Interactive comment on "Projected sea level rise and changes in extreme storm surge and wave events during the 21st century in the region of Singapore" by H. Cannaby et al.

We thank the reviewers for their constructive comments on our paper. Responses to each individual comment are included below (in red text for clarity).

Response to comments from reviewer #1

I would encourage the authors to compare their sea-level rise projections to other published projections for Singapore, such as those generated by Kopp et al. 2014 (doi:10.1002/2014EF000239) as part of their global set of tide-gauge-specific sea-level rise projections. Examination of that paper's supplementary information indicates that they have produced projections for multiple tide-gauges in SIngapore, including the Raffles Light House tide gauge. For 2100 in RCP 4.5 and 8.5, their likely ranges of 35-79 cm and 54-102 cm, respectively, are in general good agreement with the authors' projections (29-73 cm and 45-102 cm), though Kopp et al. (2014) attempts to characterize the tail risk as well (for example, for RCP 8.5, they find a 95th percentile projection of 127 cm, and 99.5th percentile projection of 193 cm, and a maximum physically plausible projection of 275 cm). Kopp et al. (2014)'s SI also provides a process-level breakdown for each tide gauge similar to the authors' Table 2.

The likely ranges from Kopp et al (2014) for several Tide Gauge sites (shown below) have been compared to our results. We note that the authors also include a "Background rate", which originates from a Gaussian process model applied to the tide gauge records, and includes GIA, tectonics and other non-climatic local effects as a linear trend. We also note that the numbers in Kopp are computed relative to the year 2000, whereas the numbers in this paper are computed relative to the mean for 1986-2005.

Tide Gauge	**RCP4.5 change @ 2100 (cm)**		**RCP8.5 change @ 2100 (cm)**	
	No GIA/Bkgd	With GIA/Bkgd	No GIA/Bkgd	With GIA/Bkgd
Raffles Light -0.97 mm/yr	55 [35-79]	45 [25-69]	76 [54-102]	66 [41-89]
Tanjong Pagar -0.29 mm/yr	62 [40-88]	59 [37-85]	83 [59-111]	80 [56-108]
Tuas -0.4 mm/yr	62 [30-96]	58 [26-92]	83 [49-119]	79 [45-114]
Mean of 3 gauge sites		**54 [29-82]**		**75 [47-103]**
SV2 Values		**52 [29-73]**		**74 [45-102]**

Based a comparison of our data to the above results the following comment has been incorporated into the text:

"Our estimates of time-mean sea level change for Singapore are in good agreement with sea level projections at tide-gauge sites in Singapore produced by Kopp et al (2014). Those authors report a likely range of 29-82 cm (47-103 cm) over the 21st Century under RCP4.5 (RCP8.5) based on the average of three tide gauge sites, after local GIA and other non-climatic effects have been taken into account."

Page 2958, line 16: The authors may find useful information for their intro on pre-observational Holocene sea-level change in Singapore from Bird MI, Austin WEN,Wurster CM, et al. Punctuated eustatic sea-level rise in the early mid-Holocene. Geology. 2010;38:803–6. doi:10.1130/G31066.1.

The following text has been added to the introduction:

"Bird et al. (2010) consider the impact of pre-observational (early Holocene) sea level change on human dispersal in coastal regions of Singapore, and provide evidence of the rapid rate at which regional sea levels changed during this period. The authors suggest sea levels rose at a rate of 1.8 m 100 yr^{-1} between 8900 and 8100 calibrated yr B.P., exhibited little change in between 7800 and 7400 calibrated yr B.P. and then a rose by 4–5 m by 6500 calibrated yr B.P."

Page 2958, line 20: As the authors correctly note later, the dominant GIA process in Singapore is continental levering. "Glacial isostatic rebound" generally refers to the uplift of the solid Earth that happens at the former location of ice sheets.

Where used "isostatic rebound" has been replaced throughout the text with "isostatic adjustment"

Page 2959, line 7: RCP 4.5 can be a "mid-range estimate of expected change" only if you place a probability distribution on policy choices. It is almost impossible to obtain without deliberate climate policy and so is not comparable to SRES B2. (Note that, in the comparison study of Rogejl et al,. 2012 (doi:10.1038/NCLIMATE1385), SRES B2 had a likely warming 2.6-3.7 C in 2100, while RCP 4.5 had a likely warming of 2.0-3.0C.

We replace "mid-range estimate" with the phrase used by Kopp et al (2014) "moderate mitigation policy scenario"

Page 2960, line 2: Work subsequent to AR5 has attempted to fill in the sea-level rise probability distribution beyond the likely range (e.g., Kopp et al,.2014, doi:10.1002/2014EF000239, and Jevrejeva et al., 2014, doi:10.1088/1748-9326/9/10/104008), so I do not think it is accurate to say that the IPCC "likely range represents the best scientific assessment of global sea level change available at present."

The existing text:

"The upper and lower limits of each time series represent the "likely range" of GMSL change, taking the IPCC AR5 assessment that there is a > 66 % chance that the observed sea level rise would fall within these bounds for a given RCP. The additional uncertainty implied by this arises from the authors' expert judgement of methodological or structural uncertainty that is not captured by the CMIP5 ensemble, and the likely range represents the best scientific assessment of global sea level change available at present."

has been replaced with:

"The upper and lower limits of each time series represent the "likely range" of GMSL change, taking the IPCC AR5 assessment that there is a >= 66 % chance that the observed sea level rise would fall within these bounds for a given RCP. The additional uncertainty implied by this arises from the authors' expert judgement of methodological or structural uncertainty that is not captured by the CMIP5 ensemble."

In addition the text in the discussion:

“There are several caveats to the sea level, surge and wave projections presented in this study and we consider each in turn in the following paragraphs. Mean sea level projections are presented as likely (66–100 % probability) ranges for the RCP4.5 and RCP8.5 scenarios of future greenhouse gas concentrations, taking into account a number of uncertainties that cannot be formally quantified with the present state of scientific knowledge. As noted previously, sea level projections do not account for the unlikely event of a collapse of the marine-based sectors of the Antarctic ice sheet.”

has been replaced with:

“There are several caveats to the sea level, surge and wave projections presented in this study and we consider each in turn in the following paragraphs. Mean sea level projections are presented as likely (66–100 % probability) ranges for the RCP4.5 and RCP8.5 climate change scenarios, taking into account a number of uncertainties that cannot be robustly quantified with the present state of scientific knowledge. We note that recent studies have attempted to provide information outside of the IPCC likely range (Kopp et al., 2014; Jevrejeva et al., 2014) and this is an important topic of ongoing discussion by the research community (Hinkel et al., 2015). As noted previously, our sea level projections do not account for the unlikely event of a collapse of the marine-based sectors of the Antarctic ice sheet.”

References included in the above paragraph have been added to the reference list.

Page 2960, line 9: Please spell out what is meant by a ’nearest neighbor’ approach. Why was a nearest neighbor approach taken in lieu of directly calculating the finger-prints for the geographic coordinates of Singapore?

The text:

“derived from the Slangen et al. (2014) fingerprints, using a “nearest neighbour” approach.”

has more accurately been replaced with:

“derived from the Slangen et al. (2014) fingerprints, using the closest 1 x 1 degree grid box”.

Page 2960, line 13: ICE 5G is an ice model, not a GIA model. To produce a GIA model, an ice model must be combined with a model specifying mantle viscosity and lithospheric thickness (e.g., ICE5G might be combined with the VM2-90 rheological model, yielding the GIA model ICE5G-VM2-90). Please clarify what rheological model was used with the ICE5G ice model.

The rheological model used is VM2 L90, usually it is referred to as ICE-5G(VM2) - see http://www.atmosp.physics.utoronto.ca/~peltier/data.php. This is now stated in the text as follows:

“Rates of glacial isostatic adjustment (GIA) for Singapore were determined using the combined ice and rheological models ICE-5G(VM2) (Peltier, 2004; http://www.atmosp.physics.utoronto.ca/~peltier/data.php), provided by Slangen et al. (2014),”

Page 2960, line 22: Other authors (e.g., Kopp et al., 2014) use the term "oceanographic" rather than "steric/dynamic" (or "steric+dynamic’, as it appears in Slangen et al. 2014). Neither term appears to be used in Church et al. (2013).

We have replaced "steric/dynamic" with “oceanographic” throughout.

Page 2960, line 26: What is the resolution of the GCM being examined to estimate the dynamic sea level terms? Are there any studies using high-resolution regional models to estimate sea-surface height, with which the GCMs might be compared?

We are not aware of any regional studies using high resolution ocean models with which to compare the GCMs.

The text:

“However, all models show relatively weak gradients in the pattern of change in the vicinity of Singapore, a result that appears to be largely independent of the underlying model resolution.”

Has now been replaced with:

“However, all models show relatively weak gradients in the pattern of change in the vicinity of Singapore. This result appears to be largely independent of the underlying ocean model resolution, which varies across the CMIP5 models from about 2° to 0.3°”

Page 2961, line 6-9: The authors linear scaling of dynamic sea-level with thermal expansion seems a weak, or at least poorly explained, point in their analysis. What is the evidence that all models show a linear relationship between local steric/dynamic sea-level change and global thermal expansion? The authors should show this evidence. But if the authors have the evidence to show this (which they should), why don’t they just use the CMIP5 projections of steric/dynamic change directly?

A new figure has been added to the supplementary material (Figure A1) showing the relationship between local steric/dynamic sea-level change and global thermal expansion for each CMIP5 model. This figure is also included at the end of this document for reference.

Effectively, we are using the steric+dynamic (now referred to as “oceanographic”) change directly. We follow the IPCC AR5 method of computing the difference in sea level based on two 20-year periods to characterise the change signal and uncertainty at the end of the 21st Century. However, we also want a method to describe how this signal emerges over time. Since the regional oceanographic sea level change scales nicely with global mean sea level for all models we use the ensemble mean thermal expansion as a basis for a smoothly evolving time-series for both oceanographic sea level change and its associated uncertainty.

Page 2962, line 12: "IPPC" is misspelled.

This has been corrected

Figure 2: While the difference between SMB and dynamic fingerprints for Antarctica makes sense (I assume it is due to SMB being dominated by East Antarctica and dynamic by West Antarctica), the reason they are different for Greenland is less obvious. Please explain.

SMB on both ice sheets is prescribed as a uniform distribution over the entire ice sheet. The dynamics are specified to regions: for Antarctica it's the Antarctic Peninsula, Amundsen Sea embayment and a small amount in East Antarctica. For Greenland, the dynamical contribution is situated on the southern tip and along the west coast of the ice sheet.

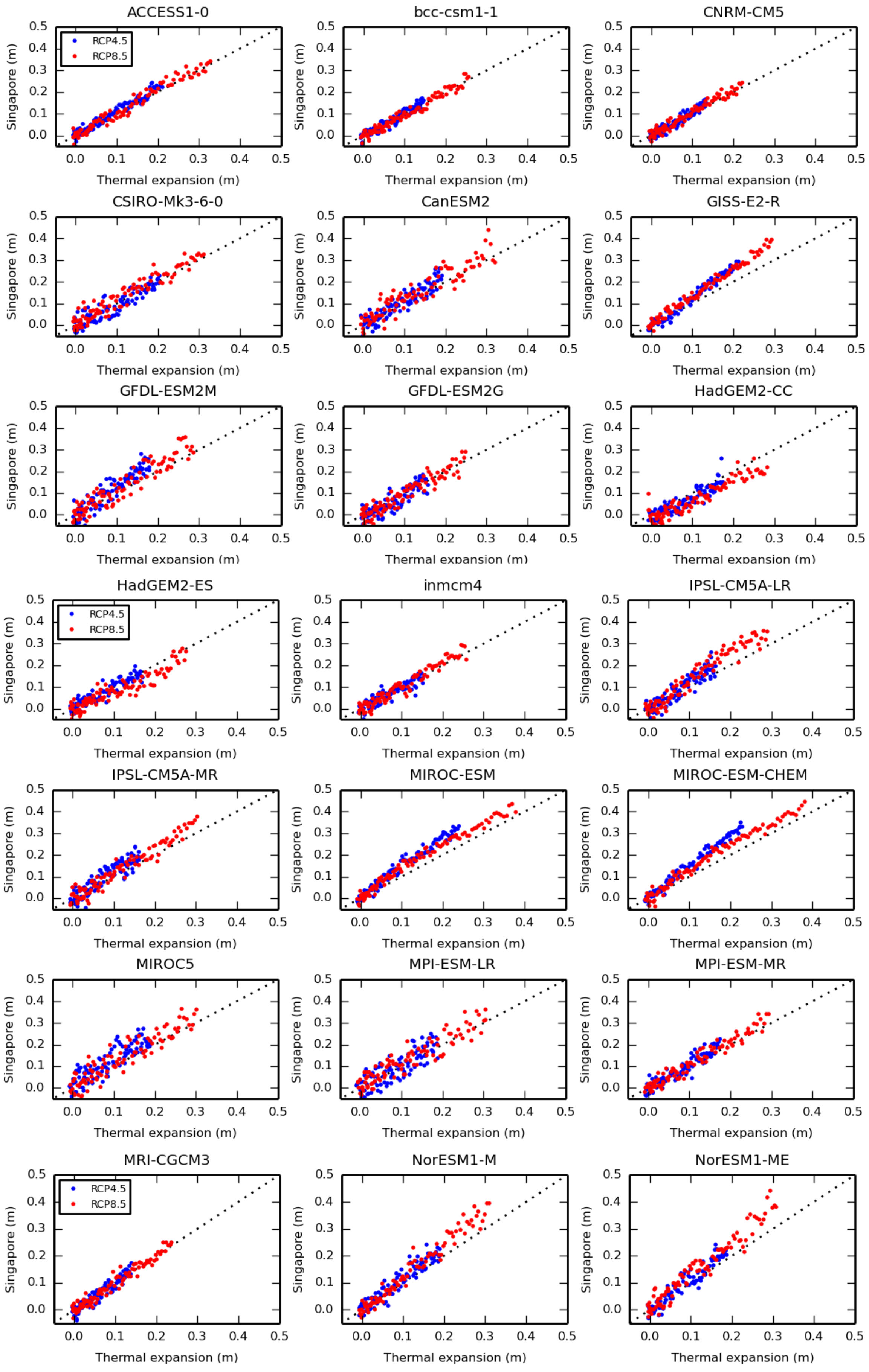
Table 4: Values in the text are quoted in mm/century, which are more useful units.

Table 4 has been converted to mm/century

Table 5: There is a mismatch between the units specified in the caption (m/century)

and the values quoted in the text (mm/century). I presume the latter is correct.

Table 5 has been converted to mm/century


ACCESS1-0
bcc-csm1-1
CNRM-CM5
CSIRO-Mk3-6-0
CanESM2
GISS-E2-R
GFDL-ESM2M
GFDL-ESM2G
HadGEM2-CC
HadGEM2-ES
inmcm4
IPSL-CM5A-LR
IPSL-CM5A-MR
MIROC-ESM
MIROC-ESM-CHEM
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MRI-CGCM3
NorESM1-M
NorESM1-ME
RCP4.5
RCP8.5
Singapore (m)
Thermal expansion (m)
0.0
0.1
0.2
0.3
0.4
0.5