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Late Pleistocene and Holocene sea-level changes in Japan: implications for tectonic histories and mantle rheology

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ABSTRACT

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It is very important to separate the tectonic and glacial-isostatic components in the observed Holocene and Late Pleistocene sea-level changes in tectonically active areas such as Japan for studying tectonic processes and for constraining mantle rheology. The separation can be achieved by considering the spatial dependence of the relative sea-level on the geometry of the coastline around the site where sea-level is evaluated. In fact, the relative sea-level caused by the last deglaciation at sites in the embayment such as Tokyo and Osaka has a sea-level curve with a high stand at mid-Holocene, and that site situated on the tip of peninsula has a sea-level curve culminating towards the present. The geometric effect also causes the regional difference of the sea-level variations in the late glacial phase. In the Japanese Islands, the regional difference of the predicted relative sea-level is about 5 m at 6000 years ago, 20 m at 10,000 years ago and 30 m at 18,000 years ago. Comparison between observations and predictions indicates that the observations at several sites in Japan are consistent with the predicted sea-level variations. More systematic data is reqiured for the period 18,000 years ago to the present in order to examine tectonic processes and mantle rheology.

Introduction

Observations of Late Pleistocene and Holocene sea-level variations contain information for establishing the tectonic histories of continental margins, island arcs and ocean islands as well as for estimating the mechanical response of the Earth to changes in surface loading by ice and meltwater. To separate the variables defining the tectonic and loading models it is first necessary to examine the sea-level records from tectonically stable areas. Sea-level in relatively stable areas such as the Australian continent reflects primarily the glacial-isostatic adjustment of the crust, and observations from such areas are important for evaluating both the mantle rheology and for constraining the bulk melting histories of the large polar ice sheets. In contrast, the sea-level variations in tectonically active areas such as the Japanese Islands may be dominated by the crustal response associated with the subduction of oceanic plates. Coastal terraces of middle Holocene age with an altitude higher than 10 m have been observed in many places in the Japanese Islands, and these have been interpreted in terms of tectonic processes with the assumption that the sea-level variations due to the last deglaciation have been constant (e.g., Ota and Machida, 1987; Yonekura and Ota, 1987; Yonekura, 1989). Because the glacial-isostatic contribution is regionally variable, it is necessary to quantitatively evaluate this contribution at each site in order to establish the tectonic histories in the Late Pleistocene and Holocene. The predictions are very sensitive to the island size and the geometry of the coastline (Nakada, 1986; Nakada and Lambeck, 1989), and have a significant spatial dependence over distances of less than 100 km. These characteristics may also be associated with

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the important problem whether the sea-level has fluctuated in the Holocene (i.e., Fairbridge, 1961; Chappell, 1987). In this study we first establish the characteristics of the glacial-isostatic sea-level variations in the Japanese Islands, and then make comparisons between observations and predictions in order to examine the vertical tectonic movements during Holocene time.

The sea-level equation

Geomorphological indicators specify the positions of the former shorelines at latitude ϕ, longitude λ at time t reltive to the present shore line at time t_0 as

$$\Delta\zeta(\phi,\lambda:t)=\zeta(\phi,\lambda:t)-\zeta(\phi,\lambda:t_0)$$

where ζ is the level at any time relative to some arbitrary crustal reference point. The sea-level change due to the last deglaciation can be expressed as the sum of three terms

$$\zeta(\phi,\lambda:t)=\zeta_r(\phi,\lambda:t)+\zeta_i(\phi,\lambda:t)+\zeta_w(\phi,\lambda:t)$$

and the relative sea-level change (RSL) with respect to the present sea-level can be written as

$$\Delta\zeta(\phi,\lambda:t)=\Delta\zeta_r(\phi,\lambda:t)+\Delta\zeta_i(\phi,\lambda:t)+\Delta\zeta_w(\phi,\lambda:t) \quad (1)$$

ζ_r (or $\Delta\zeta_r$) refers to the sea level change on a rigid Earth. It includes the equivalent sea-level (e.s.l.) defined as (meltwater volume)/(area of ocean surface), and the gravitational terms defining the attraction between ice sheets and oceans. The second term ζ_i (or $\Delta\zeta_i$) corresponds to the additional sea-level change produced by the deformation of the Earth in response to the glacial unloading. The third term ζ_w (or $\Delta\zeta_w$) is the additional deformation produced by the meltwater loading of the ocean basins. To obtain quantitative solutions of the sea-level equation, the required inputs are (1) the spatial and temporal description of the ice model, (2) a rheological model of the Earth, and (3) a geometric description of the ocean function of the ocean surface. In the next section we briefly describe these model parameters.

Model parameters

Ice model

The ice models adopted in this paper are the Arctic model ARC 3 and the Antarctic models ANT 3, ANT 3B and ANT 4B derived from incomplete series of sea-level data in the far-field from 20,000 to 6000 years ago and from the recently published continuous Barbados sea-level curve of Fairbanks (1989) (Nakada and Lambeck, 1988, 1989, 1991). The equivalent sea-level for these ice models are illustrated in Fig. 1. The Arctic ice model ARC 3 includes the Laurentide, Fennoscandia, and Barents-Kara ice sheets in which the ice model for the Laurentide and Fennoscandia ice sheets corresponds to ICE 1 of Peltier and Andrews (1976), and referred to as ARC 1 here. The equivalent sea-level for ARC 3 is 89 m of which 15 m is contributed by the Barents-Kara ice sheets, corresponding to the maximum estimates of Denton and Hughes (1981). The Antarctic ice models ANT 3 and ANT 3B contribute 37 m to the equivalent sea-level rise. Because of the lack of glaciological studies for the Antarctic ice sheets, there is an uncertainty in Antarctic melting histories, particularly during the period between 18,000 and 12,000 years ago (e.g., Denton and Hughes, 1981). The ice model of ANT 4B is used to investigate the effect of this uncertainty to the sea-level change. The melting histories for ANT 4B is the

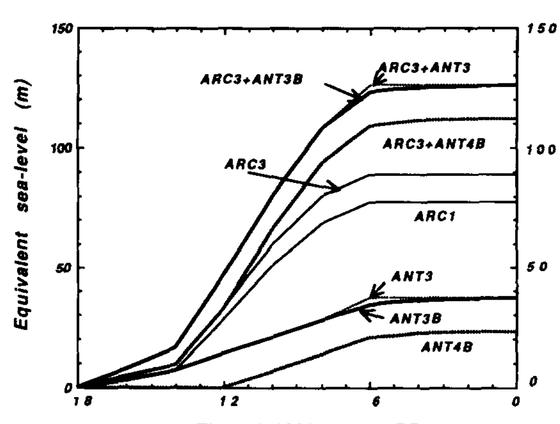


Fig. 1. Equivalent sea-level rise (e.s.l.) for a number of ice models used in this study.

same as that for ANT 3B during the past 12,000 years, and its equivalent sea-level is 23 m. The equivalent sea-level during the past 6000 years for ANT 3B and ANT 4B is about 3 m which was constrained from the Holocene sea-level observations in Australia (Nakada and Lambeck, 1989). The minor melting of the Antarctic ice sheet throughout the mid- to late-Holocene is also consistent with the glaciological study of the Antarctic ice sheet (Adamson and Pichard, 1986).

Earth model

The Earth is characterized as a Maxwell solid, in which the response to surface loading is characterized by a initial elastic deformation followed by viscous deformation such that the load-induced stresses in the body ultimately vanish. The parameters that define the initial elastic deformation are based on the seismically-defined PREM model (Dziewonski and Anderson, 1981). In the viscosity structure of the mantle, three depth-dependent viscosity models A, B and C are used. The viscosity model A has been derived from the sea-level observations at sites along the eastern coast of Australia. The lower mantle viscosity between 670 km discontinuity and core–mantle boundary is 10^{22} Pa s. The elastic lithospheric thickness and the upper mantle viscosity are respectively 50 km and 2×10^{20} Pa s. In the active island arcs, however, the effective upper mantle viscosity may be lower than that beneath the eastern Australian continental margin, and another two models B and C are adopted to examine this effect to the sea-level variations. Model B has a thin lithosphere of 25 km and upper mantle viscosity of 2×10^{20} Pa s. Model C has a 25 km lithospheric thickness and 55 km low viscosity layer of 2×10^{19} Pa s overlying mantle of viscosity 2×10^{20} Pa s down to 670 km depth. The adopted lower mantle viscosity for models B and C is 10^{22} Pa s. The thickness and the viscosity of the low viscosity layer used here are indicative only. As was indicated by Nakada and Lambeck (1989), it is very difficult to examine from the sea-level data alone whether the upper mantle has a low viscosity channel immediately below the lithosphere because of the interdependence of lithospheric thickness and upper mantle viscosity.

Ocean function

The geometry of the ocean surface on to which the meltwater is added, is defined by an ocean function defined as equal to unity where there is ocean and zero where there is land. Clark and Lingle (1979) and Wu and Peltier (1983) used a very coarse resolution of ocean function; of 5° in the near-field and along some continental margins and as large as 20° in mid oceans of the far-field away from the former glaciated regions. These coarse definitions fail to model any differential mantle flow due to the meltwater loading (Nakada, 1986; Nakada and Lambeck, 1987) and a much higher resolution is required and a 10′ spatial description of the ocean function is used.

The ocean function is, however, time-dependent with the area of sea surface expanding as the ice sheets melt. The following 3-step ocean function has been used to evaluate the effect of this time-dependent. The ocean function before 13,000 years ago is defined by the 100-m depth contour of the present ocean depth, that between 13,000 and 10,000 years ago is defined by the 50-m depth contour, and that between 10,000 years ago and present is defined by the present coastline. The corrections are at most 5% of the sea-level change for the Japanese Islands but they may be important in areas where extensive shallow continental shelves occur. In the following discussions, the 1-step ocean function which is defined by the present coastline is used throughout.

Characteristics of the theoretical sea-level curve

Before comparing the predictions with observations for discussing the vertical tectonic movements of the Japanese Islands, it is useful to quantitatively evaluate each components in the sea-level Eq. 1. The locations of the sites used in this study are illustrated in Fig.2. Figure 3a illustrates the rigid part sea-level ζ_r at several sites for the ice model of ARC 3 + ANT 3. Those at sites except Tokyo are also shown to investigate the spatial dependence of ζ_r. As indicated by Farrell and Clark

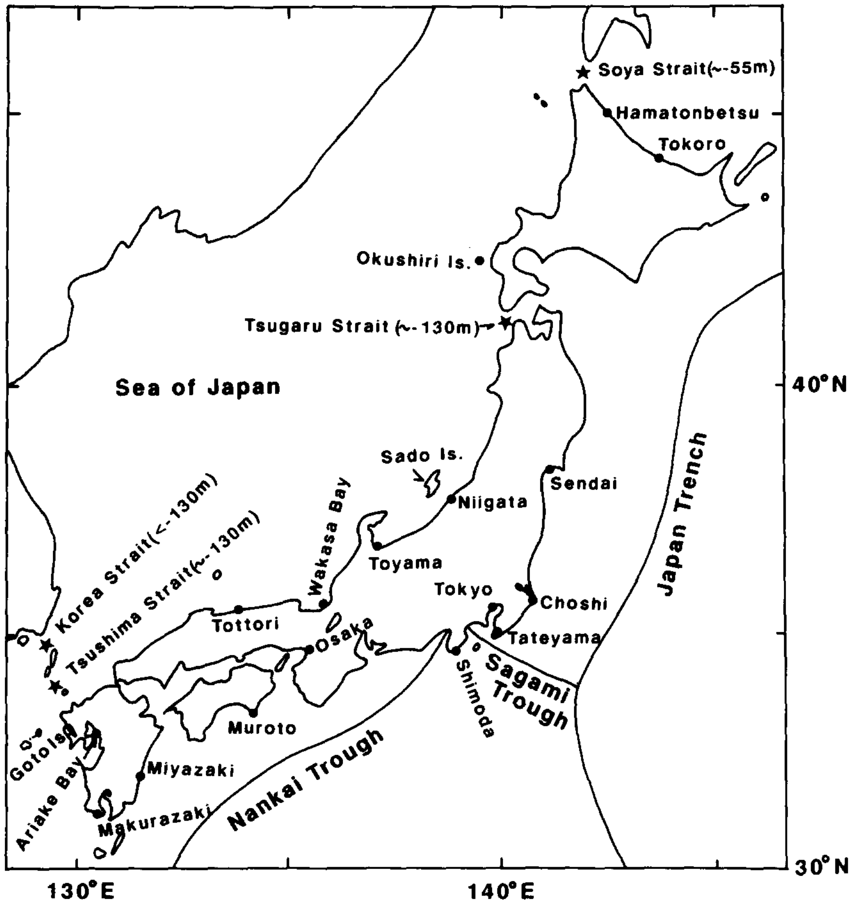


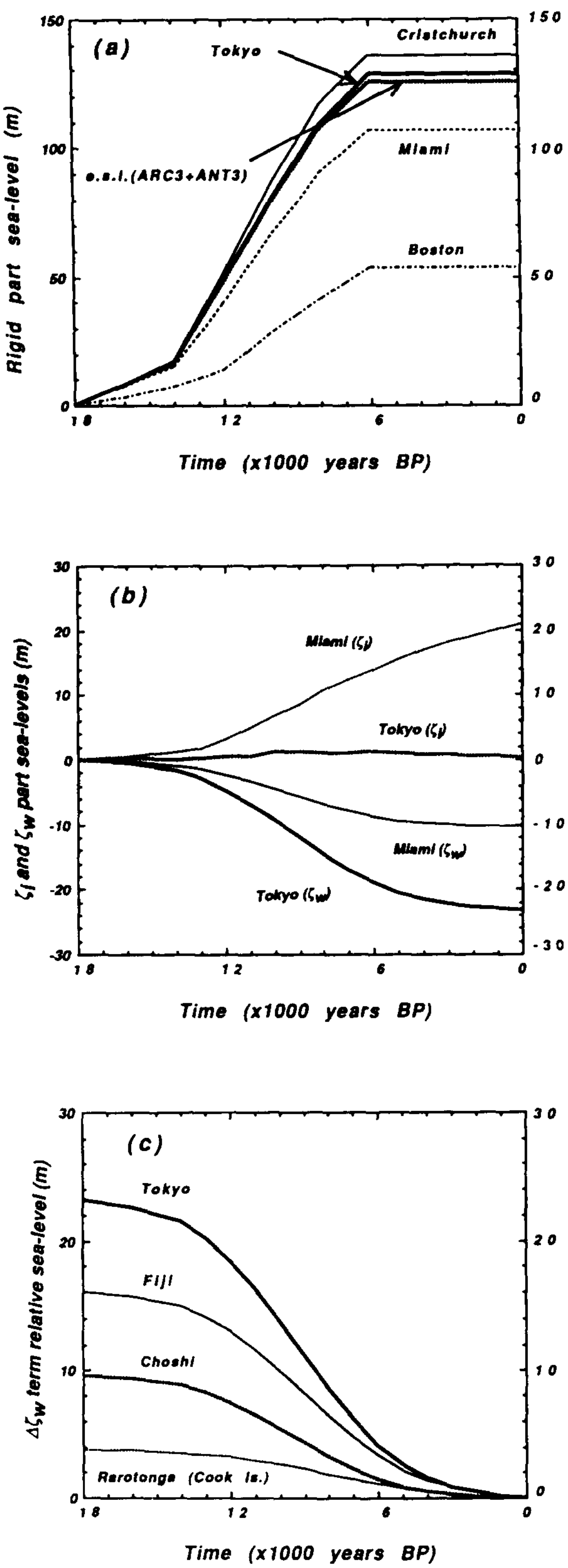
Fig.2. A map showing the geological setting of the Japanese Islands and the site name used in this study.

(1976), ζ_r is the function of the distance from the ice sheets but is nearly constant at sites throughout the Japanese region, and does not contribute to the spatial difference in the sea-level change here.

Figure 3b shows the ζ_i and ζ_w for the viscosity model A. At sites near the former ice sheets such as Miami, the ζ_i term is dominant as compared with ζ_w in the sea-level change. On the other hand, ζ_i term in the far-field such as Japan is negligibly small as compared with the sea-level change of meltwater loading term ζ_w. This means that the sea-level changes in the Japanese Islands are not sensitive to the locations of former ice sheets and mainly sensitive to the meltwater loading history. The meltwater loading term for relative sea-level $\Delta\zeta_w$ is illustrated in Fig.3c. The distance between Tokyo and Choshi is less than 100 km, but the difference of $\Delta\zeta_w$ for these two sites is significantly large and reaches about 3 m at 6000 years ago and about 8 m at 10,000 years ago. This spatial dependence for ζ_w and $\Delta\zeta_w$ is attributed to the geometry of the coastline around the site where sea-level is evaluated (Nakada and Lambeck, 1989). The difference of $\Delta\zeta_w$ between Fiji and Rarotonga is based on the size of the island (Nakada, 1986). Thus the meltwater loading term ζ_w and $\Delta\zeta_w$ are extremely sensitive to the geometry of the coastline as well as to the size of the island, and this effect necessitates the use of high spatial resolution for the ocean function.

Spatial characteristics of the sea-level predictions in Japanese Islands

The principal diagnostic characteristics of the Late Pleistocene and Holocene sea-level curves at



sites away from the ice sheets are (1) the sea-level at about 18,000 years ago, (2) the rates of sea-level rise from about 10,000 to 6000 years ago, (3) the time when sea-level reached its present level, (4) the amplitudes of the relative sea-level at about 6000 years ago, and (5) the recent sea-level rise during about the past 100 years. To discuss the general pattern for these diagnostic characteristics of the sea-level variations in the Japanese Islands, the predicted relative sea-level changes at 18,000, 10,000, 6000 and 100 years ago are illustrated in Fig.4 for the viscosity models A, B and C, and the ice models ARC 3 + ANT 3B and ARC 3 + ANT 4B.

The relative sea-levels at 18,000 years ago are illustrated in Fig.4a, in which the dotted line represents the −100 m depth contour of the present ocean depth. The sea-levels at 18,000 years ago are important for constraining the total meltwater volumes, for studying the paleo-environment, and for examining the land-bridge problem for the migration of humans and animals (Yonekura and Ota, 1986). The maximum sea-level drop around the Japanese Islands has been generally believed to be about −130 m, however, some scientists believes to be about −100 m (e.g., Saito et al., 1989). According to Fig.4a, the predictions of sea-level at 18,000 years ago exhibit a significant spatial dependence and are between −100 and −130 m. The key straits for the land-bridge problem are Tsushima Strait and Tsuruga Strait where the present ocean depth are respectively about −130 m (Fig.2), and the relative sea-level changes at these straits are illustrated in Fig.5. In the Earth models A and C, the predictions for these two straits are between −115 and −120 m although the equivalent sea-level for ARC 3 + ANT 3B is 126 m. Those for the viscosity model A and for the ice model ARC 3 + ANT 4B are about

Fig.3.(a) Rigid part sea-level (ζ_r) for the ice model ARC 3 + ANT 3. (b) Predicted sea-level produced by the deformation of the Earth in the response to the glacial unloading (ζ_i). The ice model is ARC 3 + ANT 3. The rheological model is A (lithospheric thickness, upper mantle viscosity and lower mantle viscosity are respectively 50 km, 2×10^{20} Pa s and 10^{22} Pa s). (c) Predicted relative sea-level of the meltwater loading term ($\Delta\zeta_w$). The ice model is ARC 3 + ANT 3, and the viscosity model is A.

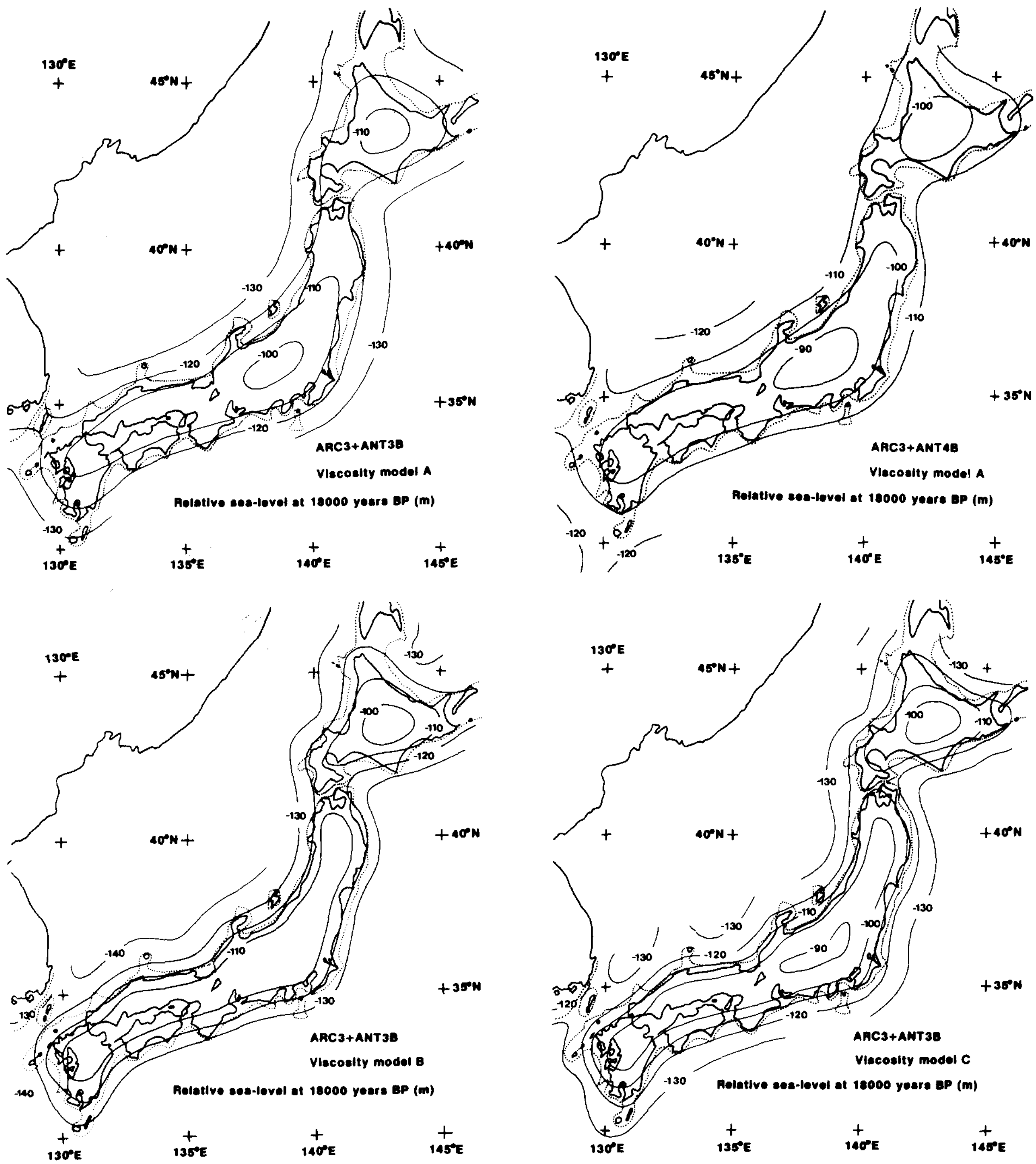


Fig.4. Relative sea-level at (a) 18,000, (b) 10,000, (c) 6000 and (d) 100 years ago. Ice models are ARC 3+ANT 3B and ARC 3+ANT 4B. The viscosity models are A, B and C. The units for the relative sea-levels at 18,000, 10,000 and 6000 years ago are in meters (m) and that for 100 years ago is millimeters (mm). The dotted line shows the −100 m contour of the present water depth.

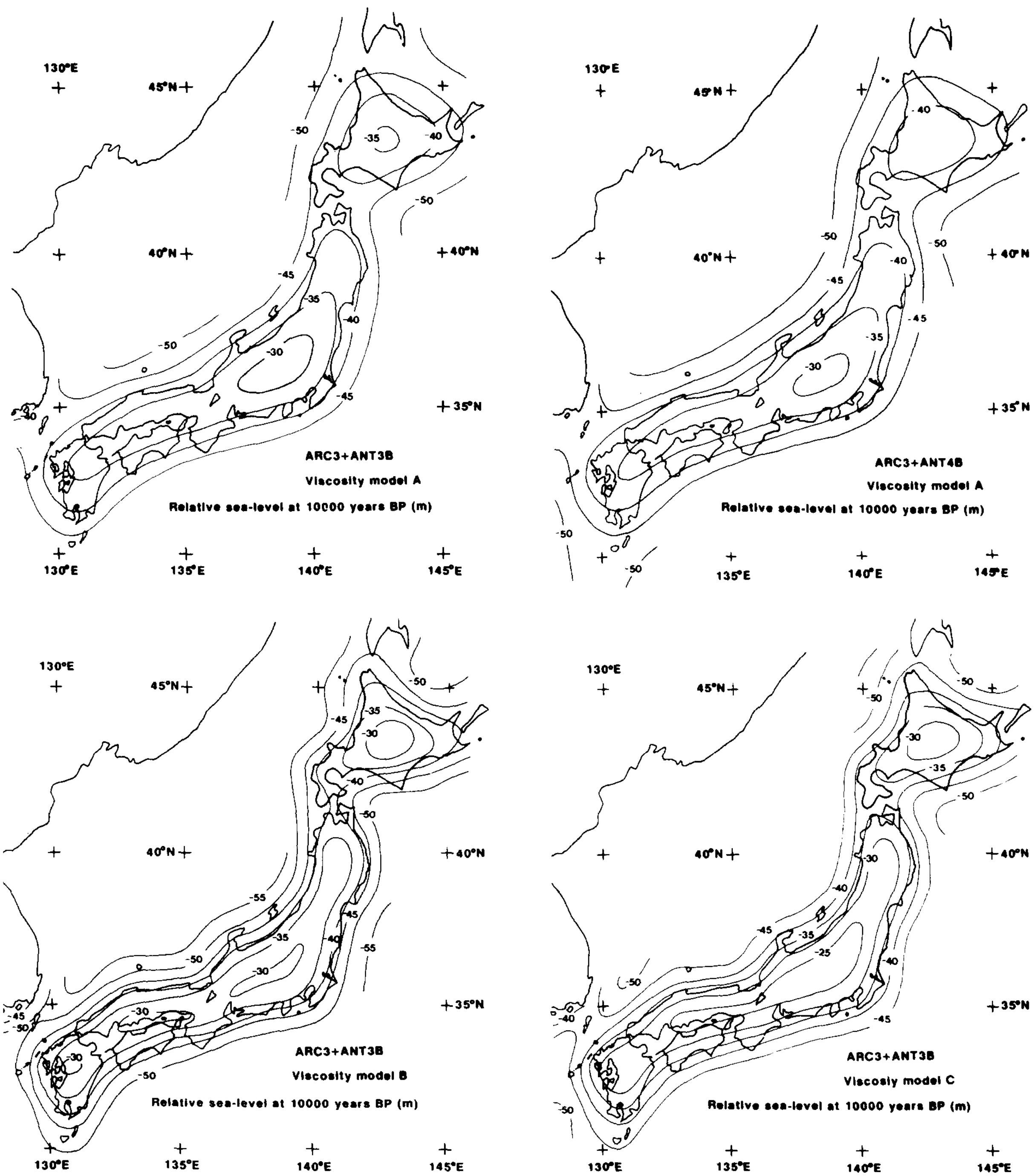


Fig. 4 continued.

−105 m. The difference of this value is based on the difference in equivalent sea-levels for the Antarctic ice models ANT 3B and ANT 4B between 18,000 and 12,000 years ago (Fig.1). According to recent paleo-environmental (e.g., Oba, 1989) and mammal fauna (Kamei et al., 1988) studies, land-bridges were not formed during the lastglacial phase, and this is consistent with our predictions

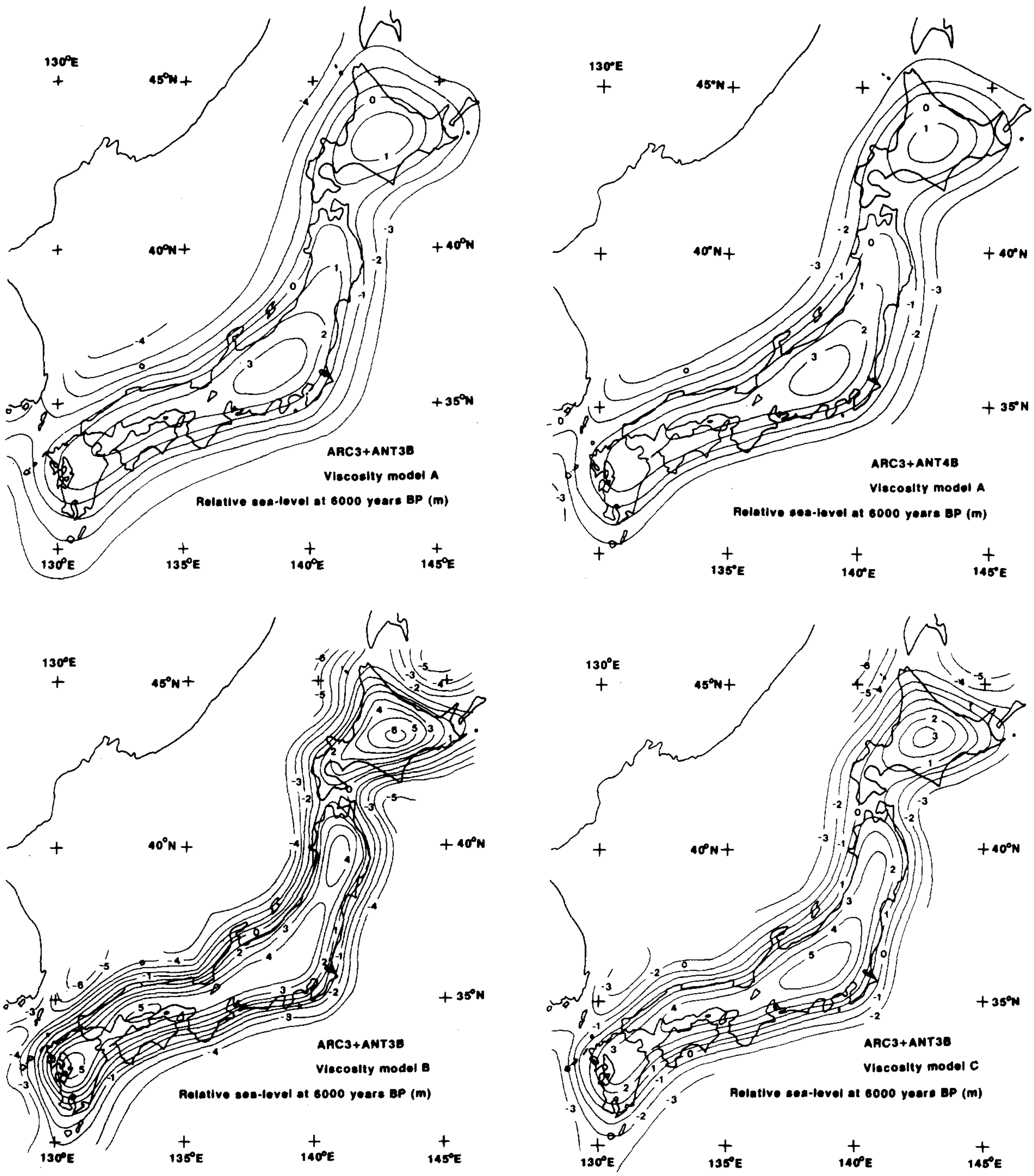
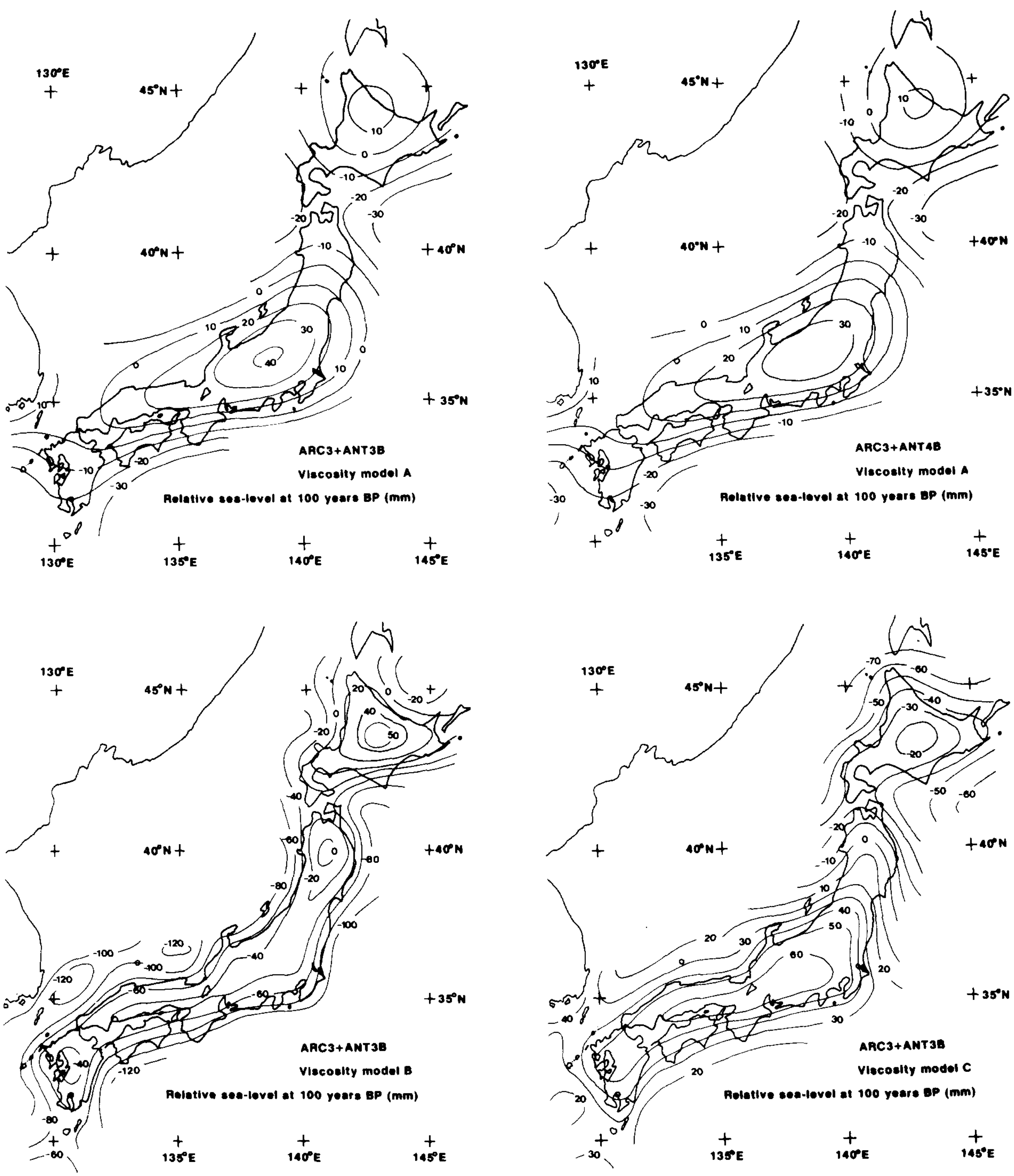


Fig. 4 continued.

of the maximum sea-level drop except for model B.

Systematic sea-levels have been obtained primarily during the past 10,000 years, and the predictions at 10,000 years ago are shown in Fig.4b. The spatial variability of the sea-level change at this time is important. For example, the predictions based on the Earth model C at sites along the



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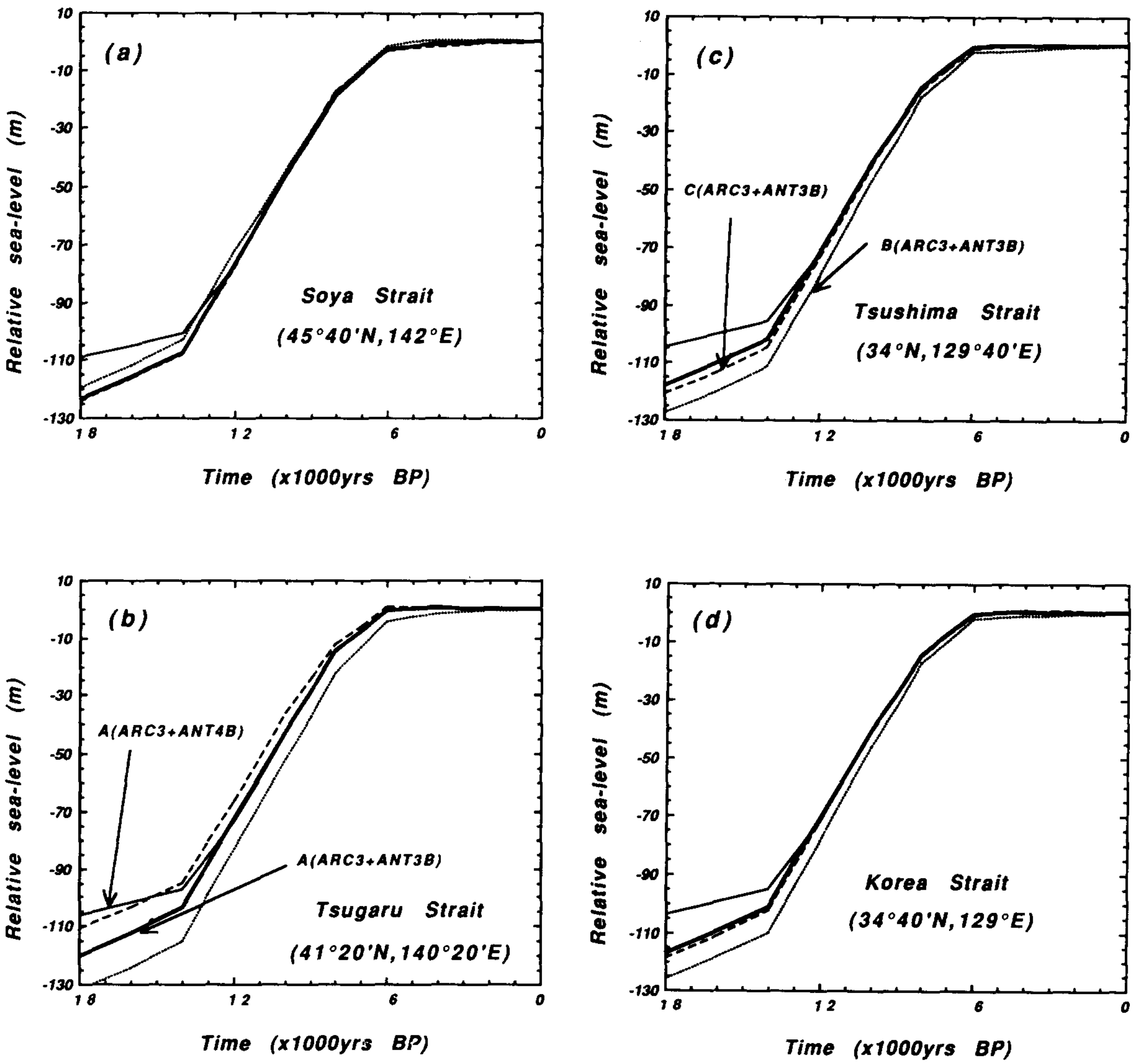

Fig.5. The predicted relative sea-level curves at sites for (a) Soya Strait, (b) Tsugaru Strait, (c) Tsushima Strait and (d) Korea Strait. The notation for the relative sea-level results is of the form, for example, A(ARC 3+ANT 3B), where A refers to the viscosity model and ARC 3+ANT 3B refers to the ice model.

coastline from Ise Bay to Kushimoto show a significant spatial dependence, and change from −25 m to −40 m. The spatial variations are also indicated in the sea-level changes at Tokyo and Osaka, where the most systematic and extensive observations have been obtained by Matsushima (1987) and Maeda (1980), and these predictions are also consistent with observations (see Fig.7).

The sea-levels at 6000 years ago are significant for evaluating the mantle viscosity, because these levels are dominantly composed of the viscous reponse of the Earth (e.g., Nakada and Lambeck, 1989). The predictions at 6000 years ago are illustrated in Fig.4c, and also indicate significant spatial dependence. For example, there is a clear Holocene high stand predicted with the amplitude of more than 2 m at Tokyo or Osaka which are located in the embayment. However, no clear Holocene high stand is predicted for sites at the tip of peninsula or islands off the main islands. These significant spatial variations are useful for examining whether the observed sea-level variations are dominated by tectonic components or glacial-isostatic components.

The relative sea-levels at 100 years ago are shown in Fig.4d, and also indicate the spatial dependence. In the prediction for Earth model C, for example, the apparent crustal uplift rate in central Honshu is 0.6 mm/yr, and the predicted subsiding rate along the coastline of Hokkaido is 0.5 mm/yr. In the coastline of Southwest Japan, the predicted crustal uplift rate is about 0.5 mm/yr. According to analyses based on tide gauge (Kato, 1983) and leveling data (Danbara, 1971), the average apparent crustal subsidence along the coast facing the Pacific Ocean in Northeast Japan is 5 mm/yr, and the average uplift rate in central Honshu is 1–2 mm/yr. In Southwest Japan, secular sea-level change derived from the tide gauge data is very complex (Kato, 1983), and it is difficult to compare the general pattern between the observations and predictions. Although there are lots of uncertainties on the interpretations for the variations in sea-level for the past 50–100 years (e.g., Barnett, 1984; Lambeck, 1988), the contribution of the ongoing glacial-isostatic adjustment to the recent crustal movement may be important even in tectonically active Japanese Islands.

Comparison between observations and predictions

The predictions and observations, whose data sources are listed in Table 1, are illustrated in Figs.6–8. It is, in fact, ideal to compare observations with predictions for constraining the mantle rheology and melting histories, and for evaluating the Holocene tectonic histories from these observations. But systematic observations have been obtained at only a few sites such as Tokyo and Osaka, and fragmentary observations have been obtained at most of the sites (e.g., Ota et al., 1981, 1987). Thus it will be better, at present, to compare the observations with predictions based on the quality of each observation. In this paper we only represent the observations and predictions at sites where fragmentary observations have been obtained (Fig.6). Thus we need more data at these sites before discussing tectonic histories and mantle rheology.

Systematic observations have been obtained at

TABLE 1

Data sources of sea-level observations used in this study

Site	Reference
Hamatonbetsu	Matsushima (1982), Maeda (1984)
Tokoro	Maeda (1984), Hirai (1987)
Okushiri Island	Miyoshi et al. (1985)
Sendai	Matsumoto (1981)
Choshi	Ota et al. (1985)
Tokyo	Matsushima (1987)
Tateyama	Frydl (1982)
Sado Island	Ota et al. (1987b)
Niigata	Ota et al. (1987b)
Shimoda	Ota et al. (1986)
Osaka	Maeda (1980)
Toyama	Fujii and Fuji (1982)
Wakasa Bay	Ota et al. (1987b)
Tottori	Ota et al. (1987b)
Muroto	Katto and Akojima (1980)
Miyazaki	Ota et al. (1987b)
Makurazaki	Ota et al. (1987b)
Ariake Bay and Goto Is.	Ota et al. (1987b)

Tokyo (Matsushima, 1987) and Osaka (Maeda, 1980) as are illustrated in Fig.7. The observations at these two sites clearly show the Holocene high stands at about 6000 years ago and this is compatible with the predictions. The important point derived from the comparison between these two data sets is that the amplitudes of the sea-level at about 10,000 years ago are also compatible with observations. Thus the observations at Osaka are about −30 m and those for Tokyo are about −35 m. As was discussed in the previous section, the sea-level variations caused by glacial-isostatic adjustment show such a spatial dependence. This consistency of the spatial dependence between observations and prediction seems to be indicative that the tectonic crustal movement in these regions are small compared with the sea-level change caused by the last deglaciation. Moreover careful comparison between observations and predictions at Tokyo and Osaka favour the Earth model A.

Geometric effect for the sea-level variations are also important for evaluating tectonic histories and for examining mantle rheology. The consistency between observation and prediction can be seen in the sea-level variations at sites in the regions of Ariake and Goto Island (Fig.1). Thus there is a evidence of higher sea-level in Ariake

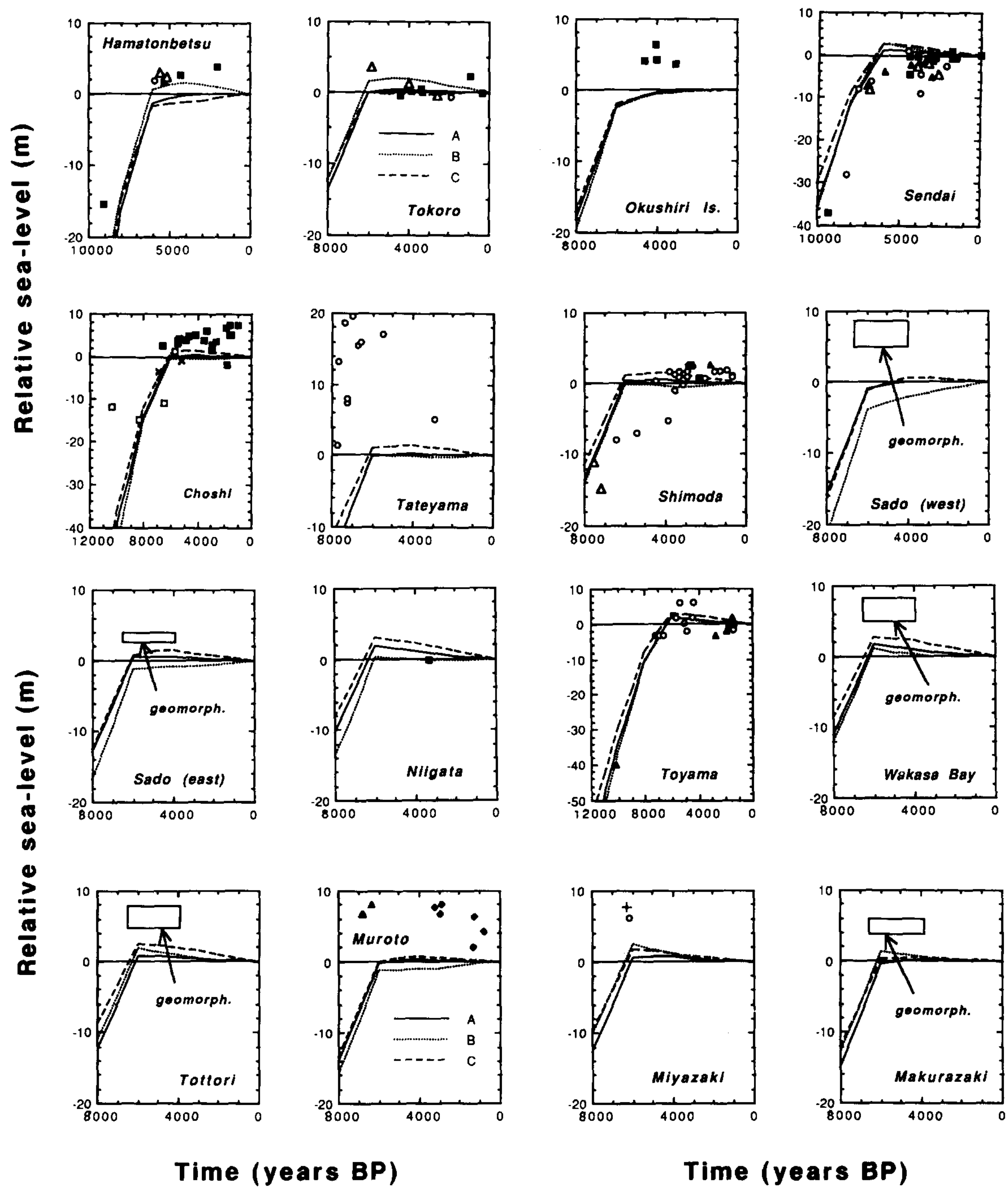

Fig.6. Observed and predicted relative sea-levels at each site. The ice model for the prediction is ARC 3+ANT 3B, and the viscosity models are A, B and C. Data sources are listed in Table 1. The symbols of the samples used for the age-depth relation in the observations are: (○) shell; (▲) wood; (■) peat; (x) humic clay; (□) humic silt; (△) oyster; (◇) calcareous worm tube; (+) tephra (Akahoya). The age evaluated from the Akahoya tephra is 6300 yr B.P.

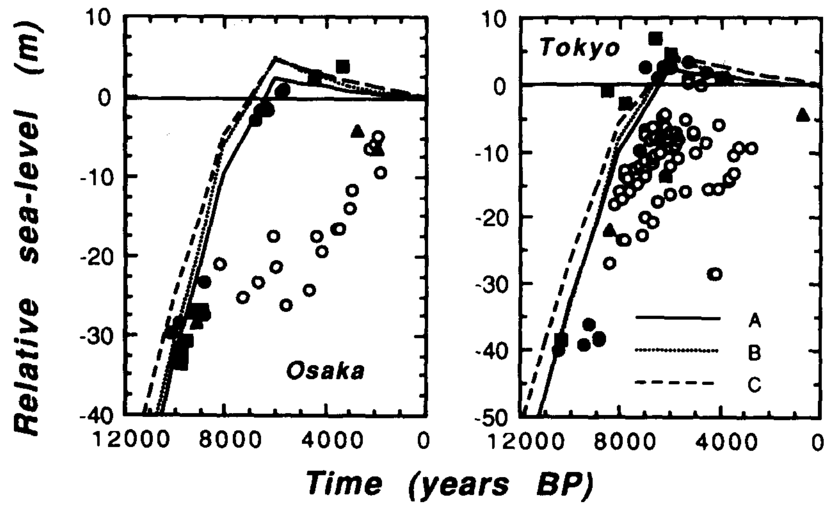

Fig.7. Observed and predicted sea-levels at Tokyo and Osaka. Ice model for the prediction is ARC 3+ANT 3B, and viscosity models are A, B and C. Data sources are listed in Table 1. The symbols of the samples used for the age-depth relation are: (●) intertidal shell; (○) subtidal shell; (▲) wood; (■) peat. In these observations, the distinction between intertidal shell and subtidal shell is systematically discussed by the paleontological method.

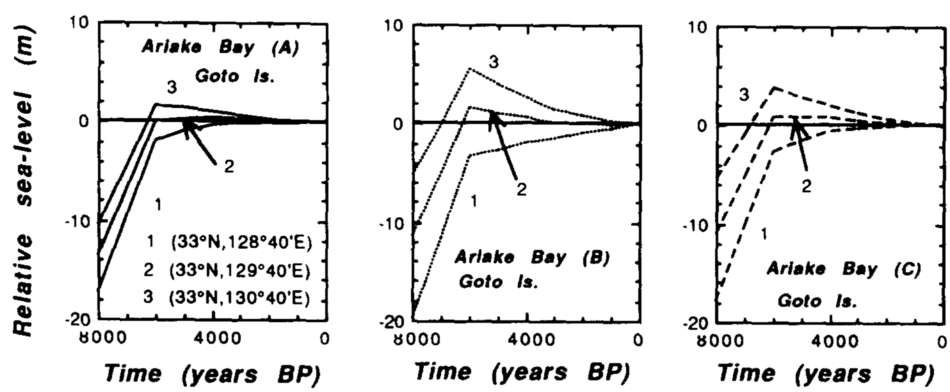

Fig.8. Predicted relative sea-levels in the region of Ariake Bay and Goto Islands. The ice model is ARC 3+ANT 3B, and the viscosity models are A, B and C.

Gulf, and no higher sea-level in Goto Island. The archeological data in and around Ariake Gulf show that the sea-level at about 6000 years ago was about 2–4 m higher relative to the present sea-level, but in Goto Island the sea-levels have not exceeded the present level (Ota et al., 1987). The predictions in this region are depicted in Fig.8. In these sites, there is a significant difference in prediction regardless of the Earth model, and the difference in prediction is qualitatively consistent with those in observations. This spatial dependence in this restricted region, where tectonic movement probably do not have spatial dependence at least in the Holocene, is important for studying mantle rheology. If we assume that there is no spatial dependence for tectonic movement in the Holocene, the differential sea-level is a function of mantle rheology. Figure 9 shows the differential sea-level variations. It is desirable to get more systematic observations in these regions for constraining the mantle rheology from the differential sea-level variations.

Concluding remarks

Japanese relative sea-level changes due to the last deglaciation have a significant spatial dependence. The predicted spatial difference of the sea-

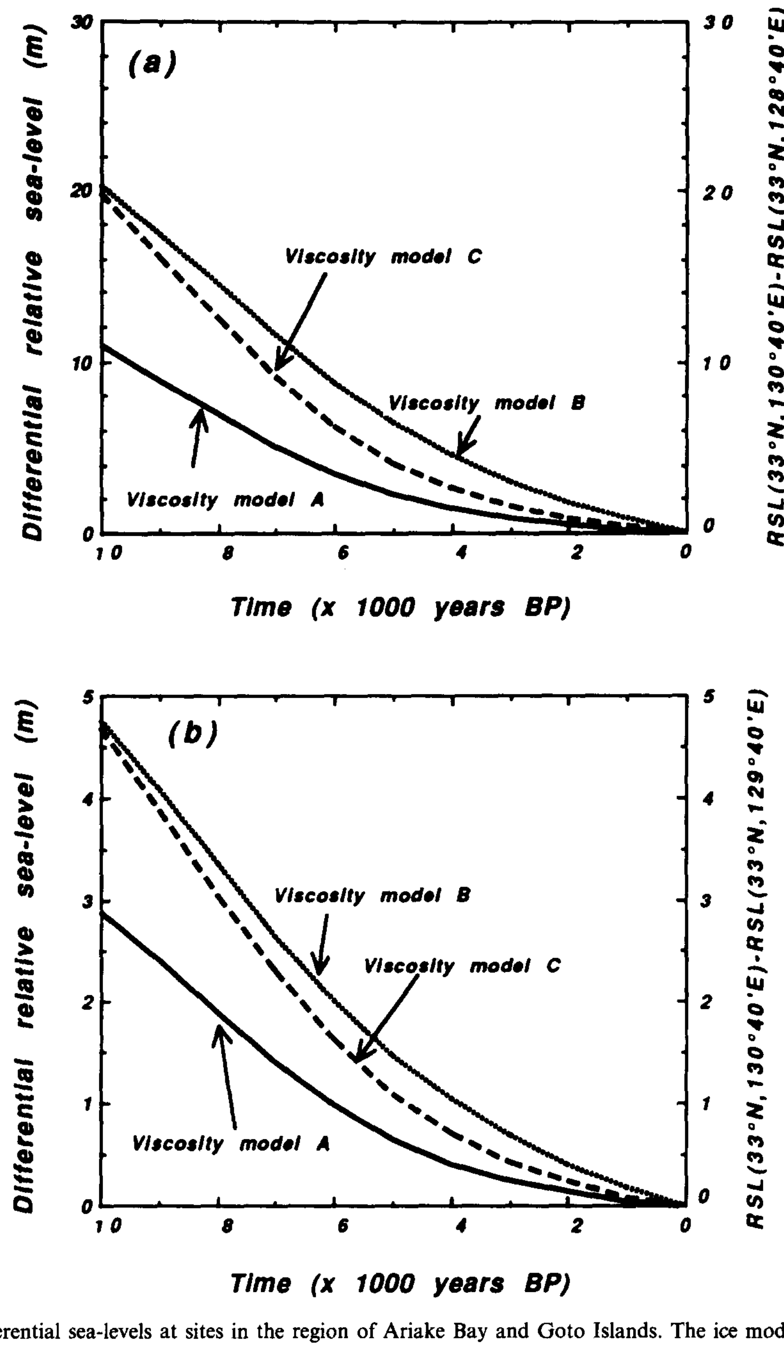

Fig.9. Theoretical differential sea-levels at sites in the region of Ariake Bay and Goto Islands. The ice model is ARC 3+ANT 3B, and the viscosity models are A, B and C.

level amounts to about 5 m at 6000 years ago, 20 m at 10,000 years ago and 30 m at 18,000 years ago. These characteristics are important for separating the tectonic and glacial-isostatic components in the observed sea-level variations. Some separation of these contributions is possible as is indicated by the examples discussed above, and it is possible to study the tectonic processes and to examine the mantle rheology based on the sea-level observations from tectonically active regions.

However, more data at sites for which significant spatial variations in sea-level caused by the last deglaciation are predicted, are required for the period 18,000 years ago and to the present.

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