Chapter 3

Ice-volume changes of mountain glaciers

The previous chapter presented different methods for estimating the rates of ice-volume changes of mountain glaciers. Early estimates by Lambeck and Cazenave (1976) and Lambeck (1980, p. 273) indicated that the European and Icelandic glaciers alone contributed as much as 0.5 mm year^{-1} to global sea-level change between $\sim$1860 and 1950. Thus, if the North American and Asian glaciers were melting in phase with and at the same rate as the European glaciers, then glacier melt has made an important contribution to the observed sea-level change during the 20th century.

Subsequently, a variety of studies (summarized in Table 3.1) have attempted more rigorous evaluations of global ice-volume loss for a range of time periods from 1860-2004 using a variety of methods. For example, Meier (1984) used measurements of long-term changes in glacier volume of a small number of glaciers, then extrapolated these observations to derive a global contribution of 0.46±0.26 mm year^{-1} to sea-level rise between 1900 and 1961. Trupin et al. (1992) used the fraction of the glacier systems investigated by Meier (1984) that had the longest observation intervals and estimated an average ice-volume loss equivalent to 0.18 mm year^{-1} global sea-level rise from 1965 to 1984. Meier (1993) updated his previous estimates by accounting for refreezing in cold glaciers from surface melting which therefore does not contribute to the ablation of the glacier. He derived an ice-volume loss equivalent to 0.4±0.2 mm year^{-1} of global sea-level rise over the period from 1880 to 1980.

Dyurgerov and Meier (1997b) studied global glacier mass balances and their contribution to sea-level changes over the period from 1961 to 1990. In their analysis the mass balance data set, taken over from Dyurgerov and Meier (1997a), uses all available sources of mass balance observations (published and unpublished) of more than 250 glaciers worldwide, covering an area of between $\sim$2500 and $\sim$6000 km^2 dependent on the year. The total global glacier area in Dyurgerov and Meier (1997b) is 540,000 km^2 (excluding the glaciers around the Antarctic and Greenland ice sheets), which is only 2% larger than the area used in the numerical model of this thesis (Section 2.3.1). The estimate of ice-volume changes by Dyurgerov and Meier (1997b) is equivalent to a global sea-level rise of 0.25 mm year^{-1} from 1961 to 1990. Another observational estimate of ice-volume changes of mountain glaciers undertaken by Cogley and Adams (1998) uses measurements of over 200 glaciers. They calculated an annual rate in mean specific mass balance of -195 ± 59 mm year^{-1} water equivalent (w.e.). Error analyses and the application of corrections due to uneven spatial coverage and a bias towards smaller glaciers, result in a glacier contribution to global sea-level rise of 0.06 to 0.32 mm year^{-1} over the period from 1961 to 1990 (Cogley and Adams, 1998). The "middle" value of 0.19 mm year^{-1} is close to the estimate of Dyurgerov and Meier (1997b) of 0.25 mm year^{-1}. This is unsurprising as both studies, although independently conducted, use to a large extent the same source of mass balance observations.

A more recent study by Dyurgerov and Meier (2000) concluded that there has been a loss in glacier volume equivalent to 3,700 km^3 of water from 1961 to 1997, which equates to 0.28 mm year^{-1} of global sea-level rise. This result is based on the 37 longest, directly measured time series of volume change covering glaciated regions in the Canadian Arctic, North America, Alaska, Svalbard, Scandinavia, the Alps, and central Asia. On the basis of mass balance observations over 75 years, Ohmura (2004) concluded that globally glaciers lost mass equivalent to 0.4 mm year^{-1} sea-level rise over the second half of the 20^{th} century. Dyurgerov and Meier (2005) presented another analysis of glacier loss of 185 km^3 year^{-1} w.e. (equivalent to 0.51 mm year^{-1} global sea-level rise) over the period from 1961 to 2003 (including glaciers and ice caps around the Antarctic and Greenland ice sheets). This compilation is based on observations of mass balances of over 300 individual glaciers world wide. It represents the most recent available compilation and is discussed in detail in Section 3.2.1. Kaser et al. (2006) obtained global estimates of glacier ice-volume changes by combining and updating independent analysis, in particular those of Ohmura (2004), Dyurgerov and Meier (2005), and Cogley (2005). Their estimate of ice-volume loss is equivalent to 0.33 ± 0.17 mm year^{-1} global sea-level rise for the period 1961 to 1990 and increases to 0.77 ± 0.15 mm year^{-1} between

2001-2004. If glaciers at the periphery of the Antarctic and Greenland ice sheets are included the estimate for the two periods increases to 0.39±0.19 and 0.98±0.19 mm year^{-1} w.e., respectively. Oerlemans et al. (2007) analysed 197 glacier length records to calculate a global signal, which they subsequently used as a proxy to estimate the volume loss. They derived a glacier contribution to sea-level rise of 55±10 mm during the period 1850-2000 and 45±7 mm during 1900-2000.

Reference	**period**		**rate**
Meier (1984)	1900-1961	*obs.*	0.46 ± 0.26
Trupin et al. (1992)	1965-1984	*obs.*	0.18
Oerlemans and Fortuin (1992)	1900-1961	*mod.*	0.20
Meier (1993)	1880-1980	*obs.*	0.4 ± 0.2
Dyurgerov and Meier (1997b)	1961-1990	*obs.*	0.25 ± 0.1
Zuo and Oerlemans (1997a)	1865-1990	*mod.*	0.22 ± 0.07
Cogley and Adams (1998)	1961-1990	*obs.*	0.19 ± 0.13
Gregory and Oerlemans (1998)	1860-1990	*mod.*	0.20 ± 0.05
Dyurgerov and Meier (2000)	1961-1997	*obs.*	0.22
Dyurgerov and Meier (2000)	1961-1997		0.28 [a]
IPCC (2001)	1910-1990	*obs.*	0.3 ± 0.1
Ohmura (2004)	1950-2000	*obs.*	0.4
Dyurgerov and Meier (2005)	1961-2003	*obs.*	0.44
Dyurgerov and Meier (2005)	1961-2003		0.51 [a]
Dyurgerov and Meier (2005)	1993-2003		0.77
Dyurgerov and Meier (2005)	1993-2003		0.93 [a]
Raper and Braithwaite (2006)	1900-2000	*mod.*	0.28
Kaser et al. (2006)	1961-1990	*obs.*	0.33 ± 0.17
Kaser et al. (2006)	1961-1990		0.39 ± 0.19 [a]
Kaser et al. (2006)	2001-2004		0.77 ± 0.15
Kaser et al. (2006)	2001-2004		0.98 ± 0.19 [a]
IPCC (2007b)	1961-2003	*obs.*	0.50 ± 0.18 [a]
IPCC (2007b)	1993-2003		0.77 ± 0.22 [a]
Oerlemans et al. (2007)	1850-2000	*obs.*	0.37 ± 0.07 [a]
Oerlemans et al. (2007)	1900-2000		0.45 ± 0.07 [a]

obs. - estimates based on observations
mod. - estimates based on numerical models
[a] estimates include independent glaciers at the periphery of the Antarctic and Greenland ice sheets

Table 3.1: List of studies dealing with the global sea-level contribution from melting of mountain glaciers in mm year^{-1} w.e. determined over various periods.

In contrast to the studies of global glacier loss summarized above that are based on observations, a number of authors have derived estimates using numerical models. For example, Oerlemans and Fortuin (1992) established a global glacier sensitivity model based on twelve well studied glaciers (see Section 2.2). Using this model they calculated a global ice-volume loss for the period from 1900 to 1961 that is equivalent to 0.20 mm year^{-1} global sea-level rise. Zuo and Oerlemans (1997a) determined an ice-volume loss from mountain glaciers for the period 1865 to 1990 equivalent to a global sea-level rise of 27 mm. This estimate is based on historical temperature data and a numerical relationship of the sensitivity of glacier mass balances to climatic changes introduced by Oerlemans and Fortuin (1992) and Oerlemans (1993). Gregory and Oerlemans (1998) applied the same model as Zuo and Oerlemans (1997a) but used a modelled temperature data set and estimated the contribution of mountain deglaciation to global sea-level rise to between 19 and 33 mm from 1860 to 1990. Raper and Braithwaite (2006) estimated a sea-level rise of 28 mm for the 20th century. This estimate is based on temperature sensitivities of mass balances of mountain glaciers derived by Braithwaite et al. (2002).

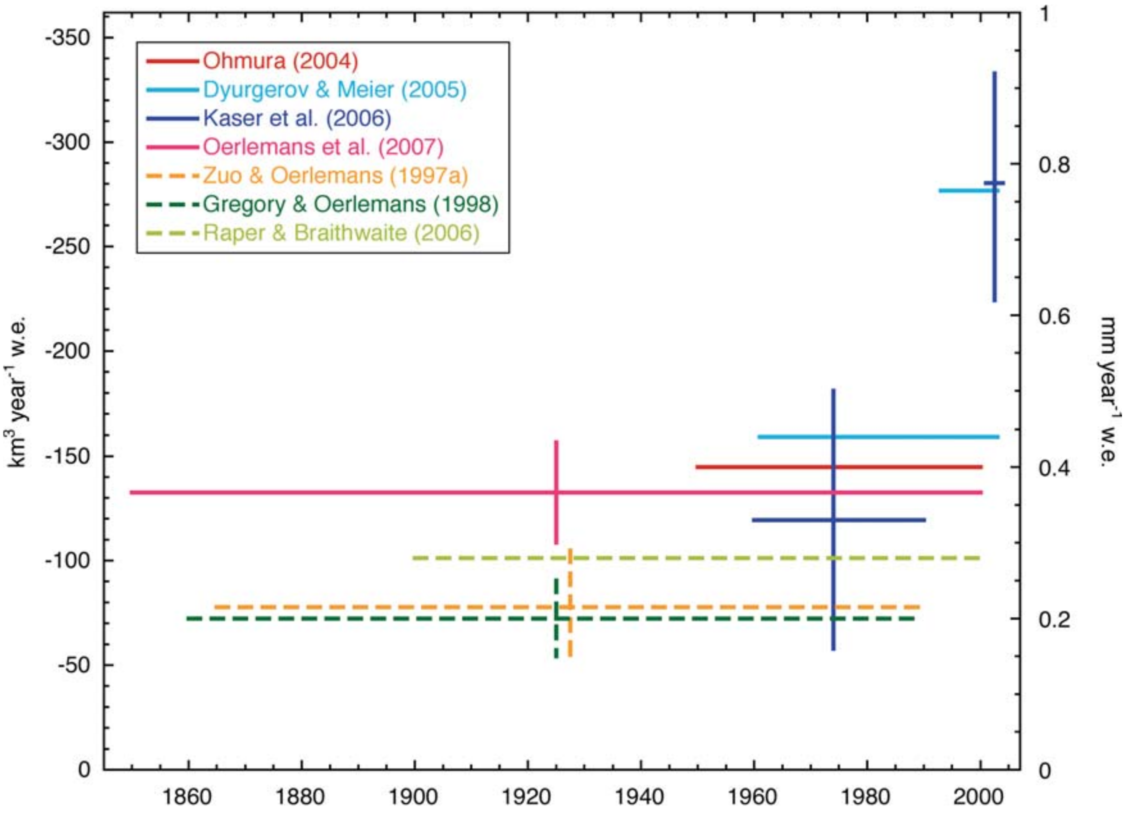

Figure 3.1: Comparison of estimates of recent melting of mountain glaciers as a contributor to global sea-level rise in mm year^{-1} w.e. for different analysis periods. Superseded studies are omitted in this plot (a more comprehensive list is given in Table 3.1). Solid lines represent studies based on observations, dashed lines are estimates derived from numerical models. An increase in ice-volume loss over recent years (past few decades) can be observed.

Although observational evidence remains sparse, the above studies suggest that mountain deglaciation contributed 0.2 to 0.5 mm year^{-1} to global sea-level rise for much of the 20th century. The IPCC (2001) report summarizes the sea-level contribution from glaciers to 0.3±0.1 mm year^{-1} between 1910 and 1990. Some evidence indicate that after about 1960 the contribution of mountain deglaciation to the rate of global sea-level rise was higher and increased even further at the end of the century (see Figure 3.1). The most recent IPCC (2007b) report suggests a contribution to global sea-level rise resulting from the melting of mountain glaciers of 0.50±0.18 and 0.77±0.22 mm year^{-1} over the periods 1961 to 2003 and 1993 to 2003, respectively.

The results of the numerical model of recent mountain deglaciation, described in the previous chapter, are given in Section 3.1. Available mass balance observations are compiled to make larger-scale and global estimates in Section 3.2. In the same section a comparison between observational estimates and the results of the numerical models is presented, both on a global and regional scale. Section 3.3 gives a final summary and conclusion on ice-volume changes of mountain glaciers determined using various methods.

3.1 Numerical estimates of recent ice-volume changes

Parameters required to determine ice-volume changes of mountain glaciers using Equation 2.3, namely the glaciated areas and the summer and non-summer temperature anomalies for each of the 100 glaciated regions, were discussed in detail in Section 2.3. The parameter Θ correcting for the initial imbalance between climate and glacier state has also been addressed and different ways to quantify Θ were presented. The last required parameter, the mass balance sensitivity, reflects the relationship of glacier mass balance to climatic changes. The result of Equation 2.3, representing a seasonally and regionally differentiated glacier model, is the change in ice volume in km^3 of water (km^3 w.e.) over a given time period (e.g. 1871-1990) for each glaciated region. Assuming the world's ocean area of 362×10^6 km^2 the ice-volume change of mountain glaciers can also be expressed in mm of global (or eustatic) sea-level rise (mm w.e.).

In the following sections, I have used the previously discussed temperature and precipitation data sets to estimate ice-volume changes for the 100 glaciated regions. These include the temperature data sets of Gregory and O'Farrell of Section 2.3.4. First calculations are made with the precipitation data set of Zuo and Oerlemans

(1997a), the main reason being to determine whether the estimates of glacier loss of Zuo and Oerlemans (1997a) can be reproduced. In addition, these estimates are compared with results using two other precipitation data sets of the CRU and O'Farrell (Section 2.3.3). Results of ice-volume changes based on six combinations of temperature and precipitation data sets are presented in the following four sections. These combinations are labelled as follows:

$\mathbf{T}_{G}\mathbf{P}_{Z\&O}$	Temperature data set of Gregory and precipitation data set of Zuo and Oerlemans (1997a)
$\mathbf{T}_{G}\mathbf{P}_{CRUaver}$	Temperature data set of Gregory and average annual means of the CRU precipitation data set
$\mathbf{T}_{G}\mathbf{P}_{CRUseries}$	Temperature data set of Gregory and time series of the CRU precipitation data set
$\mathbf{T}_{OF}\mathbf{P}_{Z\&O}$	Temperature data set of O'Farrell and precipitation data set of Zuo and Oerlemans (1997a)
$\mathbf{T}_{OF}\mathbf{P}_{OFaver}$	Temperature data set of O'Farrell and average annual means of the O'Farrell precipitation data set
$\mathbf{T}_{OF}\mathbf{P}_{OFseries}$	Temperature data set of O'Farrell and time series of the O'Farrell precipitation data set

For most of the calculations of ice-volume changes in the following sections, a global estimation of the parameter Θ (Section 2.3.5) is applied, i.e. one value is applied for all glaciated regions. Results using a regionally variable Θ are presented in Section 3.1.5 to assess the sensitivity of results to changes in this parameter. In conclusion, an overall comparison of regional and global estimates of ice-volume changes of mountain glaciers is presented in Section 3.1.6.

3.1.1 Ice-volume changes of 100 glaciated regions based on $\mathbf{T}_{G}\mathbf{P}_{Z\&O}$

Temperature anomalies (Section 2.3.4.4) calculated using the Gregory temperature data set for the 100 glaciated regions are used here to derive changes in glacier volume with Equation 2.3. Precipitation data adopted from Zuo and Oerlemans (1997a) is used to calculate an initial estimate of mass balance sensitivities. The parameter Θ is set to 0.15 K (as recommended by Zuo and Oerlemans, 1997a) and the reference period is set to 1866-1895. A latitudinal distribution of ice-volume changes during 1866-1990 is shown in Figure 3.2a and is compared to the result of Zuo and Oerlemans (1997a) in Figure 3.2b. With the exception of the temperature data sets, all other parameters remained constant in this comparison. Overall, the latitudinal variations in ice-volume changes for the 100 glaciated regions are comparable. However, regional variations are evident and are attributed to differences between the two temperature data sets.

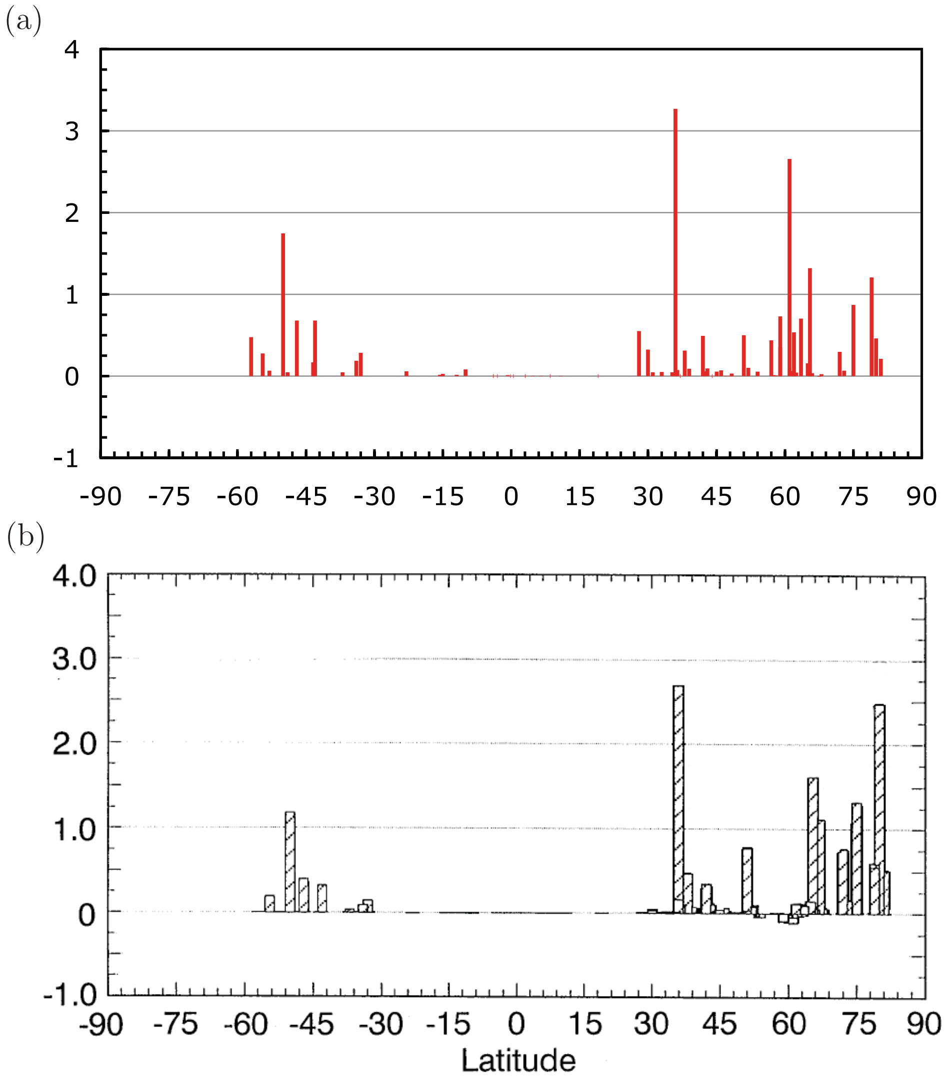

Figure 3.2: Latitudinal distribution of ice-volume changes of 100 glaciated regions for the period 1866-1990 expressed in mm w.e. comparing (a) results of the numerical model using $T_G P_{Z\&O}$ with (b) results of Zuo and Oerlemans (1997a). In both cases the parameter Θ is set to 0.15 K, the precipitation data set of Zuo and Oerlemans (1997a), and the reference period 1866-1895 are used.

Zuo and Oerlemans (1997a) calculated a total change in glacier volume of 27 mm w.e. for 125 years (1865-1990), when applying a 30-year reference period (1865-

1895) and setting Θ to 0.15 K. This is equivalent to a eustatic sea-level rise of 0.216 mm year^{-1}. Results for the total change in ice volume based on the numerical model using $T_G P_{Z\&O}$ and for different values for Θ are listed in Table 3.2. Different time intervals for the reference period are also used, ranging from 15 to 35 years and starting in 1866 and 1871, respectively. Both the length of the reference period and the choice of starting-points of this reference period affect the results. Estimations of the total change in glacier volume over a constant period but for various durations of the reference period (between 15 and 35 years) result in variations of less than ±10%. Changing the starting point of the considered period (and therefore also of the start of the reference period) results in only minor changes of around 6% to the final estimates. Varying Θ by ±0.15 K results in a change of the total estimate by approximately ±0.075 mm year^{-1} w.e. and thus represents the greatest uncertainty in the model results. If Θ was the only free parameter in the model, it would be required to be set between 0.15 and 0.30 K, so that the total ice-volume change equals the estimates of ~0.2 mm year^{-1} w.e. for the 20^{th} century (e.g. Zuo and Oerlemans, 1997a; Gregory and Oerlemans, 1998).

		Θ				
	reference period	**0.00**	**0.15**	**0.30**	**0.45**	**0.60**
1866-1990	1866-1880	0.075	0.153	0.230	0.307	0.385
	1866-1885	0.098	0.176	0.253	0.330	0.408
	1866-1890	0.099	0.177	0.254	0.331	0.409
	1866-1895	0.093	0.170	0.248	0.325	0.402
	1866-1900	0.092	0.169	0.246	0.324	0.401
1871-1990	1871-1885	0.112	0.189	0.266	0.344	0.421
	1871-1890	0.110	0.187	0.265	0.342	0.419
	1871-1895	0.101	0.178	0.255	0.333	0.410
	1871-1900	0.098	0.176	0.253	0.330	0.407
	1871-1905	0.093	0.171	0.248	0.325	0.403

Table 3.2: Estimates of global ice-volume changes of mountain glaciers in mm year^{-1} w.e. over the periods 1866-1990 and 1871-1990 of the numerical model using $T_G P_{Z\&O}$. Reference periods of different lengths (between 15 and 35 years) and several values for Θ are applied.

Assuming Zuo and Oerlemans (1997a) reasoning for setting the parameter Θ to 0.15 K is correct, the estimates of total ice-volume changes in the numerical model are always smaller than the result of Zuo and Oerlemans (1997a) or Gregory and Oerlemans (1998) (0.22 and 0.20 mm year^{-1} w.e., see Table 3.1), regardless of the time period that is considered. It is therefore likely that the lower estimates derived here are due to the choice of temperature data.

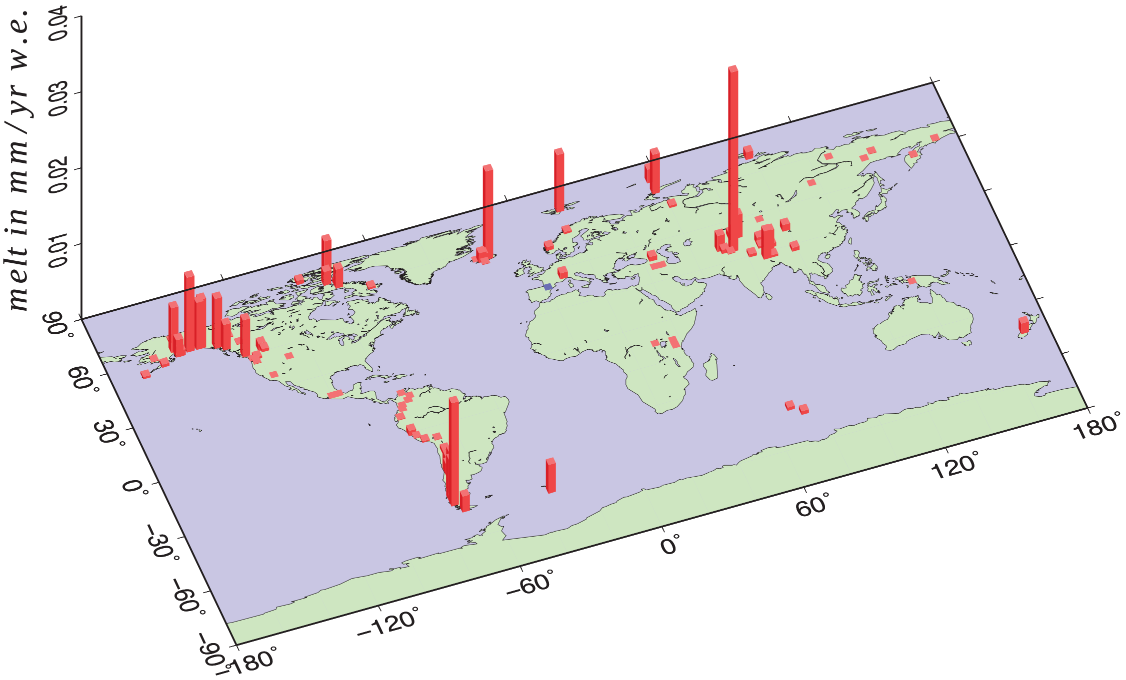

Figure 3.3: Ice-volume changes of 100 glaciated regions in mm year^{-1} w.e. over the period 1871-1990 using $T_G P_{Z\&O}$. The reference period 1871-1895 is applied and θ is set to 0.15 K. Red bars indicate glacier retreat at these specific locations, blue bars indicate regions with advancing glaciers.

Figure 3.3 shows the ice-volume changes obtained at 100 glaciated regions for the period 1871 to 1990. Over the 120-year period, the majority of the glaciated regions (99%) show an overall loss in volume (red bars). The four areas with the greatest ice-volume losses are:

- North America (Alaska and Canada) → 32% of total
- central Asia → 24% of total
- Arctic sea (Iceland, Svalbard, and Franz Josef Land) → 17% of total
- and Patagonia → 17% of total

The calculated ice-volume changes over the period 1871-1990 with the reference period 1871-1895 for each of the 100 glaciated regions are listed in Table C.1 on pages 330-332. In total, the estimated ice-volume loss is 64.45 km^3 year^{-1} w.e., which is equivalent to 0.178 mm year^{-1} of eustatic sea-level rise.

Estimating the changes in ice-volume over a more recent period (from 1961 to 1990) results in significantly higher rates (see Table 3.3). This agrees with the results of other work showing an increase in the rate of ice-volume loss for the past few decades (see Table 3.1). While all other parameters are constant, the rate of ice-volume change for the period 1961-1990 (Table 3.3) is about 0.1 mm year^{-1} w.e. larger than the rate of change for the period 1871-1990 (Table 3.2). This increase in ice-volume change is strongly related to the temperature change within the different periods, i.e. the temperature trends for the period 1961-1990 are consistently higher than over 1871-1990 (see Section 2.3.4). A change of the parameter Θ by ± 0.15 K results again in a change in the total ice volume of about ± 0.075 mm year^{-1} w.e..

		Θ				
	reference period	**0.00**	**0.15**	**0.30**	**0.45**	**0.60**
1961-1990	1871-1885	0.207	0.284	0.361	0.439	0.516
	1871-1890	0.205	0.283	0.360	0.437	0.515
	1871-1895	0.196	0.273	0.351	0.428	0.505
	1871-1900	0.193	0.271	0.348	0.425	0.503
	1871-1905	0.188	0.266	0.343	0.420	0.498

Table 3.3: Estimates of global ice-volume changes of mountain glaciers in mm year^{-1} w.e. for the period 1961-1990 of the numerical model using $\mathrm{T}_G\mathrm{P}_{Z\&O}$. Reference periods of different lengths (between 15 and 35 years) and several values for Θ are applied.

3.1.2 Ice-volume changes of 100 glaciated regions based on $\mathrm{T}_G\mathrm{P}_{CRUaver}$ and $\mathrm{T}_G\mathrm{P}_{CRUseries}$

In the numerical model of ice-volume changes of mountain glaciers the rate of annual precipitation is one of the key input parameters. Previously, precipitation rates of Zuo and Oerlemans (1997a) for each of the 100 glaciated regions have been used. In this section, the CRU data set of observed precipitation is applied (Section 2.3.3). This allows a comparison between results of ice-volume changes using this observed data set and those using the precipitation data of Zuo and Oerlemans (1997a) and hence the sensitivity of results to precipitation changes can be assessed.

As described in Section 2.3.3, with the monthly data set of the CRU, average annual means as well as time series of annual precipitation are determined for each of the 100 glaciated regions. Since CRU data for the glaciated regions is temporally incomplete over the period from 1871 to 1990 (available only from 1900 or later), annual means calculated over the available years are used to fill the gaps in the time series to produce a complete data set. Both data sets, average annual means and time series of annual precipitation, have been applied in the calculation of ice-

Θ	$\mathbf{T}_G\mathbf{P}_{Z\&O}$	$\mathbf{T}_G\mathbf{P}_{CRUaver}$	$\mathbf{T}_G\mathbf{P}_{CRUseries}$
0.00	0.101	0.076	0.088
0.15	0.178	0.140	0.164
0.30	0.255	0.204	0.240
0.45	0.333	0.267	0.315
0.60	0.410	0.331	0.391

Table 3.4: Estimates of global ice-volume changes of mountain glaciers in mm year^{-1} w.e. for the period 1871-1990 using the reference period 1871-1895. A comparison between results using $T_GP_{Z\&O}$ and results using the CRU precipitation data in form of average annual means ($T_GP_{CRUaver}$) and in form of time series ($T_GP_{CRUseries}$) are listed. Several values for the parameter Θ are applied.

volume changes. Table 3.4 compares the results over the period 1871-1990 using different precipitation data sets and applying several values for Θ.

Using the CRU precipitation data set, and in particular $P_{CRUaver}$, results in lower rates of total ice-volume changes compared to those using $P_{Z\&O}$. Figure 2.10 on page 39 shows the relationship between annual precipitation and mass balance sensitivity. With smaller values in $P_{CRUaver}$ compared to $P_{Z\&O}$ (discussed in Section 2.3.3, see also Table B.2 on page 311), the mass balance sensitivities decrease. Since the sensitivity values are then multiplied by the temperature anomalies (as defined in Equation 2.3), the total change in ice volume also decreases. Hence, this reduction in the total estimates is expected. However, note that global ice-volume changes using $P_{CRUseries}$ are bigger than those using $P_{CRUaver}$ by around 17%, indicating that the trends in precipitation (although only a few are statistically significant) have a significant effect on the estimated rate of ice-volume loss.

3.1.3 Ice-volume changes of 100 glaciated regions based on $\mathbf{T}_{OF}\mathbf{P}_{Z\&O}$

This section uses the temperature data set of O'Farrell in Equation 2.3 to estimate ice-volume changes for the 100 glaciated regions. The precipitation data set from Zuo and Oerlemans (1997a) is again applied in the initial analysis to minimise the number of new variables. Ice-volume changes over the period 1871-1990, under consideration of reference periods of different lengths and several values for the parameter Θ, are listed in Table 3.5. Maximum variations of ±35% arise when only the length of the reference period is altered while the parameter Θ and the considered period are kept constant. Table 3.5 also shows the total ice-volume

		Θ				
	reference period	**0.00**	**0.15**	**0.30**	**0.45**	**0.60**
1871-1990	1871-1885	0.135	0.212	0.289	0.367	0.444
	1871-1890	0.103	0.180	0.257	0.335	0.412
	1871-1895	0.103	0.181	0.258	0.335	0.413
	1871-1900	0.083	0.160	0.237	0.315	0.392
	1871-1905	0.075	0.152	0.230	0.307	0.384
1961-1990	1871-1885	0.317	0.394	0.471	0.549	0.626
	1871-1890	0.285	0.362	0.439	0.517	0.594
	1871-1895	0.285	0.363	0.440	0.517	0.595
	1871-1900	0.265	0.342	0.419	0.497	0.574
	1871-1905	0.257	0.334	0.412	0.487	0.566

Table 3.5: Estimates of global ice-volume changes of mountain glaciers in mm year^{-1} w.e. for the periods 1871-1990 and 1961-1990 of the numerical model using $\mathrm{T}_{OF}\mathrm{P}_{Z\&O}$. Reference periods of different lengths (between 15 and 35 years) and several values for Θ are applied.

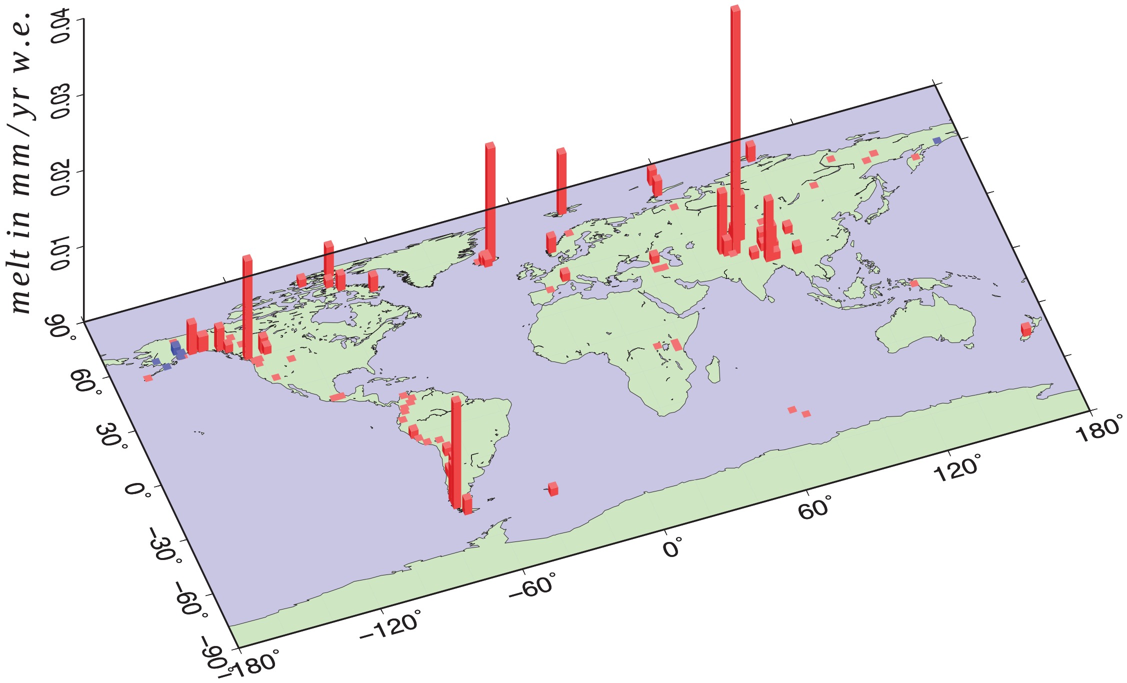

Figure 3.4: Ice-volume changes of 100 glaciated regions in mm year^{-1} w.e. over the period 1871-1990 using $\mathrm{T}_{OF}\mathrm{P}_{Z\&O}$. The reference period 1871-1895 is applied and θ is set to 0.15 K. Red bars indicate glacier retreat at these specific locations, blue bars indicate regions with advancing glaciers.

changes over the more recent time period 1961-1990. Estimates of ice-volume changes over this period are greater by about 0.18 mm w.e. compared to the estimates over 1871-1990.

Comparing estimates of global ice-volume changes using $T_G P_{Z\&O}$ (Table 3.2) with those using $T_{OF} P_{Z\&O}$ (upper half of Table 3.5), shows that results over the period 1871-1990 are reasonably insensitive to the temperature data set used. However, that is not the case for estimates derived for the recent period 1961-1990 where $T_{OF} P_{Z\&O}$ produces total ice-volume changes that are higher by a considerable 20-40%. This is consistent with the trends observed in the two temperature data sets determined over the recent decades, i.e. trends during 1961-1990 in T_{OF} are generally higher than those of T_G (see Section 2.3.4).

The ice-volume changes at 100 glaciated regions over the period 1871-1990 are graphically illustrated in Figure 3.4 and listed in Table C.1 on pages 330-332. The parameter Θ is set to 0.15 K and the reference period 1871-1895 is used. Figure 3.4 shows that in some regions (i.e. North-West Alaska) glaciers are predicted to advance, a behaviour which is not seen in Figure 3.3. Minor variations in all other regions when using either $T_G P_{Z\&O}$ or $T_{OF} P_{Z\&O}$ can be seen by comparing Figure 3.3 and 3.4, revealing the low sensitivity of results to the temperature data set used.

3.1.4 Ice-volume changes of 100 glaciated regions based on $T_{OF} P_{OFaver}$ and $T_{OF} P_{OFseries}$

In this section the precipitation data set of Zuo and Oerlemans (1997a) is replaced by the one provided by O'Farrell (details in Section 2.3.3) in order to calculate global ice-volume changes of mountain glaciers. Average annual means over the period 1871-1990 for each of the 100 glaciated regions ($T_{OF} P_{OFaver}$) and also time series of annual precipitation ($T_{OF} P_{OFseries}$) have been applied in the calculation and results of global ice-volume changes are compared to those using $T_{OF} P_{Z\&O}$ in Table 3.6.

Similar conclusions to those made in Section 3.1.2 can be drawn here: Using the O'Farrell precipitation data set results in smaller estimates of total ice-volume changes of between 9% and 25% compared to the estimates using $P_{Z\&O}$. Again, this corresponds to the lower precipitation rates in the O'Farrell data set (see Section 2.3.3). Thus, the variations in the results demonstrate once more the

Θ	$\mathbf{T}_{OF}\mathbf{P}_{Z\&O}$	$\mathbf{T}_{OF}\mathbf{P}_{OFaver}$	$\mathbf{T}_{OF}\mathbf{P}_{OFseries}$
0.00	0.103	0.069	0.087
0.15	0.181	0.134	0.162
0.30	0.258	0.199	0.238
0.45	0.335	0.263	0.313
0.60	0.413	0.328	0.388

Table 3.6: Estimates of global ice-volume changes of mountain glaciers in mm year^{-1} w.e. over the period 1871-1990 using the reference period 1871-1895. A comparison between results using $T_{OF}P_{Z\&O}$ and results using O'Farrell's precipitation data set in form of average annual means ($T_{OF}P_{OFaver}$) and in form of time series ($T_{OF}P_{OFseries}$) are listed. Several values for the parameter Θ are applied.

sensitivity of the model to the precipitation data set that is applied. Furthermore, using $P_{OFseries}$ results in higher estimates of global ice-volume changes than using P_{OFaver}. Again, this indicates that the trends in precipitation have a significant effect on the final results, with an average increase of around 21%.

3.1.5 Ice-volume changes of 100 glaciated regions based on a regionally variable Θ

As noted in Section 2.3.5 the parameter Θ, which corrects for the initial imbalance between glacier and climate state within the reference period, is likely to vary around the world. Hence, regionally variable Θs derived from T_{OF} (Table 2.7 on page 62) are used in this section to calculate global ice-volume changes. The data set T_{OF} and not T_G is chosen as the area weighted mean of Θ is the same as the global one suggested by Zuo and Oerlemans (1997a). Again, the regionally variable Θs are

➢ Europe	0.64
➢ Asia	0.33
➢ South America	0.15
➢ Patagonia	−0.04
➢ NW-America	−0.05
➢ Alaska	0.16
➢ NE-America	0.38
➢ Arctic	0.85

For glaciers that fall in none of the above regions a Θ of 0.15 K is used.

This sensitivity study shows that, on a global scale, using regionally variable Θs increases the previously calculated estimates of global ice-volume loss (see Table 3.7). In particular, the estimated ice-volume loss is equivalent to a global sea-level rise of 0.236 mm year^{-1} from 1871 to 1990 and 0.427 mm year^{-1} between 1961 and 1990.

	$\mathbf{T}_{OF}\mathbf{P}_{OFseries}$		
period	$\Theta = 0.15K$	$\Theta = 0.30K$	$\Theta = variable$
1871-1990	0.162	0.238	0.236
1961-1990	0.352	0.428	0.427

Table 3.7: Estimates of global ice-volume changes in mm year^{-1} w.e. over the periods 1871-1990 and 1961-1990 using $T_{OF}P_{OFseries}$. Comparison of results when setting the parameter Θ globally to 0.15 and 0.30 K to using a regionally variable Θ are shown.

Although the area weighted mean of Θ over the 8 regions of 0.15 K (see Section 2.3.5.3, Table 2.7) is the same as the global one proposed by Zuo and Oerlemans (1997a), the estimate for the global glacier loss increases by almost 50% over the period 1871-1990. In general, applying regionally variable Θs in the calculation results in an estimate of global sea-level rise that is about 0.075 mm year^{-1} higher than that when using Θ=0.15 K globally (see Table 3.7). This result of global ice-volume loss can also be attained when applying a Θ of 0.30 K globally. This latter value for Θ is similar to the one determined by using T_{OF} and weighting the regional Θs proportional to the glaciated area of each region (see Section 2.3.5.3).

3.1.6 Comparison of numerical results

Ice-volume changes of mountain glaciers calculated from the numerical model based on various data sets and parameter settings are presented in the previous sections. For an overall comparison in this section (Table 3.8), the reference period is chosen to 1871-1895 and Θ is generally set to 0.15 K, unless stated otherwise. Choosing the precipitation data set of Zuo and Oerlemans (1997a) results in a total ice-volume change over 1871-1990 of the 100 glaciated regions of about 65 km^3 year^{-1} of water (or 0.18 mm year^{-1} w.e.) using either of the temperature data sets. However, comparing global estimates over the period 1961-1990 using the Gregory and O'Farrell temperature data sets shows that the latter produces higher values by more that 30% (see Table 3.8). This is primarily due to the higher temperature trends in this 30-year period for T_{OF} as opposed to that of T_G.

			T_G		T_{OF}	
		gl.no.	$P_{Z\&O}$	$P_{CRUseries}$	$P_{Z\&O}$	$P_{OFseries}$
1871-1990	**GLOBAL**	**1-100**	**0.178**	**0.164**	**0.181**	**0.162 (0.236)**
	Europe	62-65	0.002	0.001	0.004	0.002 (0.005)
	Asia	69-87	0.042	0.036	0.070	0.061 (0.082)
	South America	39-44	0.002	0.002	0.002	0.002 (0.002)
	Patagonia	45-51	0.031	0.016	0.027	0.019 (0.011)
	NW-America	23-29	0.007	0.004	0.017	0.016 (0.010)
	Alaska	7-22	0.047	0.054	0.012	0.017 (0.018)
	NE-America	1-6	0.010	0.026	0.011	0.016 (0.033)
	Arctic	53-61	0.030	0.018	0.032	0.026 (0.069)
1871-1960	**GLOBAL**	**1-100**	**0.146**	**0.135**	**0.120**	**0.099 (0.173)**
	Europe	62-65	0.003	0.001	0.002	0.001 (0.004)
	Asia	69-87	0.103	0.090	0.052	0.044 (0.065)
	South America	39-44	0.004	0.005	0.002	0.001 (0.001)
	Patagonia	45-51	0.085	0.047	0.021	0.014 (0.007)
	NW-America	23-29	0.018	0.013	0.012	0.011 (0.005)
	Alaska	7-22	0.103	0.116	−0.008	−0.009 (−0.007)
	NE-America	1-6	0.028	0.071	0.008	0.011 (0.028)
	Arctic	53-61	0.063	0.033	0.029	0.022 (0.065)
1961-1990	**GLOBAL**	**1-100**	**0.273**	**0.252**	**0.363**	**0.352 (0.427)**
	Europe	62-65	0.004	0.002	0.008	0.005 (0.008)
	Asia	69-87	0.064	0.050	0.127	0.112 (0.134)
	South America	39-44	0.003	0.004	0.004	0.004 (0.004)
	Patagonia	45-51	0.038	0.018	0.046	0.032 (0.025)
	NW-America	23-29	0.009	0.005	0.031	0.030 (0.024)
	Alaska	7-22	0.085	0.099	0.074	0.093 (0.095)
	NE-America	1-6	0.012	0.030	0.022	0.031 (0.048)
	Arctic	53-61	0.051	0.037	0.043	0.037 (0.081)
1991-2000	**GLOBAL**	**1-100**			**0.470**	**0.507 (0.583)**
	Europe	62-65			0.005	0.003 (0.018)
	Asia	69-87			0.175	0.157 (0.177)
	South America	39-44			0.007	0.007 (0.005)
	Patagonia	45-51			0.066	0.045 (0.038)
	NW-America	23-29			0.033	0.032 (0.026)
	Alaska	7-22			0.113	0.152 (0.152)
	NE-America	1-6			0.047	0.064 (0.079)
	Arctic	53-61			0.012	0.036 (0.072)

Table 3.8: Comparison of global and regional ice-volume changes expressed in mm year^{-1} w.e. of global sea-level change predicted over the periods 1871-1990, 1871-1960, 1961-1990, and 1991-2000. Estimates are derived by various combinations of temperature and precipitation data sets, i.e. $T_G P_{Z\&O}$, $T_G P_{CRUseries}$, $T_{OF} P_{Z\&O}$, and $T_{OF} P_{OFseries}$. The parameter Θ is set to 0.15 K except for the numbers in brackets where regionally variable Θs are applied. No estimates for the period 1991-2000 can be calculated where T_G is used in the calculation.

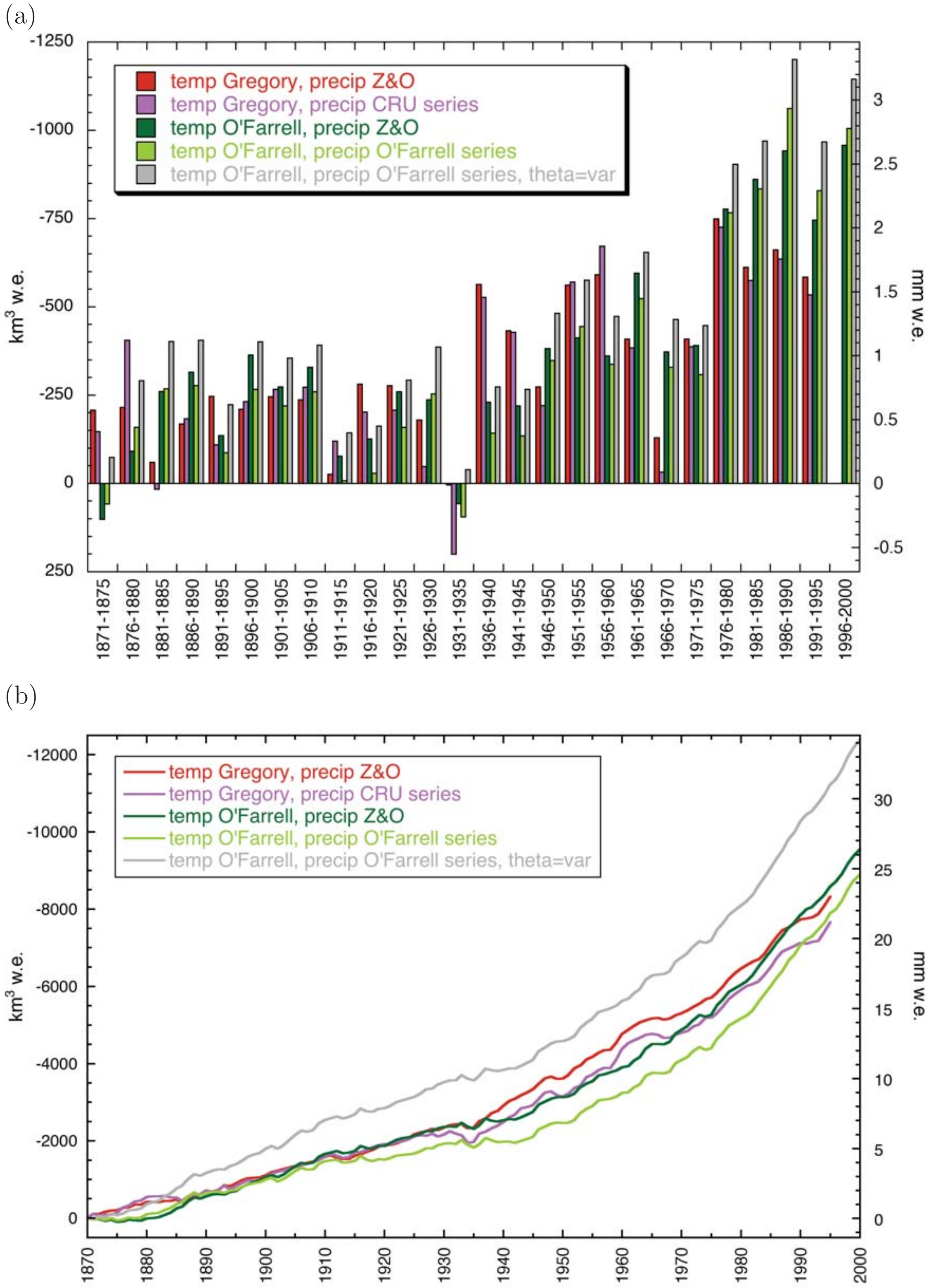

Figure 3.5: Ice-volume changes of 100 glaciated regions expressed in km^3 w.e. (and in mm global sea-level change) for (a) 5-year periods and (b) cumulative relative to 1870. Several combinations of temperature data sets by Gregory and O'Farrell and precipitation data sets by Zuo and Oerlemans (1997a), CRU, and O'Farrell are applied. In all cases the reference period 1871-1895 is used. The parameter Θ is set to 0.15 K except for the grey bars/curve where regionally variable Θs are applied.

The implementation of a precipitation data set other than $P_{Z\&O}$ in the model also affects the results. In general, the precipitation data sets of the CRU and O'Farrell reduce the global estimates by between 5 and 33%. It is noted however, that although trends in the precipitation time series are mostly relatively small (and only some are statistically significant at a 2σ level, see Tables B.3 and B.4), applying these time series (instead of average annual means) into the ice-volume calculation increases the global estimates by up to 20% (shown in Tables 3.4 and 3.6). Due to this obvious sensitivity of ice-volume estimates to trends in the time series of precipitation, only $T_GP_{CRUseries}$ and $T_{OF}P_{OFseries}$ are considered in all following calculations and analyses (and only those are listed in Table 3.8).

As illustrated in Table 3.8, when averaging over many decades (i.e. 1871-1990), global ice-volume changes are relatively insensitive to the combinations of the temperature and precipitation data sets applied. However, for ice-volume changes of 5-year periods, greater variations between the four model predictions (when Θ is globally set to 0.15 K) are computed (see Figure 3.5a). Using T_{OF} produces higher rates of ice-volume losses between 1880 and 1910, while between 1910 and 1960 the application of T_G typically results in increased losses. From about 1960 onwards, T_{OF} again produces mainly higher rates in ice-volume losses. Variations in the estimates over various periods using either T_G or T_{OF} can also be seen from Table 3.8. Figure 3.5b illustrates the cumulative ice-volume changes relative to 1870 using the four combinations of temperature and precipitation data sets (using Θ=0.15 K globally). It shows again that even with differences on annual and decadal time scales, over the period 1871-1990 the predicted ice-volume changes resulting from different data sets are comparable.

Similar conclusions can also be drawn when comparing the results of ice-volume changes of the 100 individual glaciated regions (see Table C.1 on pages 330-332) and also when comparing regional estimates (see Table 3.8). Over the period 1871-1990, using the T_G temperature data sets results in a 25-30% greater ice-volume loss in Alaska than the T_{OF}. Average estimates over the period 1871-1960 in Alaska have the opposite sign when using either T_G or T_{OF}. However, the difference between results for this region over the period 1961-1990 using the two temperature data sets is only about 10%. Also, the estimates of ice-volume changes for Svalbard's glaciers over the period 1961-1990 applying T_{OF} are just over half the estimates using T_G, although they are of the similar magnitude if averaged over the period 1871-1990 (numbers not shown in the table). This discrepancy reflects the different trends in temperature in the two data sets in that region. Ice-volume changes in

Asia are greater by up to a factor of 2 when using T_{OF} but only if averaged over 1871-1990 and 1961-1990. Over 1871-1960 the estimate in Asia using T_{OF} is only half that of T_G. For glaciers in Patagonia and Europe the application of the two different temperature data sets results in comparable ice-volume changes over the period 1871-1990. However, over 1871-1960 a decrease of ~75% and over 1961-1990 an increase of up to 100% are determined when using T_{OF} compared to T_G. In conclusion, variations in predicted mean ice-volume change in all regions during different periods indicate the dependence of estimates on the considered time period. Furthermore, in some regions considerable variations in estimates are derived when using different combinations of temperature and precipitation data sets.

Applying a regionally variable Θ in the calculation (instead of a global Θ of 0.15 K) increases the global estimate of ice-volume changes by about 0.075 mm year^{-1} w.e., as discussed in Section 3.1.5 (see also Figure 3.5). On a regional scale, the variations in the estimates are dependent on the Θ applied for that region (see numbers in brackets in Table 3.8). For example, the estimates of ice-volume changes in the Arctic for the various periods increase by at least 100% when using a Θ of 0.85 K in that region instead of a global value of 0.15 K (see also Table C.1 on pages 330-332). In contrast, predicted ice-volume losses in Alaska and South America using regionally variable Θs are almost identical to those using the global value for Θ (see Table 3.8). The reason for that is that the applied Θs (regionally and globally) are basically the same.

3.2 Observational estimates of recent ice-volume changes

The numerical model of recent mountain deglaciation developed in Chapter 2 is based on a number of assumptions and parameterisations as well as data sets of climate scenarios. As a consequence the numerical estimates of ice-volume changes presented in Section 3.1 are subject to considerable uncertainty. However, estimates based on observational evidence of mass balance changes are also uncertain due to various reasons, e.g. temporally and spatially incomplete observations which subsequently require the application of interpolation methods. Table 3.1 lists various studies of the sea-level contribution resulting from global melting of mountain glaciers over different periods based on mass balance observations.

There are many problems relating to data acquisition, processing, estimation of quality, dissemination of results and other issues which are addressed in Dyurgerov (2002) and updated in Dyurgerov and Meier (2005). The latter includes a global compilation of glacier mass balances and will be discussed in detail in Section 3.2.1. Another data set of worldwide annual mass-balance records for small glaciers is discussed in Section 3.2.2. Following, the differences between estimates based on observations and on numerical models are discussed on a global and regional scale in Sections 3.2.3 and 3.2.4, respectively. This comparison between numerically derived estimates and observations makes it possible to assess and verify the results derived in this thesis.

3.2.1 Global ice-volume changes compiled by Dyurgerov and Meier (2005)

The compilation of world-wide glacier mass balances by Dyurgerov and Meier (2005) is based on observational data on over 300 glaciers and is divided into glaciated regions, so-called glacier systems. The total glacier area estimated by Dyurgerov and Meier (2005) is $785 \pm 100 \times 10^3$ km^2. This value is larger than these established in their previous publications (e.g. Dyurgerov and Meier, 1997b), in part because isolated glaciers and ice caps around the periphery of the large ice sheets of Greenland and Antarctica have been included in the 2005 analysis. Subtracting these independent glaciers of Greenland and Antarctica in the compilation of Dyurgerov and Meier (2005) results in an area of 546,000 km^2, which is of comparable magnitude (only 3% larger) to the area used in the numerical model of this thesis.

Dyurgerov and Meier (2005) estimated a glacier wastage of 185 km^3 year^{-1} of water for the period 1961-2003, which is equivalent to 0.51 mm year^{-1} of eustatic sea-level rise, and increases to 0.93 mm year^{-1} for the period 1994-2003. If the glaciers around the periphery of the Greenland and Antarctic ice sheets are excluded, the ice-volume loss estimated by Dyurgerov and Meier (2005) is 159 km^3 year^{-1} w.e. over the period 1961-2003, which is equivalent to a contribution to global sea-level rise of 0.44 mm year^{-1} (see Table 3.9).

The glacier mass balance compilation published in Dyurgerov and Meier (2005) has been created using both *in situ* and geodetic observations. Measurements start as early as 1946 for some of the 303 individual glaciers. Mass balance observations for each year range between 4 and 110 glaciers within the period

period	**km^3 year^{-1} w.e.**		**mm year^{-1} w.e.**	
1961-2000	-173^a	-151^b	0.48^a	0.42^b
1961-2003	-185^a	-159^b	0.51^a	0.44^b
1994-2003	-336^a	-280^b	0.93^a	0.77^b

Table 3.9: Global ice-volume changes determined by Dyurgerov and Meier (2005) expressed in km^3 year^{-1} w.e. and mm year^{-1} of global sea-level change over several periods. A distinction between results including^a and excluding^b the glaciers at the periphery of the Antarctic and Greenland ice sheets is made.

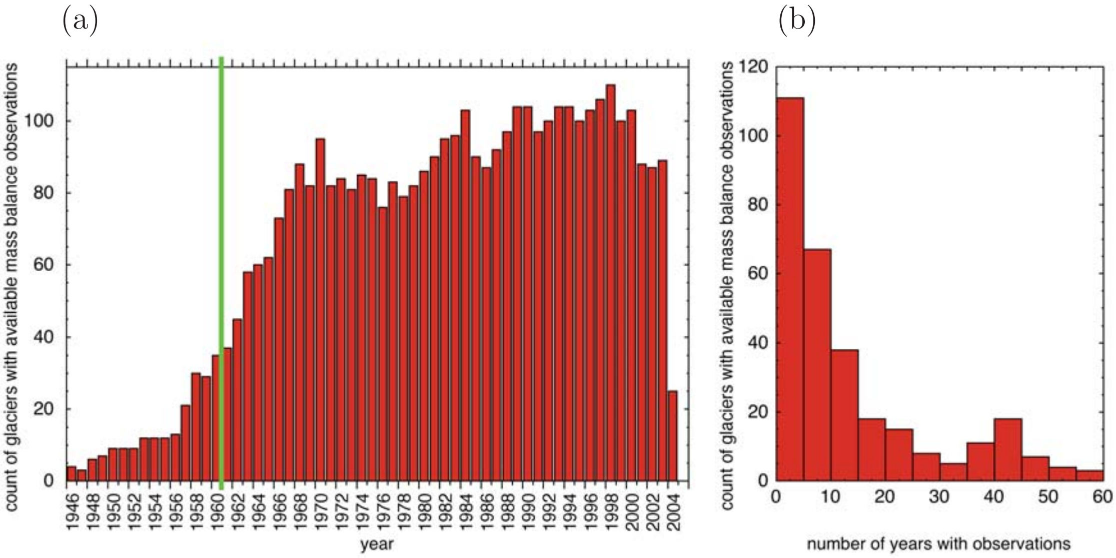

Figure 3.6: Histograms of (a) availability of annual mass balance records from 1946-2004 and (b) number of years with available mass balance observations over the period 1946-2004. The data is taken from Dyurgerov and Meier (2005).

1946-2003 (see Figure 3.6a). The number of observed glaciers expanded rapidly in the 1960s under the impetus of the International Hydrological Decade 1965-1974. A mean of 87 glaciers with available mass balance observations is determined over the period 1961-2003; this period has been chosen by Dyurgerov and Meier (2005) in order to have enough representative time series for any further analysis. The average number of years with available observations on the glaciers is 13 years out of the period 1946-2003 (see Figure 3.6b). Appendix 2 in Dyurgerov and Meier (2005) lists all available mass balance measurements of the individual glaciers used in their analyses. With this data set, compilations of larger, so-called *primary*, *regional*, and *continental systems* have been made and are critically assessed below.

- **Primary systems**

  Mass balance measurements for 49 primary glacier systems around the world (Appendix 3 in Dyurgerov and Meier, 2005) have been compiled from over 300 individual glaciers (Appendix 2 in Dyurgerov and Meier, 2005) where sufficient mass balance observations exist. While compiling the primary systems from the individual glaciers, *weighting of individual mean specific mass balance values by surface area* has been applied and subsequently *upscaled* proportionally by the area of the primary system. This 'manipulation' was necessary to account for the fact that observed glacier mass balances are biased towards small glaciers in many areas around the globe.

In order to understand the compilation-process of Dyurgerov and Meier (2005), an attempt to reconstruct the time series of the primary systems from the published data of the individual glaciers was undertaken. It was possible to reproduce the series only partly (two examples are given in Figure C.1 on page 324 and Figure C.2 on page 325), i.e. from the available data of individual glaciers the calculated ice-volume changes of the primary systems 4-8, 17-22, 26-28, 31-33, 37-42, and 44-47 are the same as given in Dyurgerov and Meier (2005). For some primary systems the time series are not or only partly reconstructable (systems 1-3, 10, 14-16, 23-25, 29, 30, 36, 43, 48, and 49). For many primary systems the given time series in Dyurgerov and Meier (2005) are extended, although there is no source data available for all years (or at least not published in the paper). According to Dyurgerov and Meier (2005) correlations between observational results have been applied in order to fill the gaps and enhance the time series. Furthermore, they note that reconstructions of annual glacier-volume changes using different approaches are used for several glacier systems. Since these various methods are not presented in detail in Dyurgerov and Meier (2005), it is not surprising that results presented in their paper are different to my reconstructions. It should also be noted that in several cases it was found that the published time series of primary systems in Dyurgerov and Meier (2005) are shifted by 1 to 3 years (without any obvious reason; namely, primary systems 9, 11-13, 34, and 35) and used that way for further calculations.

In summary, the failure to completely reconstruct the primary systems of Dyurgerov and Meier (2005) is primarily caused by the incomplete description of their compilation methods. As a consequence, the precision of their results cannot be assessed, however the magnitude of their average ice-volume changes are still very plausible. For further critical assessment, the results and methods of Dyurgerov and Meier (2005) will be discussed in detail below.

primary systems		area	volume change in	
			km^3 year^{-1} w.e.	mm year^{-1} w.e.
1	Alps	2,345	−0.43	0.0019
2	Scandinavia	2,942	0.47	−0.0013
3	Iceland	11,260	−2.52	0.0070
4	Pyrenia	11	0.00	−0.0000
5	Caucasus	1,432	−0.29	0.0008
6	Altai	1,750	−0.17	0.0005
7	Kamchatka	905	−0.07	0.0000
8	Suntar-Khayata	202	−0.02	0.0000
9	Dzhungaria	1,000	−0.07	0.0000
10	Himalaya	33,050	−13.41	0.0370
11	Kun-Lun	12,260	1.23	−0.0034
12	Tibet	1,802	0.54	− 0.0015
13	Pamir	12,260	−3.19	0.0088
14	Quilanshan	1,930	0.02	−0.000
15	Gongga	1,580	−0.40	0.0011
16	Tien Shan	15,417	−5.46	0.0151
17	East Africa	6	−0.01	0.0000
18	Axel Heiberg	11,700	−1.43	0.0040
19	Devon i.c.	16,200	−1.34	0.0037
20	Melville Island	160	−0.03	0.0000
21	Coburg Island	225	−0.12	0.0003
22	Baffin Island	37,000	−3.60	0.0099
23	Ellesmere Island	80,500	−5.76	0.0159
24	Svalbard	36,612	−6.05	0.0167
25	Greenland i.c.	70,000	−10.71	0.0296
26	Polar Ural	29	0.00	−0.0000
27	Severnaya Zemlya	18,326	−0.81	0.0022
28	Novaya Zemlya	23,645	3.31	−0.0091
29	Franz-Josef Land	13,459	−0.94	0.0026
30	Brooks	1,563	−0.36	0.0010
31	Alaska Range	13,900	−4.89	0.0135
32	Kenai Mtns.	4,600	−1.10	0.0030
33	Chugach Mtns.	21,600	7.78	−0.0215
34	St. Elias Mtns.	11,800	−11.33	0.0313
35	Coast Mtns.	10,500	3.71	−0.0102
36	Rockies + Coast	38,604	−19.51	0.0539
37	Labrador	56	0.00	−0.0000
38	Olympic	46	−0.01	0.0000
39	N. Cascades	266	−0.11	0.0003
40	M. and S. Rockies	76	−0.05	0.0001
41	Sierra Nevada	56	0.02	−0.0001
42	Mexico	11	−0.03	0.0001
43	S. Am. 0 - 20S	2,560	−1.47	0.0041
44	S. Am. 20S - N. Patagonia	2,128	−0.64	0.0018
45	S. and N. Patagonia	17,500	2.57	−0.0071
46	Irian Jaya	3	−0.0011	0.0000
47	New Zealand	1,160	−2.76	0.0076
48	Sub-Antarctic Islands	7,000	−1.37	0.0038
49	Antarctic i.c.	169,000	−21.97	0.0607
total		710,437		

Table 3.10: Glaciated areas in km^2 and average ice-volume changes in km^3 year^{-1} w.e. (and converted to mm year^{-1} global sea-level change) over the period 1961-2003 of 49 primary glacier systems from Dyurgerov and Meier (2005).

The average ice-volume changes of the primary systems from Dyurgerov and Meier (2005) are listed in Table 3.10. These regions represent about 90% (710,437 km^2) of the total glaciated area of 785,000 km^2. This discrepancy is mostly due to under-representation of glaciated areas in Alaska and Asia, which limits the accuracy with which global ice-volume change can be estimated.

One region in this compilation of primary systems that stands out in terms of average glacier-volume change is Novaya Zemlya (primary system no. 28) where a positive change is estimated. This is a result of a strong under-representation of observational data, as a measurement for only one year within the period 1961-2003 is available. Also, this number can not be confirmed by observations made at nearby glaciated regions (e.g. primary system no. 27 and 29) since no data for that particular year (nor for several years before and after) are available in those regions. The same problem of very small observational numbers also occurs in the Chugach Mountains (primary system no. 33) in Alaska. These are glaciated regions covering large areas of the landscape and hence have the potential to contribute significantly to global sea-level change. Therefore, it is critically important that these estimates have a high accuracy in order to estimate the sea-level contribution correctly. Glaciers in Irian Jaya (Papua New Guinea) and Mexico also have only one year of available observational data each. However, these glaciers are relatively small and contribute only a small amount to sea-level change and hence don't necessarily need further discussion. Furthermore, for a few larger glaciated regions, like the Coburg Island in Canada, Patagonia, and the glaciers in New Zealand, observations of only 2 to 6 years are available. The estimate for Franz-Josef Land is entirely based on the volume change determined by Macheret et al. (1999)[1] and as such presents another method of ice-volume change determination.

While it is questionable to use areas with so few observations to represent a smaller region (i.e. primary system), Dyurgerov and Meier (2005) argue that it is reasonable to use these rare data to compile an estimate valid for larger-scale regions with geographical and/or climatic similarities. This seems to be an expedient approach for estimating ice-volume changes based on observations and is briefly summarized and assessed below.

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[1] This reference is in Russian and no access was possible. Hence, no detailed information on the method they used to determine ice-volume changes in Franz-Josef Land can be given.

- **Regional systems**

  Using the data for 49 primary glacier systems, ice-volume changes of 12 larger-scale regional systems have been compiled (Table 3.11). The 12 regions where defined with regards to geographical and/or climatic similarities. Upscaling the volume changes of the primary systems in order to obtain results for regional systems is again based on the area differences between the two systems and is undertaken annually. Examples for this compiling-method for two regional systems are given in Figures C.3 and C.4.

regional systems		**area**	**volume change in**	
			km^3 year^{-1} w.e.	**mm year^{-1} w.e.**
1	**Europe** prim [1-5]	17,286	-0.75	0.0021
2	**West USA & Canada** prim [36-41]	39,194	-19.72	0.0544
3	**Canadian Arctic** prim [18-23]	151,800	-14.66	0.0405
4	**Russian Arctic** prim [26-29]	56,100	-2.49	0.0069
5	**Svalbard** prim [24]	36,612	-6.05	0.0167
6	**Greenland** prim [25]	70,000	-10.71	0.0296
7	**Alaska Coast Mtns.** prim [31-35]	90,000	-53.78	0.1486
8	**HM Asia** prim [9-16]	116,180	-30.74	0.0849
9	**Siberia** prim [6-8]	3,472	-0.43	0.0012
10	**N. and S. Patagonia** prim [44]	19,900	-16.90	0.0467
11	**South America** prim [43-44]	4,688	-0.49	0.0014
12	**Sub + Antarctic i.c.** prim [48-49]	176,000	-36.25	0.1001
total		**781,232**		

Table 3.11: Glaciated areas in km^2 and average ice-volume changes in km^3 year^{-1} w.e. (and converted to mm year^{-1} global sea-level change) over the period 1961-2003 of 12 regional glacier systems from Dyurgerov and Meier (2005).

In the compilation of Dyurgerov and Meier (2005) exceptions have been made for Alaska and Patagonia (regional system no. 7 and 10), where the annual weighting method by area differences described above has been replaced with recent detailed studies for these regions by Arendt et al. (2002) (for more details on this study see Section 3.2.4.1) and Rignot et al. (2003)[2]. Dyurgerov and Meier (2005, p. 43) state that there is 'relatively good agreement with observational results made by the standard mass balance geological method, which has been applied for dozens of years for benchmark glaciers in Alaska (Meier and Dyurgerov, 2002)'. However, I found that when using the "area-weighting-upscaling" method in Alaska (as done for all other regions), the resulting ice-volume change is only 55% of the value determined by Arendt et al. (2002). This raises the question whether this area-weighting-upscaling method produces adequate results for other regions as well. For Patagonia observations are so rare (observations are available for only two glaciers in Argentina and one glacier in Chile) that no sensible comparison can be made and the value provided by Rignot et al. (2003) is the only available estimate.

For the region of the Sub-Antarctic Islands and small glaciers of the Antarctic ice cap (regional system no. 12) the compiled ice-volume change of -36.25 km^3 year^{-1} w.e. (equivalent to a global sea-level rise of 0.10 mm year^{-1}) is almost twice the value of the primary system while the area remains the same. This discrepancy between the results of the primary and regional systems is caused by additional observations for the years 2000 to 2003 which "appear" in the time series of the regional system but are not available in the primary system.

Apart from the exceptions in some regions mentioned above, it was possible to reproduce the numbers of all other regional systems on the basis of the published time series of the primary systems of Dyurgerov and Meier (2005).

- **Continental systems**
  Data for six continental systems (Table 3.12) have been compiled using the primary glacier systems and upscaling the volume change by the area difference (same principle as for regional systems) to estimate the global ice loss of mountain glaciers. A total ice-volume change of -185 km^3 year^{-1} equivalent water (or 0.51 mm year^{-1} global sea-level rise) over a glacier area of about 785,000 km^2 is estimated by Dyurgerov and Meier (2005). This result includes independent glaciers at the periphery of the two big ice sheets of Greenland and Antarctica.

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[2] Rignot et al. (2003) estimated the ice loss of the largest 63 glaciers in the Northern and Southern Patagonia Icefields by comparing elevations models derived from early cartography and from the 2000 Shuttle Radar Topography Mission (SRTM).

continental systems		**area**	**volume change in**	
			km^3 year^{-1} w.e.	**mm year^{-1} w.e.**
1	**Europe** prim [1-5]	17,286	−0.75	0.0021
2	**Arctic** prim [18-30]	315,000	−44.43	0.1227
3	**Asia** prim [6-16]	121,575	−31.93	0.0882
4	**North America** prim [31-42]	129,300	−73.51	0.2031
5	**South America** prim [43-45]	25,000	−17.00	0.0470
6	**Sub + Antarctic i.c.** prim [48-49]	176,000	−17.14	0.0473
total		**784,161**	**−184.76**	**0.5104**

Table 3.12: Glaciated area in km^2 and average ice-volume change in km^3 year^{-1} w.e. (and converted to mm year^{-1} global sea-level change) over the period 1961-2003 of six continental glacier systems from Dyurgerov and Meier (2005).

> Similar to the compilation process of the primary and regional systems, some form of enhancement of the time series of the continental systems was obviously applied by Dyurgerov and Meier (2005). This again made it impossible to reconstruct all numbers of these glacier systems. For example, the volume loss of glaciers on the Sub-Antarctic Islands and on the Antarctic ice cap (continental system no. 6) is estimated at 17.14 km^3 year^{-1} w.e. (equivalent to a global sea-level rise of 0.05 mm year^{-1}). This is of the same magnitude as the result of the primary system (primary system no. 48 and 49), however it is approximately half the estimate of the regional system (regional system no. 12). The years of available data increase from 4 and 6 in the primary system to 10 in the regional system and 43 in the continental system. On the basis of the available information, this estimate of ice loss for the continental system no. 6 can not be reconstructed. Furthermore, for the two American continental systems that include Alaska and Patagonia (continental system no. 4 and 5), the time series could also not be reconstructed from the primary systems because the results of Arendt et al. (2002) and Rignot et al. (2003) were adopted in the compilation by Dyurgerov and Meier (2005).

Overall, the time-consuming attempt to understand and reconstruct the work of Dyurgerov and Meier (2005) was frustrating and left considerable uncertainty regarding the precision of their work. Nevertheless, it is the largest and most recent publicly available glacier compilation and must therefore form the bases of any assessment of results of the numerical models calculated in this thesis. For this purpose, the division in glacier systems of Dyurgerov and Meier (2005) needs to be reconstructed and this is explained in the following section.

3.2.1.1 Observed ice-volume changes of 100 glaciated regions

In the following approach the average ice-volume changes compiled into 12 regional systems (Table 3.11) of Dyurgerov and Meier (2005) have been applied to the locations and areas of the 100 glaciated regions of Zuo and Oerlemans (1997a). More details on these 100 regions, denoted generalised data set, are given in Section 2.3.1. This process provides the advantage to be able to compare any subsequent results using the same spatial representation of glaciated areas. The areas of the 100 regions are compiled by geographic locations and have been matched with the areas of the 12 glacier systems of Dyurgerov and Meier (2005). The corresponding rates of ice-volume changes of the regional systems have then been applied to the 100 glaciated regions and are graphically illustrated in Figure 3.7 and also listed in Table C.2 on pages 333-334. These ice-volume changes based on the data of Dyurgerov and Meier (2005) and applied to the 100 glaciated regions are denoted *D&M compilation* in the remainder of this thesis.

For comparative purposes, small glaciers at the periphery of the Antarctic and Greenland ice sheets are not included since they are also omitted in the numerical approach of Chapter 2. Furthermore, there are glaciated regions in the data set of Zuo and Oerlemans (1997a) which are not covered in the regional systems of Dyurgerov and Meier (2005). These are marked as '*n/a*' in the second column of Table C.2 and the values of the primary system have been applied here instead in order to include them as well. This was necessary for the glaciers of the Sub-Antarctic Islands as well as in Mexico, New Zealand, Africa, and Papua New Guinea. Except for New Zealand (#98) and the Sub-Antarctic Islands (#52, 99, and 100) the areas of these glaciated regions are always less than 10 km^2. Hence, the accuracy of the estimated ice-volume loss of these minor regions has little consequences to the prediction of the glacier contribution to global sea-level change.

The area of the 100 regions of Zuo and Oerlemans (1997a) represents 96.6% of the total glaciated area determined by Dyurgerov and Meier (2005), when excluding the independent glaciers around Antarctica and Greenland. This small difference reflects inconsistencies in area estimates between the two sources for some of the

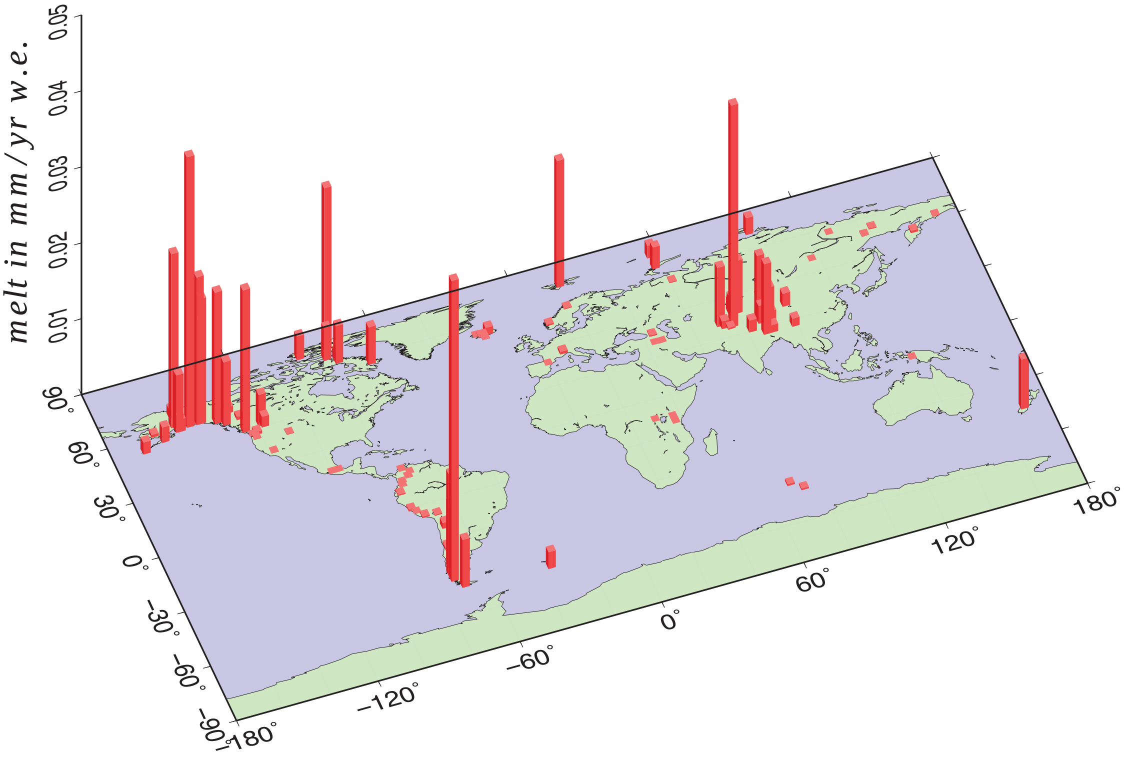

Figure 3.7: Ice-volume changes of 100 glaciated regions in mm year^{-1} w.e. over the period 1961-2003. Estimates of the 12 regional system of Dyurgerov and Meier (2005) are applied to areas of the 100 glaciated regions. Red bars indicate glacier retreat at these specific locations.

glaciated regions. For example, the area of the compiled regions of Siberia and West USA (regional system no. 2) and Canada (regional system no. 9) in Dyurgerov and Meier (2005) is 39,194 and 3,472 km^2, respectively. The corresponding regions in Zuo and Oerlemans (1997a), defined as glaciated region #21-30 plus #34-39 for regional system no. 2 and #40-47 for regional system no. 9, have an area of 19,115 and 1,745 km^2, respectively. Hence, these numbers represent only around 50% of those given in Dyurgerov and Meier (2005). For Patagonia and South America (regional system no. 10 and 11) the area in Zuo and Oerlemans (1997a) is 28,890 and 7,159 km^2, respectively, each around 50% larger than that given in Dyurgerov and Meier (2005). For the remaining regional systems of Dyurgerov and Meier (2005) it was possible to compile equivalent glacier areas from the Zuo and Oerlemans (1997a) data set, with no further discrepancies occurring.

The approach of applying the ice-volume changes from the regional system of Dyurgerov and Meier (2005) to the 100 regions of Zuo and Oerlemans (1997a) results in a total glacier wastage of 146.5 km^3 year^{-1} w.e. (equivalent to a global sea-level rise of 0.40 mm year^{-1}) for these 100 regions. This is 8% less than the original number (ice-volume loss of 159 km^3 year^{-1} w.e. or 0.44 mm year^{-1} global sea-level rise) estimated by Dyurgerov and Meier (2005) (excluding glaciers at the periphery of the Antarctic and Greenland ice sheets). Thus, when restructuring the areas and ice-volume changes of the 12 regional systems of Dyurgerov and Meier (2005) to the 100 glaciated regions, the global area and ice-volume loss remains roughly the same and hence is an expedient approach.

3.2.2 GGGMBAL: Worldwide annual mass-balance records for small glaciers

P. Adams, J. G. Cogley, and M. Ecclestone at Trent University, Canada, published on the university's website[3] a data set of worldwide annual mass-balance records for small glaciers, labelled GGGMBAL. Of the 336 glaciers, data on 15 glaciers are marked as doubtful and a further three glaciers do not have information on their areal extents. Comparing the available data with that of Dyurgerov and Meier (2005) shows that the GGGMBAL data set covers more glaciers but also that there are some differences in the available records of glaciers present in both data sets. Comparing the data histograms in Figure 3.8a (GGGMBAL data set) with Figure 3.6a (data set of Dyurgerov and Meier, 2005) reveals several differences. In particular, more glaciers with available observations for the year 2004 are present in the GGGMBAL data set than in Dyurgerov and Meier (2005) but at the same time there are years where observations of more glaciers are available in Dyurgerov and Meier (2005) than in the GGGMBAL data set (e.g. year 1998). From Figure 3.8b it is apparent that the additional glaciers in GGGMBAL are mostly of short observation duration (shorter than 10 years).

A comprehensive comparison between the GGGMBAL data set and the one published by Dyurgerov and Meier (2005) was undertaken for this thesis. Both data sets use the same core-set of glaciers; that is 286 glaciers are present in both data sets. Some other glaciers are present in Dyurgerov and Meier (2005) but not in the GGGMBAL data and vice versa. For most glaciers the time series in the two data sets are identical. However, some mass balance observations in the GGGMBAL data sets are extended to more recent years. Furthermore, it was found that for some glaciers the time series of mass balance observations were shifted by

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[3] Adams, P., J. G. Cogley, and M. Ecclestone. Global Glaciology: Mass Balance of Small Glaciers (GGGMBAL). Available online at
http://www.trentu.ca/academic/geography/glaciology/glpudown.htm
from the Department of Geography, Trent University, Ontario, Canada.

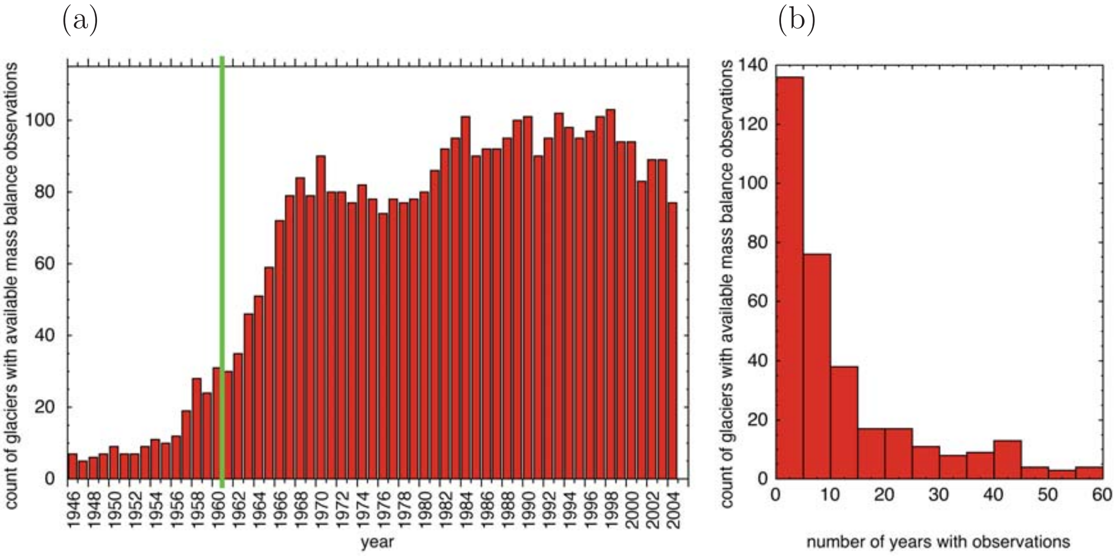

Figure 3.8: Histograms of (a) availability of annual mass balance records from 1946-2004 and (b) number of years with available mass balance observations over the period 1946-2004. The data is adopted from GGGMBAL which is available online from the website of Trent University.

one year between the two data sets. Identifying the correct time series would mean revising all individual sources and this has not been undertaken here as it would be out of the scope of this thesis. In general however, the two data sets of mass balance observations of GGGMBAL and provided by Dyurgerov and Meier (2005) are very similar.

Unlike in Dyurgerov and Meier (2005), Adams, Cogley, and Ecclestone do not provide a compiled version of regional and/or global glacier mass balances. However, for this thesis I have applied a similar approach to the one discussed in Section 3.2.1 of compiling individual glacier mass balances into primary, regional, and continental systems in order to compare them with the results of Dyurgerov and Meier (2005) and possibly solve some of the issues and problems that surfaced there. Only the regional-scale results for the Alaska system are discussed here because the compilation process is found to be highly sensitive to the glaciers and data used.

Dyurgerov and Meier (2005) published a time series for the Alaska region illustrated with the red curve in Figure 3.9. As mentioned in Section 3.2.1, Dyurgerov and Meier (2005) implement the results of Arendt et al. (2002) in order to determine the regional estimate of ice-volume changes in Alaska, but it was not possible to identify the exact method with which this implementation has been done. In the Dyurgerov and Meier (2005) data set 16 glaciers are available for the region of Alaska, whereas in GGGMBAL the number is 15. Applying the same "area-weighting-upscaling" method as in Dyurgerov and Meier (2005, also described in Section 3.2.1) using the observational data published in Dyurgerov and Meier (2005) results in the blue curve of Figure 3.9. Using the GGGMBAL data set results in ice-volume changes illustrated with a green curve in Figure 3.9. The last curve in particular is distinctively different to the published time series of Dyurgerov and Meier (2005), showing a growth in ice volume in Alaska from 1960 to 1988. This is inconsistent with other evidence (e.g. Arendt et al., 2002) and therefore must be examined in more detail.

The main differences between the two data sets in Alaska are found to be the time series for the Taku and Bering glaciers. The Bering glacier is located in the St. Elias Mountains and whereas there is no data for this glacier in GGGMBAL, Dyurgerov and Meier (2005) present data on it from 1950 to 2000. The area of the glacier is 5200 km^2 and it has an average mass balance rate of around -1000 mm year^{-1} (equivalent to an ice-volume change of -5.2 km^3 year^{-1} w.e.). The mass balance rate of Bering is strongly negative and adding the time series of this glacier to the GGGMBAL data set results in a regional estimate of ice-volume changes illustrated with a dashed light green curve in Figure 3.9, which is similar to the reproduction of the time series of Dyurgerov and Meier (2005). Small differences are still apparent as data on some other glaciers in the region are not completely identical. However, the above results demonstrate that the same outcomes are derived provided the same method and the same glaciers are used.

Mass balance observations for the Taku glacier are present in both data sets, however in the GGGMBAL data set an extended time series is given up to the year 2000 whereas in Dyurgerov and Meier (2005) the available data ends in 1986. Taku glacier is the principal outlet glacier of the Juneau ice field in the Coast Mountains. Taku has a large effect but it is not representative of other glaciers in that area. Unlike all other outlet glaciers of the Juneau ice field, Taku was advancing and thickening with an average mass balance rate of almost 400 mm year^{-1} (assuming an area of 671 km^2 this is equivalent to an ice-volume change of $+0.268$ km^3 year^{-1} w.e.) over the period 1946-1994 (see also Pelto et al., 2008). After that the average mass balance rate decreased to -180 mm year^{-1} (equivalent to an ice-volume change of -0.121 km^3 year^{-1} w.e.). This strongly positive mass balance rate of the Taku glacier over most of the second half of the 20^{th} century is not representative for the regional estimate and leads to significantly different conclusions about the regional trends in ice-volume changes. Therefore the data

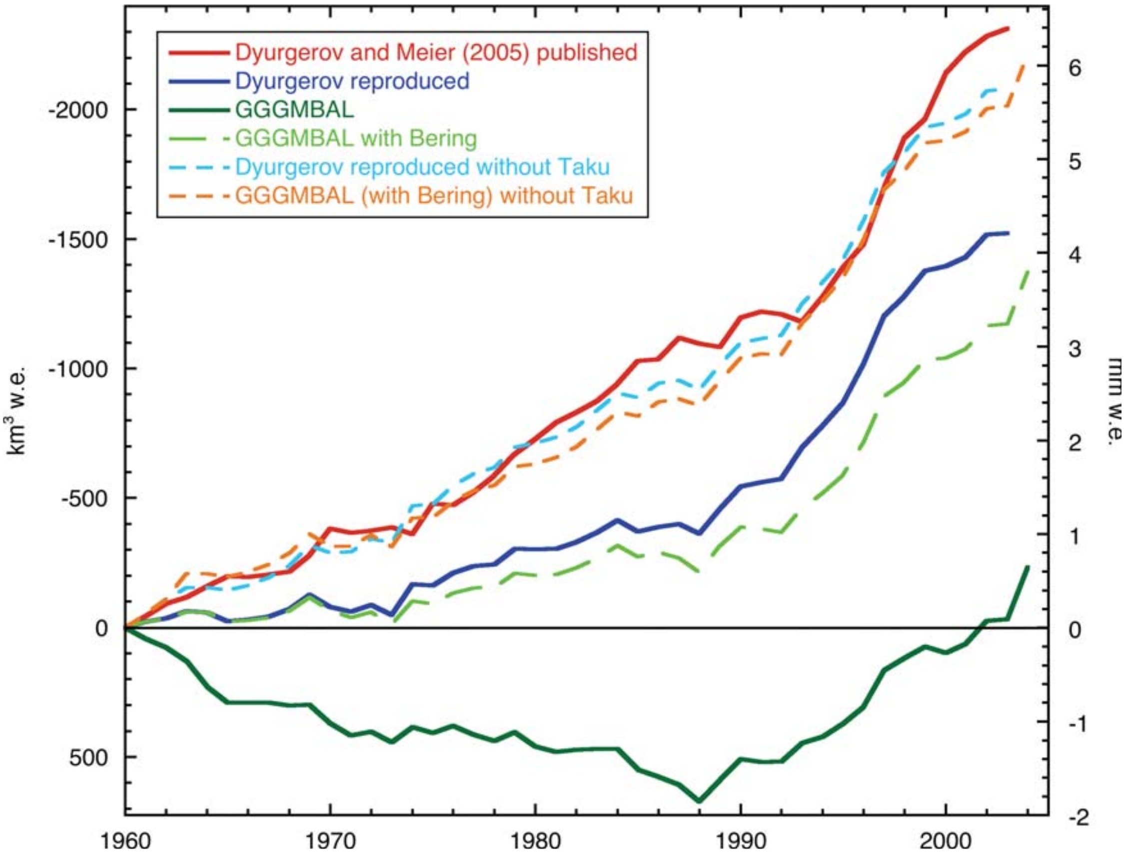

Figure 3.9: Ice-volume changes in Alaska in km^3 w.e. (and equivalent sea-level changes in mm) of the published time series of Dyurgerov and Meier (2005) plotted in red. Ice-volume changes determined from available mass balance records of Dyurgerov and Meier (2005) are shown in blue and using the data set of GGGMBAL in dark green. Adding the data of the Bering glacier to the GGGMBAL data set results in an Alaska-wide estimate represented by the dashed light green curve. Removing the Taku glacier from the data sets of Dyurgerov and Meier (2005) and GGGMBAL results in estimates for Alaska represented by the dashed light blue and dashed orange curves, respectively.

of Taku has to be used carefully when deriving a regional or Alaska-wide estimate. One simple way is to exclude the Taku glacier from the analysis. The results when removing Taku glacier from the data sets of Dyurgerov and Meier (2005) and GGGMBAL are illustrated with dashed light blue and dashed orange curves in Figure 3.9. They show that, although it is not known in detail how Dyurgerov and Meier (2005) obtained their Alaska-wide result, excluding the Taku glacier from either data set in the analysis results in similar ice-volume changes for Alaska to the published time series of Dyurgerov and Meier (2005).

Overall the above analyses show that the regional estimates are highly sensitive to the glaciers and data used. Furthermore, the method used to derive regional ice-volume changes based on a limited number of glaciers is also questionable.

In particular, it should be noted that the area for which glacier mass balance observations in Alaska are available covers only 3% of the total area in that region. Although the GGGMBAL data set might be more complete than the data set of Dyurgerov and Meier (2005), it does not provide enough new information to change the conclusions of the regional compilation (see also Kaser et al., 2006). However, it does help to give a better understanding of the limitations observational data sets have for the determination of regional and global ice-volume changes.

As only Dyurgerov and Meier (2005) published regional and global ice-volume changes, which are suitable for the modelling undertaken in this thesis, and also because the GGGMBAL data set does not provide any more information in respect to that of Dyurgerov and Meier (2005) which would improve the reliability of the regional and global estimates, only the data set of Dyurgerov and Meier (2005) has been used in the remainder of the thesis.

3.2.3 Global estimates of ice-volume changes

The numerical model of recent mountain deglaciation using various combinations of temperature and precipitation data sets, results in estimates of the equivalent global sea-level rise of 0.16 to 0.18 mm year^{-1} over the period 1871-1990 (Table 3.8). For the period 1961-1990 the numerical model produces estimates of ice-volume loss equivalent to 0.25 and 0.36 mm year^{-1} of eustatic sea-level rise, dependent on the temperature and precipitation data sets used. Using regionally variable Θs increase these estimates to 0.24 and 0.43 mm year^{-1} over the two periods. Five solutions for global cumulative ice-volume changes relative to the year 1960 are shown in Figure 3.10. As T_{OF} is also available for periods beyond 2000, ice-volume changes that are based on this data set are plotted until 2004 for further comparison purposes.

The global ice-volume change based on the compilation of mass balance observations by Dyurgerov and Meier (2005) was discussed in more detail in Section 3.2.1. This study, representing the most recent and largest compilation of glacier observations with detailed data made available, estimates a global average ice-volume loss of 159 km^3 year^{-1} w.e. over the period 1961-2003, which is equivalent to 0.44 mm year^{-1} of eustatic sea-level rise. The cumulative ice-volume loss relative to 1960 is represented with a dashed blue curve in Figure 3.10. Previous other observational studies, e.g. by Dyurgerov and Meier (1997b), can be ignored here since they have been superseded by the most recent analysis.

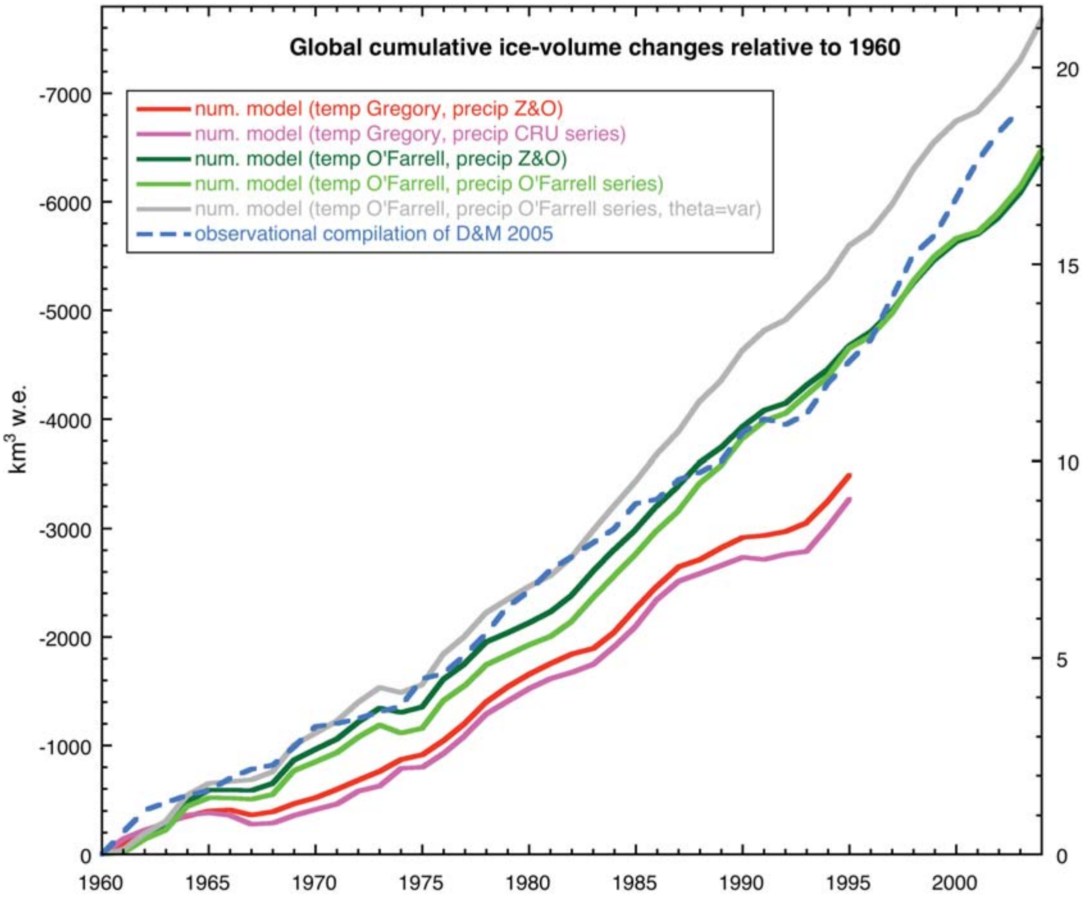

Figure 3.10: Global cumulative ice-volume changes of mountain glaciers in km^3 w.e. (and mm global sea-level change) relative to the year 1960. The result by Dyurgerov and Meier (2005) (dashed blue curve) is compared to estimates of the numerical model using various combinations of the temperature data sets of Gregory and O'Farrell and precipitation data sets of Zuo and Oerlemans (1997a), the CRU, and O'Farrell with a global Θ of 0.15 K (solid red, pink, dark green, and light green curves), as well as the estimate using regionally variable Θ values (grey curve).

Figure 3.10 illustrates that the Gregory temperature data set, whether $P_{Z\&O}$ or $P_{CRU series}$ is used, produces a global ice-volume loss that is lower than the results of Dyurgerov and Meier (2005). In contrast, using the O'Farrell temperature data set and Θ=0.15 K is in excellent agreement with that of Dyurgerov and Meier (2005). Using regionally variable Θs in the model gives slightly higher rates in ice-volume loss over the whole period than the observational value of Dyurgerov and Meier (2005). Figure 3.10 also shows that between 1980 and 1985 the ice-volume loss using the O'Farrell temperature data set shows the start of a slightly more pronounced increase in ice-volume loss than both the times series of Dyurgerov and Meier (2005) and of the numerical model using T_G. The analysis by Dyurgerov and Meier (2000), based on conventional mass balance measurements, also found an acceleration in ice-volume loss since the late 1970s. In particular, their study found an increase in average mass-balance change of over 100% from 1961-1976 to 1977-1997.

Figure 3.10 shows that the cumulative ice-volume loss of Dyurgerov and Meier (2005) accelerated in the early 1990s compared to the other estimates; the linear trend in ice-volume changes over the period 1994-2003 is about -200 km^3 year^{-1} w.e. when calculated numerically but greater than -300 km^3 year^{-1} w.e. in the compilation of Dyurgerov and Meier (2005). This is mainly caused by the increased ice-volume loss in Alaska determined by Arendt et al. (2002), which is incorporated in the Dyurgerov and Meier (2005) compilation.

The various numerical estimates derived over the period 1961-1990 (Table 3.8) also agree reasonable with the global estimate of ice-volume changes of 0.33±0.17 mm year^{-1} w.e. determined by Kaser et al. (2006); see Table 3.1. However, for the period 2001-2004, Kaser et al. (2006) estimated a greater ice-volume loss (0.77±0.15 mm year^{-1} w.e.) than predicted by the numerical model based on $\mathrm{T}_{OF}\mathrm{P}_{OFseries}$ (0.563 mm year^{-1} w.e.). Nevertheless, when using a regionally variable Θ, the model predicted a global ice-volume loss over 2001-2004 of 0.643 mm year^{-1} w.e., which is within the uncertainties determined by Kaser et al. (2006).

Despite some small discrepancies on a global scale, there is an overall good agreement between results derived numerically in this study and estimates based on observational data (e.g. Dyurgerov and Meier, 2005; Kaser et al., 2006), giving confidence in the estimates of global ice-volume changes over the past few decades that have been calculated in this thesis.

3.2.4 Regional estimates of ice-volume changes

The good agreement between global ice-volume loss derived from the numerical model in this thesis and determined from observations is promising. However, it needs to be validated whether the results of the numerical model also agree with observational studies on a regional scale. Detailed comparisons in the two regions of Alaska and Svalbard with other independent studies are presented in the following sections.

3.2.4.1 Estimates of ice-volume changes in Alaska

The glaciated area in Alaska is estimated to be around 90,000 km^2 (e.g. Oerlemans, 1993; Arendt et al., 2002; Dyurgerov and Meier, 2005). According to Zuo and Oerlemans (1997a) this represents around 17% of the total area of mountain glaciers on Earth.

Meier (1984) found that more than a third of his calculated global glacier contribution to sea level comes from the mountains bordering the Gulf of Alaska. However, he also noted that the results are limited by the lack of available data. Of the 14 glaciated mountain ranges and island groups in Alaska, Molnia (2007) found that all are characterized by significant glacier retreat, thinning, and/or stagnation, especially at lower elevations, since the late 19th century until present. Dowdeswell et al. (1997) estimated a sea-level rise of 0.008 mm year^{-1} from available mass balance measurements on 3 glaciers in Alaska (Brooks and Alaska Range) over the period 1965-1995. The compilation of glacier mass balances based on observational data determined by Dyurgerov and Meier (2005) produces an ice-volume loss in Alaska of 53.78 km^3 year^{-1} w.e. over the period 1961-2003, equivalent to 0.15 mm year^{-1} of eustatic sea-level rise (system no. 7 of Table 3.11 on page 89). However, it needs to be noted here again that this estimate uses results from the independent study of Arendt et al. (2002) and is therefore discussed in more detail below. The differences in cumulative ice-volume changes published in Dyurgerov and Meier (2005) and the average estimates of Arendt et al. (2002) (see blue and orange curves in Figure 3.11) cannot be explained with the information provided in the papers.

For the period 1961-1990 the ice-volume loss in Alaska from the numerical model using various combinations of temperature and precipitation data sets is estimated to be equivalent to between 0.074 and 0.100 mm year^{-1} of global sea-level rise, representing between 20 and 40% of the total global glacier melt. For the period 1991-2000 the average ice-volume loss is predicted to increase to 0.114 and 0.152 mm year^{-1} w.e., respectively, dependent on the precipitation data set used (see Table 3.8). As illustrated in Figure 3.11, the average estimate by Arendt et al. (2002) indicates more recent melting in Alaska than any predictions of the numerical models. However, cumulative ice-volume changes in the compilation of Dyurgerov and Meier (2005) is comparable to at least one of the predicted changes derived from the numerical model during 1961-1990, e.g. that of $\mathrm{T}_G\mathrm{P}_{CRUseries}$.

Using regionally variable Θ values in the numerical model does not affect the result

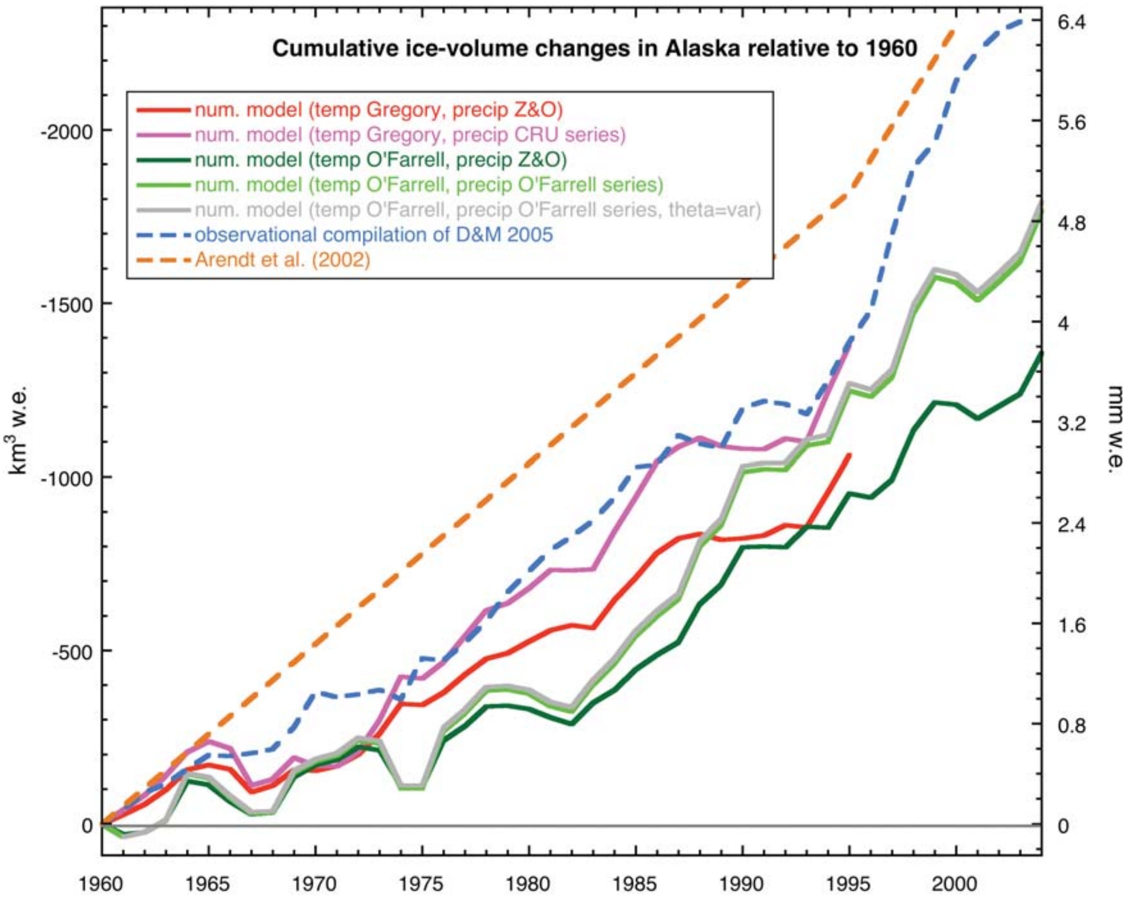

Figure 3.11: Cumulative ice-volume changes of mountain glaciers in km^3 w.e. (and mm global sea-level change) relative to the year 1960 for Alaska. The results of Dyurgerov and Meier (2005) and of Arendt et al. (2002) (dashed blue and dashed orange curves) are compared to estimates of the numerical model using various combinations of the temperature data sets of Gregory and O'Farrell and the precipitation data sets of Zuo and Oerlemans (1997a), the CRU, and O'Farrell with a global Θ of 0.15 K (solid red, pink, dark green, and light green curves), as well as the estimate using regionally variable Θ values (grey curve).

of ice-volume loss in Alaska. As already noted earlier in this chapter, this is because in the case of Alaska the regionally derived Θ is the same as the globally used number.

The slight acceleration in ice-volume loss since the early 1980s (as detected globally) can also be observed in the curve of cumulative ice-volume changes in Alaska based on the O'Farrell temperature data set (and in particular with the corresponding precipitation data set). This agrees with the study by Hodge et al. (1998), based on three glaciers in North-America and Alaska, showing that the ice-volume loss in the late 1980s increased due to both decreased winter accumulation and increased summer ablation.

The pronounced increase in ice-volume loss in the early 1990s of the Dyurgerov and Meier (2005) compilation is due to the incorporation of the study of Arendt et al. (2002). This significant increase, however, cannot be detected in the predictions derived from the numerical models.

Study of Arendt et al. (2002)

Due to some disparity in ice-volume changes in Alaska between the results of Dyurgerov and Meier (2005) and the numerical models of this study (see Figure 3.11), and also because the former adopted the results for Alaska from Arendt et al. (2002), it is important to discuss the work of Arendt et al. (2002) in more detail here.

The study by Arendt et al. (2002) deals with rapid wastage of Alaska's glaciers and their contribution to rising sea level in the second half of the 20^{th} century. The glaciated area in Alaska determined by Arendt et al. (2002) is 90,000 km^2. Based on measurements of volume- and area-changes from 67 glaciers (scattered within 7 geographic regions representing about 20% of the total glacier-area in Alaska), which were observed with airborne laser altimetry over the period 1993-1996, the authors extrapolate the volume loss to all glaciers in Alaska over the period from the mid 1950s to the mid 1990s (the *early* period). This has been done by comparing the profiles of the laser observations with topographic maps made from areal photographs acquired in the 1950s to early 1970s. In order to estimate the ice-volume changes from the mid 1990s to 2000/2001, reprofiling of 28 glaciers was undertaken since 1999. Hence, by comparing old and new profiles, the glacier changes over 5-7 years (the *recent* period) were determined. Results of average ice-volume changes determined by Arendt et al. (2002) over the two periods are listed in Table 3.13 and plotted in Figure 3.11 (dashed orange curve).

	volume change [km^3 year^{-1} w.e.]	**eustatic sea-level rise** [mm year^{-1}]
early period mid 1950s - mid 1990s	-52 ± 15	0.14 ± 0.04
recent period mid 1990s - 2000/2001	-96 ± 35	0.27 ± 0.10

Table 3.13: Changes in glacier volume expressed in km^3 year^{-1} w.e. and in mm year^{-1} of global sea-level change in Alaska determined by Arendt et al. (2002) for two different time periods. 67 glaciers are used to constrain the *early* period. Measurements on 28 glaciers are used to determine the ice-volume loss of the *recent* period.

Most glaciers reported in Arendt et al. (2002) thinned over most of their length during the early and the recent period. Only 5% were found to have thickened. A comparison of the 28 glaciers for which estimates for the early and the recent periods are available showed that the thinning rates on these glaciers increased by about 250% in the recent period. Arendt et al. (2002) noted that 75% of the measured volume changes over the early and recent periods are accounted for by a few large and dynamic glaciers (i.e. Columbia, Malaspina, Bering, LeConte, and Kaskawulsh). Arendt et al. (2002) also noted that their determined thinning rates for Alaska's glaciers are much larger than in other studies (e.g. Dyurgerov and Meier, 1997b) and attributed this to a sampling effect. For example, Dyurgerov and Meier (1997b) used only one long-term record of the Wolverine glacier to represent the glaciers of the Gulf of Alaska. However, measurements by Arendt et al. (2002) on a larger number of glaciers indicate that the thinning rates are much higher and hence the total loss in ice volume for Alaska is also greater. The estimate over the 1995-2000 period is also confirmed by the recent study of Chen et al. (2006a) using satellite gravimetry measurements from the Gravity Recovery and Climate Experiment (GRACE). The data used in Chen et al. (2006a) cover a period of only 3.5 years and hence results need to be examined with caution as they may include significant interannual variations and not so much the long term trend. Arendt et al. (2002) concluded that Alaska's glaciers have, over the second half of the 20^{th} century, made the largest single glaciological contribution to rising sea level yet measured.

The results of Arendt et al. (2002) can only be compared in a reasonable way to estimates derived from the numerical models (Section 3.1) if the same time periods are considered. The predicted change in ice volume of the numerical models in Alaska is between 0.069 and 0.116 mm year^{-1} w.e. over the period 1956-1995, dependent on the temperature and precipitation data sets used. This is only between 50 and 83% of the mean value determined by Arendt et al. (2002) for the same period (0.14 mm year^{-1} w.e.). From the numerical model using the O'Farrell temperature and precipitation data sets, where an estimate for the period 1996-2000 is possible, an ice-volume change equivalent to 0.172 mm year^{-1} of eustatic sea-level rise is determined, which is about 35% smaller than the estimate determined by Arendt et al. (2002) for the recent period. These conclusions are also valid for results where regionally variable Θs are applied in the calculation. In other words, using a regionally variable Θ has no significant effect on the predictions of ice-volume changes in Alaska.

The considerable smaller estimates of ice-volume changes derived from the numerical models in this thesis compared to the observational results of Arendt et al. (2002) can be interpreted in several ways. It is possible that the modelled temperature and/or precipitation data sets are not representative of the climate in Alaska in that period. Another interpretation is that the numerical model itself does not produce good estimates of mountain deglaciation in Alaska. Assuming that the observational approach of determining Alaska's glacier wastage by Arendt et al. (2002) is more representative of true ice-volume changes in Alaska than the numerical model, the latter needs to be recalibrated in order to match the observations (this is discussed in detail in Section 7.2.3).

3.2.4.2 Estimates of ice-volume changes in Svalbard

The glaciated area on the Svalbard archipelago as established by Zuo and Oerlemans (1997a) of 36,600 km^2 represents almost 7% of the total area of mountain glaciers world wide. The area of Svalbard's glaciers in Dyurgerov and Meier (2005) is basically the same, i.e. 36,612 km^2.

In the D&M compilation, the ice-volume loss in Svalbard (system no. 5 of Table 3.11, page 89) is estimated to be 6.05 km^3 year^{-1} w.e., equivalent to 0.017 mm year^{-1} of eustatic sea-level rise. This estimate is based on observations of 16 glaciers, of which almost half have available measurements over 10 or more years (within the period 1961-2003). The areas of these glaciers are small; in particular five glaciers have areas of less than 10 km^2 and two have areas of ∼50 and ∼100 km^2. Thus, extrapolation of this small base to the total glacial area of 36,600 km^2 is tainted with considerable uncertainties.

The numerical models of mountain deglaciation from Chapter 2 predicts an ice-volume loss in Svalbard between 4.74 and 8.43 km^3 year^{-1} w.e. (equivalent to 0.013 and 0.023 mm year^{-1} global sea-level change) over the period 1961-1990, dependent on the temperature and precipitation data sets applied (using a global value for Θ of 0.15 K). As for the example of Alaska in Section 3.2.4.1, in Svalbard the greatest ice-volume loss over the period from 1961 to 1990 is determined using $\mathrm{T}_G\mathrm{P}_{CRUseries}$ (see Figure 3.12). Results of ice-volume changes in Svalbard from the numerical model using a regionally variable Θ is a loss of 12.52 km^3 year^{-1} w.e. (equivalent to 0.035 mm year^{-1} global sea-level change) over the period 1961-1990. This increased value reflects the higher Θ-value applied for the Arctic region (0.85 K) compared to the globally used number.

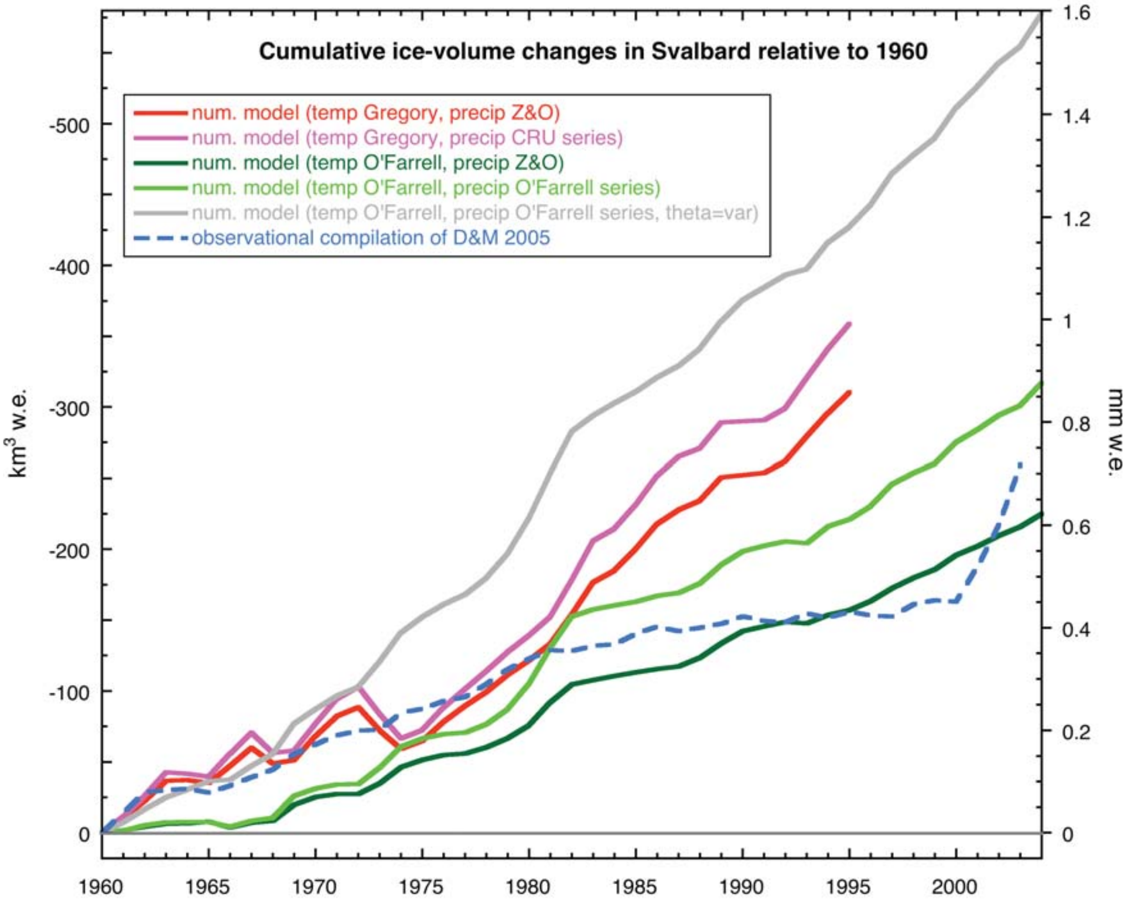

Figure 3.12: Cumulative ice-volume changes of mountain glaciers in km^3 w.e. (and mm global sea-level change) relative to the year 1960 for Svalbard. The results of the D&M compilation (dashed blue curve) is compared to estimates of the numerical model using various combinations of the temperature data sets of Gregory and O'Farrell and the precipitation data sets of Zuo and Oerlemans (1997a), the CRU, and O'Farrell with a global Θ of 0.15 K (solid red, pink, dark green, and light green curves), as well as the estimate using regionally variable Θ values (grey curve).

Dowdeswell et al. (1997) estimated a contribution to global sea level based on observations of three glaciers in Svalbard over the period 1950-1995 to 0.056 mm year^{-1} w.e.. This estimate is significantly larger than the numerical predictions by a factor of 2 to 4 when setting Θ to 0.15 K and considering the same period. However, the numerically derived ice-volume loss in Svalbard from 1951 to 1995 using a regionally variable Θ, i.e. 0.033 mm year^{-1} w.e., leads to an improved agreement with the estimate of Dowdeswell et al. (1997).

The mean specific mass balance rate of Svalbard's glaciers estimated by Hagedoorn and Wolf (2003) of -357 mm year^{-1} over the period 1980-1997 is based on studies of Hagen and Listøl (1990), Hagen (1996), and Dowdeswell et al. (1997). Assuming a glacier area in Svalbard of 36,600 km^2, this would result in an ice-volume loss of about 13 km^3 year^{-1} w.e. (equivalent to 0.036 mm year^{-1} global sea-level change). For the same period, the numerical model predicts an ice-volume loss of comparable magnitude when using T_G in combination with Θ=0.15 K and also when using T_{OF} with a regionally variable Θ.

In conclusion, as can be seen from Figure 3.12, the numerical predictions with a globally applied Θ of 0.15 K, in particular when using T_{OF}, are comparable to the estimate determined by Dyurgerov and Meier (2005) over the period 1961-2003. However, when comparisons to other studies (i.e. Dowdeswell et al., 1997; Hagedoorn and Wolf, 2003) are made, using a regionally variable Θ in the model shows better agreement.

3.3 Summary and conclusions

The first part of this chapter compares possible estimates for ice-volume changes derived from the numerical model described in Chapter 2 using various combinations of temperature and precipitation data sets as well as different parameter settings. With the available data sets, the sensitivity of results to temperature and/or precipitation changes is explored. The ice-volume loss of mountain glaciers is predicted to be equivalent to a global sea-level rise of between 0.16 and 0.24 mm year^{-1} w.e. over the period 1871-1990, between 0.27 and 0.43 mm year^{-1} w.e. over the period 1961-1990, and between 0.47 and 0.58 mm year^{-1} w.e. over the period 1991-2000. The increase in estimates during 1961-1990 and 1991-2000 reflects mainly the increase in observed temperature over recent decades. This illustrates the strong dependence of the predictions of ice-volume changes on temperature changes.

Average variations in global ice-volume loss of ±10-15% when using different precipitation data sets indicate the sensitivity of predictions to this climatic parameter. Precipitation data sets in which time series are used instead of average annual means (see Section 2.3.3) for the entire period are preferred as they include the effect of long-term time dependence of precipitation. As a consequence, for the period under consideration the time series lead to higher rates of ice loss.

Another sensitivity test has been performed with the parameter Θ, the imbalance between glacier and climate state within the reference period. This imbalance accounts for the fact that glaciers were responding to earlier climate fluctuations. A change of Θ by ±0.15 K globally results in a change in the predicted ice-volume equivalent to ±0.075 mm year^{-1} w.e. of global sea-level change. Applying regionally variable Θs result in a total estimate of ice-volume changes which is of comparable magnitude to that using a global number for Θ of 0.30 K.

On a regional scale, variations in ice-volume changes predicted by the numerical models are probably more pronounced. The case studies of Alaska and Svalbard show two examples for the range of possible ice-volume changes when derived numerically. The assessment shows that the average change over the period 1961-1990 as a result of one combination of input data sets can be up to double the estimate based on another combination, demonstrating the strong dependency on temperature and precipitation changes on a regional scale.

In general, over both periods, 1871-1990 and 1961-1990, predicted ice-volume changes on a global scale derived from the numerical models are comparable to results determined by other methods and studies (e.g Zuo and Oerlemans, 1997a; Gregory and Oerlemans, 1998; Dyurgerov and Meier, 2005; Raper and Braithwaite, 2006; Kaser et al., 2006, and others). Subsequently, in the second half of this chapter, I have compared in more detail the modelled estimates with observations of ice-volume changes of mountain glaciers on both global and regional scales.

It is demonstrated in this chapter, in particular with the two case studies of Alaska and Svalbard, that agreement between numerical estimates and observations can vary, such as that the prediction of a particular combination of temperature, precipitation, and Θ matches the observational data in one region but not in another. For example, $\mathrm{T}_G\mathrm{P}_{CRUseries}$ in combination with globally applied Θ of 0.15 K agrees with the observations in Alaska best. In contrast, $\mathrm{T}_{OF}\mathrm{P}_{OFseries}$ matches results of Dyurgerov and Meier (2005) globally and in Svalbard. In turn, the observational estimate of Dowdeswell et al. (1997) in Svalbard is best achieved when using a regionally variable Θ.

On the basis of the comparisons presented in this chapter, again it is not possible to single out one superior combination of parameter sets for the numerical model. However, to reduce the parameters in the subsequent analyses, only $\mathrm{T}_G\mathrm{P}_{Z\&O}$ in combination with a global Θ of 0.15 K and $\mathrm{T}_{OF}\mathrm{P}_{OFseries}$ with regionally variable Θs are continued to be used in the remainder of this thesis. In particular, the resulting modelled geodetic signals based on these two combinations of data sets and parameter settings are presented in Chapter 5. A comparison of the numerical estimates derived in this study with those based on observations enables the recalibration of the numerical model as a tool to improve the predictions. This is presented separately in Chapter 7.