Review:

Past Evaluation and Future Projection of Sea Level Rise Related to Climate Change Around Japan

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Using new sea level data on 71 points on Japan's coast during 1966-2003 in which crustal movement is eliminated from tide records, we evaluate long-term oceanic-origin sea levels and project sea level rises (SLR). We classify Japan's coast into seven regions of about 100 km^2 by applying cluster analysis to the sea level data. For western Japan, we propose a linear regression model enabling us to predict sea levels based on sea surface temperature (SST). SLR are projected for the 21st century using our linear regression model to SSTs of 10 coupled general circulation models (CGCMs), based on the SRES A1B scenario of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. The mean SLR in western Japan in the 21st century is 12 cm, almost the same as the SLR around Japan's coast predicted dynamically by CGCMs. We found that the SLR predicted by our linear regression model is high in the western Japan, particularly at about 17 cm/century in western Kyushu.

Keywords: sea level rise, sea surface temperature, crustal movement, global worming, sea level prediction

1. Introduction

Japan provides shore protection through disaster-prevention structures such as tide walls because Japanese coastal areas below sea level in the three large bays of Tokyo, Osaka, and Ise account for 580 km^2 occupied by 4 million residents. If these regions suffer severe flooding due to storm surges in addition to an increased coastal disaster potential due to a global sea level rise (SLR), the impact on society and the economy could be formidable (Panel on Storm Surge Control Measures in Areas below Sea level, 2006). The Ministry of Land, Infrastructure, and Transport of Japan has begun considering national land conservation against global sea level rise involved in global warming.

The Intergovernmental Panel on Climate Change Third Assessment Report (IPCC AR3) predicted a global mean SLR of 9 to 88 cm from 1990 to 2100 based on all emission scenarios, including the uncertainty of ice on land (**Fig. 1**). The median is 48 cm, 2 to 4 times larger than the global mean SLR observed in the 20th century (IPCC, 2001). Although uncertainties exist in estimates of contributions to the budget of global mean sea-level change, the main contributions for sea level change are the thermal expansion of seawater and ice melt from glaciers, ice caps, and ice sheets. The importance of their contribution to SLR was recently pointed out (Gregory and Oerlemans, 1997; Hansen, 2007). The IPCC Fourth Assessment Report (IPCC AR4) reevaluated global SLR at 21 to 48 cm in the A1B scenario.

Some authors pointed out discrepancies between changes in observed sea level and in sea level simulated by coupled general circulation models (CGCMs) in the 20th century (IPCC, 2001; Munk, 2002). CGCMs estimate the sea level change to be 2 to 6 cm due to thermal expansion and 2 to 3 cm due to melting glaciers, resulting in 4 to 9 cm. In contrast, the observed global mean SLR in the 20th century based on tide gauge records is 15 to 20 cm. Munk (2002) pointed out that an increase in 20th century ocean heat content by 2×10^{23} J based on observations (Levitus et al., 2001) results in a global mean SLR in the 20th century of 2 to 3 cm. The reason for the discrepancy remains to be clarified and is a point of contention (Levitus et al. (2001) and Munk (2002)).

Global warming is expected to cause changes in global pressure and wind systems (Fig. 4.5, in Sumi (2006)) and hence oceanic conditions of subtropical and subpolar gyres. These changes may also affect global sea levels. Changes in global pressure and wind systems due to global warming vary the frequency and/or strength of typhoons (Yoshimura and Oouchi, 2007), resulting in changes in ocean surface waves (Sasaki and Iwasaki, 2007). An increase in coastal disaster potential due to SLR may increase the frequency and/or magnitude of coastal disasters by storm surges, abnormal sea levels, and extreme waves.

The Japan Meteorological Agency (2006) showed that sea levels observed at 5 tide stations around Japan where crustal movement is small have shown no monotonous increase in the last 101 years during 1906-2006, while the sea level shows significant fluctuations of a 20-year cycle. Iwasaki et al. (2002) separated crustal movement from tide gauge records around Japan's main island of Honshu in 1969-1998 to evaluate the last 30-yr trend in oceanic-origin sea levels in eastern and western Japan,

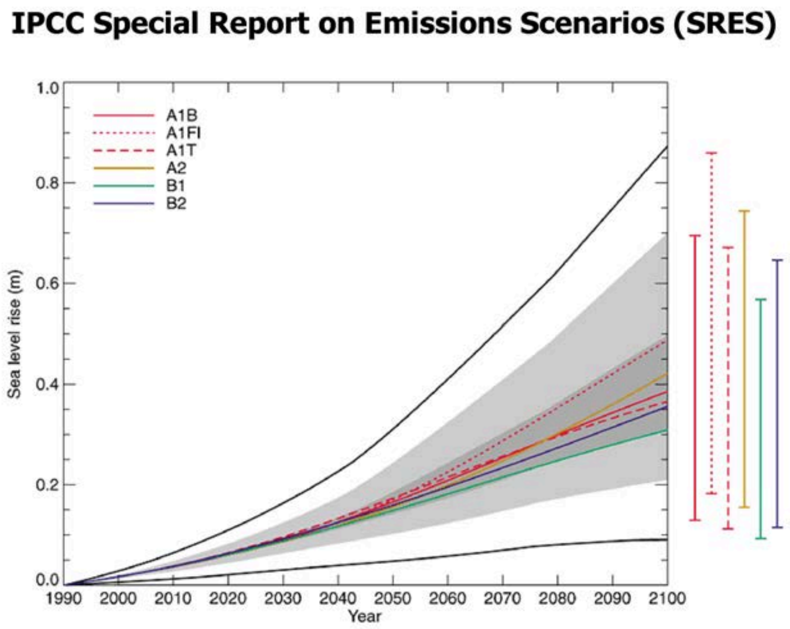

Fig. 1. Global average sea level rise 1990 to 2100 for the SRES scenarios. Thermal expansion and land ice changes were calculated using a simple climate model calibrated separately for each seven AOGCMs, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate change were added (after IPCC, 2001).

finding that the oceanic-origin sea level shows a negative trend of 3.1 mm/yr in eastern Japan and a positive trend of 2.4 mm/yr in western Japan. A long-term trend and interdecadal variability are also reported in global tide gauge records (Gregory et al., 2004; Ishii et al., 2005). The ocean general circulation model forced by realistic surface wind stress from 1960 to 2002 successfully reproduced the decadal sea level variability (Yasuda and Sakurai, 2006), although not the observed abrupt trend of 3.3 mm/yr since 1985.

Cabanes et al. (2001) indicated that SLR during 1993-1998 observed by TOPEX/Poseidon altimeter measurements is consistent with the steric SLR estimated based on seawater heat content during 1955-1996. They pointed out that tide stations used for the IPCC AR3 were distributed in a basin where thermal expansion is significant, so the estimation was overevaluated by 10 to 25 cm. Present global tide gauge records are (1) not long enough to detect long-term trends, (2) are spatially sparse, and (3) must be corrected for vertical crust displacement. Although past evaluation and future projection of sea level are required for populated local coastal areas, their quantitative evaluation and projection are not yet available with a high degree of certainty.

We reevaluate oceanic-origin sea levels, eliminating crustal movement, at 71 tide stations along the Japanese coast during 1966-2003 based on the method proposed by Iwasaki et al. (2002). In Section 2, we introduce a new dataset on oceanic-origin sea level around Japan to describe trends in sea level for the last 36 years. In Section 3, we divide Japan's coast based on cluster analysis for a time series of oceanic-origin sea level to determine the relationship between oceanic-origin sea level and SST around Japan. Based on results, we propose a linear regression model that enables us to predict sea levels in terms of SST. In Section 4, we project sea levels by applying our linear regression model to future SST predicted by 10 coupled general circulation models (CGCMs) based on the IPCC SRES A1B scenario. We compare the SLR statistically predicted above to those dynamically predicted by CGCMs in Section 5. In Section 6, we project SLR including interdecadal variations. Section 7 provides a summary and discussion.

2. Long-Term Sea-Level Changes Around Japan

We developed a new sea level dataset, eliminating crustal movement, on 71 tide stations around Japan during 1966-2003 based on the method of Iwasaki et al. (2002). The positions and point names of 71 tide stations under the control of Geophysical Survey Institute in Japan (GSI), Japan Meteorological Agency, and Hydrographic Department of Japan Coast Guard used for analysis are shown in **Fig. 2** and **Table 1**. We added 23 tide gauge data in Kyushu, Shikoku, and Hokkaido to 48 tide gauge data used by Iwasaki et al. (2002) only for Honshu (**Table 1**). We also prolonged the period of analysis from 1966-1998 to 1966-2003.

Factors of changes in sea level such as tide due to celestial bodies, inversed barometer effect associated with changes in atmospheric pressure, dynamic effect due to ocean eddy or the Kuroshio large meander, crustal movement, and thermal expansion due to anthropogenic effects are included in tide gauge records. To obtain ocean-origin long-term sea-level, we apply procedures followed by Iwasaki et al. (2002):

1. Calculating the annual mean sea-level after applying inverted barometer correction to the monthly mean sea-level.

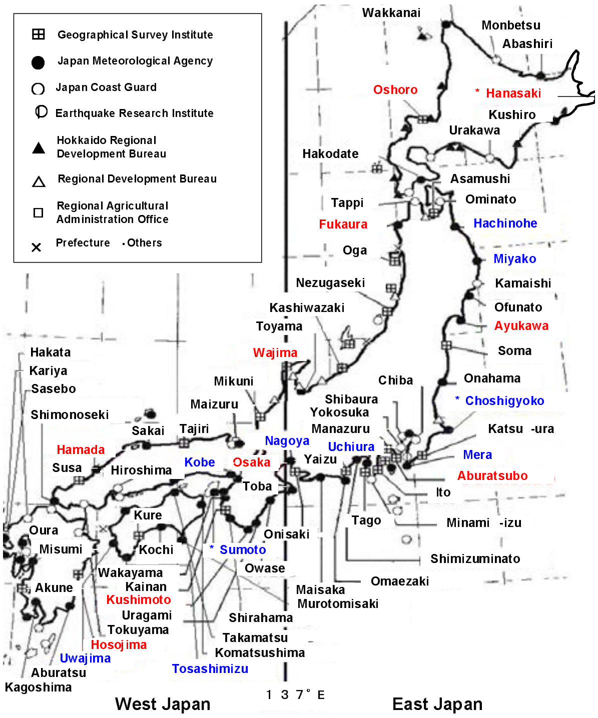

Fig. 2. Tide stations along the coast of Japan. At tide stations enclosed by rectangle, sea surface temperature was also measured. The sea around Japan can be divided into two regions by the 137 ° E longitude line, East Japan and West Japan.

Table 1. Tidal station names and corresponding numbers treated in this study.

No.	Position name	No.	Position name	No.	Place name	No.	Position name
1	Wakkanai	19	Yokosuka	37	Osaka	55	Kariya
2	Monbetsu	20	Aburatsubo	38	Kobe	56	Hakata
3	Abashiri	21	Ito	39	Takamatsu	57	Shimonoseki
4	Kushiro	22	Minami-izu	40	Hiroshima	58	Susa
5	Urakawa	23	Tago	41	Uwajima	59	Hamada
6	Hakodate	24	Uchiura	42	Tokuyama	60	Sakai
7	Asamushi	25	Shimizuminato	43	Komatsushma	61	Tajiri
8	Ominato	26	Yaizu	44	Murotomisaki	62	Maizuru(JMA)
9	Hachinohe	27	Omaezaki	45	Kouhi	63	Maizuru(JCG)
10	Miyako	28	Maisaka	46	Kure	64	Mikuni
11	Kamaishi	29	Onisaki	47	Tosashimizu	65	Wajima
12	Ofunato	30	Nagoya	48	Hosojima	66	Toyama
13	Ayukawa	31	Owase	49	Aburatsu	67	Kashiwazaki
14	Soma	32	Uragami	50	Kagoshima	68	Nezugaseki
15	Onahama	33	Kushimoto	51	Akune	69	Oga
16	Katsu-ura	34	Shirahama	52	Misumi	70	Fukaura
17	Mera	35	Kainan	53	Oura	71	Oshoro
18	Shibaura	36	Wakayama	54	Sasebo		

2. Eliminating crustal movement using difference-in-elevation data.
3. Extracting long-term sea-level change trends using linear regression analysis.

We calculate annual mean sea-level from a monthly mean sea-level data trough eliminating the effects of atmospheric pressure, tide, and short-term variation due to dynamic effect such as ocean eddies and the Kuroshio

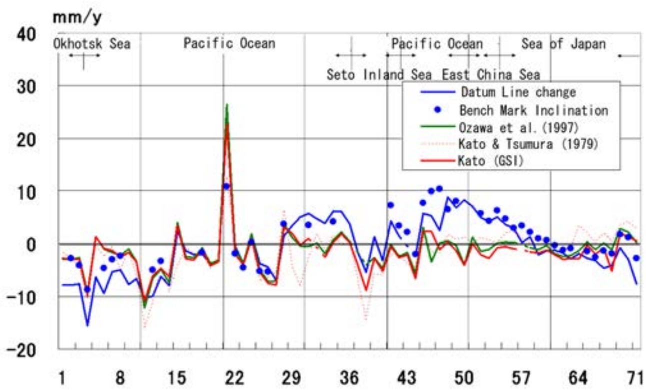

Fig. 3. Trend of crustal movement for the last 36 years around Japanese Islands. Solid blue line depicts datum line change and blue circle bench mark inclination. Green line is cited from Ozawa et al. (1997), red dotted line Kato and Tsumura (1979), and red solid line Kato (GSI).

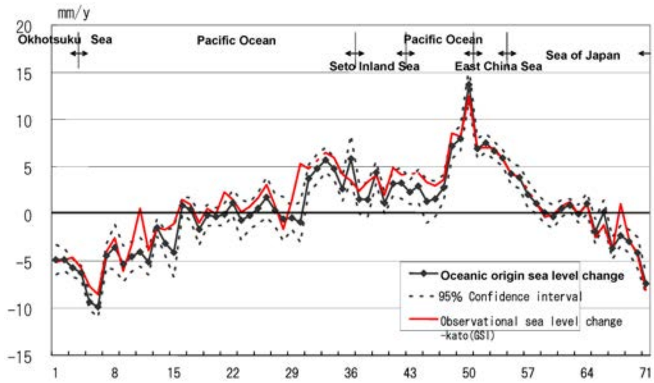

Fig. 4. Trend of oceanic origin sea level change for the last 36 years around Japanese Islands (See **Fig. 2** and **Table 1**). The axis of abscissas is tidal station number. The 95% confidence limits are shown as the dotted lines. The effect of the crustal movement is removed.

meander. After this procedure, changes included in the tide gauge records are crustal movement and changes in oceanic-origin sea level.

We use difference-in-elevation data to eliminate crustal movement (Iwasaki et al., 2002) (**Fig. 3**). The solid blue line shows the rate of crustal movement with the Japanese Datum of Leveling used as a fixed point that contains changes in the observation base of a tide station and in the benchmark of its vicinity. Red dotted line shows crustal movement found by GSI using recent data based on the method of Kato and Tsumura (1979). Solid green and red lines show similar results. Differences between solid green and red lines indicate large-scale oceanic change. These differences correspond well with results (**Fig. 4**) of sea level changes found by compensating for tide observation data as shown below. We refer to the sea level as the oceanic-origin sea level.

We estimate a 36-yr linear trend in observed sea levels during 1966-2003 at individual tide stations by applying

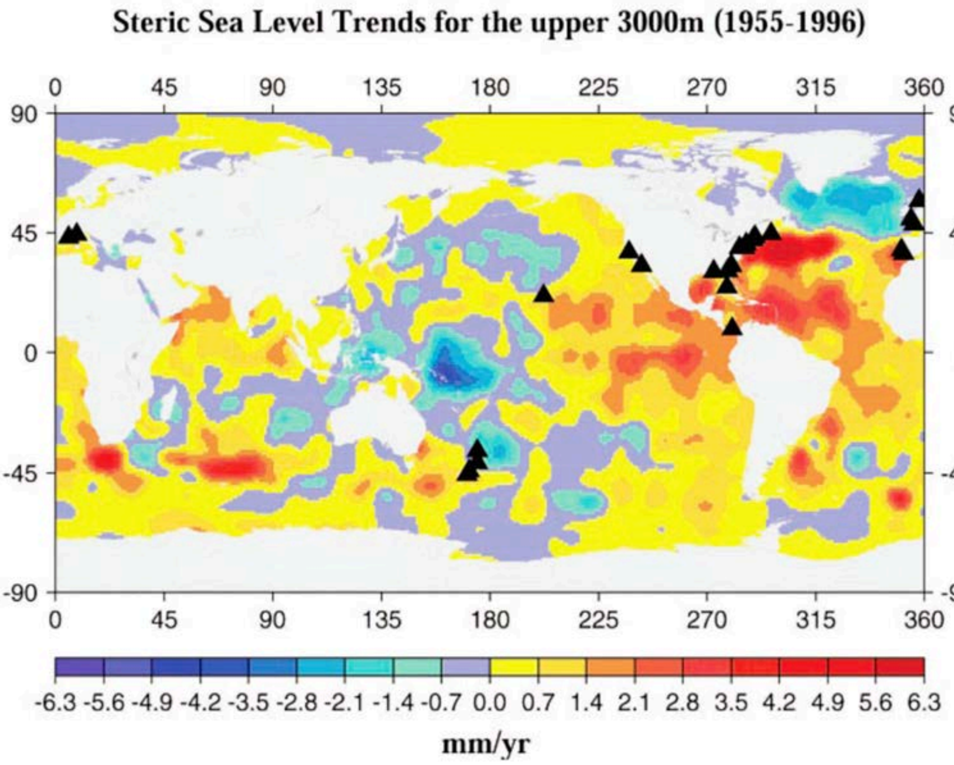

Fig. 5. Map of the graphical distribution of thermosteric sea level trends for 1955-96 computed with temperature data from Levitus et al, 2000) down to 3000 m depth (after Cabanes et al., 2001).

linear regression analysis to the time series of observed sea levels (Section 2.3 and **Fig. 4** in Iwasaki et al. (2002) explaining specific application of the above for Aburatsubo). **Fig. 4** showing the 36-yr trends in observed sea level at 71 tide stations indicates that coastal areas of Japan may be classified roughly into six regions based on the spatial features of trends in observed sea level. The first region is from Wakkanai (1) to Onahama (15) on the Pacific side of northern Japan. Region 1 has a negative trend of 5 mm/yr, decreasing toward the south. The second region from Katsuura (16) to Nagoya (30) shows no particular trend. The third region from Owase (31) to Hosojima (48) shows an increasing trend of 3 mm/year, decreasing toward the west. Region 4 from Aburatsu (49) to Shimonoseki (57) shows the largest positive trend. Region 5 from Susa (58) to Wajima (65), similar to region 2, shows no apparent trend. Region 6 from Toyama (66) to Oshoro (71) shows a negative trend increasing toward the north.

Linear trends in sea level during 1966-2003 around Japan are larger than those in steric sea-level trends during 1955-1996 by Cabanes et al. (2001). In fact, the range of trends in sea level (within ±5 mm/year) exceeds twice that in steric sea level (within ±1.4 mm/year) in **Fig. 5**, but the spatial pattern for both trends corresponds well. The negative trend in eastern Japan in **Fig. 5** agrees with that in region 1. Positive trend in western Japan in **Fig. 5** also agree with that in regions 3 and 4. Next, we examine the relationship of sea level, SST, and heat content in individual sea areas.

3. Relationship Between Sea Level Change and SST Around Japan

In Section 2, we classified sea areas around Japan based on 36-yr trends in observed sea levels. Below, we classify sea areas around Japan by applying cluster analysis to time series of observed sea levels to determine changes in regional sea levels and the relationship to SST and heat content.

After smoothing interannual variability in sea level using a 6-yr moving average, we applied cluster analysis to sea level data with good quality at 61 tide stations during 1975-2003, classifying them into nine sea areas (**Fig. 6**). The time series of mean sea levels for each region is calculated by averaging sea levels at tide stations for each region. To estimate heat content and SST, we use the Comprehensive Ocean-Atmosphere Dataset (COADS; Worley et al. 2005). We also use SST data developed by Ishii et al. (2005). Heat content of the upper 300-m depth is calculated by integrating water temperature at each layer from the sea surface down to the 300-m depth. We also prepared heat content of the upper 700-m depth. Each time series data is standardized, i.e., anomalies are divided by their standard deviation. For regions 1 to 7 covering a sea area of hundreds of kilometers, we examine the relationship of sea level, SST, and heat content of the upper 300 m depth and that of the upper 700 m depth (**Fig. 7**).

Changes in sea level correlate well to those in SST and heat content for regions 2, 3, and 4 (**Fig. 7**). Sea level changes should correlate better to heat content than to

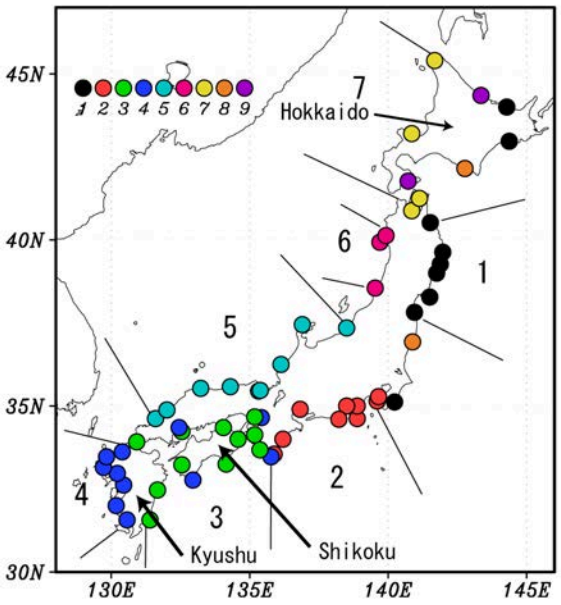

Fig. 6. Nine regions of coastal areas around Japan obtained from using cluster analysis of oceanic-origin sea level. Hereafter, the Sea Level Rise (SLR) and Sea Surface Temperature (SST) in region 1-7 are averaged in the distance as shown in this figure.

Table 2. Correlation of sea level rise (SLR) and sea surface temperature (SST) (Region 1-Region 7 as shown in **Fig. 6**) with COADS data and ISHII data during 1975-2002.

Reagion	COADS	ISHII
1	0.11	-0.06
2	0.85	0.62
3	**0.96**	**0.97**
4	**0.91**	**0.95**
5	**0.91**	0.44
6	0.36	0.30
7	-0.37	-0.72

SSTs assuming that sea level changes are caused by thermal expansion. Interestingly, sea levels correlate better to SST than heat content, due possibly to thermal expansion that affects changes in sea level at depths shallower than 300 m or long-term variability in the Kuroshio current axis. Sea level changes agree better with those in heat content than in SSTs in region 1 (**Fig. 7**), suggesting that sea level changes in this basin are related to thermal expansion due to warming of seawater shallower than 700 m. In regions 5, 6, and 7 in the Sea of Japan, the correlation between sea level and SST is good only in region 5, worsening toward the north.

We examine the relationship between trends and time evolution in sea levels for individual regions. Decreasing sea level during 1975-1990 for region 1 is more evident than SLR after 1991 (**Fig. 7**), corresponding to negative sea level trends for tide stations 8-14 (**Fig. 4**). For regions 3 and 4, standardized SST and sea level anomalies are almost -1 in 1975, but increase monotonously to approximately 2 in 2003 (**Fig. 7**), resulting in a positive trend in sea level from Shirahama (34) to Hakata (56) (**Fig. 4**).

As stated, since sea level changes agree well with those

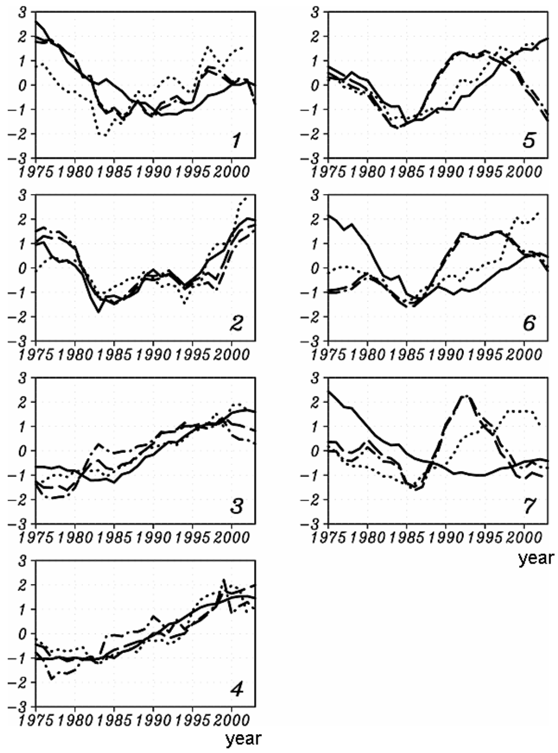

Fig. 7. Interannual variations of sea level rise (solid curve), SST (dotted curve), heat content above 300 m (broken curve), and heat content above 700 m (dashed-dotted curve) for selected seven regions. The number of regions correspond classified ocean areas as shown in **Fig. 6**. SST data are COADS and all data are normalized.

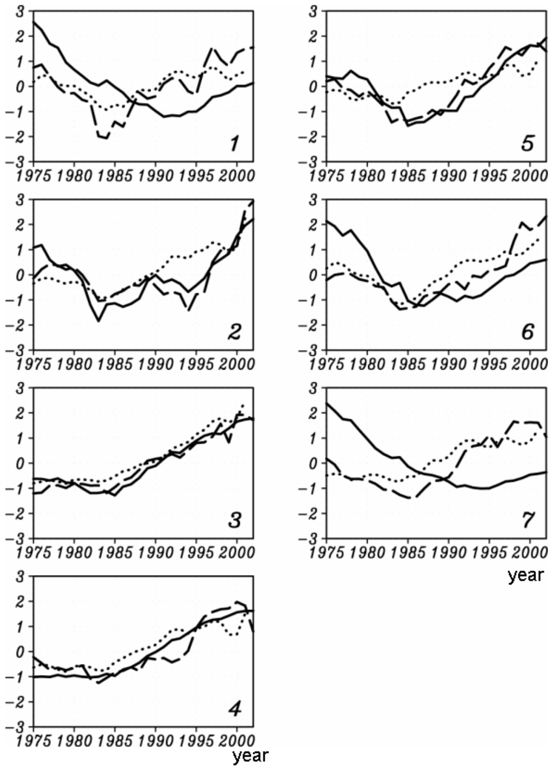

Fig. 8. Same as **Fig. 7**, but for sea level rise (solid curve), COADS's SST (broken curve), and ISHII's SST (dotted curve).

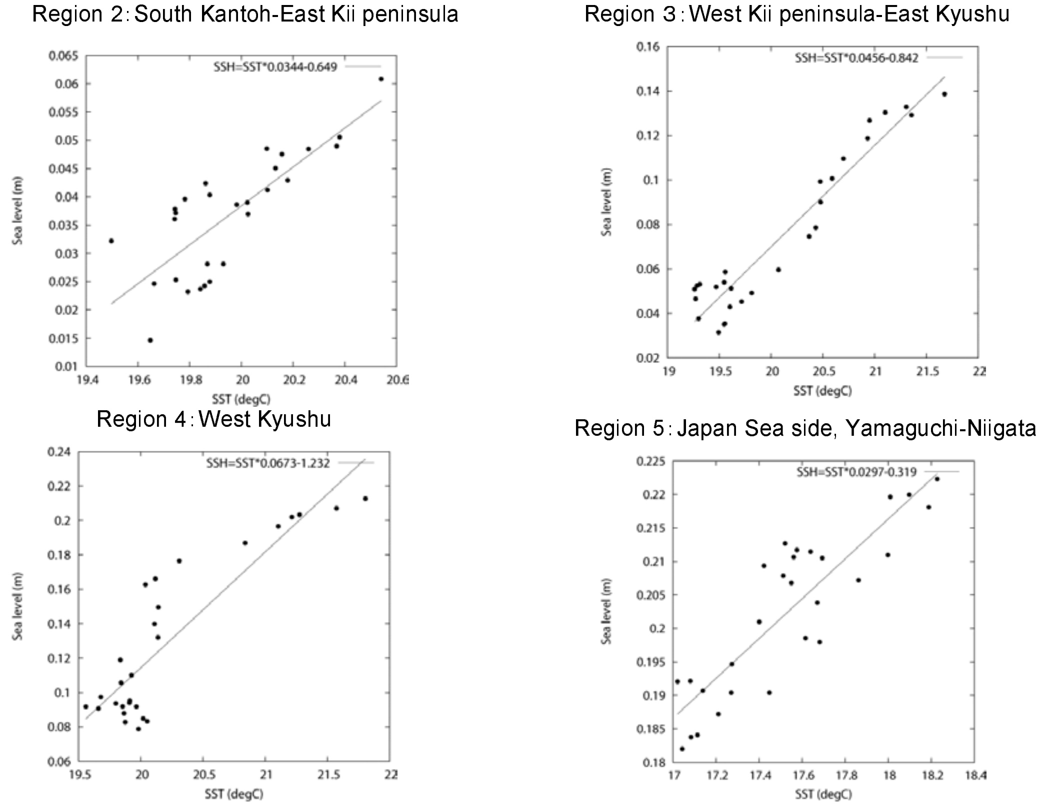

Fig. 9. Correlation between sea level rise (SLR) and SST. Solid lines depict regression ones obtained.

in SSTs for regions 2 to 5, we verify the relationship using COADS SST and SST developed by Ishii et al. (2005; ISHII SST) (**Fig. 8**). Correlation coefficients between changes in sea level and those in SSTs for regions 2 and 5 are 0.62 and 0.44 for ISHII SST (**Table 2**), but much improved for COADS SST. The discrepancy is due mainly to a large SST difference between two SST datasets in 1990s in region 2 and that during 1985-1990 in region 5 (**Fig. 8**). Both COADS SST and ISHII SST show a very good correlation coefficient exceeding 0.9 between changes in sea level and those in SSTs for regions 3 and 4 (**Table 2**). These results enable us to use SSTs as a predictor of sea level for regions 2, 3, 4, and 5 in western Japan.

Linear regression models that relate sea level to SST for regions 2 to 5 are given by (cf. **Fig. 9**):

Region 2: Sea level = SST $\times$ 0.0344 – 0.649 (1)

Region 3: Sea level = SST $\times$ 0.0456 – 0.842 (2)

Region 4: Sea level = SST $\times$ 0.0673 – 1.232 (3)

Region 5: Sea level = SST $\times$ 0.0297 – 0.319 (4)

Based on the linear regression model, we predict changes in sea level for regions 2 to 5 in the 21st century using SSTs predicted data from global warming experiments under the IPCC SRES A1B scenario.

4. Projected Sea-Level Changes Predicted by SSTs Based on A1B Scenario

To predict projected sea levels under global warming, SSTs are required as input to our linear regression model. We use future SSTs predicted by 10 CGCMs based on the IPCC SRES A1B scenario. **Fig. 10** shows a time series of SSTs in regions 2 to 5 simulated by CGCMs, together with observed SSTs obtained from the Extended Reconstructed Sea Surface Temperature Datasets (ERSST; Smith and Reynolds, 2004). SSTs simulated by CGCMs differ by about 3 degrees for the maximum and are generally higher than those observed. It is notable that SST of the IPSL_CM4 model agrees well with ERSST in magnitude and interdecadal variability (**Fig. 10**).

To calculate SLR, we use anomalies from mean SST for 1901-1999, so the mean sea level for 1901-1999 predicted by our linear regression model is 0. **Fig. 11** shows changes in past sea levels reconstructed by our linear regression model based on the IPCC 20th century experiment during 1901-2000 and those in future sea level predicted by a linear regression model during 2001-2100 based on the IPCC SRES A1B scenario experiment for regions 2 to 5. In region 4, an increase in mean sea level for 10 CGCMs in the 20th century and the 21st century is estimated by our linear regression model at about 2.6 cm and 17.2 cm (**Fig. 11**). In region 3, the increase is 1.4 cm in the 20th century and 11.7 cm in the 21st century. In region2, the increase is 1.4 cm in the 20th century and 9.0 cm in the

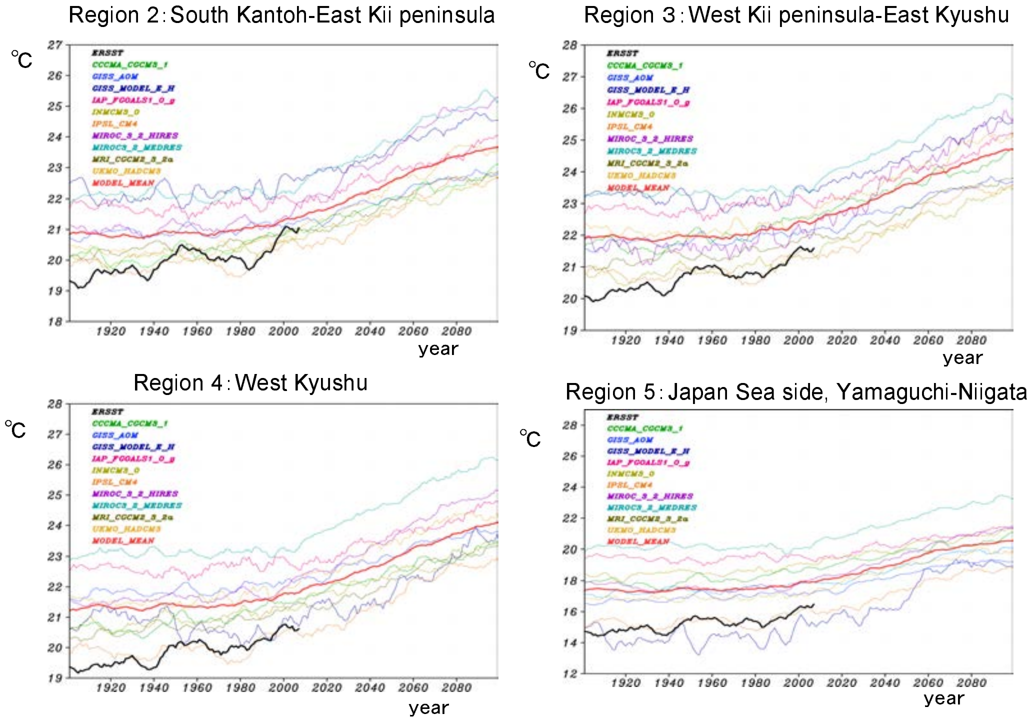

Fig. 10. Time series of interannual SST in four regions (region 2-5). (a) The data source is WCRP CMIP3 multi-model dataset that is preparing for IPCC AR4: IPCC 20c30m experiment data for 1900-1999 and IPCC SRES A1B data for 2000-2099. Black solid line depicts ERSST observational result and red solid line depicts average values of model result. Units are degC.

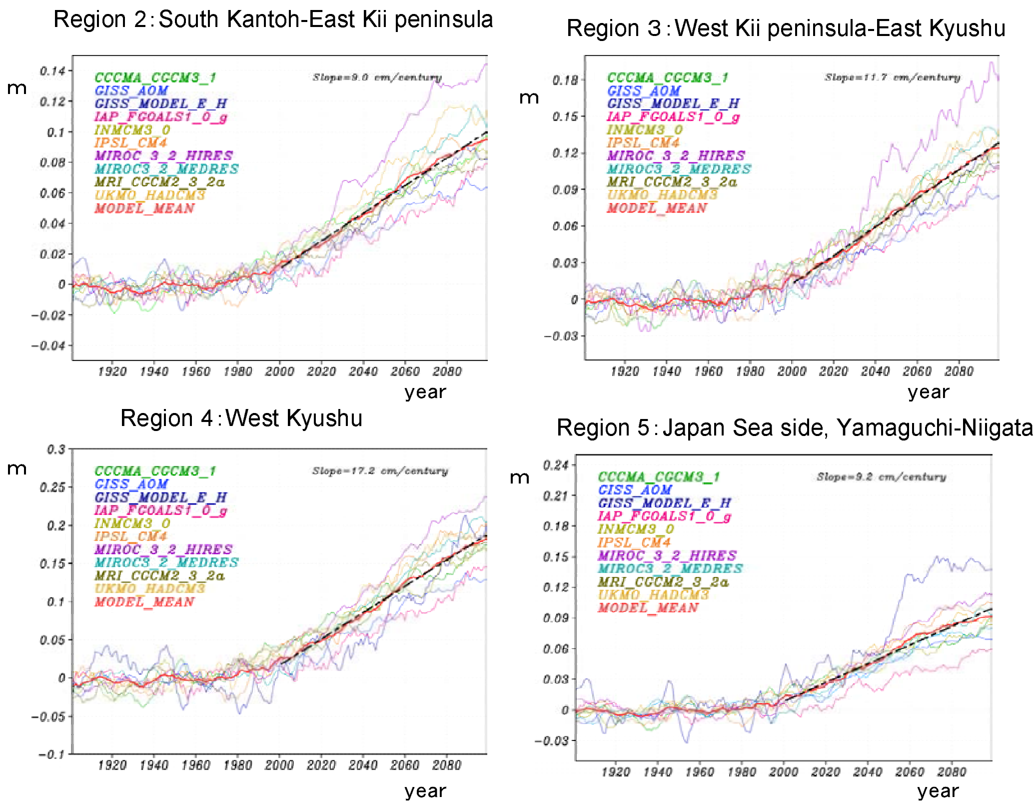

Fig. 11. Time series of predicted sea level rise obtained from the regression Eqs. (1)-(4) for four coastal regions. Predicted input SSTs are WCRP CMIP3 multi-model dataset for IPCC AR4. Zero line is mean value of sea level height for 1900-1999. Solid red line depicts model mean value and dash-dotted line depicts regression one obtained. Units are m.

21st century. In region 5, the increase is 1.5 cm and 9.2 cm in the 20th century and the 21st century. These results suggest that the increase in sea level in the 21st century is about 7 times faster than that in the 20th century.

A rise in mean sea level for 10 CGCMs in the 21st century predicted by our linear regression model is almost the same as that predicted by SST of the IPSL_CM4 model, viz., 8.2 cm (region 2), 10.7 cm (region 3), 15.7 cm (region 4), and 8.9 cm (region 5). SLR in the 21st century estimated by our linear regression models (1) to (4) is almost the same as the difference between the maximum SLR estimated by the MIROC_3_2_hires model and the minimum SLR estimated by the GISS_AOM model, suggesting large uncertainty due to CGCMs (**Fig. 11**).

As stated, the IPSL_CM4 model appears to successfully reproduce observed SST in magnitude and interdecadal variability (**Fig. 10**). Observed sea levels are well reconstructed by our linear regression model with SST of the IPSL_CM4 model in the rapid increase since 1980 (**Fig. 15**). A time lag exists, however, between observed sea levels and those estimated statistically. We see observed sea levels began to rise in 1985, while sea levels estimated statistically began to rise in 1980. The discrepancy may be due to being ahead of SSTs obtained by the IPSL_CM4 model to the observed ERSST. The rapid increase in observed sea levels may be part of the latest positive phase in interdecadal variability as discussed in Section 6.

5. Sea Level Rise Projection of CGCMs

In Section 4, we predicted sea level changes based on the statistical relationship between sea levels and SSTs derived in Section 3. Below, we examine sea level changes in the 20th and 21st centuries dynamically estimated by 6 CGCMs. **Fig. 12** shows the spatial distribution in sea levels in the 20th and 21st centuries, indicating that a positive trend for the global mean is 5 cm in the 20th century and 20 cm in the 21st century.

A significant rise is shown in the Antarctic Circumpolar Current (ACC) in the South Atlantic Ocean and South Indian Ocean. This maximum rise of approximately 50 cm in the 21st century may be due to the southward shift of the ACC associated with the southward shift of the southern polar jet (Fyfe and Saenko, 2005). The ACC flow increases due to the conservation of angular momentum. Global warming causes a "conveyer-belt"-like flow decreasing by 5 Sv as thermohaline circulation (Fig. 4.26, in Maruyama, 2006). This indicates an increase in the ACC flow because it exceeds this effect even if subtracted and then the sea surface height increases.

A prominent SLR is recognized in Kuroshio recirculation regions in the 21st century compared to the 20th century (**Fig. 13**), possibly due to the Kuroshio current intensified under global warming (Fig. 4.8, in Sumi, 2006). A CGCM of MIROC_3_2_hires model reproduces the Kuroshio meander and separation latitude as observed, since this model has the highest horizontal resolution of T106 for the atmospheric component and 0.2 degree x 0.3 degrees for the ocean component. In contrast, the Gulf Stream in the North Atlantic Ocean does not strengthen under global warming. In fact, there is no apparent change in sea level in Gulf Stream recirculation regions (**Figs. 12** and **13**).

For the Indian Ocean, SLR are found in the Arabian Sea under global warming, possibly related to weakening upwelling in this sea area associated with a weakened summer monsoon (Tanaka et al., 2005; Ueda et al. 2005).

Figure 14 shows the time series of sea levels during 1901-2100 in regions 2, 3, and 4 predicted dynamically by 6 CGCMs. Mean changes in sea level for the CGCMs are almost 0 in the 20th century, but rise 8 to 10 cm for the 21st century. For regions 2 and 3, this is almost the same as the sea level change predicted by our linear regression model, while for region 4, the statistical prediction overestimates the dynamical prediction by about 70%; the statistical model predicts an increase of 17.2 cm and the dynamical model predicts an increase of 10 cm. In **Fig. 14**, sea level predicted by our linear regression model appears to rise since the 1980s, while changes in sea level predicted dynamically by CGCMs show a rise since 2000. The reason for this difference may depend on the time lag between SSTs and heat content in the ocean for CGCMs.

Another feature of the difference between statistical and dynamical predictions is that the sequences of the magnitude of sea level change predicted by two methods differ. Specifically, our linear regression model predicts a high sea level rise by 14 cm for region 2 in 2100 in a high SST rise predicted by MIROC_3_2_hires model, while the sea level rise dynamically predicted is about 10 cm, close to the mean for CGCMs (**Figs. 11** and **14**). Although the sea level change dynamically predicted by the GISS_MODEL_E_H model is about 25 cm, which is the largest of the six CGCMs, the sea level change predicted statistically is almost the mean of CGCMs.

From these results, the sea level rise for the 100 years of the 21st century was estimated at 10 cm caused by thermal expansion around Japan during global warming based on the IPCC A1B scenario.

6. Estimation of Interdecadal Sea Level Variability

Figure 15 showing the time series of the observed sea level and the sea level estimated by linear regression model with SST of the IPSL_CM4 model indicates that the observed sea level increased since 1981. The increasing observed sea level during 1981-2000 is 2.5 mm/year for region 2, 5.7 mm/year for region 3, 6.1 mm/year for region 4, and 4.3 mm for region 5 (**Fig. 15**), so the average increasing rate for the four regions is 4.7 mm/year, resulting in an increase of 9.4 cm for the 20 years 1981-2000. This increase is divided into two components, i.e., linear trend and interdecadal variability. Sea level rise during 1981-2000 estimated statistically by SST of the IPSL_CM4 model, which can reproduce SST, agrees well with observations at 2 mm/year for region 2, 2.5 mm/year

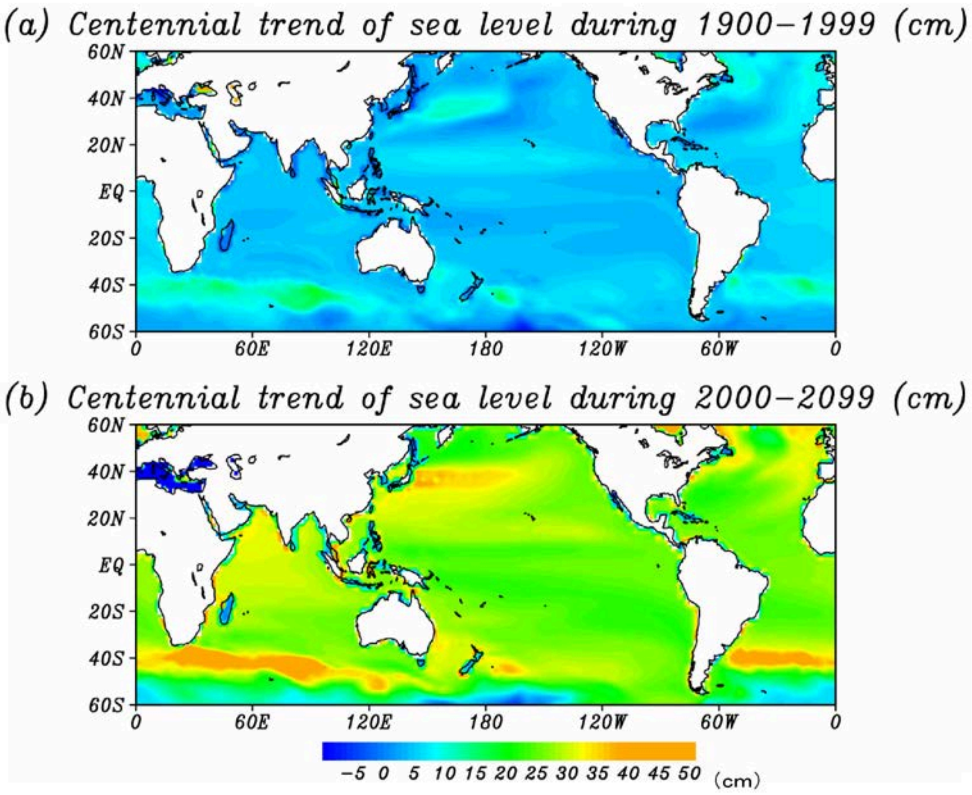

Fig. 12. Long-term tendency of sea level rise (six models mean) obtained from WCRP CMIP3 multi-model dataset. (a) IPCC 20c30m experiment data for 1900-1999 and (b) IPCC SRES A1B data for 2000-2099. Units is cm.

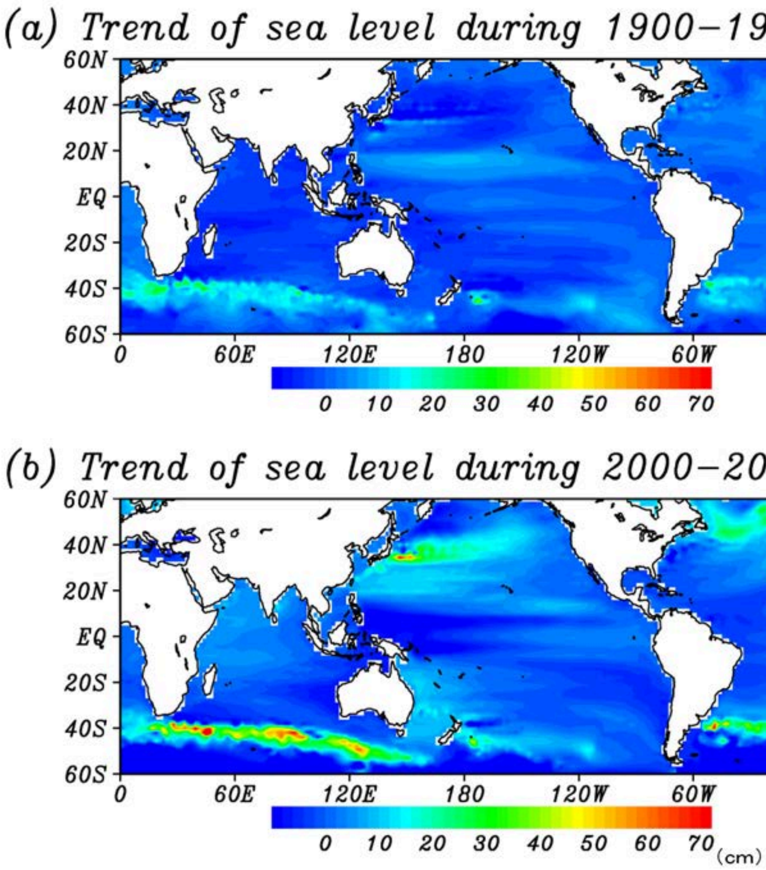

Fig. 13. Long-term tendency of sea level rise of miroc3_2_hires. (a) IPCC 20c30m experiment data for 1900-1999 and (b) IPCC SRES A1B data for 2000-2099. Units is cm.

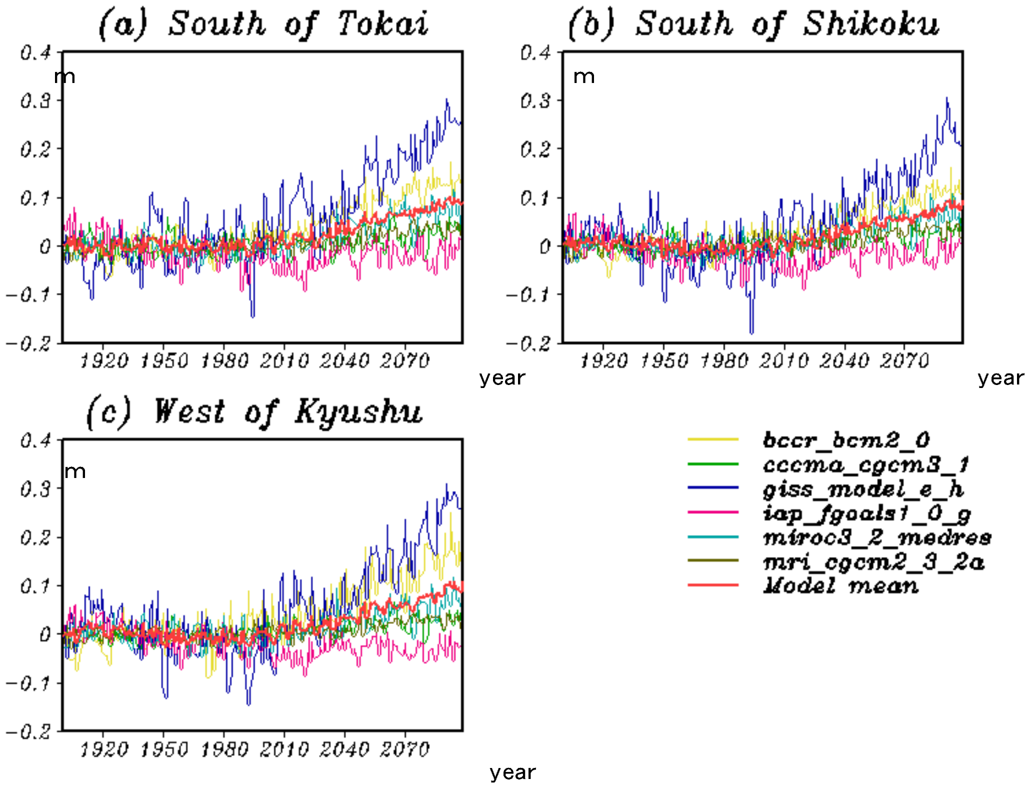

Fig. 14. Time series of predicted sea level rise obtained from WCRP CMIP3 multi-model dataset. Zero line is mean value of sea level height for 1900-1999. Units is m.

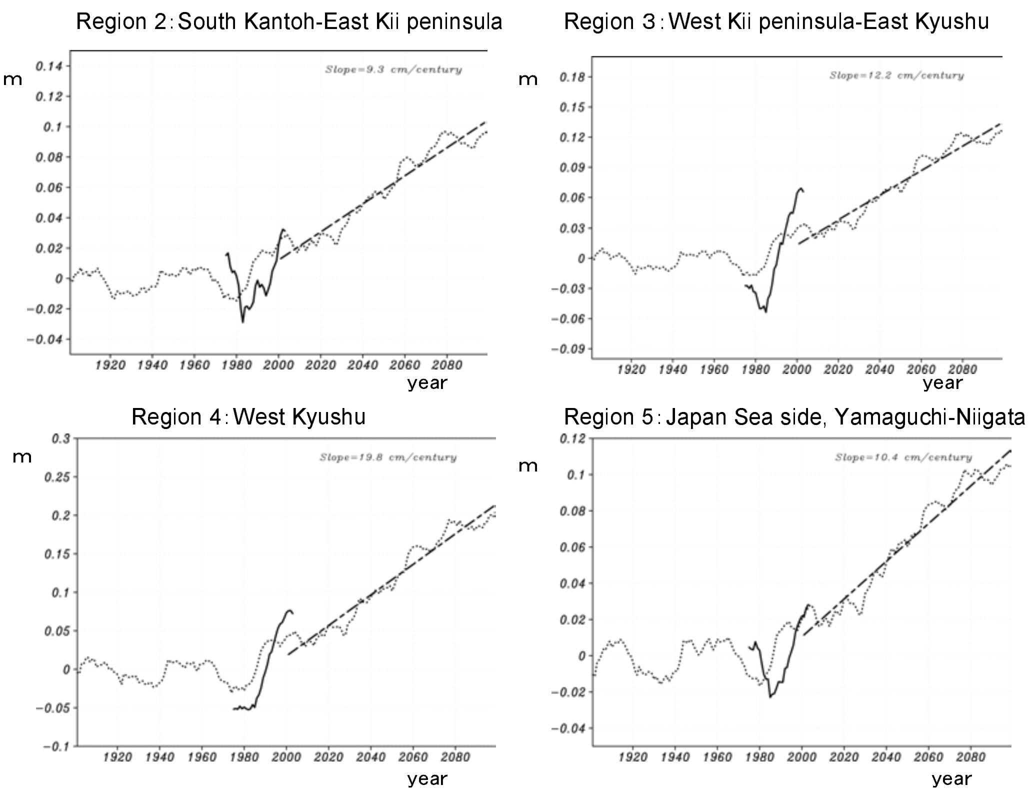

Fig. 15. Time series of the observed sea level rise from 1975 to 2002 (solid curve) and the predicted sea level rise obtained from the regression Eqs. (1)-(4) for IPSL_CM4 (dotted curve). Dash-dotted line depicts regression one obtained. Units are m.

for region 3, 3.6 mm/year for region 4, and 2 mm/year for region 5, resulting in an average sea level rise of 2.5 mm/year with an increase of 5.0 cm for these 20 years.

Trends in mean sea level statistically estimated by CGCM SSTs for 20 years for each region is 0.6 mm/year for region 2, 0.8 mm/year for region 3, 1.0 mm /year for region 4, and 0.6 mm/year for region 5, resulting in a mean of 0.75 mm/year. The interdecadal variability component in observed SLR is thus 7.9 cm (9.4 cm minus 1.5 cm) and SLR during 1981-2000 statistically estimated by SST of the IPSL_CM4 model is 3.5 cm (5.0 cm minus 1.5 cm). The amplitude of SLR in the component of interdecadal variability is thus $\pm$4.0 cm for the observed sea level and $\pm$1.8 cm for IPCL_CM4.

The rate of SLR estimated by observed sea level data differs in time lag and change by twice the result found by a relational expression between SLR and SST, but both found by the two methods indicate a similar trend (**Fig. 15**). We conclude that SLR of 7.8-15.8 cm due to thermal expansion in the 21st century may occur assuming that the amplitude of sea level variation in the interdecadal variability component does not change in the 21st century.

7. Summary and Discussion

We have developed a new dataset on oceanic-origin sea level at 71 tide stations around Japan's coast during 1966-2003 to determine changes in sea level. Changes in oceanic-origin sea level, in which crustal movement is eliminated, are estimated based on tide gauge records and difference-in-elevation data. We have classified Japan's coast into seven regions by applying cluster analysis to time series of the oceanic-origin sea level, finding that changes in oceanic-origin sea level in western Japan correlate well with those in SSTs. This enables us to use SST as a predictor of sea level. Based on these results, we derived a linear regression model enabling us to predict sea level in terms of SST.

We have also evaluated past sea levels in the 20th century and predicted sea levels in the 21st century by applying our linear regression model to SST predicted by 10 CGCMs under the IPCC A1B scenario. We have found that a model averaged SLR for western Japan in the 20th century is 1.9 cm. SLR in the 20th century estimated by SST of the IPSL_CM4 model, which reproduces well SST as observed,is 2.6 cm. These results are consistent with the global mean SLR of 2 to 3 cm estimated by Munk (2002). SLR in the 21st century in western Japan has been statistically predicted to be 11.8 cm as the mean of 10 CGCMs and 12.9 cm from the IPSL_CM4 model. We have compared SLR predicted by our statistical model with that dynamically predicted by five CGCMs in the IPCC A1B scenario for western Japan on the Pacific side (regions 2 to 4). We found that SLRs in these three regions predicted dynamically is 8 to 10 cm, close to SLR estimated by our statistical model.

These results show that our linear regression model is useful in predicting SLR in the 21st century of global warming for heat expansion. The sea level rise in the 21st century is also estimated at 7.8 to 15.8 cm assuming that the magnitude of interdecadal variability holds even under future climate conditions.

We evaluated steric SLR around Japan, but estimation of eustatic SLR remains unclear. Hansen (2007) pointed out that possible SLR may occur on the order of 1 m by ice sheet disintegration in the 21st century. Further investigations into the prediction of accurate SLR under global warming condition as well as the enigma of SLR in the 20th century (Munk, 2002) remain to be studied in the future.

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