Chapter 8

Projections into the future

Over the past few decades, public awareness and the degree of scientific research regarding future climatic changes and its effects on social and economic life have increased. In addition to the impact on availability of freshwater systems from changes in glacial runoff, there are other compounding factors, including demographic, societal, and economic developments, that should be considered when evaluating the impacts of mountain deglaciation and climate change (Kundzewicz et al., 2007). For example, increased annual runoff can produce benefits in some areas as the renewable water resources increase, but may simultaneously generate hazards as the flood risk increases. An increase in runoff could also affect areas with a shallow watertable, as a rise in the watertable could disturb agricultural use and damage buildings in urban areas (Kundzewicz et al., 2007). Thus, climate change, often referred to as 'global warming', has caused much speculation about the effect that increased rates of deglaciation will have on global sea level. This research is especially important to countries where a large proportion of the population inhabit areas that are only marginally above sea level (e.g. Bangladesh, the Netherlands, the Bahamas, etc.). Consequently, a variety of approaches have been used to forecast the glacier and ice sheet response to the anticipated 21^{st} century climatic changes, at both local and global scales.

In the IPCC (2001) report, estimates of total future sea-level changes, based on a range of AOGCM experiments, indicate a rise of between 110 to 770 mm by the end of this century and a substantial part (between 50 and 110 mm) is attributed to the melting of mountain glaciers. This estimate accounts for the change in glacier area with time and it excludes the glaciers and ice caps at the periphery of the Antarctic and Greenland ice sheets. The latest IPCC (2007b) report further noted that the contribution to global sea-level rise from mountain glaciers will be substantial for the rest of this century. On the basis of various studies on individual glaciers (in particular the studies of Oerlemans and Fortuin, 1992; Dyurgerov and Meier, 2000; Braithwaite and Raper, 2002; Oerlemans, 2005; Raper and Braithwaite, 2005, see first half of Table 8.1), Collins et al. (2007) concluded in the IPCC (2007b) report that the total global surface mass balance sensitivity of mountain glaciers to global average temperature change is equivalent to a sea-level rise of 0.49±0.13 (using the mass balance sensitivity for a uniform temperature change derived by Oerlemans, 2001; Oerlemans et al., 2005) and 0.61±0.12 mm year^{-1} K^{-1}(using the mass balance sensitivity for a uniform temperature change derived by Zuo and Oerlemans, 1997a). The actual rise in sea level is therefore dependent on the climate (in particular temperature) model used but a first order estimate of the effect this would have on sea level can be made by assuming a global temperature increase of 3 K by 2100, which is likely according to the IPCC (2007b) report. The above mentioned mass balance sensitivities then correspond to a predicted ice loss equivalent to over 150 mm global sea-level rise by 2100, from mountain glaciers alone.

A selection of representative estimates from various authors for the glacier contribution to sea-level rise is listed in Table 8.1. These studies focus on the contribution of glaciers and smaller ice caps using a variety of methods to obtain predictions for future changes; some are discussed in more detail later in the chapter. The considerable range in magnitude of the future predictions using a variety of different methods demonstrates the difficulty in determining accurate estimates. This is not particularly surprising, as the estimates from numerical modelling of recent mountain deglaciation (and corresponding sea-level changes) are also variable to some degree (see Chapter 3). This is mainly because glaciers are highly sensitive to climatic parameters such as temperature and precipitation, which are poorly known in some regions.

It has been demonstrated in earlier chapters that the predicted ice-volume loss and the modelled corresponding geodetic signals are in agreement with observational data over recent periods, possibly not so much in detail but on a broader scale and within the uncertainty range. Thus, using the approach of deriving ice-volume changes of mountain glaciers, i.e. the model developed in Chapter 2 including the required climate models introduced and assessed there, is believed to be an adequate way to make good projections for the future contribution to global sea-level rise.

Reference	m year^{-1} K^{-1}	period	mm
Oerlemans and Fortuin (1992)	−0.40		
Dyurgerov and Meier (2000)	−0.37		
Braithwaite and Raper (2002)	−0.41		
Oerlemans et al. (2005)	−0.32		
Raper and Braithwaite (2005)	−0.35		
Gregory and Oerlemans (1998)		1990-2100	132
Van de Wal and Wild (2001)		70 years	57
Raper and Braithwaite (2006)		by 2100	117
Meier et al. (2007)		by 2100	100-250 [a]
IPCC (2001)		1990-2090	50-110
IPCC (2007b)			0.49 [b] 0.61 [b]

[a] estimate includes independent glaciers at the periphery of the Antarctic and Greenland ice sheets

[b] expressed in mm year^{-1} K^{-1} global sea-level rise (for a global temperature increase of 3 K this corresponds to about 150 mm global sea-level rise) these numbers are derived from different mass balance sensitivities (of Oerlemans, 2001; Oerlemans et al., 2005; Zuo and Oerlemans, 1997a) for a uniform temperature change

Table 8.1: List of studies dealing with predicted sea-level rise as a result of future mountain deglaciation estimated over various periods. Results are expressed in m year^{-1} K^{-1} of mass balance sensitivity to temperature changes or in mm of global sea-level rise over a given time period.

Firstly however, to obtain accurate future projections it is important to know how much ice is stored in mountain glaciers at present because it is a finite volume and will eventually be exhausted by continued melting. Raper and Braithwaite (2005) estimated the potential sea-level rise from mountain glaciers. In their analyses they separated between *glaciers* and *small ice caps* with areas of 401,000 and 121,000 km^2, respectively (not including glaciers around the Antarctic and Greenland ice sheets). The relationship between areas and volumes of glaciers developed in Raper and Braithwaite (2005) results in an ice mass stored in glaciers and small ice caps of $36 \pm 8 \times 10^3$ and $52 \pm 4 \times 10^3$ km^3 equivalent water, respectively, corresponding to 99±23 and 142±12 mm global sea-level change. Consequently, glaciers and small ice caps have the potential to contribute 241±26 mm to global sea-level rise, of which 41% comes from glaciers and 59% from small ice caps. Since the total area of glaciers and small ice caps in Raper and Braithwaite (2005) is comparable to that defined for mountain glaciers in this thesis, the total volume derived in Raper and Braithwaite (2005) will be used for further assessment below.

Predictions of future ice-volume changes and associated relative sea-level changes using the deglaciation model developed in Chapter 2 are presented below. In addition, the estimates derived here at global and regional scales are assessed by comparing them with results of other studies.

8.1 Projected ice-volume changes and geodetic signals by 2100

Section 3.2 demonstrated that the numerical model of recent mountain deglaciation developed in Chapter 2 is able to reproduce recent observational estimates (e.g. Dyurgerov and Meier, 2005), as is illustrated in Figure 8.2 (orange highlighted area). The same approach is now used here to make predictions of future ice-volume changes. Temperature and precipitation predictions up to 2100 provided by Siobhan O'Farrell (see Sections 2.3.3 and 2.3.4) are used in the following modelling. Figure 8.1 shows expected temperature and precipitation changes during this century and the curves illustrate that they are projected to increase with a possible acceleration towards the end of the 21^{st} century. For precipitation rates, time series of annual precipitation rates ($P_{OFseries}$) are used (see Section 2.3.3 for details). The initial imbalance Θ between glacier and climate state is applied in different ways to create two parameter settings: *(A)* a globally uniform Θ of 0.15 K is used and *(B)* regionally variable Θs (see Section 3.1.5) are used with a revised value for Θ of 0.50 K in Alaska in order to match the observational estimates there (as was concluded in the previous chapter).

Predicted cumulative ice-volume changes in the 21^{st} century for the two scenarios mentioned above are shown in Figure 8.2 (yellow highlighted area). In total, these changes are equivalent to a eustatic sea-level rise of 162 and 177 mm, respectively, over the period 2001-2100. This demonstrates that the total contribution to global sea-level rise is sensitive only to a small extent to different initial parameter settings. According to these results and the estimate of current glacier mass by Raper and Braithwaite (2005), up to 70% of the total ice mass stored in mountain glaciers will be gone by 2100.

The results presented above are mainly dependent on how the temperature and precipitation conditions in the glaciated regions change, and how accurately they can be projected into the future for use in the climate models. Furthermore, this approach needs to be treated with caution as (i) changes in glacier area with time and (ii) rapid dynamic changes resulting in glacier instabilities are not considered. Neglecting to take (i) into account would generally overestimate the result, whereas ignoring (ii) underestimates the mass loss of glaciers. However, it is difficult to estimate the extent to which these two effects cancel each other out.

Estimates of changes in glacier area (and associated volume changes) can be calculated for individual glaciers assuming the area-volume relationship $V = 0.0285 \times S^{1.357}$ of Chen and Ohmura (1990, see also Section 2.3.1). For example, a glacier at the Seward Peninsula (Alaska), with a predicted average ice-volume loss of 0.0064 km^3 year^{-1} w.e. over the first decade of the 21st century and an initial area of 10 km^2, would be mostly melted by 2050 (see Table 8.2). A glacier in the St. Elias Mountains (Alaska), with an average ice-volume loss of 0.0905 km^3 year^{-1} w.e. predicted over the period 2001-2010 and an area of 100 km^2, would only just survive until 2070. The predicted ice-volume loss at the Svalbard archipelago of 0.0050 km^3 year^{-1} w.e. indicates that glaciers with an area of 10 km^2 or smaller are unlikely to survive the 21st century (Table 8.2). In summary, only glaciers with an initial area of the order of a few hundred km^2 are likely to survive this century, while all smaller glaciers will probably disappear by 2100 or earlier according to the melting rates predicted here.

glacier	**Seeward**	**St. Elias Mountains**	**Svalbard Archipelago**	**Svalbard Archipelago**
initial area	10 km^2	100 km^2	10 km^2	100 km^2
initial vol.	0.648 km^3	14.752 km^3	0.648 km^3	14.752 km^3
year				
2000	0	0	0	0
2010	−0.064	−0.905	−0.050	−0.498
2020	−0.171	−2.365	−0.096	−0.963
2030	−0.300	−4.205	−0.139	−1.388
2040	−0.438	−6.079	−0.195	−1.958
2050	−0.582	−8.022	−0.269	−2.695
2060	−0.785	−10.710	−0.352	−3.534
2070		−14.087	−0.450	−4.532
2080		−17.531	−0.548	−5.521
2090			−0.684	−6.760
2100				−8.011

Table 8.2: Ice-volume changes expressed in km^3 w.e. of glaciers in Alaska and Svalbard with predicted for particular years relative to 2000. The calculation is conducted using the area-volume relationship of Chen and Ohmura (1990) with different initial areas and volumes.

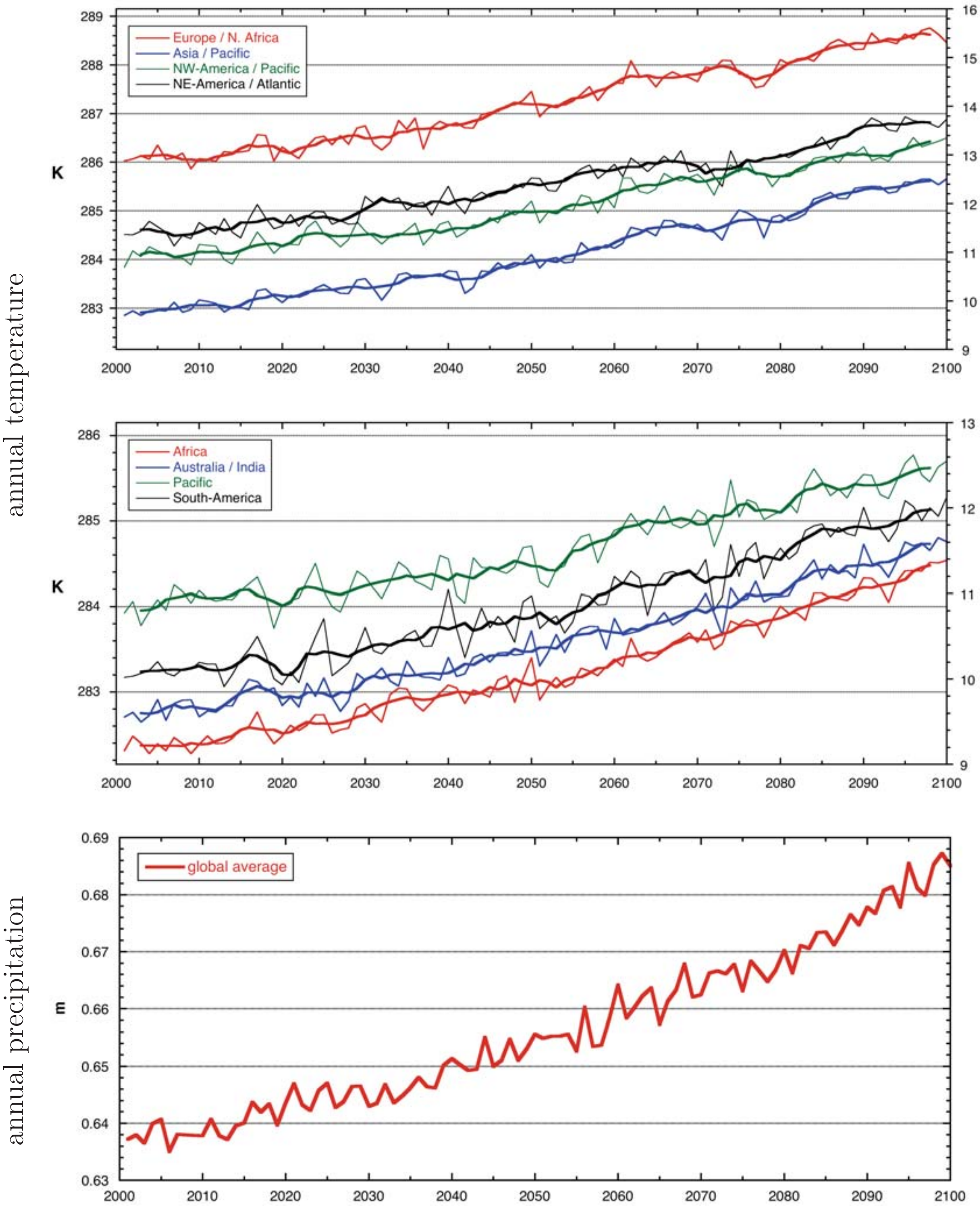

Figure 8.1: Annual temperature in K and annual precipitation in meter projected over the period from 2001 to 2100 (data provided by Siobhan O'Farrell). For illustration purposes, temperature is also expressed in °C and plotted on the right axis. Large-scale temperature variations are given for four sectors within both the northern and southern hemisphere (see Section 2.3.4.1) and precipitation is given on a global scale. The thick lines in the temperature plots are 5-year means.

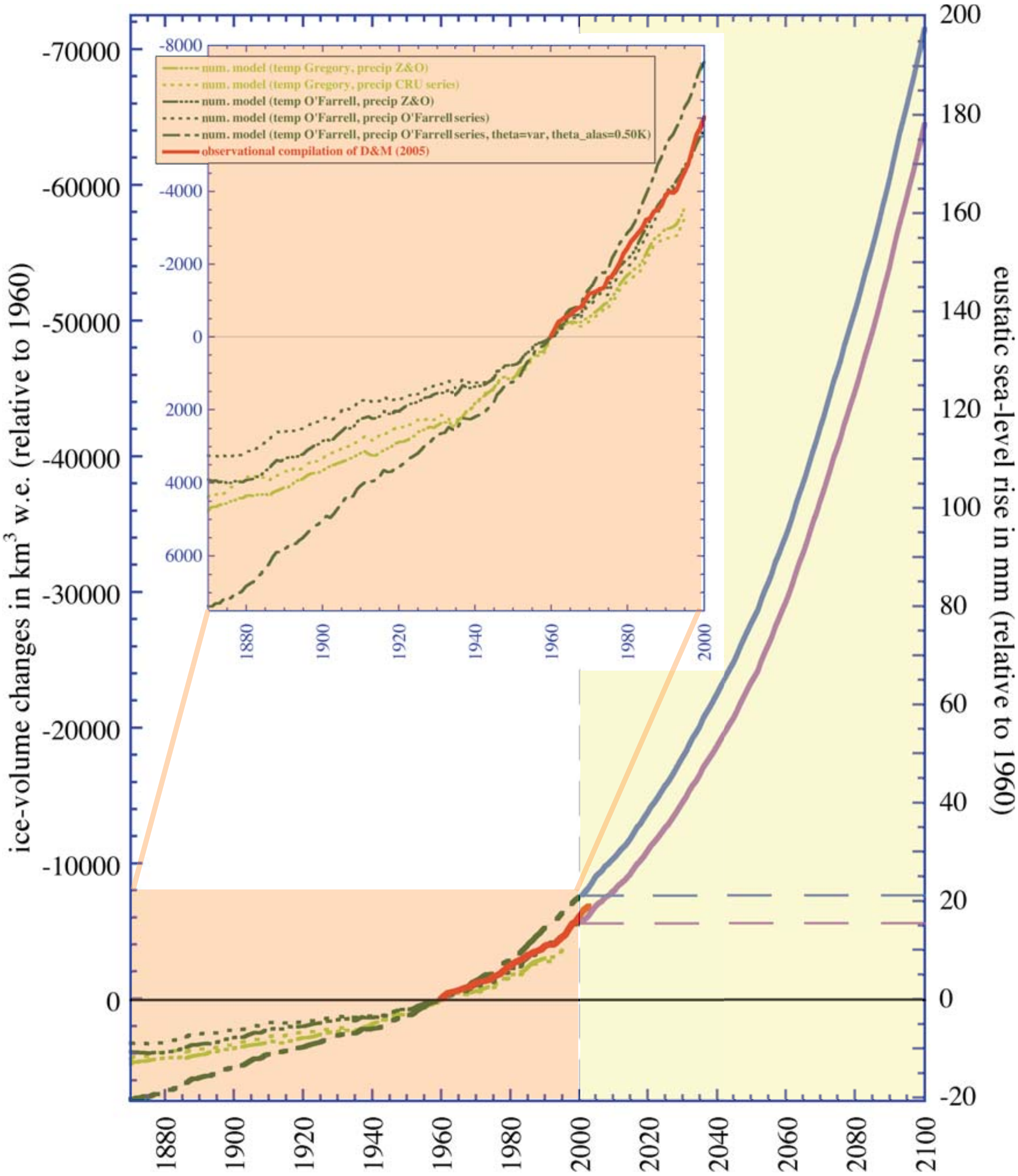

Figure 8.2: Global ice-volume changes (or equivalent global sea-level rise) relative to 1960 resulting from mountain deglaciation alone. Numerical estimates of this study for past changes (up to 2000) are plotted in green. The estimate of Dyurgerov and Meier (2005) is plotted in red. Projections of future ice-volume changes up to 2100 are derived from the numerical model based on $T_{OF}P_{OFseries}$ with a globally uniform Θ of 0.15 K in purple, and regionally variable Θs with $\Theta_{Alaska} = 0.50$ K in blue.

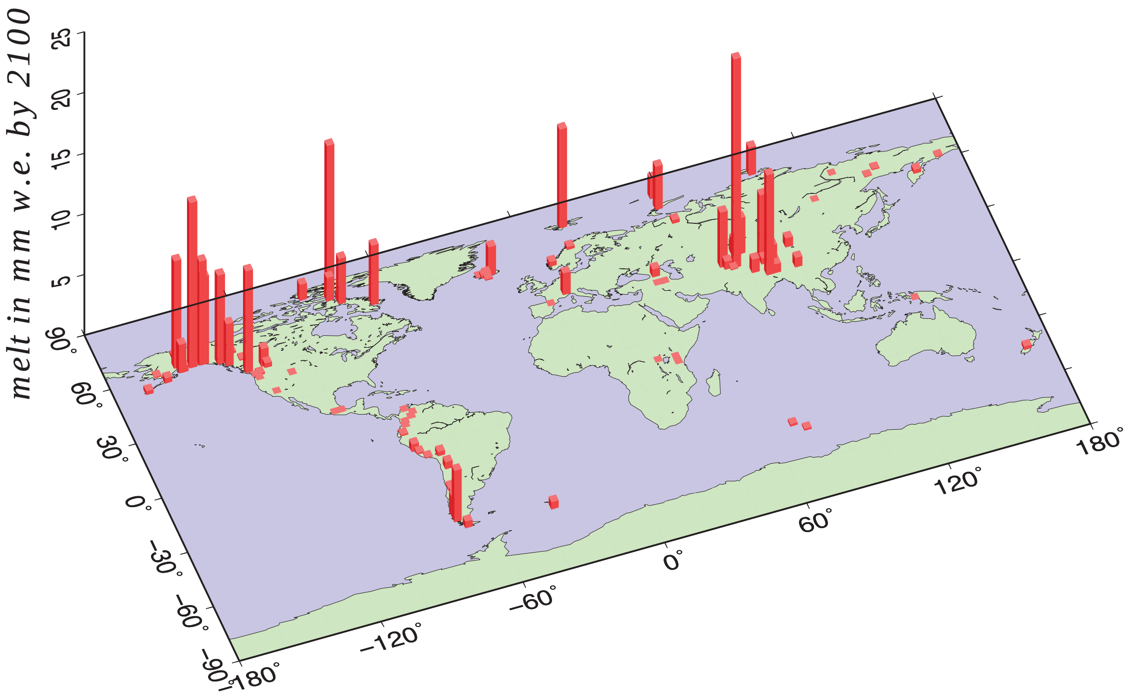

Figure 8.3: Estimates of ice-volume loss of 100 glaciated regions predicted over the period 2001-2100 in mm w.e. calculated from the numerical model based on $T_{OF}P_{OFseries}$ using regionally variable Θs and $\Theta_{Alaska} = 0.50$ K.

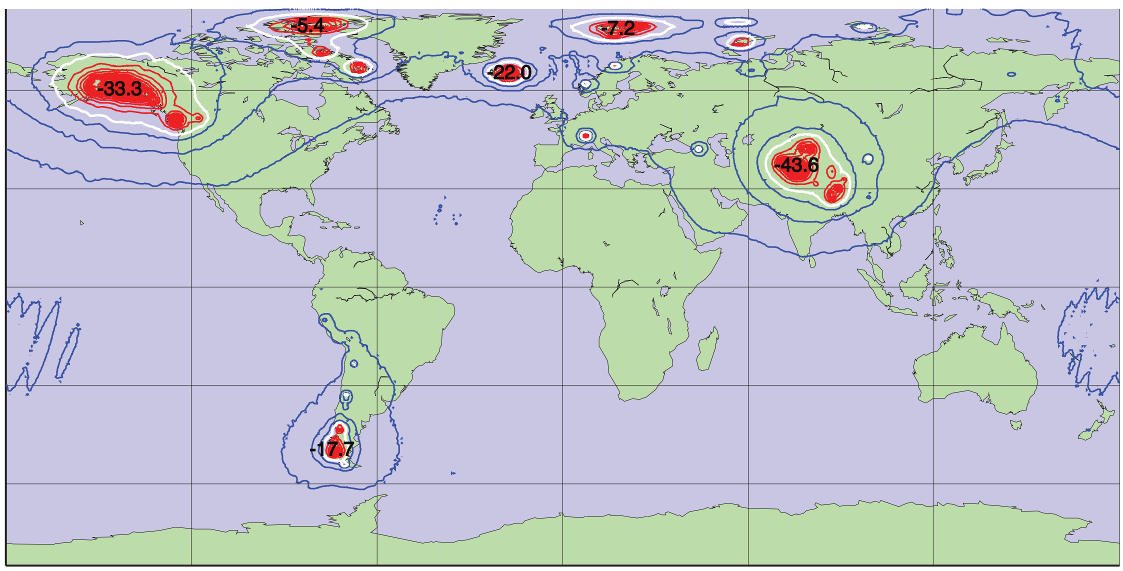

Figure 8.4: Spatial distribution of relative sea-level changes predicted over the period 2001-2100 in mm year^{-1} due to mountain deglaciation. Ice-volume changes are calculated from the numerical model based on $T_{OF}P_{OFseries}$ using regionally variable Θs and $\Theta_{Alaska} = 0.50$ K. Red contour lines represent relative sea-level fall (contour interval is 1 mm year^{-1}), blue contour lines represent relative sea-level rise (contour interval is 0.5 mm year^{-1}). White represents the zero contour line (no change). Numbers refer to local maxima in mm year^{-1}. Detailed plots of Alaska and Svalbard are shown in Figures 8.5 and 8.6, respectively.

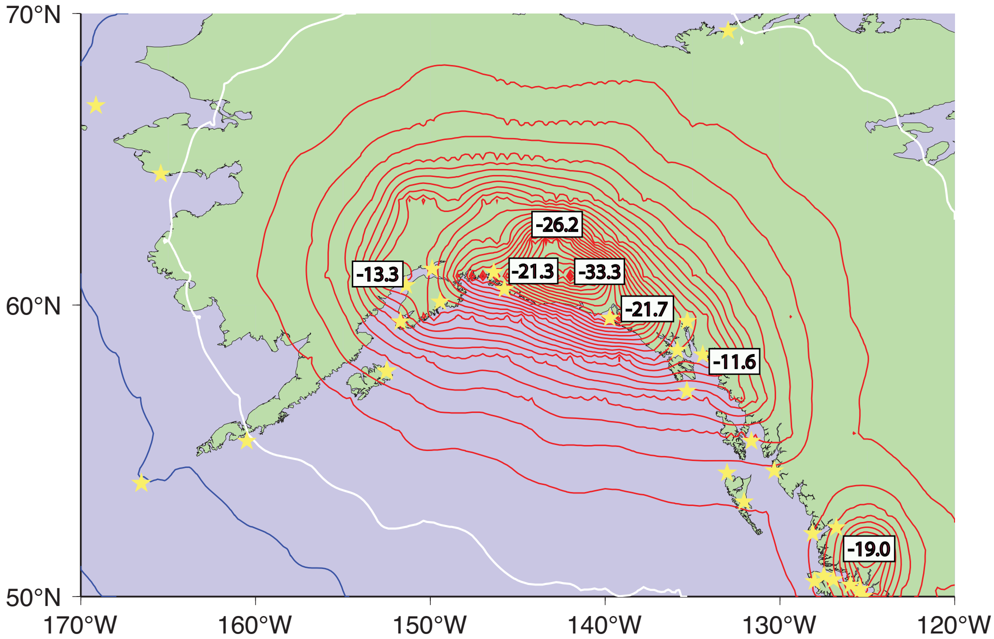

Figure 8.5: Spatial distribution of relative sea-level changes in Alaska predicted over the period 2001-2100 in mm year^{-1} due to mountain deglaciation. Ice-volume changes are calculated from the numerical model based on $T_{OF}P_{OFseries}$ using regionally variable Θs and $\Theta_{Alaska} = 0.50$ K. Red contour lines represent relative sea-level fall (contour interval is 1 mm year^{-1}), blue contour lines represent relative sea-level rise (contour interval is 0.5 mm year^{-1}). White represents the zero contour line (no change). Stars indicate the locations of tide gauge sites. Numbers refer to local maxima in mm year^{-1}.

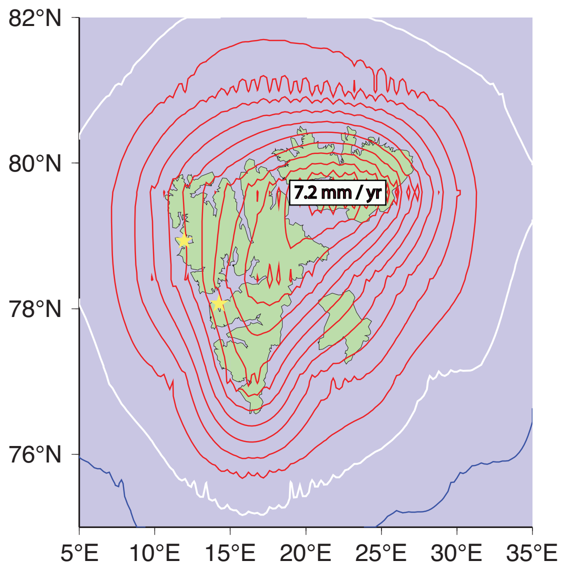

Figure 8.6: Spatial distribution of relative sea-level changes in Svalbard predicted over the period 2001-2100 in mm year^{-1} due to mountain deglaciation. Ice-volume changes are calculated from the numerical model based on $T_{OF}P_{OFseries}$ using regionally variable Θs and $\Theta_{Alaska} = 0.50$ K. Red contour lines represent relative sea-level fall, blue contour lines represent relative sea-level rise. The contour interval is 0.5 mm year^{-1}. White represents the zero contour line (no change). Stars indicate the locations of tide gauge sites. The number refers to the local maxima in mm year^{-1}.

Figure 8.3 shows the spatial distribution of the ice-volume loss during 2001-2100 predicted for 100 glaciated regions calculated from the numerical model based on $\mathrm{T}_{OF}\mathrm{P}_{OFseries}$ using regionally variable Θs and $\Theta_{Alaska} = 0.50$ K. According to this result North-West America, central Asia, and North-East America are the biggest contributors to the global estimate, accounting for 33%, 27%, and 14%, respectively. Glaciers on the archipelago of Svalbard alone contribute almost 5%.

Using these estimates of the spatial and temporal distribution of mountain deglaciation, the corresponding sea-level changes can be predicted. They are shown in Figure 8.4, with more detailed plots for Alaska and Svalbard in Figures 8.5 and 8.6, and are dominated by regional sea-level fall caused by isostatic uplift in response to deglaciation. Since the spatial distribution of projected future mountain deglaciation, like that of recent changes, is controlled by the locations of the glaciers, it is unsurprising that the corresponding global pattern of future relative sea-level changes is similar to that of past changes (compare Figure 8.4 and Figure 5.7). However, regional predictions of the changes are greater than at present by one order of magnitude. In particular, estimates of maximum local rates of geodetic signals from mountain deglaciation in Alaska and Svalbard may reach considerable values of -33.3 and -7.2 mm year^{-1}, respectively, over the course of this century. However, as existing tide gauge stations are located at some distance to the glaciated regions, the predicted rates at the stations do not exceed approximately -24 and -5 mm year^{-1}, respectively, for the two regions. Rates of relative sea-level rise at far-field sites (i.e. away from the melting glaciers) and open-ocean rates reach up to 2 mm year^{-1} averaged over the 21st century.

8.1.1 Global and regional comparisons

The predictions of mountain deglaciation outlined in the previous section are based on one particular approach. To evaluate whether this approach produces adequate representations of possible future ice-volume changes, they can be assessed by comparing them with results of other studies. For example, Gregory and Oerlemans (1998) estimated future glacier melt using the same approach as Zuo and Oerlemans (1997a) for recent mountain deglaciation, a model that accounts for regional and seasonal variations in climate. Gregory and Oerlemans (1998) used the atmosphere-ocean general circulation model HADCM2 from the Hadley Centre (Johns et al., 1997) and estimated a global glacier melt over the period 1990-2100 equivalent to a sea-level rise of 132 mm, 20-30% smaller than the projections derived in this thesis. Although their temperature model predicts a slightly higher global increase over the 21^{st} century (see Figure 1 in Gregory and Oerlemans, 1998) than the T_{OF} model (about 2.4 K), the temperature model used in Gregory and Oerlemans (1998) is expected to be superseded by the more recent model used in this thesis. In addition, the glacier-area weighted average temperature increase in T_{OF} for the 100 glaciated regions is high, i.e. ∼6 K over the 100-year period and is most likely the main reason for the higher estimates of ice-volume loss derived in this thesis compared to that of Gregory and Oerlemans (1998). Furthermore, Gregory and Oerlemans (1998) did not account for the initial imbalance between glacier and climate state and this is an additional reason for their smaller estimate. However, Gregory and Oerlemans (1998) concluded that the largest contribution to the total glacier melt comes from North-West America and central Asia, similar to the results determined here.

Van de Wal and Wild (2001) also used the seasonally and regionally differentiated glacier model to calculate the contribution to global sea level over a 70-year period. Additionally, they accounted for precipitation changes and the reduction in glacier area over time. They predicted a rise in global sea level of 57 mm over 70 years. This estimate is also slightly smaller than those derived here, partly for the same reason as for the Gregory and Oerlemans (1998) case, i.e. the temperature model used in Van de Wal and Wild (2001) increases globally by 2.7 K, which is greater than the global increase but considerably less than the area-weighted increase in T_{OF}. The numerical model used in this thesis generally does not account for changes in the glacial area and therefore may overestimate the total contribution to sea-level rise. However, there are some inconsistencies in the approach of Van de Wal and Wild (2001): they tuned the relationship between glacial area and volume to reach a total global ice volume equivalent to a sea-level rise of 0.5 m. However, the area Van de Wal and Wild (2001) used does not include glaciers at the periphery of the Antarctic and Greenland ice sheets and therefore the total volume assumed is too large. The implications for their results are unclear at this stage unless a complete reanalysis of their method is undertaken, which is outside the scope of this thesis. Despite these drawbacks the conclusion in Van de Wal and Wild (2001) that the contribution to sea-level rise from precipitation changes is negligible compared to the effect temperature changes has on the final ice-volume changes is supported by the results of this thesis. In particular, it was found that when considering variations in precipitation over time, the globally averaged predictions increase by ∼10%.

Braithwaite and Raper (2002) noted that there are four requirements for projecting future sea-level changes from glacier melt: (i) the global distribution of glacier areas, (ii) the temperature sensitivity of glacier mass balance in each region, (iii) the expected change of climate in each region, and (iv) changes in glacier geometry resulting from climate change. They discussed these issues in detail but found that none of these variables are well constrained at present. As projections of ice-volume loss (or equivalent sea-level rise) depend upon the chosen climate scenario, Braithwaite and Raper (2002) expressed their results in terms of mass balance sensitivity to a temperature change of 1 K. Their estimate of average global mass balance sensitivity of -0.41 m year^{-1} K^{-1} is similar to those of other studies (e.g. Oerlemans, 1993; Dyurgerov and Meier, 2000, see Table 8.1). A similar order of magnitude estimate can be calculated from the ice-volume loss derived in this thesis (i.e. ~170 mm w.e. over the period 2001-2100) and an assumed temperature increase over the same period of 2.4 K (global increase in the T_{OF} data set). The resulting mass balance sensitivity is -0.48 m year^{-1} K^{-1}, confirming the estimate derived by Braithwaite and Raper (2002).

A more recent study by Raper and Braithwaite (2006) estimated the melt contribution from mountain glaciers and ice caps separately and found that ice caps melt more slowly than glaciers. Their mass balance model takes into account the changes in glacier area with time and also allows the glaciers to reach equilibrium. The projected sea-level rise by 2100 resulting from the melting of glaciers and ice caps in Raper and Braithwaite (2006) is relatively low, i.e. 46 and 51 mm, respectively.

The most recent estimate of future sea-level contribution from glacier melt by Meier et al. (2007) predicts a rise of 100 to 250 mm by 2100. This estimate includes glaciers at the periphery of the Greenland and Antarctic ice sheets and thus cannot be directly compared to the previous estimates. In their model, the results of ice loss are driven by meteorology, by drawdown of the ice reservoir resulting from dynamic changes in glacier behaviour, and by terminus dynamics. They noted that dynamic changes of glaciers (in particular of tidewater glaciers) can happen noticeably faster than one would predict from surface mass balance estimates or climate-balance modelling. Their model does not include the change in glacier area with time, as they note that more than half of the total ice volume is stored in large glaciers with a thickness much larger than the projected thinning rates. Nevertheless, a large number of glaciers have a mean thickness of only a few tens of meters and are likely to disappear in this century, as was already concluded earlier in this chapter. Meier et al. (2007) noted that in terms of understanding the ice melt contribution to global sea-level rise, it is the glaciers and small ice caps, not the big ice sheets, that are most important today and will continue to be most important throughout this century.

On regional scales, the predictions of the numerical model derived in this thesis only partly agree with estimates of other studies. For example, Oerlemans et al. (2005) estimated the contribution of Arctic glaciers (including Canadian Arctic, Alaska, Iceland, Svalbard, Zemlya Frantsa Iosifa, Novaya Zemlya, Severnaya Zemlya, and Scandinavia) to future sea-level of about 22 mm over the 21^{st} century. For the same regions the ice-volume loss predicted in this thesis is 92 mm w.e. (see Table 8.3), approximately four times the estimate of Oerlemans et al. (2005). However, Oerlemans et al. (2005) showed that there are significant differences in the projections depending on the climate model used, i.e. the results range from -3 to $+56$ mm global sea-level rise over the 21^{st} century (note that these estimates include the contribution of the Greenland ice sheet). Hence, the projections of sea-level rise as a result of the melting of Arctic glaciers are strongly dependent on the climate model applied and this reason most likely outweighs any uncertainties resulting from the simplification of the approach used.

Furthermore, Oerlemans et al. (2005) noted that because of the difficulty of quantifying the initial imbalance between glacier and climate state they set this value to zero but they admit that increasing Θ to 0.50 K increases the total ice loss significantly. In addition, the mass balance sensitivities used in Oerlemans et al. (2005) are based on detailed studies of only a few glaciers, which are then extrapolated to derive regional estimates. Hence, it is unsurprising that their regional mass balance sensitivities (Table 1 in Oerlemans et al., 2005) are only partly in agreement with those determined in this thesis (see last column of Table 8.3). As has been demonstrated in earlier chapters, accounting for the imbalance parameter Θ is critical for estimating ice-volume losses accurately. Furthermore, it has been shown that it is very likely that the values for Θ vary regionally, and may be as high as or greater than 0.50 K for some systems. As this parameter setting has been considered in the predictions of this thesis, it can be concluded that the ice-volume loss derived here is sufficiently accurate to estimate the future contribution to sea-level rise.

Oerlemans et al. (2005) estimated that the contribution to global sea-level rise resulting from the glacial melting in Alaska will be approximately 12 mm over the 21^{st} century (again this is a result for one particular climate model). The best

	gl	area	dV	dT	sl	mm year^{-1} K^{-1}
Canadian Arctic >74°N	**1**	80,000	−4339.5	7.2	15.3	−64
	2	11,700	−485.7	6.8		
	3	16,200	−698.9	7.9		
Canadian Arctic <74°N	**4**	18,500	−1364.6	5.9	9.6	−139
	5	18,500	−1790.6	6.9		
	6	5,000	−214.2	8.4		
	7	722	−89.0	5.1		
Alaska	**8**	13,900	−3205.7	6.0	47.7	−809
	9	800	−193.7	5.6		
	10	230	−34.3	4.7		
	11	960	−116.4	3.1		
	12	1,250	−153.7	3.5		
	13	100	−192.5	4.2		
	14	4,600	−852.8	4.3		
	15	8,300	−1819.8	4.9		
	16	21,600	−4939.1	4.6		
	17	11,800	−3111.2	5.2		
	18	10,500	−2661.4	4.6		
Iceland	**53**	8,300	−861.1	2.8	3.1	−319
	54	953	−73.9	2.4		
	55	925	−109.5	4.3		
	56	600	−48.6	2.3		
	57	160	−20.2	4.6		
Svalbard	**58**	36,600	−2956.0	7.5	8.2	−108
Zemlya Frantsa Iosifa	**59**	13,700	−617.2	8.1	1.7	−56
Novaya Zemlya	**60**	23,600	−1296.6	7.7	3.6	−71
Severnaya Zemlya	**61**	18,300	−840.8	8.7	2.3	−53
Norway / Sweden	**62**	1,080	−96.3	4.6	0.7	−236
	63	1,630	−141.0	3.1		
	Σ	330,510	−33324.3		**92.2**	

Table 8.3: Changes in glaciers in nine regions of the Arctic (same as Oerlemans et al., 2005) over the period 2001-2100 calculated from the numerical model based on $\mathrm{T}_{OF}\mathrm{P}_{OFseries}$ with regionally variable Θs and $\Theta_{Alaska} = 0.50$ K. The *areas* are given in km^2 and ice-volume changes dV in km^3 w.e. including the corresponding temperature change dT in K over the period 2001-2100 for individual regions derived in this thesis. The contributions to global sea-level rise (sl) are given in mm for the nine regions over the 100-year period. The last column lists average mass balance sensitivities to temperature changes of the nine regions expressed in mm year^{-1} K^{-1}.

regional estimate derived in this thesis predicts a sea-level rise of 47.7 mm as a result of glacier melting in Alaska over the period 2001-2100 (see Table 8.3). In this region, temperature is predicted to rise by approximately 4.6 K over the same period. The observationally based recent ice-volume loss in Alaska is estimated to be 0.27 mm year^{-1} w.e. (Arendt et al., 2002). From the anticipated temperature increase until the end of this century as well as from the observed acceleration of ice-volume loss in recent years, it is not very likely that the future ice-volume loss in Alaska will decrease compared to the present rate. Therefore, the projection derived in this thesis (which is 50% greater than the recent value) is understood to be more accurate than the estimate of Oerlemans et al. (2005) which is less than half the recent rate of ice-volume loss.

For the Svalbard archipelago, Oerlemans et al. (2005) estimated that the contributions to global sea-level rise resulting from the glacial melting will be approximately 2.5 mm over the 21st century. In this thesis, the contribution over the period 2001-2100 is predicted to be 8.2 mm with an estimated temperature rise of ∼7.5 K. Similarly to the Alaska case above, observationally based analyses by Dowdeswell et al. (1997), Hagedoorn and Wolf (2003), and Dyurgerov and Meier (2005) estimated a recent ice-volume loss for Svalbard equivalent to a global sea-level change of approximately 0.056, 0.036, and 0.017 mm year^{-1}, respectively, and these estimates can be regarded as minimum constraints for future melt. Furthermore, as these estimates are based on observations of only a few glaciers and therefore may suffer from large uncertainties, it can be concluded here that the ice-volume loss for the Svalbard archipelago derived in this thesis is an accurate prediction.

In contrast to the study of Oerlemans et al. (2005) which is based on energy-balance modelling, de Woul and Hock (2005) analysed mass balance sensitivities of Arctic glaciers to temperature and precipitation changes using a degree-day model. Their derived mass balance sensitivities for glaciers in Alaska and Svalbard for a 1 K warming are 740 and 449 mm year^{-1}, respectively. In the case of Alaska the estimate of de Woul and Hock (2005) is comparable to that derived in this thesis of 809 mm year^{-1} K^{-1} (see last column in Table 8.3), but for Svalbard the number derived here is only 25% that of de Woul and Hock (2005).

Predictions of ice-volume loss derived in this thesis globally and for the two example regions of Alaska and Svalbard vary compared to estimates determined in other studies and with different approaches. However, these differences can reasonably be explained by the variations in the climate model predictions and are most likely less due to inaccuracies of the models themselves. Hence, at this stage there is no great need to develop any sophisticated models and using the relatively simple model of mountain deglaciation of Chapter 2 is adequate to predict good first order estimates of future glacier melt.

8.2 Summary and conclusions

Numerical modelling of future volume changes of mountain glaciers presented in this study predicts a loss equivalent to a global rise in sea-level of between 162 and 171 mm over the period from 2001 to 2100 (Figure 8.2). This estimate is consistent with results presented in previous work but with differences in detail which can be understood in terms of the methods and assumptions used in the various studies. With increased deglaciation, the flow of the rivers that are draining these glaciated regions will increase. However, this only happens on the short-time scale, as many small glaciers are predicted to disappear over the course of this century. Hence, in the long term, water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in regions supplied by meltwater from major mountain ranges. This will have a major impact on society as more than one-sixth of the world population currently live in these regions and depend on glacial meltwater supplies (Kundzewicz et al., 2007).

In conclusion, during this century a considerable portion ($\sim$170 mm) of future global sea-level rise (of $\sim$200 to 600 mm according to the IPCC, 2007b, report) is predicted to be a result of the melting of mountain glaciers. It is noted here again that changes in sea-level are not geographically uniform. This is also true for future variations, whether they are caused by mountain deglaciation or any other processes. In some areas, sea level will rise by several times the global average, whereas in other areas sea level will actually fall. Thus, the vulnerability to and socio-economic impact of rising sea levels depend on the region under investigation.