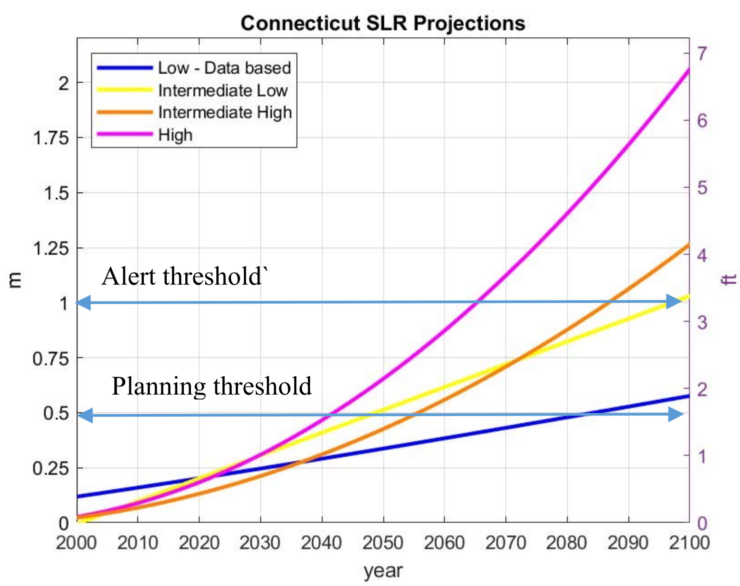
Sea Level Rise in Connecticut

James O'Donnell

Department of Marine Sciences and Connecticut Institute for Resilience and Climate Adaptation

Measurements of sea level by instruments in the water and satellite altimeters provide unambiguous evidence that the annual mean level of the ocean surface is rising. Coastal communities should expect that the frequency of coastal flooding will increase. The National Oceanic and Atmospheric Administration (NOAA) report CPO-1 (Parris et al. 2012) provided guidance on the magnitude of potential changes in the global mean sea level based on analyses of both models and data. Four projections were shared so that managers could select what they judged to be appropriate. To provide more local guidance for Connecticut we have reviewed and modified the projections to include the effects of local oceanographic conditions, more recent data and models, and local land motion. A concise summary of the results are shown in Figure 1.



Sea level rise projections for Connecticut based on local tide gage observations (blue), the IPCC (2013) RPC 4.5 model simulations near Long Island Sound (yellow line), the semi-empirical models (orange line) and ice budgets (magenta line) as in CPO-1.

Though we show the results of four different approaches for forecasting future annual mean sea level in Long Island Sound in Figure 1, the differences between them are not great until after mid-century. We do not expect a significant refinement in the accuracy of longer term forecasts until the character of future emissions of greenhouse gases can be predicted. We note that the yellow line anticipates that emissions peak in 2040 and then fall rapidly, however, sea level late in the century is sensitive to emission between now and 2050. We recommend that planning anticipates that sea level will be 0.5 m (1ft 8 inches) higher than the national tidal datum in Long Island Sound by 2050. It is likely that sea level will continue to increase after 2050. We recommend that global mean sea level measurements and projections be monitored and new assessments be provided to towns at decadal intervals, or more frequently, to ensure that planning be informed by the best available science.

1. Introduction

The population of coastal counties in the United States increased by approximately 40% between 1970 and 2012. This trend is predicted to continue and lead to an additional increase of 8% by 2020 (NOAA, 2013). Recently, Neumann et al (2015) explored the likely changes the number of people living in low elevation coastal areas around the world under several plausible development scenarios. They found that even with the lowest growth rate assumptions the population in these areas could rise by more than 50% between 2000 and 2030 and double by 2060. The prospect of a substantial increase in population density at the coasts makes planning for the consequences of increased sea levels that are expected to accompany global warming (Parris et al, 2012; Church et al., 2013; Vermeer and Rahmstorf, 2009) a high priority.

The location where the ocean surface intersects the land has played an important role in public policy for centuries. So changes in the mean level of the ocean can have important economic and political consequences. Titles to property often extend to the Mean High High Water (MHHW) level for example, and in the many political jurisdictions the land and property below the level at which the estimated risk of flooding by seawater in a year exceeds 1/100 (commonly referred to as the hundred year flood elevation) are subject to use/development regulations that are restrictive. The land use in the zone below the level where the estimated risk exceeds 1/500 is also regulated. These levels are related to the Mean Sea Level (MSL).

Since there are periodic variations in water level due to the astronomical cycles and aperiodic variations due to meteorological forcing of the ocean, accurate determination of the mean level at any location requires time averaging of many measurements. The consequences of tidal variations can be removed when the measurements extend for 19 years and NOAA has defined the current National Tidal Datum Epoch (NTDE) as 1983 to 2001 to set the mean sea level. However, there are longer period oscillations in the ocean and atmosphere that cause sea levels to vary slightly. The spatial average of the time-mean sea level across the globe is termed the *global mean sea level* here. It changes as a consequence of the addition/loss of water to/from the ocean from land, the atmosphere or cryosphere and by thermal expansion/contraction. Since the ocean is in constant motion, measurement locations are sparse, and tectonic processes can move land vertically, measuring the global mean sea level is extremely difficult.

The United States Army Corp of Engineers (USACE, 2013) has recognized the need to include sea level rise in planning for all public works projects in areas influenced by tidal processes and has published guidelines that requires regional variations in rates of sea level change to be considered in every USACE activity. More specifically, they also require the consideration of “low,” “intermediate,” and “high” future rates of global mean sea level rise and provide guidance on how the global mean sea level will change until the year 2100 following recommendations of NOAA Technical Report OAR CPO-1 (Parris et al., 2012). Henceforward, we refer to this work as NOAA CPO-1. Similarly, the State of Connecticut in Public Act 13-179 requires that the state and municipal Plans of Conservation and Development, the state Civil Preparedness Plan, and municipal Evacuation and Hazard Mitigation Plans consider the effects of the anticipated sea level change scenarios published in NOAA CPO-1. This document recognized that there are processes in the ocean and lithosphere that cause the rate of change of sea level at a particular location to differ substantially from the global mean and outlined how this could be conducted. The Connecticut Legislature also recognized that the projections should be revisited at least once a decade and Public Act 13-179 also directed that this should be undertaken by The University of Connecticut. In this document we review recent observations at the NOAA water level gages at New London and Bridgeport and compare recent trends those published in the NOAA CPO-1 report. We then update and refine the information in the report as directed and provide recommendations on sea level rise projections that accounts for local conditions in southern New England to assist planning by coastal municipalities in Connecticut.

In the next section of this report we summarize the NOAA CPO-1 sea level rise projections of the potential trends in global mean sea level and their underlying rationale. We then describe the expected differences between global mean sea level and values in Long Island Sound at the shores of Connecticut. In Section 4 we present recent observation of sea level in Long Island Sound and evaluate whether changes have taken place. Since the NOAA CPO-1 projections were developed there have been considerable advances in the science of climate change and sea level rise so in Section 5 we summarize recent projections and their relationship to the earlier work. We conclude in Section 6 with recommendations for sea level trends and their uncertainty bounds for use in planning and provide recommendations for their use and review.

2. NOAA Global Mean Sea Level Projections

The primary goal of the NOAA CPO-1 sea level rise projections was to provide the first nationally coordinated guidelines for coastal planning and policy development in the United States. Though the report focused on projections for the global mean sea level, it acknowledged that regional variations associated with changes in ocean circulation and vertical land motions were important and provided advice on how users could to include these effects in their planning. A wide range of literature describing past, and possible future, changes in global mean sea level was considered in the preparation of the report. The evidence from direct measurements of water level is summarized by IPCC (2007), Kopp et al. (2009), Church, J. A. and N.J. White. (2011), and National Research Council (1987 and 2012).

Four approaches to the development of future projections were employed. The simplest was the extrapolation of observations. Using an extensive array of tide gage data, Church and White (2011) calculated that global mean sea level has been rising at a rate of approximately 1.7 mm/yr since 1900. Using the mean sea level during the National Tidal Datum Epoch (NDTE), the 19-year interval 1983 – 2001, as the datum and linearly extrapolating the rate from the middle of the NDTE (1992) to 2100 yields a value of 0.2m, or equivalently 0.7ft. This trend in shown by the blue line in Figure 1 and is termed the “Low” scenario in the NOAA CPO-1 report. The prediction formula is summarized in Table 1.

The second approach to prediction of the future sea levels is to use mathematical models to simulate how the earth’s climate system will change in the future under a range of plausible scenarios for emission of gasses that modify radiative transport in the atmosphere (greenhouse gases or GHGs). The International Panel on Climate Change (IPCC) developed six alternatives GHG emission reference scenarios in IPCC (2001) and then used many models to simulate the changes in environment that would result. The average and distribution of metrics like ocean and atmosphere temperatures and sea level were then reported. In scenario B1 the continued acceleration in the emission of GHGs was expected until 2050 when the reductions would begin. This scenario (IPCC, 2007) leads to a concentration of 650 PPM by 2100 (150% of the 2016 level) and a warming of the global average surface air temperature of between 1.1 and 2.9 C (the 5-95% range). The predicted rise in global mean sea level was 0.20 to 0.43 m (or 0.65 to 1.41 ft). The NOAA CPO-1 report adopted the 95% percentile value for the "Intermediate-Low" sea level rise prediction in 2100. To provide a time evolution in sea level estimates (z) they adopted the quadratic formulae parametrization

$$z(t) = s(t - t_0) + b(t - t_0)^2 \quad (1)$$

introduced in NRC (1987) were t represents the prediction year and $t_0 = 1992$, the middle of the NTDE. To ensure that this was consistent with the trend in observations for small $t - t_0$ requires $s = 0.17 \times 10^{-3}\ m/yr$ and if, in addition, $z(2100) = 0.5\ m$, then $b = 2.71 \times 10^{-5} m/yr^2$. This trend is shown by the yellow line in Figure 1.

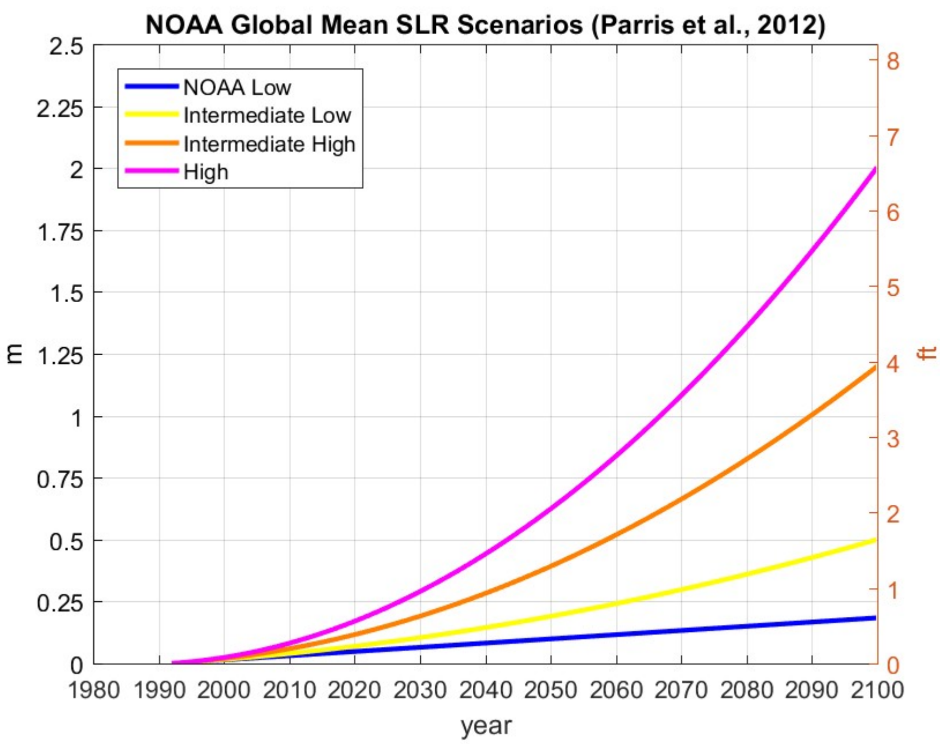


Figure 1. NOAA CPO-1 (Parris et al., 2012) sea level rise projections relative to mean sea level during the NDTE (1983-2001). The lines show four sea level rise scenarios and are computed from the formulae in Table 1.

Table 1. Prediction of future sea levels in the four scenario of NOAA CPO-1 (Parris et al., 2012) and shown in Figure 1 uses the formulae and coefficients listed below. Note that t represents the year the prediction is required and $t_0 = 1992$.

Scenario	Formulae $z = s(t - t_0) + b(t - t_0)^2$		2100 level, $z(2100)$	
	$s\ (meters/yr)$	$b\ (meters/yr^2)$	Meters	(feet
Low	1.7×10^{-3}	0	0.2	0.7
Intermediate Low	1.7×10^{-3}	2.71×10^{-5}	0.5	1.6
Intermediate High	1.7×10^{-3}	8.71×10^{-5}	1.2	3.9
High	1.7×10^{-3}	1.56×10^{-4}	2.0	6. 6

The models used to generate sea level rise predictions in the IPCC (2007) report were acknowledged to have elementary representations of the effects of warming of the ocean and atmosphere on the rate of melting of ice. Rahmstorf (2007) postulated that the rate of global mean sea level was linearly proportional to the global mean surface temperature and estimated the constant of proportionality from data. He then used the temperatures predicted by the global simulations of IPCC (2001) with the empirical relationship to estimate the global mean sea level. The results for 2100 ranged from 0.5 to 1.4 m above the 1990 level, substantially higher than the global model simulations. This third, semi-empirical, approach has been extended by several research groups. Horton et al. (2008) repeated the Rahmstorf (2007) calculation with the more sophisticated global models that were included in the IPCC (2007) report. The papers of Vermeer and Rahmstorf (2009), Grinsted et al. (2009) and Jevrejeva et al. (2010) subsequently improved the empirical model of the effect of temperature on sea level, augmented the data used in the analyses, and introduced technical improvements to the parameter estimation procedure. The ranges of the global mean sea level 2100 predictions for these semi-empirical models using temperature predicted in Scenario A2 in IPCC (2007) is provided in Table 2. The NOAA CPO-1 report adopted the mean of the upper and lower bounds, 1.2 m (3.8 ft), as the "Intermediate High" prediction for the year 2100. Using $b = 8.71 \times 10^{-5}\ m/yr^2$ in Equation (1) yields the trend shown by the orange line in Figure 1.

Since the results of the semi-empirical sea level forecasts require rapid melting of glaciers, Pfeffer et al. (2008) considered whether glacial flow rates in Greenland and the Antarctic Peninsula could provide sufficient water to augment thermal expansion and match the predicted rise in sea level. This forms the basis of the forth forecast approach. They found that increases in sea level between 0.8 and 2 m sea level by 2100 were plausible. The upper limit of this range was chosen as the "High" scenario for the NOAA CPO-1 report. The magenta line in Figure 1 shows the quadratic trend to this value using Equation (1) with $b = 1.56 \times 10^{-4}\ m/yr^2$

Table 2. Ranges of the global mean sea level predictions for 2100 using the semi-empirical models and temperatures from Scenario A2 in IPCC (2007).

Model	**2100 Predictions** and range			
	Lower (meters)	Upper (meters)	Lower (feet)	Upper (feet)
Vermeer and Rahmstorf (2009)	0.98	1.55	3.2	5.1
Grinsted et al. (2009)	1.25	1.8	4.1	5.9
Jevrejeva et al. (2010)	0.7	1.5	2.3	4.9
Horton et al. (2008)	0.7	0.9	2.3	3.0
Mean	**0.91**	**1.4**	**3.0**	**4.7**

3. Regional Variations in Changes in Mean Sea Level

The rate of change of mean sea level relative to the coast at any location is the results of the change in the global mean, changes in the level of the land and changes in the effect of ocean circulation and atmospheric circulation patterns. The vertical land movement at tide station with long records was estimated by Zervas et al. (2013). They assume that the effect of oceanic and atmospheric processes occur at a regional scale and then subtract the common trends in the data to reveal the underlying spatial structure of the vertical land movements. Table 3 shows the result of the analyses for stations in Long Island Sound. All the stations are becoming lower at approximately the same rate. The differences between the values are less than the width of the 95% confidence interval and all values are consistent with a Connecticut coast mean VLM of -0.7 mm/yr.

Table 3. The rate of vertical land movement (VLM) at tide station with long records in Long Island Sound estimated by Zervas et al. (2013).

Station Name	**NOAA Station Number**	**VLM (mm/yr)**	**95% interval (mm/yr)**
New London	8461490	-0.67	0.1
Bridgeport	8467150	-0.76	0.15
Kings Point	8516990	-0.67	0.07
Mean		**-0.70**	0.1

The current rate of relative sea level rise (that detected by the tide gages) should therefore be expected to be the global rate minus the VLM. In the future there may be a change to the ocean and atmosphere properties and that can only be detected by model simulations that resolve the critical processes accurately.

4. Recent Observations of Sea Level in Long Island Sound

The longest water level data records at the Connecticut coastline are located at New London and Bridgeport. The stations at Willets Point and Kings Point are close together in New York, at the eastern end of the East River. Water level data at the Willets Point station began in July, 1931 and terminated in November, 2000. The record at Kings Point started in November, 1998 and is continuing. The overlap in the data records allowed assessment of the differences in the mean levels and the records to be concatenated. The instruments are maintained by NOAA at the locations shown in Figure 2. The data from the stations is available at the web sites listed in Table 4. The level of the station datum and the mean sea level relative to the geodetic datum NAVD88 are listed in Table 4.

Table 4. Water level data sources (https://tidesandcurrents.noaa.gov/stationhome.html?id=XXXXXXX, where XXXXXXX is the Station Number below)

Station Name	Station Number	Lat. (Deg.)	Lon. (Deg.)	Station datum NAVD88 (m)	MSL relative to station datum	MSL relative to NAVD88
New London	8461490	41.355	-72.087	1.634	1.542	-0.092
Bridgeport	8467150	41.173	-73.182	1.774	1.708	-0.066
New Haven	8465705	41.283	-72.908	--	6.630	---
Montauk	8510560	41.048	-71.96	1.655	1.554	-0.101
Willets Point	8516990	40.81	-73.765	2.810	2.752	-0.058
Kings Point	8516945	40.81	-73.765	---	---	---

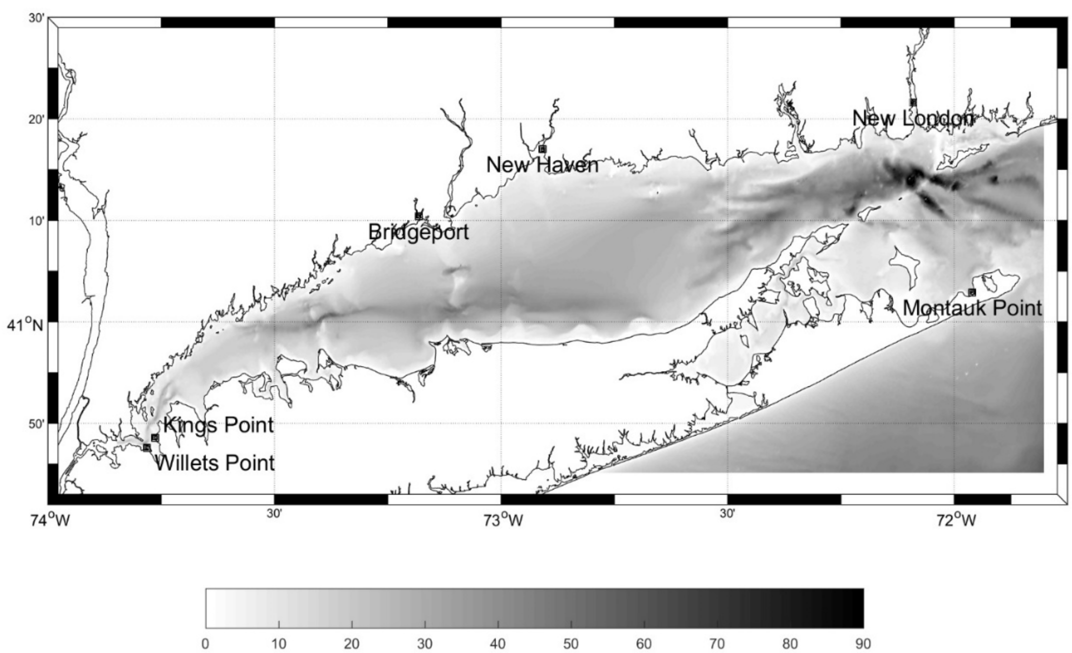


Figure 2. Coastal geometry and bathymetry of Long Island Sound showing the locations of the NOAA water level gages.

The longest records of water level measurements acquired in Long Island Sound are shown in Figure 3. The elevations in the Figure are plotted relative to the mean value at the station during the 19 year National Tidal Datum Epoch (NTDE) which is defined as the years 1983 to 2001. The elevation of the station datum and the elevation of the NDTE mean sea level are listed in Table 4. The blue lines show the monthly averages of hourly measurements, and the solid red lines show the annual averages. The seasonal variation in the monthly mean, as indicated by the two standard deviation interval is shown by the red dashed lines to vary between 10 and 20 cm.

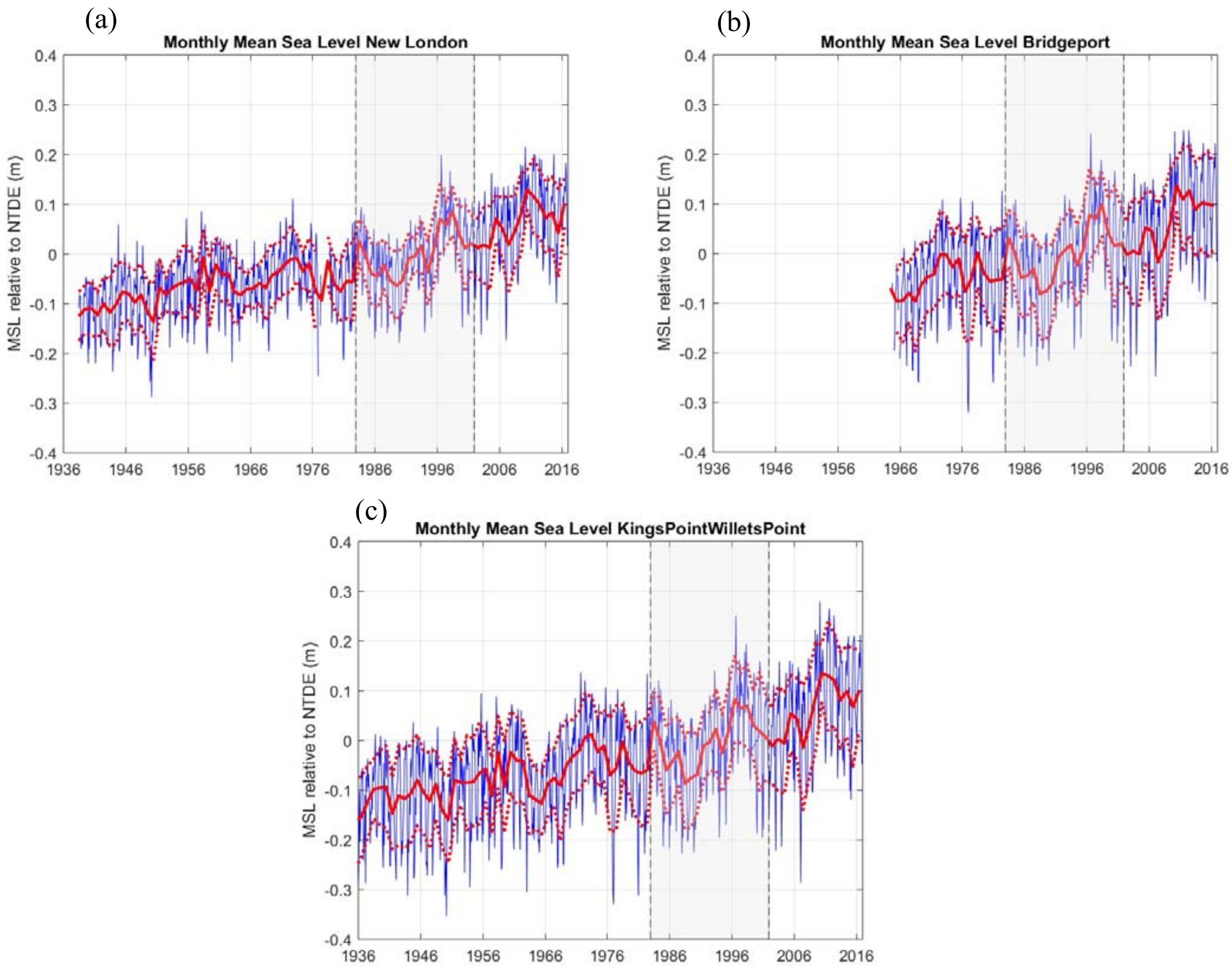


Figure 3. The time series of the monthly average of sea level observed at (a) Bridgeport, (b) New London, and (c) Kings Point – Willets Point are shown by the blue lines. The annual averages are shown by the solid red lines and the 68% confidence interval is bounded by the dashed red lines. Station locations are listed in Table 4 and shown in Figure 2. The grey stripe shows the period defined as the national tidal datum epoch (NTDE). The mean of each record during this interval is zero.

The red lines in Figure 3 clearly show the long term increasing trend in sea level underlying quasi periodic variations with a period of approximately 10 years. Note that these trends are measured relative to the individual station datums. It is well established that vertical land movements are common at tide gages due to tectonic processes and adjustment to the retreat of ice at the end of the last ice ages. Kopp et al. (2015) provide a cogent explanation of these processes and integrates estimates at a global network of observation stations. Zervas et al. (2013) provides estimates at the NOAA tide gages and Table 3 shows the values in Long Island Sound. The right-most column of Table 4 shows the observed mean sea level relative to the NAVD88 datum reported by NOAA. The difference in level from Montauk to Willetts Point is very small, only 4 cm, and shows that with the water level rises from the ocean to the East River.

The decadal scale oscillations in annual mean sea level that are evident in Figure 3 have amplitudes in the range of 5-10 cm. These cause the quantitative determination of the local rate of sea level rise to be uncertain and thereby limit detection of changes in the rate. Recently, McCarthy et al. (2015) showed that the oscillations in the annual mean difference between coastal water levels in southern New England and the South Atlantic Bight (south of Cape Hatteras) waters correlated with atmospheric forcing as indicated by the North Atlantic Oscillation (NAO) index (Hurrell et al, 2001). They also showed that they were coherent with fluctuations in the magnitude of the Atlantic overturning circulation and, consequently, the rate of northward heat transport. Temperature changes in the inter-gyre region of the North Atlantic determine the Atlantic Multi-decadal Oscillation (AMO) index which is well known to correlate with hemispheric-scale weather patterns. The sea level fluctuations are, therefore, manifestations of the coupling of atmospheric and ocean circulation variability.

Figure 4 shows the shows the annual mean sea level records from Bridgeport, New London and Willets Point. The differences between the records is very small and they are obviously highly correlated. Ordinary least-squares regression (following the method employed by NOAA in Storch and Zwiers, 2001) applied to the whole record of annual means at New London and Willets-Kings Point yields the rates of increase of relative mean sea level of 2.4 mm/yr and 2.8 mm/yr. Since the 95% confidence intervals of these estimates is 0.3 mm/yr, these are not significantly different. The Bridgeport observations did not begin until 1963 and so the record is 35% shorter than the others. The rate of sea level rise between 1963 and 2016 is 3.3 ± 0.7 mm/yr. When the data from 1976-2016 is used all three stations are consistent with values of 4.0 ($\pm$ 1.8), 4.1 ($\pm$ 2.6), and 4.1 ($\pm$ 2.4) mm/yr for the Bridgeport, New London and Willets Points stations. The confidence intervals for these estimates are larger because the data duration is shorter. These results are summarized in Table 5 and Figure 4 in which the red line indicates an increase of sea level relative to the gages at 4.1 mm/yr.

Table. 5. The results of linear regression analysis for the data shown in Figures 3 and 4. The second and third columns show the rate of change of mean sea level (relative to the gage datum) and the associated 95% confidence interval (CI). The confidence interval accounts for the serial correlation in the data following the approach of Storch and Zwiers (2001). To assess the possibility that the slope had changed the data was partitioned at 1976 and the regression repeated. The results are provided in the column on the right of the table.

Station Name	Whole record		Pre 1976		Post 1976	
	Rate mm/yr	95% CI	Rate mm/yr	95% CI	Rate mm/yr	95% CI
New London	2.4	0.3	2.3	0.6	4.1	1.8
Bridgeport	3.3	0.7	-	-	4.0	2.6
Willets Point	2.8	0.3	3.2	1.3	4.1	2.4

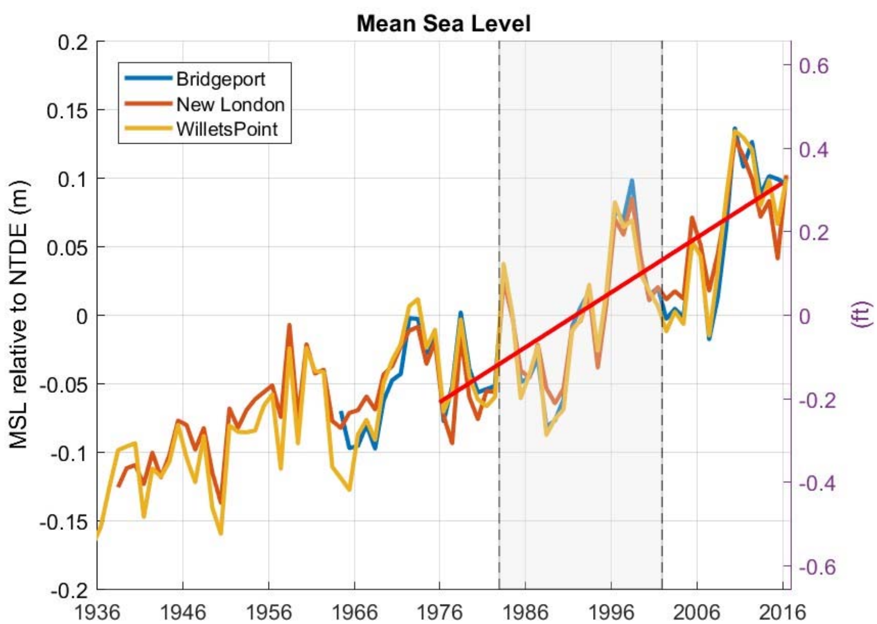


Figure 4. The annual average sea level observed at Bridgeport, New London, and Willets Point between 1936 and 2016. The grey strip defined the National Tidal Datum Epoch (NTDE) and the average of the observations at each station in this interval is set to zero to define the datum. These curves are the same as shown in Figure 3a-c. The red line shows the trend of 4 mm/yr since 1976.

5. Recent Analyses of Global Mean Sea Level

The rate of sea level rise at the Connecticut shore since 1976 shown in Figure 4 is much larger than the 1.7 mm/yr used in NOAA CPO-1. This can be compared to the recent estimates of the global average mean sea level reported by Church and White (2011). They used the global network of sea level gage data and an averaging approach that compensates for the heterogeneity of sampling in time and space. They have also provided several updates to the analyses at the web site http://www.cmar.csiro.au/sealevel/sl_data_cmar.html. The blue line in Figure 5 shows their annual global mean sea level estimates with the average in the NTDE (1983-2001) set to zero. The light blue stripe show the 68% confidence interval of the estimate obtained from their averaging process. The band is wider in the 19th and early 20th century as a consequence of the observation network being sparser in the early period of the record. The spatial averaging results in a series with much less decadal-scale variability than in Long Island Sound (Figure 4). Church and White (2011) pointed out that the analysis shows an obvious increase in the rate of increase in the global mean sea level between the first to the second half of the series. From 1880 to 1935 global mean sea level rose at the rate 1.1$\pm$ 0.7 mm/yr and from 1936 to the end of the record the trend was 1.8 $\pm$ 0.3 mm/yr. Several short periods of falling mean sea levels are noticeable and Church and White (2011) propose explanations for these. For example, the cooling in the ocean after the eruptions of Mount Agung (Indonesia) in 1963, El Chichon (Mexico) in 1982, and Mount Pinatubo (Philippines) in 1991, may have contributed the dips in the mean sea level trend a few years after these eruptions (Church et al. 2005; Gregory et al. 2006; Domingues et al. 2008). They also pointed out that at the end of the record available to them the rate of change increased to 2.8 $\pm$ 0.8 mm/yr for the interval 1993 to 2009.

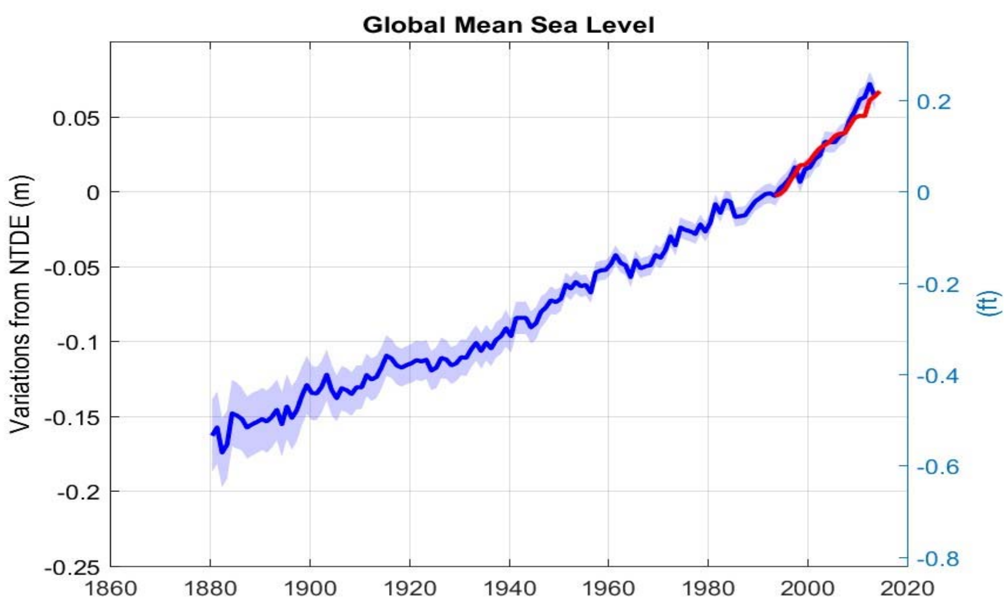


Figure 5. The blue line shows estimates of the annual average global mean sea level estimated from measurements from a global array of tide gages. Annual mean values smoothed with a 7 point box-car filter are shown. The red dashed line shows the 68% estimation interval. The black line on the right shows the trend obtained from altimeter data. Note that the elevation datum is the mean level in 1990. Adapted from Church and White (2011) using data from http://www.cmar.csiro.au/sealevel/sl_data_cmar.html.

Since 1993 the water surface level across much of the ocean have been observed by satellite-borne altimeters. The spatial coverage of these measurements complement the long records available at tide gages and directly avoids the aliasing of the spatial variability. Church and White (2011) also analyzed available data and the results of their calculation of global average mean sea level shown by the red line in Figure 5. They found that the rate of increase in the global mean sea level, after correction for GIA, was 3.2 ± 0.4 mm/yr. This was slightly higher than the 2.8 ± 0.8 mm/yr yielded by the analyses of tide gage data, but not significantly different.

A synthesis of available estimates of the trends from satellite observations is described by Nerem et al. (2010). The comparison is regularly updated at (http://sealevel.colorado.edu/) and their results are summarized in Table 6. When the confidence intervals are taken into account the results of the various analyses are consistent. The mean value weighted by the inverse of the variance is 3.4 ± 0.4 mm/yr. The Church and White (2011) tide gage analysis has also been updated (the data is included in Figure 5) and for the period 1993 to 2015 the rate of change is 3.5 ± 0.4 mm/yr in agreement with the altimeter-derived results.

Table 6. A compilation of estimates of the rate of change of the global mean sea level obtained from satellite-borne altimeters from http://sealevel.colorado.edu/.

Altimeter Derived Rate of Change of Global Mean Sea Level	**Rate mm/yr**	**CI (68%) (mm/yr)**
Univ. of Colorado http://sealevel.colorado.edu/	3.4	0.4
Centre National D'Estudes Spatiales (France) http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html	3.4	0.6
CSIRO (Australia) http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html	3.3	0.4
NASA Goddard http://podaac-ftp.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V3	3.4	0.4
NOAA https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/	3.3	0.4

6. Observation-Based Projections for Connecticut

It is evident that the observation of sea level in Long Island Sound shown in Figure 4, the analyses of the global network of tide gages and the satellite measurements shown in Figure 5 agree that the trend that should be anticipated for mean sea level at the shoreline of Connecticut is much higher than the 1.7 mm/yr used in NOAA CPO-1 and shown by the blue line in Figure 1. Further, since the uncertainty in the trends can also be estimated these should be used be included in planning guidance.

Since the effects of decadal scale variability is substantially reduced in the analyses of the global mean sea level the uncertainty in the trend is much smaller than that obtained from the analyses of the measurement obtained in Long Island Sound. However, the local rate of vertical land motion, -0.7 ± 0.1 mm/yr (see Table 3), must be subtracted from the global trend of 3.4 ± 0.4 mm/yr to yield 4 ± 0.4 mm/yr as the expected rate. Note that this is equivalent to the trend obtained from the observations from tide gage data from Long Island Sound between 1976 and 2016 and shown in Figure 4.

In Figure 6 we show an extrapolation of the relative mean sea level in Long Island Sound based on the 4.0 mm/yr trend to 2100 by the solid black line. This is substantially higher than the data-based projection of Parris et al. (2012) which is shown by the yellow line. The thin dashed lines show the 95% interval of the estimate of the sea level rise rate and the thick dashed line show the 95% interval of the prediction of the annual mean values until 2100. This is substantially wider than the trend uncertainty since the amplitude of the decadal-scale variability due to local factors exceeds 10cm.

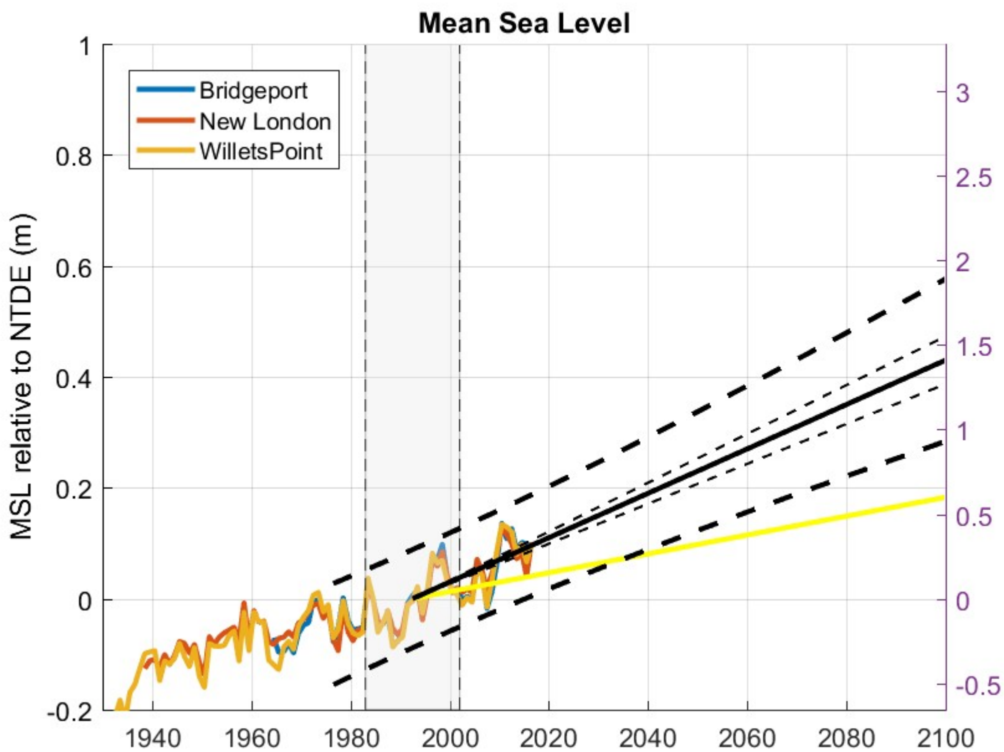


Figure 6. The annual average sea level observed at Bridgeport, New London, and Willets Point between 1936 and 2016 are shown using the same colors as in Figure 4. The solid black line shows the trend of 4 mm/yr and the thin dashed lines show the ± 0.4 mm/yr range of the predicted slope based on the global mean tide gage and altimeter observations. The thicker dashed lines show the 95% prediction interval for the annual mean sea level in Long Island Sound extrapolated to 2100. The yellow line shows the projection of global mean sea level published by NOAA CPO-1 and shown as the blue line in Figure 1. Note that the axis on the right shows the level in feet.

The information in Figure 6 is repeated in Table 7 to assist in planning calculations. The expected value (the solid black line in Figure 6) for the years shown in the leftmost column are listed in the second column. The upper bound of the 95% confidence interval for the annual mean sea level (the upper thick black line in Figure 6) are listed in the third column. For comparison, the projections of NOAA CPO-1 are shown in the fourth column (yellow line in Figure 6). The values on the units of feet are repeated in the three column on the right of the Table. This projection anticipates that water level gages in Long Island Sound should in 2050 be expected to record a mean values that is 0.23 m above the mean of the NTDE. Further, there is a 97.5% likelihood that the annual mean sea level will be less than 0.39m.

Table 7. Predictions of the change in mean sea level at the coast of Connecticut relative to the mean value during the NTDE. For the years shown in the first column, the second column show the expected (mean) value and the third column shows the upper bound of the 95% confidence interval. The fourth column show the “low” projection from NOAA CPO-1 for comparison. The three columns on the right show the same information in units of feet. The values are also shown by the solid black line in Figure 6.

Year	Mean (m)	Upper 95% (m)	NOAA (m)	Mean (ft)	Upper 95% (ft)	NOAA (ft)
2030	0.15	0.25	0.06	0.5	0.81	0.21
2040	0.19	0.29	0.08	0.63	0.96	0.27
2050	0.23	0.34	0.10	0.76	1.11	0.32
2060	0.27	0.39	0.12	0.89	1.27	0.38
2070	0.31	0.43	0.13	1.02	1.42	0.43
2080	0.35	0.48	0.15	1.15	1.58	0.49
2090	0.39	0.53	0.17	1.29	1.74	0.55
2100	0.43	0.58	0.18	1.42	1.9	0.60

7. Model Projections of Sea Level

The NOAA CPO-1 “intermediate low” future sea level projection (yellow line in Figure 1) were based on process models of the climate system that are utilized the results of the IPCC (2007) fourth assessment report (AR4). The IPCC simulations adopted a range of assumptions about the future trajectory of the rate of global emissions of radiatively active gases, or greenhouse gases (GHGs). These assumptions were termed “emission scenarios” and the various options are discussed in detail by van Vuuren et al. (2011). The NOAA CPO-1 report used the results of scenario B1 in which the rate emissions of CO_2 (and other GHGs) were assumed to continue to increase until approximately 2050 after which technological innovation would lead to decreases. The IPCC process aggregated the results of 58 simulations from 14 different mathematical models of the earth’s climate system for each GHG emissions scenario. This were termed an “ensemble” of simulations. The mean and distribution of the critical variables were then computed and archived. The ensemble global mean surface air temperature change between the baseline interval (1980 to1999) and 2090 to 2099 in scenario B1 was 1.8 C. The corresponding 95% confidence range was 1.1 to 2.9 C. The change in the global mean sea level between these intervals was predicted to be 0.28 m and the 95% confidence rage was 0.18 to 0.38.

The IPCC AR4 report has recently been superseded by IPCC (2013), the fifth assessment report (AR5), which was based on improved models that incorporated more recent advances in climate science. The character of future GHG emissions considered in AR5 were also slightly revised and termed “representative concentration pathways” or RCPs. The simulation in which the emissions were most similar to scenario B1 in terms of both GHG emissions and their effect on the earth’s heat budget is RCP4.5. Figure 7 shows the assumed variation in the rate of emissions by the blue lines. The IPCC (2013) report project that the RPC will lead to the global average surface air temperature in the last two decades of the 21st century (2081-2100) being 2.2 C warmer than the average between 1886 and 2005. The 90% confidence interval of this estimate is 1.4 to 3.1 C.

The IPCC (2013) report contrasts the projections of RCP4.5 with those of more aggressive emission reduction (RCP2.6, magenta line in Figure 7) in which emissions are assumed to peak, and begin to reduce, earlier, and RPC6.0 (yellow line in Figure 7) in which the peak occurs in 2075 at a higher level before reductions occur. A continuing growth in emissions is simulated in RPC8.5 (red line in Figure 7). The projected effects of the RPCs on global mean sea level, and that near Connecticut are discussed in this section.

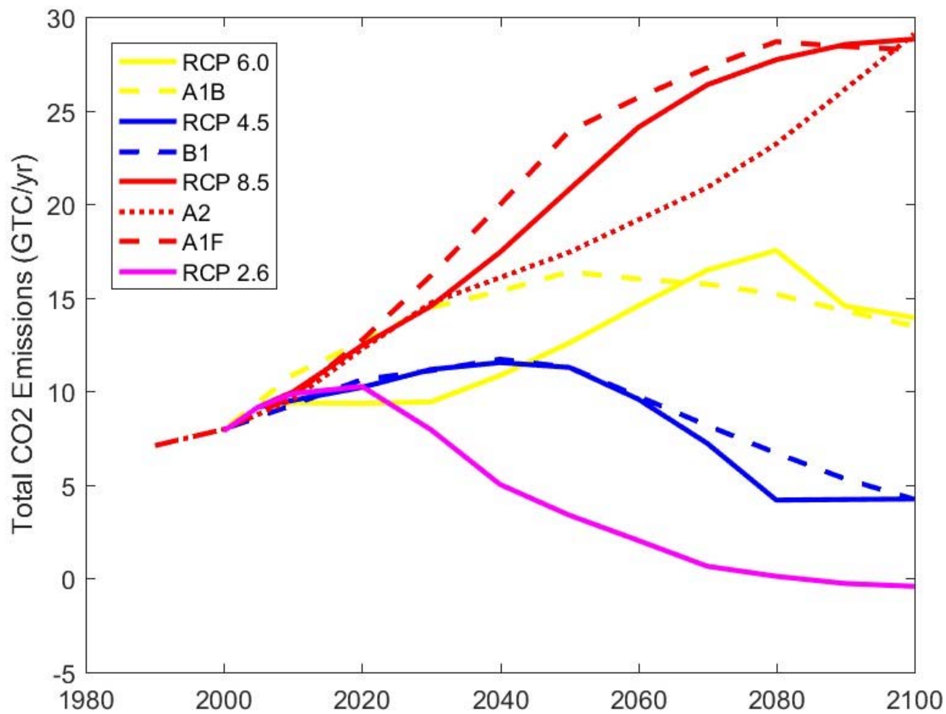


Figure 7. A Comparison of the trajectory of global emissions of greenhouse gases considered in the IPCC's AR4 and AR5. The blue dashed line shows scenario B1 of AR4 which is the basis of the "intermediate low" sea level rise scenario in the NOAA CPO-1 report. The solid blue line shows the emissions in representative concentration pathway RPC 4.5 of AR5. (Based on data from http://sres.ciesin.org/final_data.html and http://tntcat.iiasa.ac.at:8787/RcpDb).

In Figure 8 we show the predicted evolution of the global mean sea level for four RCPs. The solid lines show the ensemble means and the surrounding shaded bands indicate the 5-95% confidence intervals. The four graphs share similar characteristics. In each the mean sea level increases monotonically with time. The confidence intervals also widen with time at approximately the same rate so that by 2100 the 5-95% range is approximately 30 to 40cm. The main differences are in the sea level at 2100 and that in RPC 6.0 and 8.5 the rate of change of the sea level increases noticeably after 2050.

The differences in the sea level trends are clearer in Figure 9 which shows the results of all four scenarios and the confidence interval for the RCP 4.5 projection. Figure 9(a) demonstrates that,

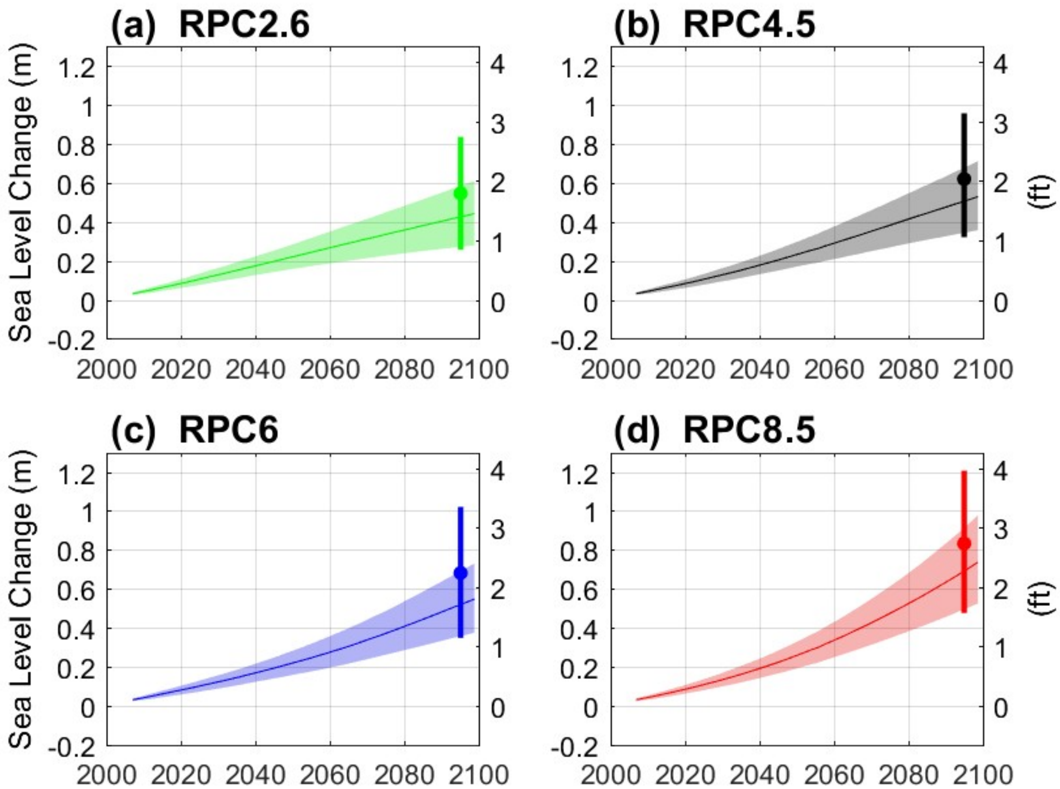


Figure 8. The evolution of the ensemble mean (solid lines), and 5-95% confidence interval (shaded bands) for the global mean sea level predicted by the IPCC (2013) models for RCPs (a) 2.6, (b) 4.5, (c) 6, and (d) 8.5. In each graph the circle and bar shows the ensemble mean and 5-95% confidence interval for the predicted sea level at the model grid point shown in Figure 9 averaged between 2090 and 2100.

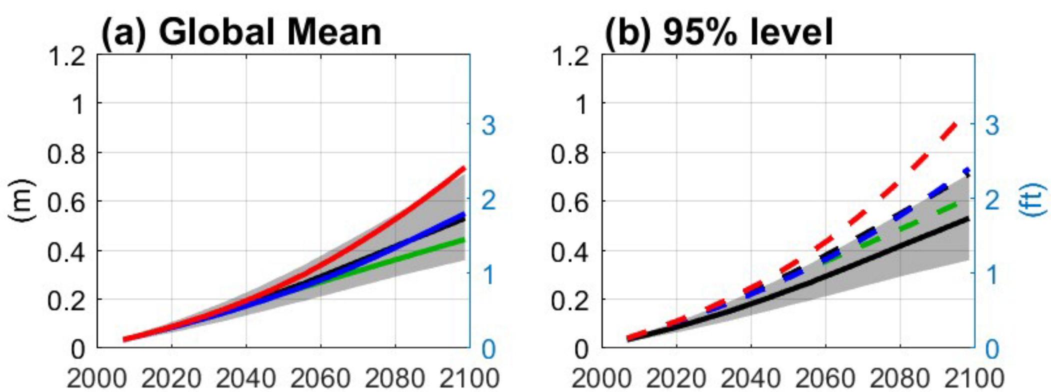


Figure 9. (a)The IPCC (2013) predicted trends in global mean sea level (green, black, blue and red represent RPC 2.6, 4.5, 6.0 and 8.5 respectively) with the 5-95% confidence interval for RPC 4.5 shaded grey. (b) The 95% confidence bound for each RCP using dashed lines with the same color code as (a). The RPC 4.5 mean (solid black line) and 5-95% confidence interval (grey stripe) are also shown for reference.

as far as mean sea level is concerned, the solutions for RPC 4.5 and 6.0 (black and blue lines) are indistinguishable between in the interval shown. As is evident in Figure 7, these two RPC have very similar GHG emissions until 2050 and Figure 9(a) suggests that the reduction in GHG emissions that is anticipated in RPC 4.5 after 2050 has little effect on sea level until after 2100. The long lag between changes in the rate of emissions and the effect on sea level is also reflected in the difference between the RPC 4.5 and 8.5 (black and red lines). Even though the rate of emissions in RPC 8.5 is 50% larger than in RPC 4.5 by 2050, the difference in the change in global mean sea level is small, both the RPC 4.5 and 8.5 solutions are within the 5-95% confidence interval of the RPC4.5 value.

The NOAA CPO-1 "intermediate low" sea level change projection was based on the 95% values in the IPCC (2007) AR4 simulations. The 95% bound on the confidence intervals of the four projections in the IPCC (2013) AR5 are shown in Figure 9(b) and these are all very similar until after 2050 when the RPC 8.5 become higher than 4.5 and 6.0. Table 8 lists the values of the change in global mean and upper bound of the 5-95% confidence interval for RCP 4.5 and 8.0. In 2050 the difference in the 95% level of the expected rise in global mean sea level is only 5 cm, however, by 2100 it is 35 cm.

Table 8. The predictions of the change in global mean sea level averaged in decades surrounding the year listed in the leftmost columns. Columns 2 and 3 list the means and upper 95% values from the RPC 4.5 simulation and columns 4 and 5 show the same results from RCP 8.5. The four columns on the right show the same information in feet.

	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Year	Mean (m)	Upper 95% (m)	Mean (m)	Upper 95% (m)	Mean (ft)	Upper 95% (ft)	Mean (ft)	Upper 95% (ft)
2030	0.13	0.16	0.13	0.17	0.42	0.54	0.44	0.56
2040	0.17	0.22	0.19	0.24	0.57	0.73	0.63	0.79
2050	0.22	0.28	0.26	0.33	0.72	0.93	0.84	1.07
2060	0.27	0.35	0.33	0.43	0.87	1.14	1.09	1.4
2070	0.31	0.41	0.42	0.54	1.02	1.35	1.38	1.78
2080	0.36	0.48	0.52	0.68	1.17	1.58	1.72	2.23
2090	0.40	0.55	0.64	0.84	1.33	1.81	2.09	2.74
2100	0.43	0.60	0.72	0.95	1.43	1.97	2.36	3.12

It is very important to note that the dynamics of the atmosphere and ocean cause the mean sea level change resulting from warming to be spatially variable. The details of the mechanisms that cause the differences are summarized clearly by Kopp et al. (2014). Changes in the ocean circulation and the rate of northward transport of heat in the northwestern Atlantic Ocean have a significant impact of mean sea level in southern New England. Figure 10(a) shows the global variation of the changes in mean sea level in 2100 in RCP 4.5. The purple shades in the northwest Atlantic show that the warming leads to a much greater increase in the mean sea level around New England and the Canadian Maritime Provinces thane almost anywhere else in the world. The magnitude of the change is sensitive to the climate model and parameter set that is used as is shown in Figure 10(b) which displays the standard deviation (approximately the 68% interval) of the ensemble of predictions of the projected mean sea level in 2100.

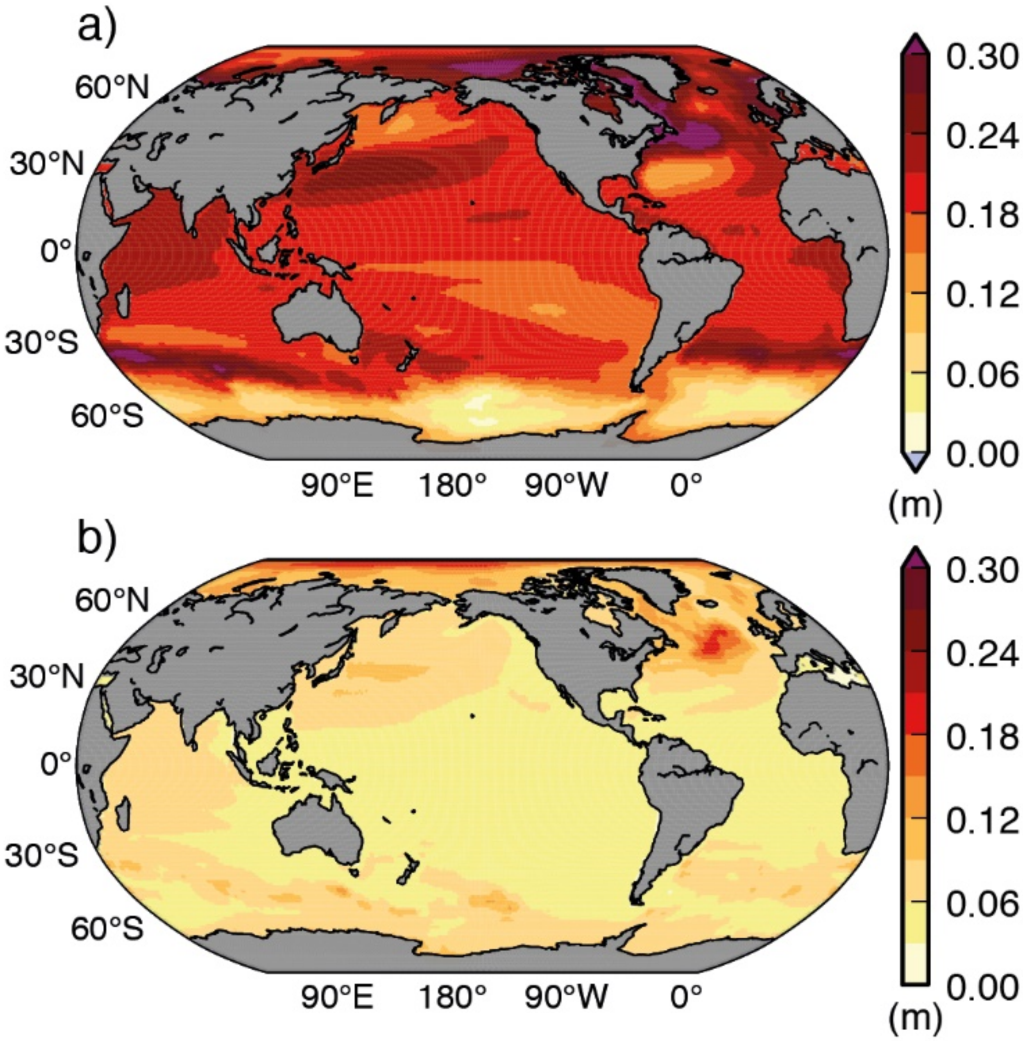


Figure 10. (a) Ensemble mean sea level changes for the period 2081–2100 relative to the reference period 1986– 2005 for RCP 4.5. (b) The root-mean square deviation about the ensemble mean (meters). Reproduced from Figure 13.16 of IPCCC (2013).

The expected sea level change around New England in 2100 is shown in Figure 11. This is simply an expanded view of the information in Figure 10(a). At this scale the resolution of the analysis is clear. Note that though the models used to construct the ensemble have higher resolution, the solutions are averaged to the common 1× 1 degree grid shown. Consequently, variations on the scale shorter than the length of Long Island Sound can't be resolved. The mean and 5-95% confidence intervals for the mean sea level change for the interval 2090 to 2100 in each of the four RCPs at the grid point shown by the green square in Figure 11 near the southern New England shore is shown in Figure 8 by the circles and bars. The ensemble solutions for all four RPCs near the coast of southern New England are almost equal to the 95% confidence interval of the global mean. In addition, the width of the confidence interval the coastal solutions are significantly wider than that for the global mean. Planning for sea level rise in southern New England should, therefore, be based on the mean and 95% of the local ensemble values.

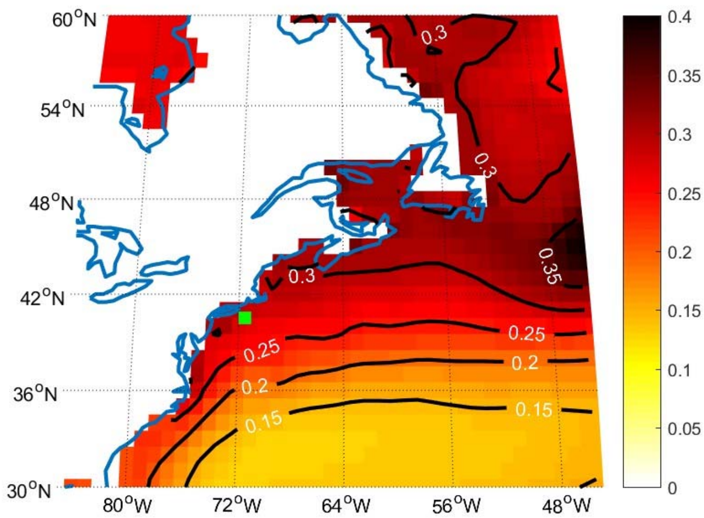


Figure 11. A close up of the IPPC ensemble mean sea level projection for 2100 in the northwest Atlantic. The coastline is shown in blue. The unit for the contour lines and color scale is meters. The green square shows the location chosen to represent the sea level near the southern New England shore.

To use the results of the IPCC simulations as guidance for the expected change in sea level in Connecticut the difference in the vertical datums used in the IPCC models and in the NOAA tide gages, and the consequences of vertical land movement must be taken into account. The IPCC (2013) used the mean of the interval 1986-2005 as the datum for sea level. Since the data from the NOAA gages discussed in Section 4 used the NTDE (1983 to 2001), a small, -4 mm, adjustment must be added to the IPCC sea level projections. The vertical land motion in coastal Connecticut is shown in Table 3 to be -0.7 mm/yr (subsidence) and this requires an increase in the sea level projection. Figure 12 shows the evolution of the ensemble mean and 5 to 95% confidence interval for RPC 4.5 at the location of green cell in Figure 11 near the coast of southern New England with the correction for vertical land motion. The variation is remarkably linear and the rate of change of the mean is 6.6 mm/yr and the trend in the 95% increases at 9.7 mm/yr. The values for each decade are listed in Table 8.

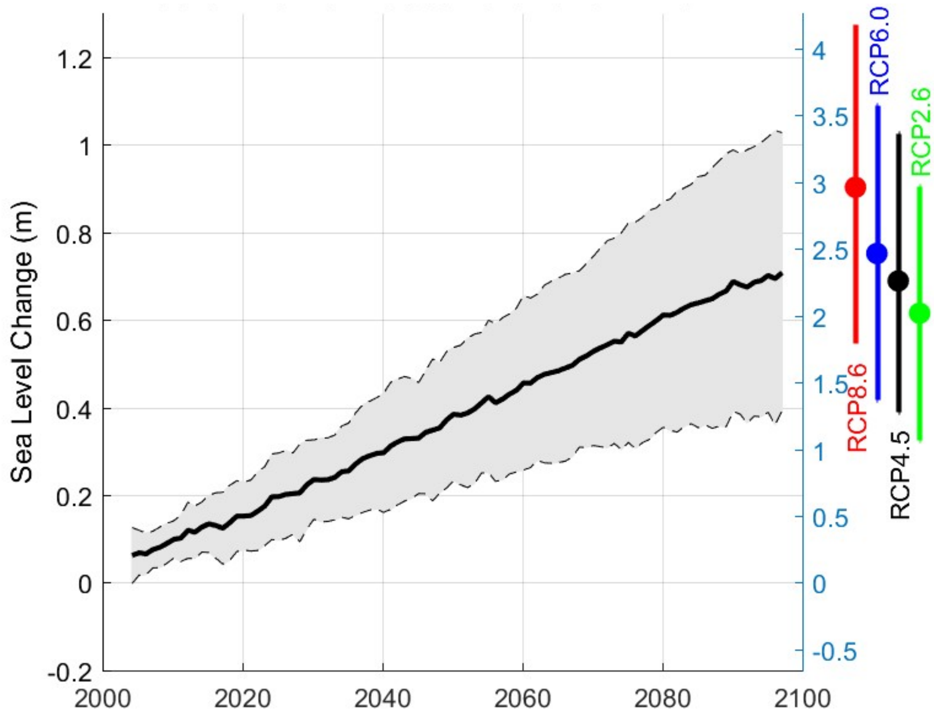


Figure 12. Sea level projection from IPCC (2013) for RCP 4.5 at the cell shown by the green cell in Figure 11 with the rate of vertical land motion added are shown by the solid black line. The 5 to 95% confidence interval is represented by the grey stripe. On the right of the figure the average sea level, and 5 to 95% range, for the interval 2090 and 2100 is shown for the 4 RCPs in IPCC (2013).

Table 8. Predictions of the change in mean sea level at the coast of Connecticut relative to the mean value during the NTDE based on the IPCC (2013) RPC 4.5 simulations. For the years shown in the first column, the second column show the expected (mean) value and the third column shows the upper bound of the 95% confidence interval. The fourth column show the intermediate low projections from NOAA CPO-1 for comparison. The three columns on the right show the same information in units of feet. The values are also shown in Figure 6.

Year	Mean (m)	Upper 95% (m)	NOAA (m)	Mean (ft)	Upper 95% (ft)	NOAA (ft)
2030	0.25	0.36	0.1	0.83	1.19	0.34
2040	0.33	0.47	0.14	1.07	1.53	0.47
2050	0.4	0.57	0.19	1.31	1.87	0.62
2060	0.47	0.67	0.24	1.55	2.21	0.79
2070	0.54	0.78	0.3	1.79	2.55	0.98
2080	0.62	0.88	0.36	2.02	2.89	1.18
2090	0.69	0.98	0.43	2.26	3.23	1.4
2100	0.76	1.09	0.5	2.5	3.57	1.64

8. Semi-Empirical Models.

An important weakness of the models used in the IPCC (2007) report and, consequently, the CPO-1 report, to simulate the impact of higher concentrations of CO_2 in the atmosphere on warming the ocean and increasing mean sea level, was is the representation of the effect of warming on the rate of melting of ice sheets. Observations were very limited and the mechanisms not well understood. Rahmstorf (2007) showed that there was a correlation between observations of the global average surface air temperature and the rate of sea level rise observed between 1881 and 2001. He then exploited this correlation to translate the temperatures predicted by a climate system model to obtain what he termed a semi-empirical estimate of the mean ocean level. Though this approach intrinsically assumed that the mechanistic links between a warming atmosphere and melting ice would remain the same, he showed it predicted a significantly higher mean sea level than the model.

Vermeer and Rahmstorf (2009) followed up this work by refining the correlation and applying it to translate the temperature predictions of the models used in IPCC (2007) to semi-empirical sea level forecasts. These were again substantially higher than the predictions of the process models. Grinsted et al. (2009) used a similar approach that exploited a much longer record of sea level and temperature proxies, but the conclusion was again that the sea level rise predictions made by the process models were too low to be consistent with the empirical link between mean air temperature and sea level.

To create the "Intermediate High" projection, the orange line in Figure 1, the CPO-1 report averaged the results of Vermeer and Rahmstorf (2009) and Grinsted et al. (2009). They then approximated the time evolution by a quadratic function $E(t) = m(t - t_o) + b * (t - t_0)^2$ where $t_0 = 1992$, $m = 1.7 \times 10^{-3}$, and $b = 8.71 \times 10^{-5}$.

To localize this estimate for applications at the shore of Connecticut the effect vertical land motion (subsidence) must be included. We therefore introduced the estimate from Table 3 and modified the CPO-1 equation to $E(t) = (m + 0.0007)(t - t_o) + b * (t - t_0)^2$.

9. Ice Budget Models

A large source of uncertainty in sea level forecasts arises from our limited understanding of the rate of melting of ice in Greenland and Antarctica. The CPO-1 report used estimates of the highest, physically plausible, rates of glacier motion presented by Pfeffer et al. (2008) to estimate the upper bound on sea level rise rates. They approximated the trend by the same quadratic function as in Section 8, but with $b = 15.6 \times 10^{-5}$. To include the effect of land subsidence in Connecticut we added 0.0007 the value of m.

10. Summary and Conclusions.

To provide planning advice for sea level rise that accounts for local conditions and follows the approach of CPO-1 we assemble in Figure 13 revised versions of the NOAA projections. Instead of projecting the best fit line through the observations of the annual estimates of global mean sea level, the blue line (the Low projection) is the upper bound of the prediction interval of the linear regression through the data from tide gages in Long Island Sound. This accounts for the substantial decadal-scale variability that occurs in the region. Note that the line doesn't intersect the other lines at 2000 since the best fit line (see Figure 6), which is at the center of the prediction interval, does. If the best fit line was used, as in CPO-1, then even if the trend estimate was correct, there would be a 50% probability each year that the mean sea level would exceed the estimate. The upper bound of the range is therefore a much more prudent planning tool.

The orange line in Figure 13 is the upper bound of the ensemble of projections in the IPCC (2013) model forecasts for the annual mean sea level near southern New England in scenario RCP 4.5. It is a localized and updated version of the Intermediate Low projection in CPO-1. Note that Figure 12 show that the mean and range of the other scenarios at 2100 and that the difference in the upper bounds of RPC4.5 and RCP 8.6 at that time is only 0.25 m. At 2050 it is approximately half of that.

The orange and magenta lines in Figure 13 are Intermediate High and High projections of CPO-1 adjusted for the local vertical land motion and so they result in slightly higher values in 2100.

The main difference between Figure 13 and Figure 1 (from CPO-1) is that the lower two curves in Figure 13 are higher than in Figure 1. This is because the IPCC (2013) models (yellow line) included an improved representation of ice melting, and the data-based projection shows the upper bound of the likely interval rather than the median, and only data since 1980. An important feature of the graph is that the projections diverge rapidly after 2050. The difference between the lowest and highest lines is approximately 0.3 m at 2050 and almost 1.5 m at 2100.

A common and useful planning outlook in many applications, e.g. home mortgages, is 30 years. Since 0.5 m (approximately 20 inches) is the mid-point of the projections at 2050, shown in Figure 13 as a red line, it provides a reasonable and prudent guideline for planning purposes. Figure 13 makes clear that the mean sea level will increase after 2050. This is a very robust prediction. So instituting a planning threshold using 2050 projections only makes sense if future reassessment is anticipated. However, alerting the public with property in the altitude zone impacted if a 1.0 m increase in mean sea level was to occur is also prudent.

It is important to emphasize that the model-based projection (yellow) line is the upper bound of the ensemble predictions and it assumes that the models are correct. If future scientific discoveries require models to be updated then the projections will have to be revised. Similarly, on-going data collection programs may show that the data-based projection may also require adjustment. This also motivates a periodic reassessment of the planning threshold. Since science moves slowly, and it is likely that a decade of data will be required to detect changes to recent rate of change in means sea level, updates at a minimum of 10 year intervals would be wise.

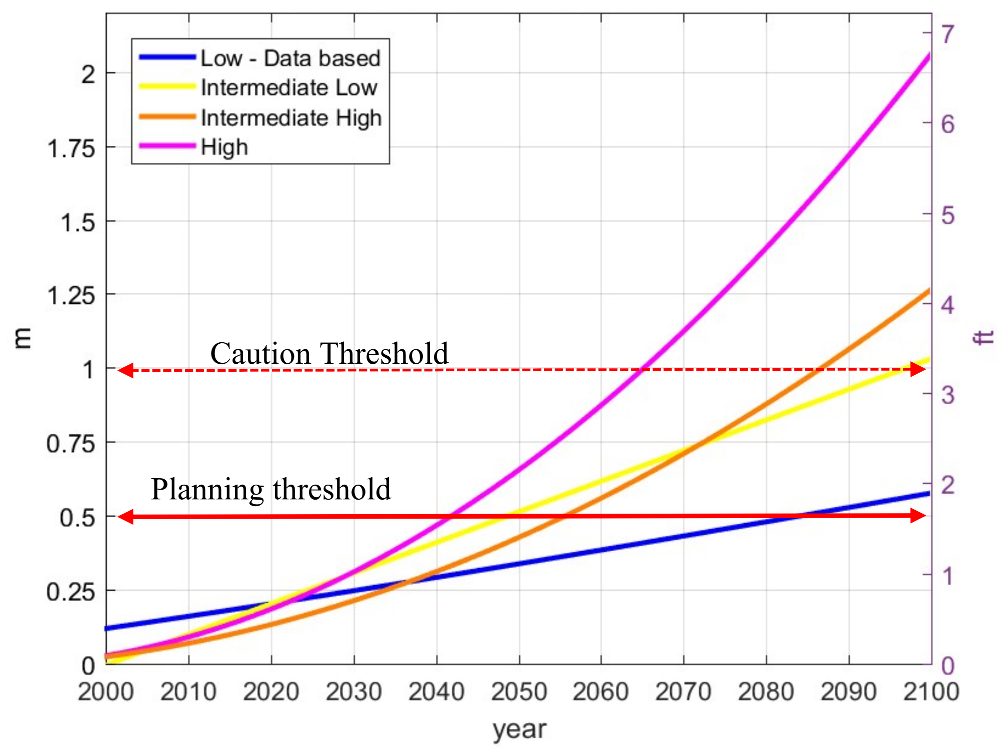


Figure 13. The blue line shows the upper bound on the prediction interval for the extrapolation of the annual average sea level at the Long Island Sound tide gages as shown in Figure 6. The yellow line shows the upper bound of the ensemble of predictions of the mean sea level off southern New England in simulations of RCP4.5 from IPCC (2013) and shown in Figure 12. The Orange and Magenta lines are the same as in CPO-1, but with the effect of vertical land movement included. The thick red line shows the 0.5 m level which is the center of the range of predictions at 2050.The red dashed line is the upper bound of the model predictions at 2100.

References.

Church J.A., N.J. White and J. Arblaster (2005) Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. Nature 438:74–77. doi:10.1038/nature04237

Church, J. A. and N.J. White. (2011). Sea-level rise from the late 19th to the early 21st Century. Surveys in Geophysics, doi:10.1007/s10712-011-9119-1

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, (2013). Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Domingues CM, J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090–1093. doi:10.1038/nature07080

Gregory J.M., J.A. Lowe, and S. F. B. Tett (2006) Simulated global-mean sea-level changes over the last half-millenium. J Clim 19:4576–4591

Grinsted, A., J. C. Moore, and S. Jevrejeva (2009), Reconstructing sea level from paleo and projected temperatures 200 to 2100AD, Clim. Dyn., doi:10.1007/s00382-008-0507-2.

Horton, R., C. Herweijer, C. Rosenzweig, J. Liu, V. Gornitz, and A. C. Ruane (2008), Sea level rise projections for current generation CGCMs based on the semi-empirical method, Geophys. Res. Lett., 35, L02715, doi:10.1029/2007GL032486.

Hurrell, J. W., Y. Kushnir, and M. Visbeck, (2001). The North Atlantic Oscillation. Science, 291, 603-605

IPCC (2001), Metz, B.; Davidson, O.; Swart, R.; Pan, J., eds., Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0-521-80769-7 (pb: 0-521-01502-2).

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jevrejeva, S., J. C. Moore, and A. Grinsted (2010), How will sea level respond to changes in natural and anthropogenic forcings by 2100, Geophys. Res. Lett., 37, L07703, doi:10.1029/2010GL042947.

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi (2014), Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, Earth's Future, 2, 383–406, doi:10.1002/2014EF000239.

Kopp, R.E., F. J. Simons, J. X. Mitrovica, A. Maloof, and M. Oppenheimer (2009). Probabilistic assessment of sea level during the Last Interglacial stage, Nature, 462, 863–867, doi:10.1038/nature08686.

McCarthy G, I. Haigh, J. Hirschi, J. Grist and D. Smeed (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations Nature 521 508–10

National Research Council (1987). Responding to Changes in Sea Level: Engineering Implications. National Academy Press: Washington, D.C.

National Research Council (2012). Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press.

Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum (2010). Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. Marine Geodesy 33, no. 1, supp. 1: 435.

Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment. PLoS ONE 10(3): e0118571. pmid:25760037

NOAA (2013). National Coastal Population Report: Population Trends from 1970 to 2020, http://oceanservice.noaa.gov/facts/coastal-population-report.pdf

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss (2012) Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1. 37 pp.

Rahmstorf, S. (2007) A semi-empirical approach to projecting future sea-level rise. Science 315(5810):368–370

Storch, H. v. & F. W. Zwiers (2001) Statistical analysis in climate research. Cambridge, UK ; New York: Cambridge University Press

USACE (2013) Incorporating sea level rise in civil works programs. Regulation No. 1100-2-8162 31 December 2013. (https://www.flseagrant.org/wp-content/uploads/USACE_SLR_guidance_ER_1100-2-8162.pdf

van Vuuren, D.P., Edmonds, J., Kainuma, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, S.K. Rose (2011). The representative concentration pathways: an overview. Climatic Change 109: 5. doi:10.1007/s10584-011-0148-z

Vermeer, M. and S. Rahmstorf (2009) Global sea level linked to global temperature. Proceedings of the National Academy of Science of the USA, 106, 21527-21532.

Zervas, C., S. Gill, and W. Sweet (2013) Estimating vertical land motion from long-term tide gauge records, Technical report NOS CO-OPS 065, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Center for Operational Oceanographic Products and Services: Silver Spring, MD, [Available at http://tidesandcurrents.noaa.gov/publications/Technical_Report_NOS_CO-OPS_065.pdf]