Chapter 5
Case Study II: Sea Level Change at Peninsular Malaysia and Sabah-Sarawak

Abstract For the region of Peninsular Malaysia and Malaysia's Sabah-Sarawak northern region of Borneo Island, long sea level records do not exist. In such case the Atmospheric-Oceanic Global Climate Model (AOGCM) projections for the 21st century can be downscaled to the Malaysia region by means of regression techniques, utilizing the short records of satellite altimeters in this region against the GCM projections during a mutual observation period. In this case study on the assessment of sea level change along the coastlines of Peninsular Malaysia and Sabah-Sarawak, the spatial variation of the sea level change is estimated in time by assimilating the global mean sea level projections from the AOGCM simulations to the satellite altimeter observations along the subject coastlines. Details of this case study were presented in Ercan et al. (2013) at Hydrol Process, 27(3):367–377.

Keywords Rregression techniques, • Satellite altimeter observations • GCM projections • Global mean sea level

5.1 Introduction

For the region of Peninsular Malaysia and Malaysia's Sabah-Sarawak northern region of Borneo Island, long sea level records do not exist. In such case the Atmospheric-Oceanic Global Climate Model (AOGCM) projections for the twenty-first century can be downscaled to the Malaysia region by means of regression techniques, utilizing the short records of satellite altimeters in this region against the GCM projections during a mutual observation period. In this case study on the assessment of sea level change along the coastlines of Peninsular Malaysia and Sabah-Sarawak, the spatial variation of the sea level change is estimated in time by assimilating the global mean sea level projections from the AOGCM simulations to the satellite altimeter observations along the subject coastlines. Details of this case study were presented in Ercan et al. (2013).

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Climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above (Randall et al. 2007). However, due to their coarse spatial grid resolution, their description of the spatial variation of the sea level change at regional and smaller spatial scales is too coarse. In analyzing Fig. 10.32 in Meehl et al. (2007a) for the projected geographical variation of local sea level change, if one compares this spatial variation with the observed spatial distributions of the sea level change in Figs. 5.15a and 5.16a in Bindoff et al. (2007), one may conclude that the projected spatial distribution of sea level change by AOGCMs does not account for the observed spatial distribution, especially over the Southeast Asia region. Therefore, a prudent projection in a region where the local ground-based observations are for a short time period, could use the AOGCM projections for the global average sea level change, but then distribute these projections in space over the Peninsular Malaysia and Sabah-Sarawak coastlines according to the observed patterns based on the satellite altimetry data. Hence, in this study the spatial distribution of the sea level change along the Peninsular Malaysia and Sabah-Sarawak coastlines that was observed by satellite altimeters in time, is merged with the AOGCM projections of the global mean sea level change during the twenty-first century in order to better predict the spatial variation of the local sea level change along the coastal regions of Malaysia.

The confidence in the predictions of AOGCM simulations comes from the founding of the models in accepted physical principles and from their ability t reproduce observed features of current climate and past climate evolution (Randall et al. 2007). In this study the global mean sea level estimates in monthly intervals from various AOGCM simulations under climate scenarios 20C3 M (the scenario representing the climate of the twentieth Century), and three SRES greenhouse emission scenarios (B1, A1B and A2) were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007b). The number of AOGCM simulations that were performed by each model for each of the four scenarios is tabulated in Table 5.1. A total

Table 5.1 Number of AOGCM simulations (models and applied emission scenarios) used to assess sea level rise around Peninsular Malaysia and Sabah-Sarawak coastlines Ercan et al. (2013)

Model	Number of simulations per scenario			
	20C3 M	SRES B1	SRES A2	SRES A1B
CGCM3.1 (2004)[a]	1	1	1	1
GISS-AOM (2004)[b]	2	2	0	2
GISS-ER (2004)[c]	9	1	1	5
MIROC3.2(hires) (2004)[d]	1	1	0	1
MIROC3.2(medres) (2004)[d]	3	3	3	3
ECHO-G (1999)[e]	3	3	3	3
MRI-CGCM2.3.2a (2001)[f]	5	5	5	5

[a]McFarlane et al. (1992), Flato (2005), Pacanowski et al. (1993)
[b]Russell et al. (1995), Russell (2005)
[c]Schmidt et al. (2006), Russell et al. (1995)
[d]K-1 Developers (2004)
[e]Roeckner et al. (1996), Legutke and Maier-Reimer (1999)
[f]Shibata et al. (1999), Yukimoto et al. (2001)

of 73 projections were analyzed for the seven AOGCMs available: 24 projections for the 20C3 M scenario, 16 projections for the SRES B1 scenario, 13 projections for the SRES A2 scenario, and 20 projections for the SRES A1B scenario. References to the AOGCMs used were reported in Ercan et al. (2013).

5.2 Observed Satellite Altimeter Data

In this case study, linear regression analyses were performed both for monthly tidal gauge and monthly satellite altimeter observations along Peninsular Malaysia and Sabah-Sarawak coastlines. The results of these analyses showed that slopes of the linear trend lines are significantly greater for the satellite altimeter observations when compared to those for the tidal gauge observations. Meanwhile, there is no missing data in satellite altimeter observations for any month during the observation period, and the uncertainties in satellite altimeter observations are well described. Furthermore, it was possible to correct the errors in the satellite observations. Therefore, the satellite altimeter data were utilized as the basis for assimilating the future sea level projections that are derived from the global mean sea level projections from the AOGCM simulations during the twenty-first century, to locations around Peninsular Malaysia and Sabah-Sarawak coastlines.

The combined TOPEX/Poseidon, Jason-1 and Jason-2/OSTM sea level fields in monthly intervals (CSIRO 2010) were used in the satellite altimeter data linear trend analyses. For the satellite altimeter data, the annual and semi-annual signals were removed; and the inverse barometer and glacial isostatic adjustment (GIA) corrections were done (CSIRO 2010). In order to perform a sensitivity analysis for these corrections, the satellite altimeter data with and without these corrections were analyzed. The sea level rise rates that were calculated by linear regression analyses of the satellite altimeter data around Peninsular Malaysia coastline with and without the application of the three correction methods are tabulated in Table 5.2.

Around Peninsular Malaysia coastline, the sea level rise rates that were calculated from the satellite altimeter data when the annual and semi-annual signals were removed, are less by an average of 0.29 mm/year for Peninsular Malaysia when compared to the rates without removing the signals. The Inverse Barometer is the correction for variations in the sea surface height due to atmospheric pressure variations (Ponte and Gaspar 1999; Dorandeu and Le Traon 1999). Around Peninsular Malaysia coastline, the sea level rise rates that were calculated from the satellite altimeter data with the inverse barometer correction are smaller with an average of 0.43 mm/year for Peninsular Malaysia when compared to the rates without any correction. Modern measurements of the rate of sea level rise are significantly contaminated by the influence of the ongoing process of Glacial Isostatic Adjustment (GIA) due to the most recent deglaciation event of the Late Quaternary ice-age (Peltier 2009). The GIA correction applied to Topex/Poseidon-derived altimetric measurements was demonstrated in Peltier (2002). Using the ICE-4G (VM2) model of the GIA process, described in Peltier (1994, 1996), analyses demonstrated that such measurements would be biased down by approximately

Table 5.2 Sea level rise rates (mm/yr) calculated by linear regression analyses of the satellite altimeter data around Peninsular Malaysia coastline with and without applying the correction methods Ercan et al. (2013)

Longitude/Latitude	Case 1[a]	Case 2[b]	Case 3[c]	Case 4[d]	Case 5[e]
Peninsular Malaysia					
100E/6 N	6.33	6.63	6.21	5.94	6.08
99E/5 N	6.47	6.82	6.53	6.11	6.45
104E/1 N	4.49	4.90	4.17	3.95	3.87
105E/2 N	4.23	4.65	3.91	3.70	3.68
104E/3 N	3.37	3.73	3.03	2.94	2.88
104E/4 N	3.22	3.59	2.87	2.79	2.73
104E/5 N	3.26	3.58	2.85	2.90	2.78
103E/6 N	4.04	4.34	3.59	3.59	3.46
103E/7 N	4.15	4.46	3.67	3.68	3.49
102E/7 N	4.94	5.23	4.49	4.46	4.29
101E/7 N	5.80	6.05	5.38	5.33	5.20
99E/6 N	5.75	6.05	5.73	5.46	5.70
99E/7 N	5.15	5.40	5.04	4.82	5.02
Average	4.71	5.03	4.42	4.28	4.28
GMSL[f]	2.94	3.38	2.92	2.81	3.22

[a]No correction
[b]GIA correction was performed
[c]semi-annual signals were removed
[d]Inverse barometer correction was performed
[e]Annual and semi-annual signals were removed; Inverse barometer and GIA corrections were performed
[f]Global Mean Sea Level

0.3 mm/year. Table 5.2 depicts that the sea level rise rates that were calculated from the satellite altimeter data with GIA correction are greater with an average of 0.32 mm/year for Peninsular Malaysia than the rates without any correction. The sea level rise rates that were calculated from the satellite altimeter data, when all the three corrections are applied, are smaller with an average of 0.43 mm/year for Peninsular Malaysia than the rates without any correction. When all the three corrections are applied, the averages of the sea level rise rates around Peninsular Malaysia coastline that were calculated from the satellite altimeter data between January 1993 and March 2010 are 1.06 mm/year larger than the global average.

5.3 Assimilating AOGCM Simulations to Satellite Observations

The determination of the variation of the sea level change with respect to the spatial location along the Peninsular Malaysia and Sabah-Sarawak coastlines is based on the linear trend analyses of the observed satellite altimetry data. Using monthly satellite altimeter data of January 1993–December 2000 and using monthly twentieth century global mean sea level predictions of various AOGCMs, one can write the below regression equation at each satellite altimeter location i and for AOGCM j, and estimate the equation coefficients a_{ij} and b_{ij} such that $\sum_k \left(\varepsilon_{i,j,k}\right)^2$ is minimized for each altimeter location and AOGCM (Ercan et al. 2013).

$$y_{SA,i,j,k} = a_{i,j} y_{GMSL\_20c3m,j,k} + b_{i,j} + \varepsilon_{i,j,k} \tag{5.1}$$

Here y_{SA} is the satellite observation of the sea level, y_{GMSL_20c3m} is 20th century global mean sea level (GMSL) prediction, and ε is the error term. Then one can estimate the sea level y at satellite altimeter location i at time k using twenty-first century global mean sea level projections of AOGCM j for SRES B1, A1B and A2 scenarios by (Ercan et al. 2013)

$$y_{sresb1,i,j,k} = a_{i,j} y_{GMSL\_sresb1,j,k} + b_{i,j} \tag{5.2}$$

$$y_{srea1b,i,j,k} = a_{i,j} y_{GMSL\_srea1b,j,k} + b_{i,j} \tag{5.3}$$

$$y_{sresa2,i,j,k} = a_{i,j} y_{GMSL\_sresa2,j,k} + b_{i,j} \tag{5.4}$$

where a_{ij} and b_{ij} are linear regression coefficients estimated from Eq. (5.1) for satellite altimeter location i and AOGCM j. After solving Eqs. (5.2)–(5.4) for each satellite altimeter location i and for each AOGCM j at time k in the twenty-first century, means and 95 percent confidence bands of the sea level rise rates and corresponding sea level rise estimates could be obtained for twenty-year intervals in the twenty-first century using the three emission scenarios. The linear regressions between the observed local sea level and global mean sea level in the late twentieth century, simulated by AOGCMs, are assumed to hold during the twenty-first century. However, the nonlinearity in AOGCM projections are reflected in the local sea level projections through the regression relationships that are established by means of the historical data.

5.4 Sea Level Change

Means and lower and upper bounds of 95 percent confidence intervals of the sea level change rate projections around Peninsular Malaysia and Sabah-Sarawak coastlines are depicted in Figs. 5.1, 5.2, 5.3, respectively using the ensemble of all the three SRES scenarios and all the available AOGCMs (tabulated in Table 5.1). These figures show the average sea level change rates in twenty-year increments in the twenty-first century and the average rate during 2001–2100. The highest sea level rise rate occurs at 100E/6 N location with mean 5.17 mm/yr with a confidence interval of (0.02, 23.03) mm/yr at Peninsular Malaysia and at 119E/4 N location with mean 10.64 mm/yr with a confidence interval of (0.00, 43.86) mm/yr at Sabah and Sarawak during 2001–2100. The lowest sea

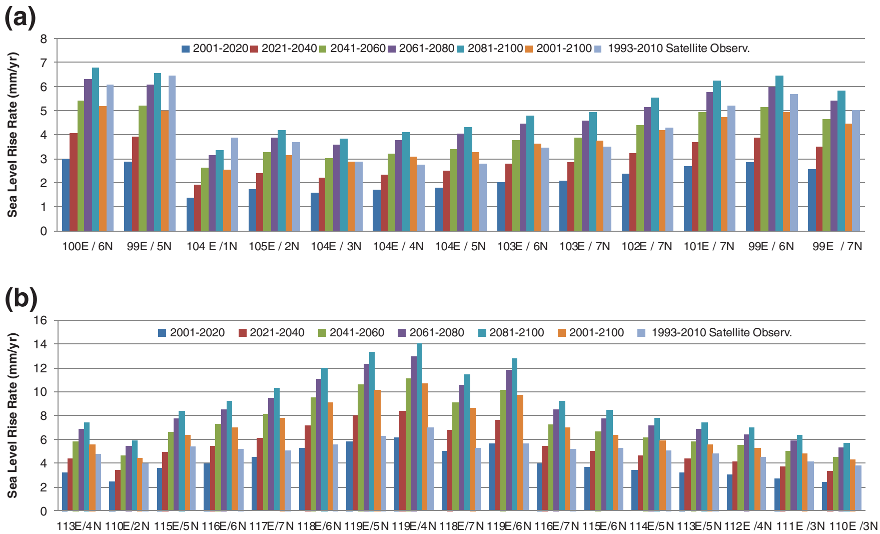

Fig. 5.1 Mean sea level rise rate (mm/yr) projections by means of the assimilated available AOGCM projections using the ensemble of SRES B1, A1B and A2 scenarios in the twenty-first century: **a** around Peninsular Malaysia coastline, **b** around Sabah and Sarawak coastline Ercan et al. (2013)

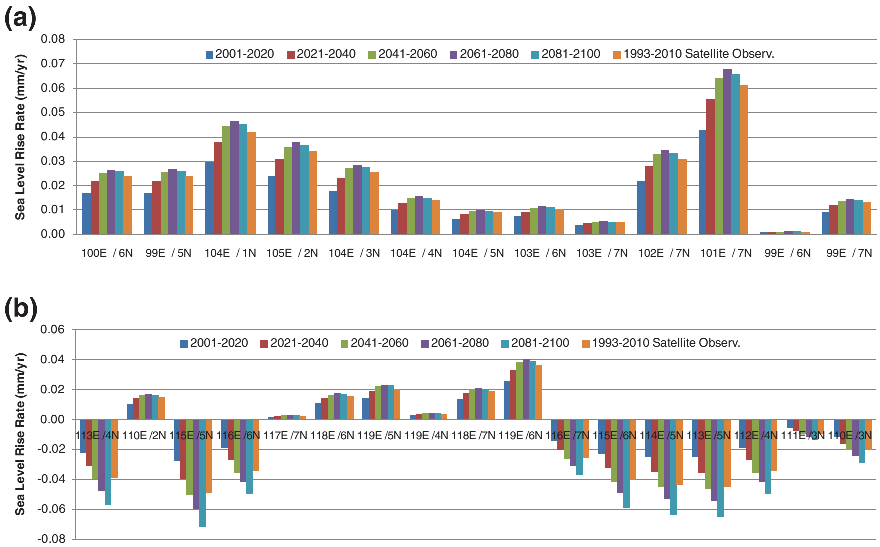

Fig. 5.2 Lower bounds of 95 percent confidence interval of sea level rise rate (mm/yr) projections by means of the assimilated available AOGCM projections using the ensemble of SRES B1, A1B and A2 scenarios in the twenty-first century: **a** around Peninsular Malaysia coastline, **b** around Sabah and Sarawak coastline Ercan et al. (2013)

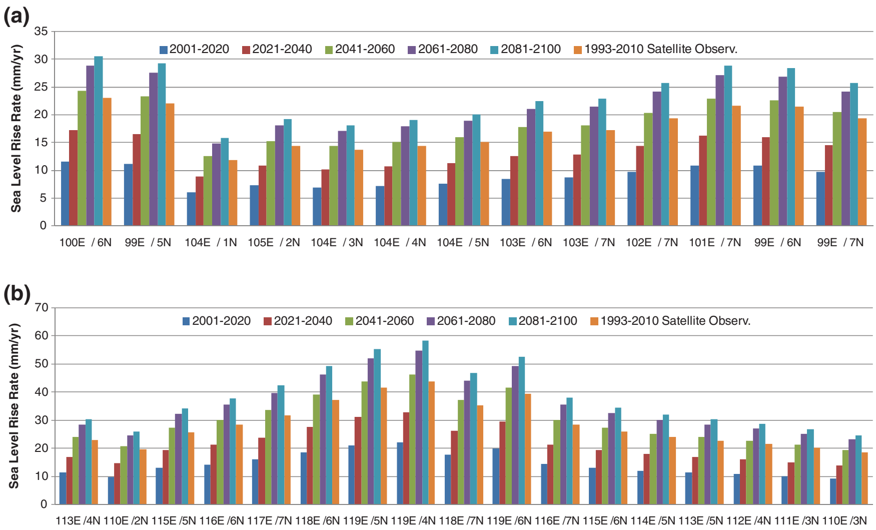

Fig. 5.3 Upper bounds of 95 percent confidence interval of sea level rise rate (mm/yr) projections by means of the assimilated available AOGCM projections using the ensemble of SRES B1, A1B and A2 scenarios in the twenty-first century: **a** around Peninsular Malaysia coastline, **b** around Sabah and Sarawak coastline Ercan et al. (2013)

Table 5.3 Summary of mean sea level rise rate (mm/yr) predictions and 95 percent confidence intervals from all available AOGCM projections around Peninsular Malaysia and Sabah and Sarawak coastlines for the ensemble of SRES B1, A1B and A2 scenarios (LB: lower bound; UB: upper bound)

	Time Interval					
	2001 2020	2021–2040	2041–2060	2061–2080	2081–2100	2001–2100
Peninsular Malaysia						
LB	0.02	0.02	0.02	0.02	0.02	0.02
Mean	2.19	3.02	4.06	4.77	5.15	3.90
UB	8.92	13.24	18.67	22.15	23.54	17.73
Sabah-Sarawak						
LB	−0.01	−0.01	−0.01	−0.02	−0.02	−0.01
Mean	4.02	5.47	7.29	8.51	9.21	6.98
UB	14.45	21.43	30.23	35.86	38.11	28.70

level rise rate occurs at 104E/1 N location with mean 2.53 mm/yr with a confidence interval of (0.04, 11.89) mm/yr at Peninsular Malaysia and at 110E/3 N location with mean 4.32 mm/yr with a confidence interval of (-0.02, 18.52) mm/yr at Sabah and Sarawak during 2001-2100. In the twenty-first century, Figs. 5.1-5.3 show clearly that the means and upper bounds of 95 percent confidence intervals of sea level rise rates are increasing with time toward the future both for Peninsular Malaysia and for Sabah and Sarawak coastlines.

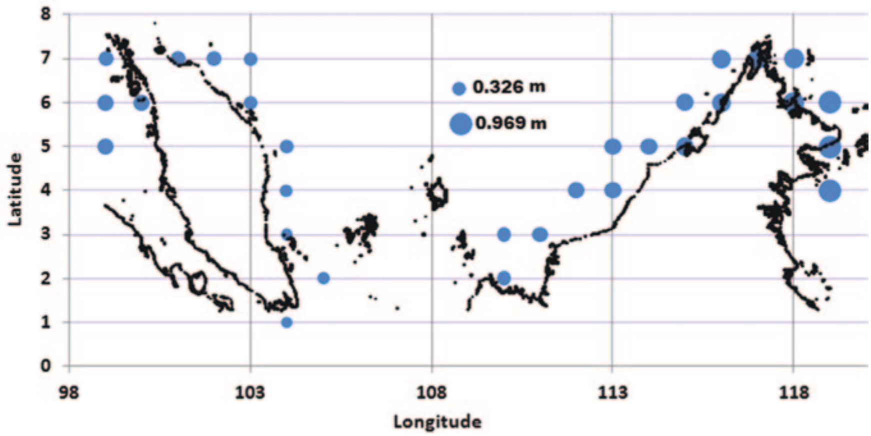

Fig. 5.4 Means of the sea level rise projections around Malaysia coastlines using the ensemble of SRES B1, A1B and A2 scenarios in 2100 Ercan et al. (2013)

Summary of mean sea level rise rate projections in mm/yr with the corresponding 95 percent confidence intervals from all available AOGCM projections around Peninsular Malaysia and Sabah and Sarawak coastlines for the ensemble of SRES B1, A1B and A2 scenarios are tabulated in Table 5.3. When all the three SRES scenarios for the whole coast of Peninsular Malaysia during 2001–2100 are considered, the mean sea level rise rate is 3.90 mm/year with the confidence interval of (0.02, 17.73) mm/yr. On the other hand, when all the three SRES scenarios for the whole coast of Sabah and Sarawak during 2001–2100 are considered, the mean sea level rise rate is 6.98 mm/year with the confidence interval of (−0.01, 28.70) mm/yr.

The sea level rise can be estimated by multiplying the sea level rise rate estimate by the duration. Means of the sea level rise projections in 2100 (since year 2000) are depicted on the map of Peninsular Malaysia and Sabah-Sarawak in Fig. 5.4, where sea level rises are represented by the size of the circles.

In 2100, the highest sea level rise occurs at 100E/6 N location with mean 0.517 m with a confidence interval of (0.002, 2.303) m at Peninsular Malaysia; and at 119E/4 N location with mean 1.064 m with a confidence interval of (0.000, 4.386) m at Sabah and Sarawak. In 2100, the lowest sea level rise occurs at 104E/1 N with mean 0.253 m with a confidence interval of (0.004, 1.189) m at Peninsular Malaysia; and at 110E/3 N location with mean 0.432 m with a confidence interval of (−0.002, 1.852) m at Sabah and Sarawak.

5.5 Conclusions

In this case study on the assessment of sea level change along the coastlines of Peninsular Malaysia and Sabah-Sarawak, the spatial variation of the sea level change was estimated by assimilating the global mean sea level rise projections from the AOGCM simulations to the satellite altimeter observations along these coastlines.

The sea level around the Peninsular Malaysia coastlines is projected by means of the assimilated AOGCM projections to rise with a mean between 0.253 and 0.517 m in 2100. The upper bound of the 95 percent confidence interval for the sea level rise around Peninsular Malaysia is between 1.189 and 2.303 m in 2100. The highest sea level rise occurs at the north-east and north-west regions of Peninsular Malaysia. The sea level rise estimates that are based solely on the local observations by satellite altimeters around Peninsular Malaysia are between 0.273 and 0.645 m in 2100 (assuming the observed rate continues in the twenty-first century). These estimates are close to the mean projections that are assimilated from the AOGCM projections to the Peninsular Malaysia coastal areas by means of the local observations, and are within the 95 percent confidence intervals of the mean projections.

The sea level around Sabah and Sarawak coastlines is projected by means of the assimilated AOGCM projections to rise with a mean between 0.432 and 1.064 m in 2100. The upper bound of the 95 percent confidence interval for the sea level rise at Sabah and Sarawak is between 1.852 and 4.386 m in 2100. The highest sea level rise at Sabah and Sarawak is estimated to occur at north and east sectors of Sabah. The sea level rise estimates that are based solely on the local observations by satellite altimeters around Sabah and Sarawak are between 0.382 and 0.700 m in 2100. These estimates are close to the mean projections that are assimilated from the AOGCM projections to Sabah and Sarawak coastal areas by means of the local observations, and are within the 95 percent confidence intervals of the mean projections.

Elevation maps of the coastal regions of the study area with high horizontal grid resolution and high vertical accuracy are necessary for the performance of realistic sea inundation analyses. The vertical accuracy should be at least in the order of centimeters in order to capture the spatial details of the sea level rise. While it is difficult to specify a specific value for the horizontal grid resolution, it should capture local high and low areas.

References

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A (2007) Observations: oceanic climate change and sea level. In: Solomon S et al. (eds) Climate change 2007: The Physical Science Basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate. Cambridge University Press: Cambridge, New York, pp 385–432

Commonwealth Scientific and Industrial Research Organisation (CSIRO) (2010) http://www.cmar.csiro.au/sealevel/sl_data_cmar.html. Downloaded in Sept. 2010

Dorandeu J, Le Traon PY (1999) Effects of global mean atmospheric pressure variations on mean sea level changes from TOPEX/Poseidon. J Atmos Oceanic Technol 16(9):1279–1283

Ercan A, Mohamad MF, Kavvas ML (2013) Sea level rise due to climate change around the Peninsular Malaysia and Sabah and Sarawak coastlines for the 21st century. Hydrol Process 27(3):367–377. doi:10.1002/hyp.9232

Flato GM (2005) The Third Generation Coupled Global Climate Model (CGCM3) (and included links to the description of the AGCM3atmospheric model). http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml

K-1 model developers (2004) K-1 coupled model (MIROC) description. Technical report 1. Center for Climate System Research, University of Tokyo

Legutke S, Maier-Reimer E (1999) Climatology of the HOPE-G Global Ocean General Circulation Model. Technical report No. 21, German Climate Computer Centre (DKRZ): Hamburg, Germany, pp 90

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007a) Global climate projections. In: Solomon S et al. (eds) Climate change 2007: The Physical Science Basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press: Cambridge, New York

Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer RJ, Taylor KE (2007b) The WCRP CMIP3 multimodel dataset: a new era in climate change research. Bull Am Meteorol Soc 88:1383–1394

McFarlane NA, Boer GJ, Blanchet J-P, Lazare M (1992) The Canadian Climate Centre second-generation general circulation model and its equilibrium climate. J Climate 5(10):1013–1044.

Pacanowski RC, Dixon K, Rosati A (1993) The GFDL Modular Ocean Model Users Guide, Version 1.0. GFDL Ocean Group Technical Report No. 2, Geophysical Fluid Dynamics Laboratory: Princeton, NJ

Peltier WR (1994) Ice-age paleotopography. Science 265:195–201

Peltier WR (1996) Mantle viscosity and ice-age ice-sheet topography. Science 273:1359–1364

Peltier WR (2002) Global glacial isostatic adjustment: paleo-geodetic and space geodetic tests of the ICE-4G(VM2) model. J Quat Sci 17:491–510

Peltier WR (2009) Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for the influence of global glacial isostatic adjustment. Quat Sci Rev 28:1658–1674

Ponte RM, Gaspar P (1999) Regional analysis of the inverted barometer effect over the global ocean using Topex/Poseidon data and model results. J Geosphys Res, 104(C7): 15587–15601

Roeckner E, Arpe K, Bengtsson L, Christoph M, Claussen M, Dümenil L, Esch M, Giorgetta M, Schlese U, Schulzweida U (1996) The Atmospheric General Circulation Model ECHAM4: Model Description and Simulation of Present-Day Climate. MPI Report No. 218, Max-Planck-Institut für Meteorologie: Hamburg, Germany, pp 90

Russell GL, Miller JR, Rind D (1995) A coupled atmosphere–ocean model for transient climate change studies. Atmos.-Ocean 33(4):683–730

Russell GL (2005) 4x3 atmosphere–ocean model documentation. http://aom.giss.nasa.gov/doc4x3.html

Randall DA, Wood RA, Bony S, Colman R, Fichefet T, Fyfe J, Kattsov V, Pitman A, Shukla J, Srinivasan J, Stouffer RJ, Sumi A, Taylor KE (2007) Cilmate models and their evaluation. In: Solomon S et al. (eds) Climate change 2007: The Physical Science Basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press: Cambridge, New York

Schmidt GA, Ruedy R, Hansen JE, et al. (2006) Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. Journal of Climate 19(2):153–192.

Shibata K, Yoshimura H, Ohizumi M, Hosaka M, Sugi M (1999) A simulation of troposphere, stratosphere and mesosphere with an MRI/JMA98 GCM. Papers in Meteorology and Geophysics 50(1):15–53

Yukimoto S, Noda A, Kitoh A, Sugi M, et al. (2001) The new Meteorological Research Institute global ocean–atmosphere coupled GCM (MRI-CGCM2)-Model climate and variability. Papers in Meteorology and Geophysics 51(2):47–88