Projected Change—Sea Level

14

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Abstract

Global warming is causing sea levels to rise, primarily due to loss of land-based ice masses and thermal (steric) expansion of the world oceans. Sea level does not rise in a globally uniform manner, but varies in complex spatial patterns. This chapter reviews projections of the individual contributions to sea-level rise. These are used to assemble a mid-range scenario of a 0.70 ± 0.30-m sea-level rise over the twenty-first century (based on the SRES A1B scenario) and a high-end scenario of 1.10 m. The sea-level projection was regionalised to the Baltic Sea area by taking into account local dynamic sea-level rise and weighting the components of the sea-level budget by their static equilibrium fingerprint. This yields a mid-range Baltic Sea sea-level rise that is ~80 % of the global mean. Ongoing glacial isostatic adjustment (GIA) partly compensates for local sea-level rise in much of the region. For the mid-range scenario, this equates to a twenty-first century relative sea-level rise of 0.60 m near Hamburg and a relative sea-level fall of 0.35 m in the Bothnian Bay. The high-end scenario is characterised by an additional 0.5 m.

Keywords

Regional • Sea level rise • Climate change

14.1 Introduction

Global warming is causing sea levels to rise, primarily due to loss of land-based ice masses and thermal (steric) expansion of the world oceans (Meehl et al. 2007). The rise in global mean sea level (GMSL) is projected to accelerate over the twenty-first century (Meehl et al. 2007; Rahmstorf 2007a; Grinsted et al. 2010; Jevrejeva et al. 2010, 2012b). Sea level does not rise in a globally uniform manner, but has been observed to vary in complex spatial patterns (e.g. Douglas 2001; Bindoff et al. 2007). The projected changes in regional relative sea level (RSL, see definition of key terms in Chap. 9, Box 9.1) will deviate markedly from the global mean for a variety of reasons. In the Baltic Sea region, there is a large ongoing land uplift caused by glacial isostatic adjustment(GIA) due to the loss of the Fennoscandian ice sheet at the end of the last glacial period. In the Bothnian Bay, the RSL changes due to this adjustment are of the order of 1 m per century (Hill et al. 2010). The dynamic sea surface topography response to climate change will be far from uniform, and similarly, mass loss from ice sheets will not distribute evenly across the world oceans (Mitrovica et al. 2001; see Chap. 9). A practical and common approach to projecting regional sea-level rise is to project the individual major contributions to GMSL rise and combine this budget with the corresponding spatial fingerprints of each contributor (e.g. Slangen et al. 2011; Perrette et al. 2013; Spada et al. 2013). Published regional sea-level rise projections have generally focused on the global scale and have had insufficient detail to resolve the Baltic Sea. It has therefore been necessary to construct new sea-level projections specifically for this chapter using published fingerprints combined with a review of the projected sea-level budget.

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There will be changes in sea-ice cover, salinity and atmospheric forcing of the Baltic Sea (see Chap. 13). These changes in local boundary conditions may influence decadal sea-level variability (e.g. Hünicke and Zorita 2006) and the statistics of extreme storm surges and wave heights (Chap. 13), but may not be major contributors to century-scale changes in mean sea level: some studies show that stronger winds and increased run-off may contribute in the order of 5-cm local sea level (LSL) rise for some locations in the Baltic Sea (Hünicke 2010; Meier et al. 2004, 2006, 2011). This contribution is not considered in this chapter as this effect is included separately in models of changing storm surge statistics (Chap. 13).

14.2 Sea-level Budget

There are different approaches to making sea-level rise projections. The traditional approach has been to build models of the individual major contributors and from these project the evolving budget (e.g. Meehl et al. 2007). As an alternative, semi-empirical models have been constructed where the rate of global sea-level rise is statistically related to global temperature (Rahmstorf 2007a; Horton et al. 2008; Vermeer and Rahmstorf 2009; Grinsted et al. 2010) or radiative forcing (Jevrejeva et al. 2009, 2010, 2012b; Moore et al. 2010). Semi-empirical models generally project greater twenty-first century sea-level rise than the budget from process-based models. For example, the semi-empirical model by Grinsted et al. (2010) resulted in projections of twenty-first century sea-level rise that are about a factor of three greater than those from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The gap is partly explained by dynamical ice sheet discharge, which was not modelled by AR4 generation ice sheet models. Since then, there has been a large ongoing effort to improve the projections of land-based ice loss. The improvements have increased the process-based projections since AR4 (e.g. Spada et al. 2013), and the gap between process-based and semi-empirical projections has narrowed in recent years to the point where confidence intervals overlap. There is, however, still considerable uncertainty in the evolution of the sea-level budget. There is disagreement over the level of confidence that should be assigned to current semi-empirical versus process-based projections (Holgate et al. 2007; Rahmstorf 2007a, b, 2010; Schmith et al. 2007; von Storch et al. 2008; Vermeer and Rahmstorf 2009, 2010; Taboada and Anadón 2010; Rahmstorf et al. 2012b). Process-based models have not been able to fully account for the rate of twentieth-century sea-level rise (Rahmstorf 2007a, 2010; Rahmstorf et al. 2012a), except when combinations of process models with exceptionally large twentieth-century contributions are picked (Gregory et al. 2013). Furthermore, there is still a high degree of structural uncertainty in models of ice sheet loss. For example, modelling of dynamical ice sheet discharge and ice–ocean interaction is relatively immature, and projections of dynamical ice loss are often not driven by a specific emission scenario (e.g. Bindschadler et al. 2012). This uncertainty is also reflected in the large spread of estimates given in an expert elicitation of ice sheet experts (Bamber and Aspinall 2013). For these reasons, there is a lack of confidence in process-based model projections of sea-level rise. On the other hand, the statistical methods used to calibrate some semi-empirical models have been criticised in the literature (Holgate et al. 2007; Rahmstorf 2007b; Schmith et al. 2007; Taboada and Anadón 2010; Vermeer and Rahmstorf 2010; Rahmstorf et al. 2012b; Grassi et al. 2013). In addition, the physical justification for the semi-empirical model formulations has been questioned (von Storch et al. 2008; Vermeer and Rahmstorf 2010; Jevrejeva et al. 2012a). Ice sheet mass loss has a nonlinear equilibrium response (e.g. Levermann et al. 2013), which cannot be captured by current semi-empirical models. However, recent modelling studies have found that ice sheet volume response on century timescales is remarkably linear in imposed forcing (Bindschadler et al. 2012; Winkelmann and Levermann 2012) which suggests that semi-empirical models can approximate ice sheet mass loss over a few centuries.

For regional sea-level projections, it is necessary to know the detailed budget as the different contributors will have very different spatial 'fingerprints' in the Baltic Sea. Semi-empirical models of GMSL rise do not inform on the partitioning between contributors and cannot be used directly in regional sea-level rise projections. Thus, this chapter reviews process-based estimates and combines these with published regional fingerprints to construct mid-range and high-end scenarios of the projected rise in regional sea level. This exclusive focus on process-based estimates over semi-empirical models should be kept in mind when assessing the likelihood of the resulting regional sea-level rise scenarios.

The mid-range regional sea-level rise scenario is based on an assessment of projections using the SRES A1B scenario for 2090–2099 with respect to 1980–1999. On century timescales, the major sea-level contributors (land ice loss and thermosteric expansion) will respond to the integrated climate forcing history. A practical approach to estimating the LSL response for scenarios other than A1B can be estimated by scaling the A1B projections with the relative steric response between the two scenarios (see Table 14.1). This makes it possible to estimate LSL for the new generation of representative concentration pathways (RCPs) in the CMIP5 model inter-comparison project from the A1B projections presented in this chapter. The steric scaling ratio of

Table 14.1 The 5–95 % ranges in the projected steric contribution to global mean sea-level rise by 2090–2099 relative to 1980–1999 (Meehl et al. 2007; Yin 2012)

Greenhouse gas scenario	Steric sea-level rise (m)	Percentage contribution to A1B rise
B1	0.10–0.24	76
B2	0.12–0.28	89
A1B	0.13–0.32	100
A1T	0.12–0.30	93
A2	0.14–0.35	109
A1FI	0.17–0.41	129
RCP2.6	0.09–0.22	69
RCP4.5	0.13–0.27	90
RCP6.0	0.14–0.29	95
RCP8.5	0.20–0.40	135

The projected sea-level rise for each scenario is also expressed as a percentage relative to the sea-level rise projected under the A1B scenario (see Sect. 14.2)

133 % between the RCP8.5 and SRES A1B scenarios is in close agreement with Nick et al. (2013) for the Greenland ice sheet (GrIS) dynamical response. The rate of glacier wastage will depend on the surface area exposed, and the glaciers will thus have a muted response to warming as the global glaciated area shrinks over time. This results in an important nonlinear response which this simple steric scaling does not account for. Applying the simple scaling coefficients in Table 14.1 to the Marzeion et al. (2012) glacier mass loss projections results in a 3 cm positive bias for RCP8.5. The error introduced by this convenient scaling approach will be smaller than the uncertainties in the A1B LSL projections themselves.

14.3 Steric Expansion

Increasing greenhouse gas (GHG) concentrations are causing a radiative imbalance of the Earth, which will cause the Earth to heat until thermal radiation once more balances incoming solar radiation. The majority of the extra heat retained due to the energy imbalance imposed by the emission scenario selected will be absorbed by the ocean, and as a consequence, the volume of the oceans would on average increase due to thermosteric expansion (Table 14.1). Steric expansion will be greatest in the open ocean where the water column is deepest (Landerer et al. 2007; Yin et al. 2010). This would lead to a differential increase in the steric sea surface heights (SSH), which would drive a redistribution of ocean mass from the ocean interior to shallower regions (Landerer et al. 2007; Yin et al. 2010). Changes in ocean circulation and in the hydrological cycle will also induce thermosteric and halosteric changes. The combined sea surface topography response is a complex spatial pattern of sea-level rise. The sea surface topography has been simulated by the ensemble of models in the CMIP3 archive (Meehl et al. 2007; Yin et al. 2010; Slangen et al. 2011), but the Baltic Sea region is very poorly resolved by the majority of the models. The dynamic sea surface topography has therefore been separated into a global average steric response, and the deviation from the mean referred to as the dynamic sea level (DSL) (following Landerer et al. 2007; Meehl et al. 2007; Yin et al. 2009, 2010) depicted in Fig. 14.1. The full CMIP3 ensemble of projections will be used for the A1B global steric contribution, but for the DSL contribution in the Baltic Sea region, the calculation is restricted to the mean of three models (GFDL CM2.1; MIROC 3.2 HiRES; MPI ECHAM5) (see Fig. 14.1). The

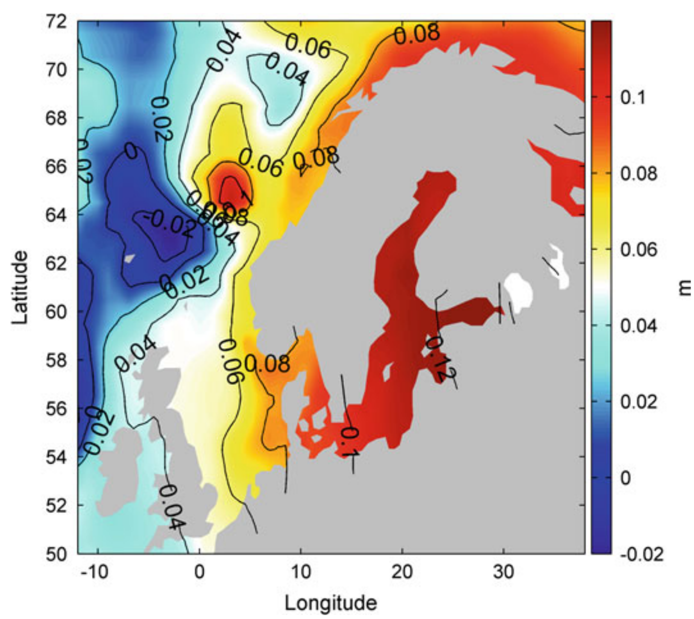

Fig. 14.1 Spatial pattern of the dynamic sea level (DSL) response (m) projected for the SRES A1B scenario for 2095 relative to the 1990 baseline. The DSL response is calculated as the average response of GFDL CM2.1, MIROC 3.2 HiRES, MPI ECHAM5 (Meehl et al. 2007). The three models are from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (provided by J. Gregory) and selected on the basis that they should resolve the Baltic Sea

uncertainty in the DSL response near the Baltic Sea is estimated to be ±20 cm by considering the spread in the ensemble (Yin et al. 2010; Pardaens et al. 2011). This uncertainty is greater than the projected DSL changes in the region.

Freshwater fluxes arising from a negative GrIS mass balance have been shown to perturb the North Atlantic circulation and thus induce changes in SSH (Stammer 2008; Hu et al. 2009, 2011; Stammer et al. 2011). The model runs in the CMIP3 archive have not been forced with the additional freshwater flux coming as a consequence of decay of land-based ice masses. Hu et al. (2011) modelled the combined effect of forcing a model with both the SRES A1B scenario and a freshwater hosing from the GrIS. Using an unrealistically large hosing flux equivalent to 60 cm of global sea-level rise results in an additional global average steric contribution of about 2 cm by the end of the twenty-first century and that the hosing has little detectable influence on DSL near Scandinavia and in the Baltic Sea. Stammer et al. (2011), however, found that atmospheric feedbacks increase the hosing response significantly in the North Atlantic.

14.4 Geoid Changes

Large masses of land ice such as that contained in the GrIS gravitationally attract the oceans around them. This gravitational pull will be reduced if the ice mass is reduced through a negative mass balance. Reducing the ice load will also cause an immediate elastic rebound of the solid Earth, as well as perturb the Earth's rotation. These effects will combine to form a new static equilibrium in the sea-level configuration (Mitrovica et al. 2001, 2009; Bamber and Riva 2010; Kopp et al. 2010). The net static equilibrium sea-level response is that the sea-level contribution from melting land ice will not be distributed evenly across the Earth but will be characterised by a spatial fingerprint. Sea level will even drop up to ~2000 km away from the source (Mitrovica et al. 2001). As a consequence, the Baltic Sea region will only feel a small fraction of the global average sea-level contribution from the GrIS mass loss, but a slightly greater than average response from the Antarctic Ice Sheet (see Fig. 14.2). The steric response of the oceans leads to a mass redistribution towards shelf areas. This also induces self-attraction and shelf loading effects that lead to an additional minor LSL rise

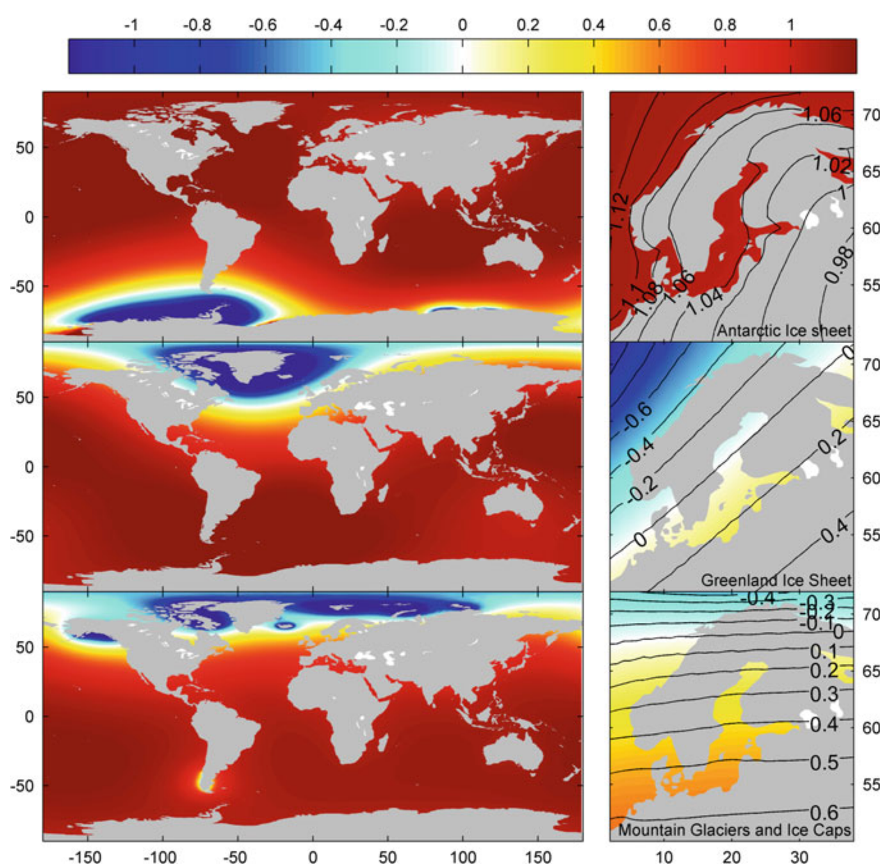

Fig. 14.2 The spatial fingerprint of sea-level rise expressed as a ratio to the global mean sea level equivalent loss from **a** the Antarctic ice sheet (Bamber and Riva 2010); **b** the Greenland ice sheet (Bamber and Riva 2010); **c** mountain glaciers and ice caps (Slangen et al. 2011)

of roughly 8 % of the steric and DSL contributions (Richter et al. 2013).

It is important to use realistic estimates of the patterns of ice loss when calculating the spatial fingerprints (Mitrovica et al. 2011). This chapter uses the present-day spatial patterns of ice loss for the two large ice sheets (Bamber and Riva 2010) and the projected pattern of mass loss from mountain glaciers and ice caps (Slangen et al. 2011). The total static equilibrium response is then calculated by scaling these fingerprints with the projected mass loss of land ice from these three sources: the GrIS, the Antarctic Ice Sheet, and mountain glaciers and ice caps.

14.5 Mountain Glaciers and Ice Caps

Glacier inventories are incomplete, but there are an estimated 300,000–400,000 glaciers and small ice caps in the world (Dyurgerov and Meier 2005). Detailed observations of these glaciers are sparse, and this leads to substantial uncertainty in their present-day volume and present-day rates of mass loss. The uncertainty in total volume (Grinsted 2013) will propagate to the projections of the contribution from mountain glaciers and ice caps (Slangen and van de Wal 2011). Some projections of the glacier contribution to global sea-level rise are based on a semi-empirical approach, where mass loss is related to global temperature change (e.g. Meehl et al. 2007). Marzeion et al. (2012) modelled the global glacier response of the globally complete Randolph Glacier Inventory (Arendt et al. 2012) to the CMIP5 ensemble of general circulation models (GCMs). Bahr et al. (2009) estimated how far present accumulation area ratios (AARs) are from being in equilibrium, and from that estimate a lower bound of glacier mass loss. The AAR-derived lower bounds are substantially greater than other projections. The contributions have been summarised in Table 14.2.

14.6 Greenland Ice Sheet

The surface mass balance (SMB) of the GrIS has been projected to contribute to global sea-level rise as SMB becomes increasingly negative. Several studies have modelled the GrIS SMB response to the projected climates in the CMIP3 simulations. These studies in general project a greater range than that reported in the IPCC AR4 (Graversen et al. 2011; Yoshimori and Abe-Ouchi 2012) and also project a generally greater mass loss. Regional climate projections of GrIS SMB are typically not coupled to ice sheet wastage and thus do not include the elevation mass balance feedback. This feedback is small over a single century, but it has been estimated that including it would increase the SMB contribution by ~4 % over the twenty-first century (Edwards et al. 2013). Models of dynamical ice loss are lacking, and no models include a prognostic model of all key dynamical processes such as calving, grounding line migration and the impact of changing basal hydrology on ice dynamics. Observations suggest that dynamic ice loss scales with the SMB for the GrIS (Rignot et al. 2008). Dynamic mass loss projections are mostly based on heuristic estimates and statistical extrapolations of present-day trends and accelerations, which are not directly related to any GHG emission scenario (see Table 14.3). To conclude, there are large uncertainties in projections of GrIS mass loss. This uncertainty is much reduced for sea-level projections in the Baltic Sea due to the spatial fingerprint of GrIS mass loss.

Table 14.2 Review of projected contributions of mountain glaciers and ice caps to global mean sea-level rise for 2090–2099 relative to a baseline of 1990–1999

Source	Contribution (m sea-level equivalent)	Present-day volume (m sea-level equivalent)	Method
Radić and Hock (2011)	0.08–0.16		Surface mass balance model (A1B)
Radić and Hock (2010)		0.50–0.65	
Meehl et al. (2007)	0.08–0.15	0.15–0.72	Semi-empirical (A1B)
Meier et al. (2007)	0.10–0.24		Statistical extrapolation
Pfeffer et al. (2008)	0.17–0.55		Statistical extrapolation + heuristic dynamic
Bahr et al. (2009)	0.18–0.38	0.86	Accumulation area ratio conservative estimate of equilibrium (may not be reached by 2100)
Slangen et al. (2011)	0.10–0.20	0.50	A1B uncertainty study
Marzeion et al. (2012)	0.13–0.22		RCP6.0
Katsman et al. (2008)	0.07–0.19	0.10–0.40	A1B
Katsman et al. (2011)	0.07–0.20	0.15–0.60	High-end estimate

Table 14.3 Estimated contributions from Greenland ice sheet mass loss to global mean sea-level rise for 2090–2099 relative to a baseline of 1990–1999

Source	Contribution (m)	Method
Surface mass balance		
Meehl et al. (2007)	0.0–0.08	Positive degree day (A1B)
Fettweis et al. (2008)	0.03–0.05	Temperature index from the energy balance model (A1B)
Fettweis et al. (2013)	0.03–0.10	Regional climate model
Mernild et al. (2010)	0.12	Energy balance model (A1B)
Yoshimori and Abe-Ouchi (2012)	0.03–0.17	Positive degree day, systematic examination of uncertainties (A1B)
Franco et al. (2011)	0.05	GCM output mapped through a regression of Greenland climate anomalies on RCM output (A1B)
van Angelen et al. (2013)	0.07	RCM + snow model (RCP4.5)
Dynamical		
Pfeffer et al. (2008)	0.09–0.47	Heuristic
Price et al. (2011)	>0.06	Estimate of committed dynamical loss
Graversen et al. (2011)	0.03	Stationary tuned outlet-glacier sliding (shallow ice)
Rignot et al. (2011)	0.07	Statistical extrapolation of acceleration
Katsman et al. (2011)	0.10	Heuristic
Nick et al. (2013)	0.04–0.09	RCP4.5 scaled-up response from four major outlets
Total		
Katsman et al. (2008)	0.02–0.17	Semi-empirical
Meier et al. (2007)	0.05–0.25	Extrapolation
Graversen et al. (2011)	0.00–0.17	Shallow ice, tuned sliding in outlet glaciers (A1B)
Seddik et al. (2012)	0.10–0.17	Full stokes, PDD, range from: tuned sliding and doubled sliding
Bamber and Aspinall (2013)	0.08–0.31	Expert elicitation. Converted to total loss assuming constant acceleration from the present day (Shepherd et al. 2012)

14.7 Antarctic Ice Sheet

The Antarctic Ice Sheet SMB is projected to increase in a warmer climate. The increased moisture-holding capacity of warmer air would bring increased precipitation to the continent. This effect is modelled to dominate over increased ablation in the marginal areas of the ice sheet, and SMB modelling projects a negative contribution to sea-level rise. SMB models are typically not coupled to ice dynamics and so do not account for any mass balance induced increases in ice discharge which can offset 15–35 % of the mass gained from increased snowfall (Winkelmann et al. 2012). The dynamic mass loss of the Antarctic Ice Sheet is, as for the GrIS, primarily estimated using heuristic approaches and statistical extrapolation. Pollard and De Conto (2009) employed a novel approach to simulate grounding line mass flux over the past 5 million years and found the West Antarctic Ice Sheet to be particularly sensitive to warming with a 3 m contribution to sea-level rise for 2 °C warming. Estimates of current Antarctic Ice Sheet mass balance are negative and dominated by mass loss in regions of the West Antarctic Ice Sheet which are thought to be most dynamically sensitive (Rignot et al. 2011). Results are summarised in Table 14.4.

14.8 Glacial Isostatic Adjustment

During the last glacial period, ice sheets 1 km thick covered Fennoscandia, the British Isles and North America. The loss of these ice sheets is causing an ongoing viscoelastic response of the Earth. In particular, the unloading of the Fennoscandian ice sheet causes a present-day isostatic uplift of the order of ~1 m per century in the Bothnian Bay (e.g. Hill et al. 2010). Local land uplift will be perceived at the coast as a drop in RSL, and for the Baltic Sea region, the magnitude of this effect in many places exceeds present-day LSL rise. There are many methods for estimating the present-day GIA. The GIA can be modelled given a global ice sheet history and viscoelastic Earth structure. The present-day GIA can be detected in land movement (by levelling and GPS), in RSL trends (paleoshorelines, tide gauges) and in gravity data (by absolute gravimetry and satellite data from the GRACE mission).

Table 14.4 Estimated contributions from the Antarctic ice sheet mass loss to global mean sea-level rise for 2090–2099 relative to a baseline of 1990–1999

Source	Contribution (m)	Method
Surface mass balance		
Meehl et al. (2007)	−0.12 to −0.02	Positive degree day
Genthon et al. (2009)	−0.10	PDD CMIP3 corrections
Krinner et al. (2007)	−0.12	GCM
Bengtsson et al. (2011)	−0.04	High-res GCM
Ligtenberg et al. (2013)	−0.05 to −0.03	Regional climate model
Dynamical		
Pollard and de Conto (2009)	0.33	~3 m/2 °C/1000 years (WAIS volume)
Pfeffer et al. (2008)	0.12–0.55	Heuristic
Katsman et al. (2011)	0.07–0.49	Statistical extrapolation/ heuristic max
Rignot et al. (2011)	0.07	Statistical extrapolation
Spada et al. (2013)	0.12–0.38	Mid-range/high-end estimate
Total		
Rignot et al. (2011)	0.36	Statistical extrapolation
Katsman et al. (2011)	−0.01 to 0.41	Heuristic (moderate-severe)
Katsman et al. (2008)	−0.02 to 0.14	Semi-empirical
Meier et al. (2007)	0.05–0.06	Statistical extrapolation
Pfeffer et al. (2008)	0.14–0.62	Heuristic
Spada et al. (2013)	0.05–0.30	Mid-range/high-end estimate

This assessment uses the GIA estimate of Hill et al. (2010), which is designed to optimally reproduce present-day instrumental observations in the Baltic Sea region.

14.9 The Compiled Budget

This section constructs an overall sea-level budget based on the projections for the major individual contributors to global sea-level rise detailed in the previous sections. One potential issue with this approach is that all the components must be completely independent to avoid double accounting. In particular, the small glaciers near the ice sheet margin may in some studies be counted as part of the ice sheet contribution. Groundwater mining (Wada et al. 2010; Konikow 2011) and reservoir construction (Chao et al. 2008) add an additional non-climatic contribution to sea level. Reservoir building is currently slowing, while groundwater mining is expected to increase with the rise in world population (Shiklomanov and Rodda 2003), and it is expected that these sources will contribute to a net sea-level rise in the future (Rahmstorf et al. 2012b; Wada et al. 2012).

Table 14.5 Mid-range and high-end estimates of the sea-level rise budget for the twenty-first century

	Mid-range estimate (m) A1B	High-end estimate (m)
Global sea level contributor		
Greenland ice sheet (SMB)	0.07 ± 0.07	0.12
Greenland ice sheet (DYN)	0.07 ± 0.07	0.12
Antarctic ice sheet (SMB)	−0.07 ± 0.05	−0.05
Antarctic ice sheet (DYN)	0.21 ± 0.21	0.40
Mountain glaciers and ice caps	0.15 ± 0.05	0.18
Global mean steric	0.22 ± 0.09	0.25
Groundwater mining and reservoir storage	0.05 ± 0.07	0.08
Total GMSL	0.70 ± 0.3	1.10
Semi-empirical GMSL models	0.96 ± 0.4	
Local sea level contributor		
Baltic Sea hosing response	Excluded ± 0.10	0.20
Baltic Sea fingerprint error (Geoid and DSL)	Excluded ± 0.30	
Regional self-attraction and loading	Excluded ± 0.03	
Baltic Sea inverse barometer	Excluded ± 0.02	
GIA uncertainty (Hill et al. 2010)	Excluded ± 0.10	

The upper part of the table shows contributors to global mean sea level (GMSL), and the lower part lists terms that do not contribute to GMSL but which can have a significant impact locally in the Baltic Sea

The local inverse barometer contribution has only a minor impact on RSL rise in the Baltic Sea region (Stammer and Huttemann 2008) and is excluded. Based on the individual estimates given in Tables 14.1, 14.2, 14.3 and 14.4 and taking into account the uncertainties in the budget, a GMSL rise of 0.70 ± 0.3 m is projected under the SRES A1B scenario, for the period 1990–2095 (see Table 14.5). This tally of contributions overlaps with the range of published semi-empirical models for GMSL which project 0.96 ± 0.4 m rise (Rahmstorf 2007a; Horton et al. 2008; Grinsted et al. 2010; Jevrejeva et al. 2010; Rahmstorf et al. 2012b). The use of semi-empirical models has been discussed in the literature (Holgate et al. 2007; Rahmstorf 2007a, b; Schmith et al. 2007; von Storch et al. 2008; Vermeer and Rahmstorf 2009, 2010; Taboada and Anadón 2010; Rahmstorf et al. 2012b), but it is not understood why semi-empirical models consistently give greater rates of sea-level rise than the tally-based approach. This chapter relies on the tally-based approach.

The mid-range estimates in the budget are combined with their respective spatial fingerprints to provide LSL projections for the Baltic Sea region. The change in LSL is combined with the local GIA to yield local projections of RSL rise (Fig. 14.3). Locally, there may be additional sources of

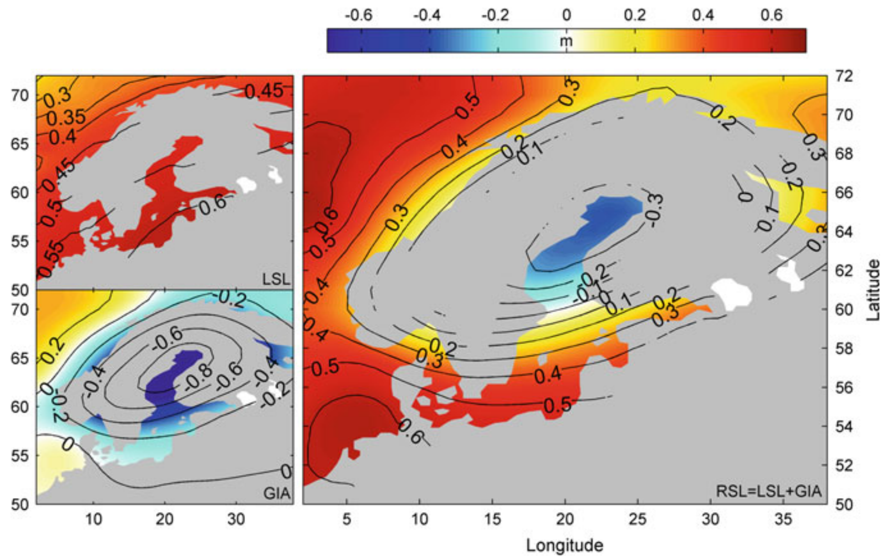

Fig. 14.3 *Right panel* shows the projected regional sea-level rise for 2090–2099 relative to the 1990–1999 baseline under the SRES A1B scenario, decomposed into local sea-level rise (*upper left*) and glacial isostatic adjustment (*lower left*; Hill et al. 2010). There may be additional local sources of vertical land movement that should be considered in adaptation

uplift/subsidence that should be taken into account in infrastructure planning. For example, the Frederikshavn tide gauge shows evidence of sinking due to gas leakage from an underground reservoir. The dominant uncertainty in the GMSL budget is the dynamic contribution of the Antarctic Ice Sheet. Furthermore, the uncertainty in RSL projections will be greater than for GMSL projections because of uncertainty in the spatial fingerprints and in the spatial distribution of change in DSL.

The projected sea-level budget is poorly constrained, and for some infrastructure decisions, a high-end scenario may be warranted (e.g. Lowe et al. 2009; Katsman et al. 2011; Spada et al. 2013). Therefore, a heuristic high-end scenario (Fig. 14.4) is constructed from high estimates of the projected budget, incorporating the possibility of an error in the spatial fingerprints in the Baltic Sea. The high-end heuristic is targeted at the combined 95th percentile based on the estimated uncertainty ranges in Table 14.5 while allowing for a more intense forcing scenario than the SRES A1B scenario (see Table 14.1). Of particular importance in the Baltic Sea is the long-tailed uncertainty of the Antarctic Ice Sheet, dynamic contribution for which the high-end estimate of 40 cm used is similar to that of Spada et al. (2013). However, this should not be interpreted in terms of a strict confidence bound given how the uncertainty ranges have been derived. At present, this high-end estimate is not considered likely from a process model perspective; however, there are several other lines of evidence that point to even greater sea-level rise being plausible. The total ice sheet contribution adopted here is 25 cm lower than the very likely upper range derived from an expert elicitation (Bamber and Aspinall 2013). Furthermore, the high-end scenario is more

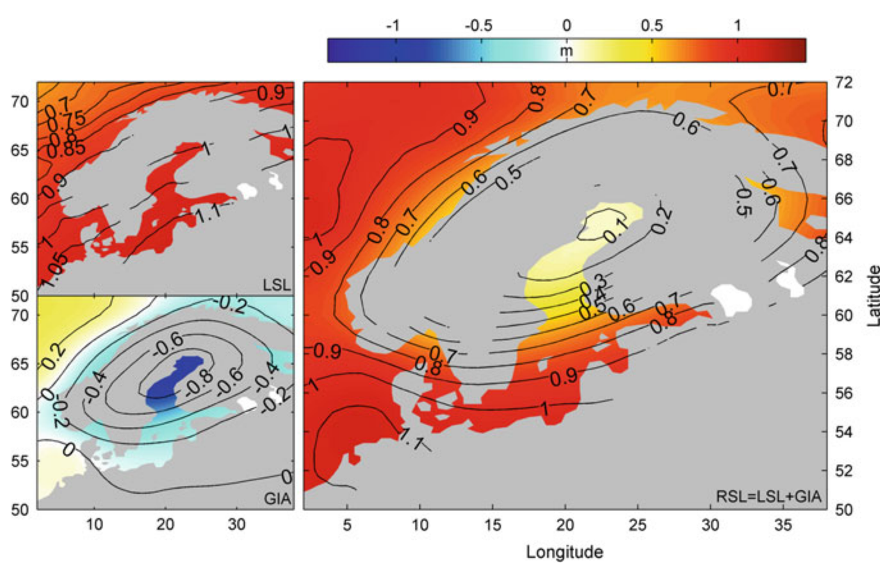

Fig. 14.4 A high-end estimate of projected sea-level rise in the Baltic Sea. *Right panel* shows the projected regional sea-level rise for 2090–2099 relative to the 1990–1999 baseline, decomposed into local sea-level rise (*upper left*) and glacial isostatic adjustment (*lower left*; Hill et al. 2010)

in line with central semi-empirical projections than the mid-range estimate (see Table 14.5; and Perrette et al. 2013). The individual contributions are expected to co-vary with global mean warming and thus climate sensitivity. Allowing for some uncertainty, covariance will further increase the likelihood of the high-end scenario.

14.10 Conclusion

By reviewing recent projections of the individual major contributions to global mean sea-level rise, it has been possible to assemble estimates of global mean sea-level rise over the twenty-first century: a mid-range scenario of 0.70 ± 0.30 m (based on the SRES A1B scenario) and a high-end scenario of 1.10 m (Table 14.5). This sea-level projection was regionalised by taking into account local dynamic sea-level rise (Fig. 14.1) and weighting individual components of the sea-level budget by their static equilibrium fingerprint (Fig. 14.2). This reveals a local sea-level projection that is ~80 % of the global mean for the mid-range scenario (Fig. 14.3). Ongoing GIA partly compensates for local sea-level rise in much of the Baltic Sea region. For the mid-range scenario, this equates to a twenty-first century relative sea-level rise of 0.60 m near Hamburg and a relative sea-level fall of 0.35 m in the Bothnian Bay (Fig. 14.3). The high-end scenario is characterised by an additional 0.5 m (Fig. 14.4). The dominant sources of uncertainty in sea-level projections for the Baltic Sea are the future rate of mass loss from the Antarctic Ice Sheet, uncertainties in the spatial fingerprints of each contributor to GMSL rise and the uncertainty in the spatial expression of DSL (Table 14.5). To better constrain sea-level projections, it is necessary to validate models of the most uncertain contributors to GMSL rise and LSL rise against their observed contributions in the coming decades.

Several studies have investigated the impact of LSL rise scenarios on the Baltic Sea coastline. These scenarios have usually been based on global sea-level models (Johansson et al. 2004; Staudt et al. 2004; Meier et al. 2006; BACC Author Team 2008) or adopted idealised sea-level rise scenarios such as 30 cm per century or 1 m per century (Kont et al. 2008; Pruszak and Zawadzka 2009). The LSL rise scenarios in these studies did not consider the spatial fingerprinting of land ice loss and so miss important regional effects. Nonetheless, the sea-level rise scenarios considered in these studies are still relevant as they fall inside the uncertainty envelope (Table 14.5).

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