLR on storm surge height

The implications of sea level rise are not only long-term in nature. A commonly held belief is that since sea level rise is rather slow and gradual, society has enough time to adapt to these new realities and thus immediate alarm is not warranted. However even small changes in sea level rise have a profound implication on the impact of storm surges, which occur annually and typically with devastating consequences on coastal areas.[22] Sea level rise basically acts as the baseline reference point to which storm surge height is added. If the baseline rises at a faster rate than what was originally believed (or invested upon), storm surges become even more unpredictable in their damage capability.

The IPCC AR4 suggested that, globally, estimates of the potential destructiveness of hurricanes/ cyclones show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity, and such trends are strongly correlated with tropical sea surface temperature. Based on a range of model projections, the report states that it is likely (greater than 66% probability) that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation associated with ongoing increases of tropical sea surface temperatures (IPCC, 2007). A recent IWTC statement[23] has also asserted that "…if the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase" and "…it is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperature." Given the consensus of an ever increasing temperature, the severity of storm surges is one aspect of climate change that countries will have to contend with even in the short-term.

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Appendix 1 — Source of Data on Major Contributory Factors to SLR

Ocean Thermal Expansion

Estimates of change in global mean temperature and sea level rise due to thermal expansion are usually made using climate models; and AOGCMs have been shown to be the most satisfactory way of estimating ocean thermal expansion (Gregory, 1993; Cubasch et al., 1994; Bryan, 1996; Jackett et al., 2000; Russell et al., 2000; Gregory and Lowe, 2000). The advantage of using such models is the models include dynamical components describing atmospheric, oceanic and land surface processes, as well as sea ice and other components. There are now over 20 AOGCMs from different centers available for climate simulations.[24],[25]

Greenland Ice Sheet, Antarctic Ice Sheet

Standard techniques used to measure the mass balance of large ice masses are as follows:

- The mass budget approach compares input from snow accumulation with output from ice flow and melt water runoff
- Repeated altimetry measures surface elevation changes
- Temporal variations in gravity over the ice sheets reveal mass changes
- Changes in day length and in the direction of the Earth's rotation axis also reveal mass redistribution.

The mass budget approach:

- Snow accumulation is often estimated from annual layering in ice cores, with interpolation between core sites using satellite microwave measurements or radar sounding. Increasingly, atmospheric modeling techniques are also applied.
- Ice discharge is calculated from radar or seismic measurements of ice thickness, and from in situ or remote measurements of ice velocity, usually where the ice begins to float and velocity is nearly depth-independent. A major advance in recent years has been widespread application of Interferometric Synthetic Aperture Radar (InSAR) techniques from satellites to measure ice velocity over very large areas of the ice sheets. Calculation of mass discharge also requires estimates for runoff of surface melt water. Surface melt amounts usually are estimated from modeling driven by atmospheric re-analyses, global models or climatology, and often calibrated against surface observations where available.
- However, ice sheet mass inputs and outputs are difficult to estimate with high accuracy. Although broad InSAR coverage and progressively improving estimates of grounding-line ice thickness have substantially improved ice discharge estimates, incomplete data coverage implies uncertainties in discharge estimates of a few percent. Glacier velocities also can change substantially, sometimes in months or years, adding to the overall uncertainty of mass budget calculations.

Repeated altimetry measures surface elevation changes:

- Surface elevation changes reveal ice sheet mass changes after correction for changes in depth-density profiles and in bedrock elevation, or for hydrostatic equilibrium if the ice is floating.

Satellite radar altimetry (SRALT) has been widely used to estimate elevation changes together with laser altimetry from airplanes and from the Ice, Cloud and land Elevation Satellite (ICESat). Modeled corrections for isostatic changes in bedrock elevation are small (a few millimeters per year), but with uncertainties nearly as large as the corrections in some cases. Corrections for near-surface firn density changes are larger and also uncertain.

- Radar altimetry has provided long-term and widespread coverage for more than a decade.

Temporal variations in gravity over the ice sheets reveal mass changes:

- Since 2002, the GRACE satellite mission has been providing routine measurement of the Earth's gravity field and its temporal variability. After removing the effects of tides, atmospheric loading, etc., high-latitude data contain information on temporal changes in the mass distribution of the ice sheets and underlying rock. Estimates of ice sheet mass balance, however, are sensitive to modeled estimates of bedrock vertical motion, primarily arising from response to changes in mass loading from the end of the last ice age.)

Other Methodologies:

- Data on changing length of day from eclipse records, the related ongoing changes in the spherical-harmonic coefficients of the geo-potential, and true polar wander also reveal mass redistribution. At present, unique solutions are not possible from these techniques, but hypothesized histories of ice sheet changes can be tested against the data for consistency, and progress is rapidly being made.

Glaciers and icecaps (not immediately adjacent to Greenland and Antarctic ice sheets)

Although written reports (and records) of glacier length changes go far back as 1600 in a few cases; records of directly measured glacier mass balances are few and stretch back only to the mid-20th century. Because of the very intensive fieldwork required, these records are biased towards logistically and morphologically 'easy' glaciers. Uncertainty in directly measured annual mass balance is typically ± 200 kg / m2 /yr due to measurement and analysis errors (Cogley, 2005).

Mass balance data are archived and distributed by the World Glacier Monitoring Service (WGMS(ICSI-IAHS), various years-b). From these and from several other new and historical sources, quality checked time series of the annual mean specific mass balance (the total mass balance of a glacier or ice cap divided by its total surface area) for about 300 individual glaciers have been constructed, analyzed and presented in three databases (Ohmura, 2004; Cogley, 2005; Dyurgerov and Meier, 2005). Recent findings from repeat altimetry of glaciers and ice caps in Alaska and Patagonia have also been incorporated in these databases.

Snow on land

The premier data set used to evaluate large-scale snow covered area dates to 1966, and is the weekly visible wavelength satellite maps of northern hemisphere snow cover produced by the US National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite Data and Information Service (NESDIS; Robinson et al., 1993). Trained meteorologists produce the weekly NESDIS snow product from visual analyses of visible satellite imagery. These maps are well validated against surface observations, although changes in mapping procedures in 1999 affected the continuity of data series at a small number of mountain and coastal grid points. For the southern hemisphere, mapping of snow covered area began only in 2000 with the advent of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data.

Since 1978, space-borne passive microwave sensors offer the potential for global monitoring of not just snow cover, but also snow depth and "Snow Water Equivalent", unimpeded by cloud cover and winter darkness.

Permafrost

The source of information on permafrost temperature is monitored data. Systematic permafrost temperature monitoring started in northern Alaska in the 1940s, in Russia in the 1950s, in northern Canada in the early 1980s, in the Tibetan Plateau in the late 1980s, and in Europe in the 1990s.

Appendix 2 —
The Emission Scenarios of the IPCC Special Report

In 1992 the IPCC released emissions scenarios to be used for driving global circulation models to develop climate change scenarios. The so-called IS92 scenarios were the first global scenarios to provide estimates for the full suite of greenhouse gases. Acknowledging the limitations of the first set of scenarios, the IPCC published a Special Report on Emissions Scenarios (SRES) in 2000 (IPCC, 2000) that form the basis of analyzing the impact of human demographic, economic, political and technological changes on future emissions. The SRES report supersedes the IS92 emission scenarios. To describe alternative activities the report consists of four major 'storylines' or scenarios that develop quantitative estimates of the socio-economic drivers of greenhouse and aerosol emissions, including factors such as population, GDP and technology and in turn emission scenarios. The purpose of these outputs is to provide a consistent input to both climate models and impact assessment models. To avoid any potential bias, the IPCC states that each group of scenarios is equally sound and thus do not attach any probability (or likelihood) to any one scenario.

The first group or family of scenarios (A1) feature a world with rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence between regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A1 is subdivided into A1FI (fossil-fuel intensive), A1T (high-technology), and A1B (balanced), with A1FI generating the most CO2 emissions and A1T the least. The A2 storyline and scenario family describes a more heterogeneous world, where the underlying theme is self-reliance and preservation of local identities. Convergence in fertility rates occurs very slowly across regions leading to an increasing global population. Economic development is regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The second group and family scenarios (B1) create a very different world from the A-series in terms of overall emissions intensity. This scenario describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. The last group, B2, describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It possesses continuously increasing global population at a rate greater than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Each storyline was fed into an integrated assessment climate model to predict future greenhouse gas emissions[26] and their ambient concentrations.

Endnotes

1. Satellite measurements since 1993 provide unambiguous evidence of regional variability of sea level change. Sea level changes do not occur uniformly across all areas of the world. The largest SLR since 1992 has taken place in the Western Pacific and Eastern Indian Oceans. Nearly all of the Atlantic Ocean shows SLR during the past decade, while sea levels in the Eastern Pacific and Western Indian Oceans are falling (IPCC 2007).

2. Despite its conservative projections, the IPCC (2007) asserted that, "Paleo-climate information supports that the warmth of the last half century is unusual in at-least the previous 1300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4-6 meters of sea level rise."

3. As seawater warms up, it expands, increasing the volume of the global sea level and thermosteric SLR.

4. The contribution of terrestrial storage (e.g., water stored in the ground, lakes and reservoirs) is difficult to estimate with confidence as systematic information is not available for various regions of the world, and the interactions between SLR, aquifer withdrawals, lakes and reservoirs is mostly unknown. Thus terrestrial storage was omitted (IPCC, 2007). It is also important to note that changes in sea ice do not directly contribute to sea level change since the ice is already floating and displacing water, although it can contribute to salinity changes through the input of fresh water. Changes in the mass of ice shelves, which are already floating, can affect the flow of adjacent ice that is not floating, and thus can affect SLR indirectly (IPCC, 2007). Hence the sea level equivalent (SLE) of sea ice, ice shelves and seasonally frozen ground is approximately zero (Lythe et al., 2001; Zhang et al., 2003).

5. Approximately 360 Gt of ice = 1 mm of sea level equivalent.

6. Smaller contributors have been omitted.

7. This difference indicates a deficiency in current scientific understanding of sea level change and may imply an underestimate in projections (IPCC, 2007).

8. A recent analysis of the steric and ocean mass components of sea level, however show that the sea level rise budget for the period January 2004 to December 2007 can be closed. Using corrected and verified Jason-1 and Envisat altimetry observations of total sea level, upper ocean steric sea level from the Argo array, and ocean mass variations inferred from GRACE gravity mission observations, it has been found that the sum of steric sea level and the ocean mass component has a trend of 1.5 ± 1.0 mm/a over the period, which is in agreement with the total sea level rise observed by either Jason-1 (2.4 ± 1.1 mm/a) or Envisat (2.7 ± 1.5 mm/a) within a 95% confidence interval (Leuliette and Miller, 2009).

9. See Appendix A for an explanation of methods.

10. Climate models are an imperfect representation of the earth's climate system and climate modelers employ a technique called ensembling to capture the range of possible climate states. A climate model run ensemble consists of two or more climate model runs made with the exact same climate model, using the exact same boundary

forcings, where the only difference between the runs is the initial conditions. An individual simulation within a climate model run ensemble is referred to as an ensemble member. The different initial conditions result in different simulations for each of the ensemble members due to the nonlinearity of the climate model system. Essentially, the earth's climate can be considered to be a special ensemble that consists of only one member. Averaging over a multi-member ensemble of model climate runs gives a measure of the average model response to the forcings imposed on the model.

11. In particular, many of the AOGCM experiments do not include the influence of Mt. Pinatubo, the omission of which may reduce the projected rate of thermal expansion during the early 21st century.

12. Ablation is the surface removal of ice or snow from a glacier or snowfield by melting, sublimation, and/or calving (ice sheering off to form icebergs).

13. As glacier volume is lost, glacier area declines so the ablation decreases.

14. A recent study of snow accumulation areas of glaciers and icecaps has concluded that, at present, observed accumulation areas are 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 forced 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 (Bahr et al., 2009).

15. Antarctic mass variability is difficult to measure because of the ice sheet's size and complexity. Standard estimates use a variety of techniques, each with intrinsic limitations and uncertainties.

16. IPCC AR3 suggested a SLR of 0.09 to 0.88 m by the year 2100 unless greenhouse gas emissions are reduced substantially (IPCC, 2001).

17. The Pine Island Glacier loss accelerated 38% since 1975, and most of this occurred over the last decade. More recently this has increased to 42% and has become ungrounded over most of its ice plain from 1996 to 2007. The Smith glacier loss has also accelerated by 83% and is now ungrounded as well.

18. European Space Agency's ENVISAT images have detected new rifts on the Wilkins ice shelf in November, 2008. The Wilkins ice shelf has been stable for most of the last century and began retreating in the 1990s. In February 2008, an area of about 400 km2 broke off, between May and July, the ice shelf experienced further disintegration and lost 1,350 km2. The new rifts on the ice shelf could lead to the opening of an ice bridge which has been preventing the ice shelf from fully disintegrating and breaking away from the Antarctic peninsula (http://www.sciencedaily.com/releases/2008/11/081128132029.htm). If the ice shelf actually breaks away from the peninsula, it will not cause a rise in sea level since it is already floating, however it may allow ice sheets on land to move faster and adding new water to the seas.

19. The oldest ice types have essentially disappeared, and 58% of multiyear ice now consists of relatively young 2- and 3-year-old ice compared to 35% in the mid-1980s.

20. Arctic ice coverage in the summer of 2007 reached a record minimum, with ice extent declining by 42% compared to conditions in the 1980s. The much-reduced extent of the oldest and thickest ice, in combination with other factors such as ice transport that assist the ice-albedo feedback by exposing more open water, help explain this large and abrupt ice loss.

21. The emphasis on demonstrating a consensus in IPCC reports has put the spotlight on expected outcomes, generating a reliance on exact numbers in the minds of policy-makers. With the general credibility of the science of climate change established, it is now equally important that policy-makers understand the more extreme

possibilities that consensus may exclude or downplay (Oppenheimer et al., 2008).

22. In the last 200 years, at least 2.6 million people may have drowned due to storm surges and causing a range of other damages and disruptions (Nicholls, 2003). The tropical cyclone Sidr in Bangladesh in November 2007 and cyclone Nargis in the Irrawady Delta of Myanmar in May 2008 are recent reminders of the potentially devastating impacts of severe weather events and storm surges in less developed countries. According to the Bangladesh Disaster Management Information Centre (report dated Nov 26, 2007) 3,243 people were reported to have died and the livelihoods of 7 million people were affected by the tropical cyclone Sidr (http://www.reliefweb.int/rw/RWB.NSF/db900SID/EDIS-79BQ9Z?OpenDocument). In Mayanmar, 100,000 people were reported to have died and 1.5 million people were affected by Nargis (http://www.dartmouth.edu/%7Efloods/Archives/2008sum.htm).

23. International Workshop on Tropical Cyclones (IWTC).

24. Although the large-scale dynamics of these models are comprehensive, parameterizations are still used to represent unresolved physical processes such as the formation of clouds and precipitation, ocean mixing due to wave processes and the formation of water masses, etc. Uncertainty in parameterization is the primary reason why climate projections differ between different AOGCMs.

25. Estimates of change in global mean temperature and sea level rise due to thermal expansion can also be made with Simple Climate Models (SCMs) and Earth System Models of Intermediate Complexity (EMICs). SCMs represent the ocean-atmosphere system as a set of global or hemispheric boxes, and predict global surface temperature using an energy balance equation, a prescribed value of climate sensitivity and a basic representation of ocean heat uptake. Such models can also be coupled to simplified models of biogeochemical cycles and allow rapid estimation of the climate response to a wide range of emission scenarios. EMICs, on the other hand, include some dynamics of the atmospheric and oceanic circulations, or parametrizations thereof and often include representations of biogeochemical cycles, but they commonly have reduced spatial resolution. These models can be used to investigate continental-scale climate change and long-term, large-scale effects of coupling between Earths system components using large ensembles of model runs or runs over many centuries.

26. Included are anthropogenic emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), hydrochlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs), the aerosol precursor and the chemically active gases sulfur dioxide (SO2), carbon monoxide (CO), nitrogen oxides (NOx), and non-methane volatile organic compounds (NMVOCs).

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