Chapter 9

Summary and conclusions

Geomorphological and geological evidence, such as aerially exposed coral terraces and submerged coastal plains and caves, have shown that sea level has constantly changed through time (e.g. Lambeck and Bard, 2000). This evidence is supported by the interpretations of sea-level records constructed from biological indicators, such as terrestrial or freshwater plants that have been flooded by marine waters, submerged forests, and elevated fossil peats (e.g. Laborel and Laborel-Deguen, 1999) as well as archaeological indicators (e.g. Sivan et al., 2001). Reconstructions of global and regional climate change on a variety of geologic time-scales, are mainly based on $\delta^{18}O$ data (e.g. Chappell et al., 1996). On a global scale, these climate variations are largely associated with glacial-interglacial cycles and thus linked to major variations in relative sea level (Lambeck and Chappell, 2001). Interglacial periods, such as the last 6,000 years, are associated with elevated global sea levels, due to the melting of ice stored on continents.

Outcomes of various studies have led to the realisation that sea level has been progressively rising for the last 100 or so years and it will continue to rise throughout this century. Evidence also suggests that the rate of sea-level rise increased over recent years. That is the consensus derived by many scientists and climate modellers after decades of research (IPCC, 2001, 2007b). However, dependent on the method used, the rate of sea-level rise varies in time and space. According to the IPCC (2001) report, sea level has been rising at a rate of 1 to 2 mm year^{-1} over the last century. Attempts to explain the observations via numerical modelling of the contributing components result in smaller total estimates. The lack of agreement between the observational and modelled estimates of sea-level rise demonstrates that our current understanding of the complex interplay between all the processes involved is still inadequate.

Understanding the causes of past and recent variations in sea level is essential in order to make meaningful predictions of future changes. With this reasoning in mind, this thesis has focused on the contribution to sea-level changes, both at a local and global scale, that has resulted from mountain deglaciation. Although the amount of ice stored in mountain glaciers is only a small fraction of that locked up in the Antarctic and/or Greenland ice sheets, the ice-volume loss of the former contributed substantially to the rate of global sea-level rise over recent periods.

Observations made at individual glaciers have shown that they have been retreating at least since the end of the 19^{th} century with an acceleration in the ice-volume loss monitored over recent periods. A seasonally and regionally differentiated numerical model was developed in Chapter 2 (based on the approach of Zuo and Oerlemans, 1997a) to allow for both global and regional estimates of ice-volume changes. On the basis of observational constraints, the retreat of the glaciers was parameterised in terms of climate variables. A variety of data sets (i.e. temperature and precipitation) and parameter settings (e.g. mass balance model, initial imbalance between climate and glacier state) were carefully assessed. The differences between the data sets illustrate the difficulty of obtaining representative climate variables for glaciated regions.

This modelling allows for constraints to the total contribution of global sea-level rise that results from melting of mountain glaciers, covering an area of almost 530,000 km^2. In this thesis, an average ice-volume loss equivalent to a global sea-level rise of between 0.16 and 0.24 mm $year^{-1}$ is estimated over the period from 1871 to 1990. During 1961-1990 the average estimate increased to between 0.25 and 0.43 mm $year^{-1}$ and again accelerated to between 0.47 and 0.58 mm $year^{-1}$ over the period from 1991 to 2000. The range of these estimates, mainly a result of the different climatic data sets used, illustrates the uncertainty of modelling climate parameters (in particular temperature and precipitation) and defining parameter settings for glaciated regions as well as the difficulty of formulating recent mountain deglaciation numerically in a way that is adequate to accurately estimate global ice-volume losses. Hence, the goal of this thesis, to better constrain the contribution to recent and future sea-level changes as a result of mountain deglaciation, is not easy to achieve. However, the numerically calculated estimates in this study are comparable (at least on a global scale) to the results of previous studies that were based on extrapolated observational data (e.g. Dyurgerov and Meier, 2005; Kaser et al., 2006; Lemke et al., 2007, and references therein), as has been demonstrated in Chapter 3. Consequently, this numerical modelling has the capability to make projections for future changes in mountain glaciers.

Mountain glaciers in four principal regions, i.e. North-America, Patagonia, central Asia, and the Arctic Sea, have made the largest contribution to the total melt-water added to the oceans with continued deglaciation. The resulting relative sea-level changes and surface deformation due to the deglaciation do not appear uniform over the globe. The spatial variability, discussed in Chapter 4, is mainly determined by the deformation of the solid Earth due to unloading of the continents and the change in gravitational potential due to the changing ice-water load. Variations in relative sea level caused by the change in gravitational potential due to the deformation of the solid Earth and by the change in the Earth rotation parameters are close to negligible. This is due to the small dimensions of mountain glaciers and the short loading history.

Due to the non-uniform sea-level response to changes in surface loads, described in Chapter 4, the greatest variations in sea level are predicted where the largest changes in ice loss are taking place, as was illustrated in Chapter 5. Sea-level changes resulting from the melting of mountain glaciers determined in this study, show a similar global pattern to that already obtained by Nakiboglu and Lambeck (1991). Sensitivity studies of geodetic signals, performed in Chapter 4 and 5, show that the annual ice-volume loss from nearby glaciers, the spatial distribution of glacier areas, and the Earth models used, all affect the magnitudes of the predictions. From these analyses, the following conclusions were drawn: (i) a more precise representation of glaciated regions is required in order to obtain meaningful estimates of sea level and uplift for comparison with observed geodetic signals, (ii) variations in predicted geodetic signal in a region are directly proportional to the changes in the calculated ice-volume loss of glaciers located nearby, (iii) geodetic signals are largely independent of the elastic Earth model used when represented by three layers, although (iv) a low viscosity asthenosphere included in the Earth model can affect the magnitudes of the predicted geodetic signals significantly.

In this study, the estimated rates of relative sea-level changes at existing tide gauge sites in Alaska can reach more than -3 mm year^{-1} over the period from 1961 to 1990. At tide gauge sites in Svalbard, relative sea-level changes of approximately -1 mm year^{-1} are predicted. Alaska and Svalbard were only two examples where detailed analyses have been performed in this thesis. Glaciers in Patagonia also experienced a major recent loss in ice mass (e.g. Chen et al., 2007) and corresponding geodetic signals are believed to be of comparable magnitude to those in Alaska or Svalbard. Predicted relative sea-level changes due to recent mountain deglaciation at PSMSL tide gauge sites in the far field (e.g. in Australia) show mostly relative sea-level rise of around 0.2 to 0.3 mm year^{-1}. Located farther from the retreating mountain glaciers, the eustatic sea-level component is the dominant factor at these sites.

Due to the unloading process, land uplift occurs on the Earth's surface within and near the margins of the ice load. These vertical displacements were also discussed in Chapter 5 and have a maximum rate of $\sim$6 mm year^{-1} in Alaska and Asia over the period from 1961 to 1990. In Svalbard and Iceland vertical displacements at a rate of approximately 2 mm year^{-1} are predicted. Land movements in Patagonia are estimated to be $\sim$4 mm year^{-1}. These estimates are of a magnitude that can potentially be observed with geodetic techniques (Altamimi et al., 2002) and therefore it is possible to distinguish between different models or to put additional constraints on the estimated ice-volume changes.

In most cases, the above estimates of geodetic signals can not be "blindly" compared to observations. This is because the observations at these sites do not contain only the effect of recent mountain deglaciation, but also signals from other sources, climate-related or not. These were discussed in Chapter 6 and include tectonic activity and the deglaciation following the LGM and the LIA. Furthermore, contributions from recent changes in the Greenland and Antarctic ice sheets and changes in terrestrial water storage also affect geodetic signals on different levels. The spatial variability of thermal expansion affects the tide gauge stations directly but also results in second order relative sea-level changes due to changes in ocean bottom pressure. Analyses showed that the projected sea-level rise caused by these second order variations is negligible until the early 21st century but is amplified by 10% by 2200. The sea-level changes corresponding to the above listed factors all have different but distinct geographical patterns and also differ in magnitude. Hence, regardless of the area of interest, all individual contributions need to be carefully constrained in order to be able to explain the observational value.

It was demonstrated in Chapter 6 that in some cases the contribution from mountain glaciers can be larger than those resulting from other processes, e.g. from the deglaciation following the LGM. This again demonstrated the necessity of constraining mountain deglaciation more precisely. Moreover, the predicted signal at some sites that result from past glaciation/deglaciation cycles is negligible compared to that caused by recent mountain deglaciation. This allows for the separation of the components and hence the signal caused by the latter can be isolated. Tectonics can play a major role in some areas and must be considered when analysing geodetic observations. In particular, the magnitude of vertical displacements in tectonically active regions (e.g. in subduction zones) will often exceed those caused by recent mountain deglaciation, making it difficult to separate these signals.

Predictions of geodetic signals are predominantly dependent on the rate of surface load changes in the surrounding region. As the predicted signals can be large, using geodetic monitoring techniques could possibly provide a method to separate between the different estimates of ice-volume changes that are derived numerically or are based on glaciological observations. It was shown for the two case studies of Alaska and Svalbard, that for direct comparison between numerically derived estimates of geodetic signals and observations, processes other than recent mountain deglaciation have also contributed to the observed variation and need to be considered for successful modelling (Chapter 7). For example in Alaska, detailed information on the spatial and temporal distribution of earlier (and also recent) deglaciation histories are required to account for special regional circumstances in the Glacier Bay region and consequently to predict geodetic signals more accurately in order to understand the different contributions to the observed value. Furthermore, it was shown that in this region the Earth model may need to include a low viscosity asthenosphere, as the existence of such a layer is able to better explain the observations.

For the Svalbard case, accurate modelling of the geodetic signals due to recent mountain deglaciation is difficult as the regional ice-volume loss is poorly constrained. Hence, more information, including past deglaciation histories and the regional Earth model, are required in order to be able to explain the observed geodetic signals in this region.

At the current rate of global warming, the predicted future changes indicate that many of the small glaciers will be gone by the end of this century or even earlier. This alarming scenario will have consequences on environmental, social, and economic levels (e.g. fresh water supply, population distribution, and tourism) in many regions and will also affect global and local sea level. On a global scale, ice-mass of mountain glaciers equivalent to $\sim$1.5 mm year^{-1} sea-level rise is predicted to melt during the 21st century. In view of the total sea-level rise predicted over this century (approximately between 200 and 600 mm according to the IPCC, 2007b, report), this result indicates that mountain deglaciation continues to represent a major contribution. However, this globally averaged value is in great contrast to the local variations in relative sea level that are predicted at sites located close to the retreating glaciers. As the spatial variability of relative sea-level change in these regions is predominantly a result of the combined effects of the crustal rebound and the change in gravitational potential, predicted changes in relative sea level show a local fall and can reach rates of approximately -30 mm year^{-1}. However, for other regions, e.g. Australia, Indonesia, central America, etc., local sea level is predicted to rise at or above the global average rate ($\sim$1.5 mm year^{-1}) over the course of this century due to mountain deglaciation alone.