# Chapter 1

# Introduction

Over the past few decades, the level of interest in climate change and its consequences on people and the environment, including the related global sea-level rise, have increased immensely, both in the scientific community and the general public. Within the climate debate, changing sea level plays an important part. This is largely because a major proportion of the world's population lives in cities that are located close to the coast or near large river deltas (e.g. London, Amsterdam, Venice, New York, New Orleans). In the case of sea level, the top 10 countries/territories of the developing world with the highest impact on population (as a percentage of their national value) are Vietnam, Egypt, Mauritania, Suriname, Guyana, French Guiana, Tunisia, United Arab Emirates, the Bahamas and Benin, where a one meter rise would turn at least 56 million people into environmental refugees (Dasgupta et al., 2007). Additionally, for many low elevation islands (e.g. the Pacific island Tuvalu; Patel, 2006) and atolls, as well as developed estuarine coasts and countries like Bangladesh, the scope for inland migration is limited. Consequently, even a minor rise in sea level will have major social and economic impacts world wide.

These areas are hotspots of coastal vulnerability (Nicholls et al., 2007). However, sea-level rise is not necessarily the only factor that contributes to coastal vulnerability. The natural variability of coastal landforms is also a result of extreme events (e.g. storms), erosion due to changing wind patterns, offshore bathymetry changes, or reduced fluvial sediment input. Furthermore, as coastal population in many of the world's deltas, barrier islands and estuaries grow, this results in a widespread conversion of natural coastal landscapes to agriculture, aquaculture, silviculture, as well as industrial and residential uses. Some coastal countries and communities have the adaptive capacity to minimise the impacts of climate change, others (in particular developing countries) have fewer options and hence are much more vulnerable to climate change. Coastal vulnerability will thus vary considerably at regional and local scales, while Nicholls et al. (2007, p. 317) noted that 'the impacts are virtually certain to be overwhelmingly negative'. The IPCC (2007a) report concluded that the most appropriate response to sea-level rise for coastal areas is a combination of adaptation to deal with the inevitable rise and mitigation to limit the long-term rise to a manageable level. Essential to these adaptation plans is a solid understanding of the spatial and temporal variability of present and future sea-level change.

Evidence for past sea-level change is abundant in the geological record and rapid changes of amplitudes of several meters to tens of meters have been documented. For example, during the last deglaciation a rise of as much as 20 meters may have occurred within about 1000 years at ∼14,000 years BP (Meltwater pulse 1A), and comparable changes have occurred during times of glaciation (e.g. Fairbanks, 1989; Yokoyama et al., 2000). Most of these large changes occurred as a result of a mass exchange between the ice sheets and oceans, whereas thermal expansion or contraction of the ocean water volume played only a minor role. These rapid changes were possible because they occurred when large ice sheets extended onto the shelves and were potentially unstable and responsive to changes in the ocean-ice contact conditions. During the interglacials, such as the last 10,000 or so years most of the ice sheets have disappeared and the potential for instability is reduced although, particularly in the case of West Antarctica, not excluded. However, in some recent discussions it has been suggested that even the Greenland ice sheet may be unstable in the face of global temperature increase (e.g. Chen et al., 2006b).

Since the end of the last glaciation, at about 6,000 BP, sea levels have stabilised near their present levels. Since then, the changes have been smaller and driven primarily by changes in mountain glaciers, residual melting of the last great ice sheets, and thermal expansion. In addition, sea level is usually measured as the shift between the sea surface and land, and hence land movements of either tectonic origin or caused by the isostatic response to past redistribution of ice-water loads have to be carefully considered as these can be a substantial part of the total change. In some situations, the rate of rebound of the crust due to former deglaciation may exceed the rise in sea level resulting from the increased ocean volume and regional sea level will actually fall (e.g. in Scandinavia and Gulf of Bothnia).

On shorter than glacial time scales, relative sea-level changes are caused by local tectonic movements of the crust or by climate and meteorological factors. These are often episodic, rapid and short lived. On time scales of days to decades, changes in sea level are caused by changes in air pressure distribution over the oceans, winds, precipitation, terrestrial water storage, polar and mountain deglaciation, and changes in temperature in surface layers of the ocean.

High resolution, high precision records for recent times are available for only about the last 100-150 years and earlier records are based on geological, geomorphological, and archaeological evidence (e.g. Laborel and Laborel-Deguen, 1999; Lambeck and Bard, 2000; Sivan et al., 2001). Although they are primarily of relatively low resolution, they do indicate that no major increase in ocean volume occurred in the past 2-3 millennia (Lambeck, 2002) until about 100-150 years ago, approximately at the time of the industrial revolution (Church et al., 2001). This leads to the hypothesis that since the $19^{th}$ century, sea-level rise (ignoring land movements) or ocean volume increase has been the result of mainly thermal expansion and mountain glacier melt, both of which may be attributable to global warming. The contribution of thermal expansion on present-day sea levels has been discussed in this thesis only briefly but explored by others in more detail (e.g. Antonov et al., 2005) and I have focused here on the effects of mountain deglaciation with particular focus on its recent past and future contribution to sea-level changes.

Tide gauge measurements and satellite altimetry observations are presently the most important methods for sea-level observation. With the first mountings of tide gauge stations in Sweden, the Netherlands, France, and England at the end of the $18^{th}$ century, continuous monitoring of sea-level change began. Hence, historical sea-level changes, mainly over the last 100 or so years, can be determined on the basis of tide gauge records. These measurements are of relative nature, since the observation is done with respect to the Earth's surface. Thus, tide gauges, being attached to the land, have the limitation that the observed change at the site can also be a result of vertical land movements and not related to climate change. This can reduce the number of useful records drastically, as discussed in Douglas (1991). Another limitation of tide gauge measurements as an indicator for global sea-level change is the poor spatial distribution, e.g. tide gauges are located only at continental margins and ocean islands.

The latter problem can be bypassed by using satellite altimetry observations where nearly global coverage of the sea surface is possible. In contrast to tide gauges, the reference of satellite altimetry systems is the mass-centre of the Earth and hence absolute measurements of sea-level changes can in principle be made.

Unfortunately, satellite altimetry has its limitations as well. Firstly, altimetry measurements started only in the early 1990s (Cabanes et al., 2001) and this restricts the time period over which estimates can be made. Secondly, due to the relatively short length of such observations, these estimates can still contain decadal variations which are not related to long-term climate change. Nerem et al. (1999) assessed the variability in global mean sea level and found that roughly one decade of precise altimeter measurements is sufficient to average out the natural variability to obtain a long term rate, but in order to measure an acceleration in the trend, approximately 30 year of observations are required. Both those limitations strongly indicate the need for longer altimeter time series. Another error source can be the various corrections that are required, such as for glacial isostatic adjustment, atmospheric delay (dry/wet troposphere and ionosphere), atmospheric loading, and solid Earth and ocean tides, that need to be applied to the observations in order to construct the sea level (Hwang et al., 2002). An important result of satellite altimetry, however, is the discovery of the non-uniform geographical distribution of sea-level change (e.g. Cazenave and Nerem, 2004). In particular, in the western Pacific and the eastern Indian Ocean rates of sea-level rise are up to 10 times the average. In contrast, sea level has been dropping in some regions, such as the eastern Pacific and western Indian Oceans. Over the entire Atlantic Ocean, the altimetry measurements show sea-level rise during the period 1993-2003. However, regional trends of sea-level change might be attributed to the decadal-scale variability in the relatively short altimeter time series and hence caution must be taken when interpreting these data.

Due to the various differences between the two main methods of measuring sea level, estimates of sea-level change can vary. The study by Douglas (2001) determined a sea-level rate of 1.76±0.55 mm year$^{-1}$. After correcting for post glacial rebound (Peltier, 2001) this estimate increased to 1.84±0.36 mm year$^{-1}$ for the past 70 years. Church et al. (2004) used TOPEX/Poseidon altimetry data combined with historical tide gauge data and computed a global-averaged sea-level rise of 1.8±0.3 mm year$^{-1}$ over the period from 1950 to 2000. Holgate and Woodworth (2004) estimated a similar rate of 1.7 mm year$^{-1}$ sea-level rise during 1948-2002, based on 177 tide gauges with near global coverage. Church et al. (2001) assessed all available studies on tide gauge observations and concluded that sea level was rising at a rate of 1 to 2 mm year$^{-1}$, with a mean value of 1.5 mm year$^{-1}$ over the past century. In the latest IPCC (2007b) report, Bindoff et al. (2007) estimated a global sea-level rise, based on observations, of 1.8±0.5 mm year$^{-1}$ over the period 1961-2003.

Estimates of global mean sea-level rise determined from the satellite TOPEX/Poseidon and Jason are regarded as highly accurate (Cazenave and Nerem, 2004) and we can expect estimates of sea level rise to be more precise since the first of these came into service in 1992. With the data obtained from these satellites over the period 1993-2003, an estimated global sea-level rise of 2.8±0.4 mm year$^{-1}$ is determined (Nerem and Mitchum, 2001a,b). After removing the effects of postglacial rebound this value increases to 3.1 mm year$^{-1}$. Using data from all available studies, Bindoff et al. (2007) concluded that sea level has been rising at a rate of 3.1±0.7 mm year$^{-1}$ over the period 1993-2003. Overall, the above observational results indicate that sea level has been rising over the last century and also suggest that over at least the last decade an acceleration in the rate of global sea-level rise has occurred.

Causes for recent past and current sea-level rise are attributed to a number of factors (see Figure 1.1). The most important contribution to the 20$^{th}$ century sea-level rise was likely to be thermal expansion of the oceans as they warmed (0.5±0.2 mm year$^{-1}$). Global fluctuations in sea level may have also resulted from the growth and melting of continental glaciers (0.3±0.1 mm year$^{-1}$). Estimated Antarctic and Greenland mass imbalance (accounting for the long-term readjustment since the Last Glacial Maximum plus climate-related response) contributed −0.2 to 0.5 mm year$^{-1}$ to global sea-level rise (the negative estimate is mainly attributed to the recent contribution from the Antarctic ice sheet which according to some studies may be increasing in ice volume). The least certain contribution is the change in terrestrial water storage, ranging from −1.1 to +0.4 mm year$^{-1}$. These estimates for the individual contributions are updated by the latest IPCC (2007b) report for the more recent periods of 1961-2003 and 1993-2003 (see Figure 1.2). A pronounced increase over recent years in all individual contributions can be seen from these estimates.

The assessment of the various contributions to sea-level rise of the IPCC (2001) report show that the average model estimate for the 20$^{th}$ century (Figure 1.1) is lower (0.7±1.5 mm year$^{-1}$) than observational evidence. In particular, the observed value is more than twice as large as the total estimate of the individual contributions (although with an overlap of their uncertainties). Sea-level changes over more recent periods assessed in the IPCC (2007b) report show a better closure between observations and modelled values. In particular, for the period 1993-2003 the middle values differ by only 0.3 mm year$^{-1}$. However, note that the contribution

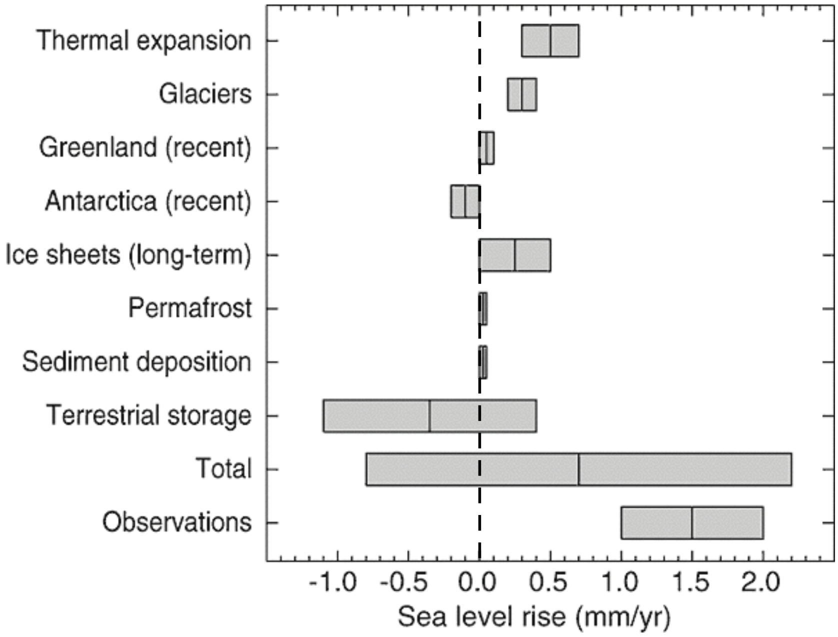


Figure 1.1: Contributions to sea-level changes over the period 1910-1990 according to the IPCC (2001) report (Chapter 11, Figure 11.9, p. 665).

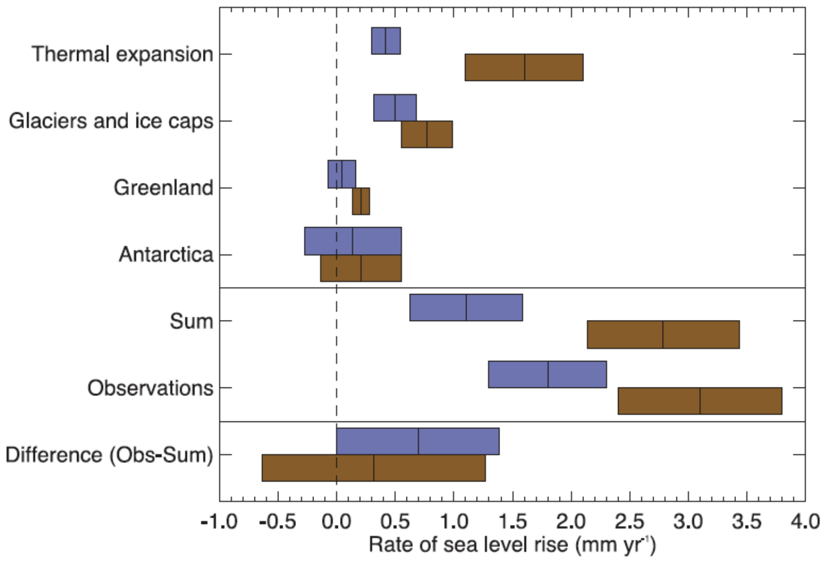


Figure 1.2: Contributions to sea-level changes over the periods 1961-2003 (blue) and 1993-2003 (brown) according to the IPCC (2007b) report (Chapter 5, Figure 5.21, p. 419). The report omitted those terms with a small contribution (very likely less than 0.2 mm year$^{-1}$) and also the contribution from terrestrial water storage because it is very poorly constrained.

from changes in terrestrial water storage is not included in this budget of modelled sea-level change.

The difference between the observations and modelled results can be attributed to an underestimation of the processes causing sea-level rise. Alternatively, the rate of sea-level rise observed with tide gauges or satellite altimetry may be interpreted incorrectly. Reasons advanced for the difference between climate related contributions and the observed sea-level rise in the $20^{th}$ century include:

**estimates of thermal expansion are underestimated:** Hydrographic measurements from oceanographic vessels and subsurface buoys are still the only tool for probing the subsurface of the ocean and these measurements suffer considerable gaps both in time and space. In particular, the Southern Ocean is poorly covered at all depths whatever the time span. Although deployment of a global network of measuring temperature and salinity with several thousand profiling floats (ARGO) started in 2000, for earlier periods the spatial distribution of temperature and salinity observations is very limited.

**tide gauge based sea-level rise is overestimated:** This is mainly attributed to the poor spatial sampling records at a few tide gauges, with available long sea-level records stemming mostly from the northern hemisphere. Another critical issue is the adjustments of records for vertical land movements. This includes glacial isostatic rebound effects and other geological processes.

**underestimated or unaccounted eustatic contributions:** Variations in the amount of water stored on land is mainly caused by changes in terrestrial water storage, mountain glaciers, and ice caps. Some of these factors are very difficult to quantify. For example, the land hydrology contribution to sea-level change assessed by the IPCC (2007b, p. 419) report ‘either is small ($<$0.5 mm year$^{-1}$) or is compensated for by unaccounted or underestimated contributions’.

Many research groups have attempted to solve the differences between the measured and predicted estimates of sea-level changes. However, the difference between the two, i.e. the factor 2 difference between observations and climatic contributions over the past 50 years, remains an enigma (Munk, 2002). This indicates that even if the total sea-level change can be precisely determined observationally, the cause of sea-level change will not be determined until we know the relative contributions of the main components, which are still highly uncertain. Understanding the relative contributions is, in turn, critically important to extrapolating future sea-level changes.

Global average estimates of sea-level changes may only be of limited value as there are many regional processes that result in a rise or fall in relative sea level affecting one coastline and not another. This occurs because of (i) different wavelengths of tectonic and other land movements and (ii) tendency for the ocean to follow an equipotential surface. This spatial variability occurs in all factors contributing to sea-level change: thermal expansion of ocean waters, changes in meltwater load, crustal rebound from glaciation, sediment deposition and compaction, uplift or subsidence in coastal areas in relation to various tectonic processes (e.g. seismic disturbance and volcanic activity), and fluid withdrawal. Together they can result in the significant spatial variation seen in observations of sea-level change.

The discussion above demonstrates the need to advance both observations and modelling of sea-level changes. The first is secured with the launches of satellite missions (e.g. GRACE, ICESAT), improved ground based satellite techniques such as GPS and DORIS, and most importantly, the satellite altimetry data of Jason and any other planned missions for the future. In contrast, modelling sea-level change requires an understanding of the actual physical processes, not simply a description of what happens. This also enables us to make extrapolations into the future (or past). The understanding of the different contributions to changes in global, regional, and local sea level and their estimates is the motivation for this thesis. Particular focus is given to the investigation of the contribution to relative sea-level changes due to recent melting of mountain glaciers.

Glacier fluctuations are of great interest for several reasons, including water resource management, avalanche forecasting, glacier dynamics, hydrology, and hydrochemistry, as well as the response of glaciers to climate change. In the past few decades there has been a tremendous increase in the interest in glacier-climate relationships, partly because of the link to measured sea-level rise. Glacier mass balance is monitored at numerous sites worldwide, and remote sensing methods for monitoring snow accumulation and snow/ice surface melting are rapidly improving. Furthermore, during the past few decades, a large variety of melt models have been developed, ranging from simple temperature-index to sophisticated energy-balance models. There is also a recent trend towards modelling with both high temporal and spatial resolution.

Mountain glaciers have relative high mass turnover and react much faster (with a response time in the order of decades to centuries) to changes in climatic forcing than the two ice sheets of Greenland and Antarctica (with a response time of several centuries). Hence, in spite of the small volume involved, it is believed that glaciers and small ice caps contribute significantly to sea-level fluctuations on the century scale.

Over the next century, mountain glaciers are expected to continue to make a major contribution to sea-level rise due to global warming and the associated changes in precipitation. Again, this is not so much because of the absolute amount of possible sea-level rise caused by the melting of mountain glaciers (the total volume stored in mountain glaciers is estimated to be equivalent to a sea-level rise of about 50 cm, compared to an estimate of about 65 m for the two polar ice sheets; IPCC, 2001), but because of the much shorter response time. Thus, it is not surprising, that this field of research has been very active in recent years.

In order to calculate geodetic signals (i.e. changes in relative sea level and vertical deformation of the Earth's crust) resulting from glacial loading and unloading, two major processes have to be quantified: (i) the spatial and temporal distribution of surface loads and (ii) the response of the Earth and the sea level to these changes. The latter involves complex mathematical calculations and is dependent on a range of parameters, including the Earth rheology, the spatial and temporal distribution of the surface loads, and the shape of the ocean basin. The variability of geodetic signals can also be measured with the help of new geodetic techniques and hence new observational constraints are possible.

Predicting relative sea-level changes resulting from recent mountain deglaciation is valuable in itself, but scientifically it also provides opportunities to infer Earth parameters from observations. Comparing observations of geodetic signals with predictions makes it possible to evaluate the physical properties of the Earth and ice loads. This enables us to provide a comprehensive model of past and present sea level changes and shoreline configurations, which in turn is essential to make predictions of future sea-level change.

## 1.1 Thesis structure

Chapter 2 addresses the methods currently used for estimating glacier mass balance. Compared to the total area of ice on land of 16,000,000 km$^2$, the area covered by mountain glaciers is small. Nevertheless, this area of more than 500,000 km$^2$ has been retreating since the $19^{th}$ century in most parts of the world. A method to model the ice-volume changes of mountain glaciers over time is presented and the data sets required to make these calculations are introduced.

The IPCC (2001) report assessed available studies on sea-level rise and concluded that there has been an increase in global sea level at a rate of 0.2 to 0.4 mm year$^{-1}$ that has resulted from the melting of mountain glaciers since the beginning of the $20^{th}$ century (Church et al., 2001). In Chapter 3 a numerical model for calculating ice-volume changes of mountain glaciers is used to derive global and regional estimates. A range of outcomes is presented which indicates the difficulty of modelling global mountain deglaciation accurately. In the same chapter, a compiled data set of glacier mass balances based on observational data (Dyurgerov and Meier, 2005) is critically assessed. Differences between observational results and the ice-volume changes derived from the numerical model are addressed. Additionally, estimates from both approaches are compared on a global and regional scale.

Chapter 4 discusses the theory of the response of the Earth and the sea level due to changes in surface loads. The sea-level equation with its main contributions is introduced and results of a case study in Svalbard are given. The impact on results in Alaska and Svalbard using various Earth models is also discussed.

In Chapter 5, the spatial distribution of both relative sea-level changes and vertical displacements resulting from recent changes in mountain glaciers is calculated. Detailed analyses are presented for the two case study regions: Alaska and Svalbard. Discussion as to whether these changes can be identified in geodetic tide gauge, GPS and VLBI measurements is also presented.

Chapter 6 discusses the contributions to present-day sea-level changes from sources other than recent mountain deglaciation. In particular, the contributions due to the deglaciation following the Last Glacial Maximum and the Little Ice Age are assessed. A short literature review is given on the recent contribution of the Antarctic and Greenland ice sheets to present-day sea-level changes. Sea-level changes due to hydrological variations on continents and due to ocean bottom pressure changes caused by thermal expansion are discussed. Tectonic movements can contribute significantly to relative sea-level changes in many areas. While a complete assessment of this process would require a more comprehensive study, this chapter provides a brief insight through the case study of Alaska.

A further comparison between observations and predictions can be made using geodetic signals, i.e. relative sea-level changes and vertical surface deformation.

Chapter 7 compares observations of geodetic signals with the predicted values from recent mountain deglaciation of Chapter 5 and also taking into account other contributing factors discussed in Chapter 6. This evaluation permits the reassessment and/or recalibration of the numerical model of recent mountain deglaciation in order to improve the agreement with observational data sets.

Chapter 8 gives a short discussion on predicted melting of mountain glaciers to the end of this century and the corresponding effect on local and global sea level.

Finally, Chapter 9 summarises the work and presents some conclusions.