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Effect of hydroisostasy on postglacial transgression on the shelf and coast of Primorye as revealed by computer modelling

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Abstract. Factors affecting the process of postglacial transgression on the shelf and coast of the Primorye (the territory of modern Primorsky Kray) in the Russian Far East are considered. The main regional feature consists in a significant lag of the sea level rise at the beginning of the Holocene following the completion of the Younger Dryas cold stadial. While some researchers explain this phenomenon in terms of descending tectonic movements that predominated in this region over the course of the Cenozoic era, traces of the Holocene climatic optimum sea level highstands along the coastline contradict the conclusion that tectonic submergence was uniform. In order to explain this contradiction, the hypothesis of hydroisostatic load compensation due to the viscoelastic properties of the mantle layers following the end of the last period of glaciation and involving the influx of huge volumes of water to the basin of the Sea of Japan is proposed. Dominating tectonic submergences of the western rim of the Sea of Japan and the Primorye coast were interrupted by hydroisostatic emergence during the Atlantic period between 5–6 ka BP. The use of a computer simulation of postglacial transgression in the SELEN 2.9 and SELEN 4.0 software environments demonstrates a transgression lag under hydroisostatic influence along with the increasing viscosity of mantle layers. The viscosity of mantle layers in the Primorye region is shown to be lower than for the Japanese Archipelago, which is located closer to the recent subduction zone.

Keywords: postglacial transgression, mantle viscosity, hydroisostasy, vertical movements, Primorye, Russian Far East.

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Introduction

In the Primorye region of the Russian Far East, where traces of Holocene coastlines raised above the contemporary sea level can be observed along the entire coast, significant postglacial transgression lag can be explained in terms of the eustatic factor. According to the data of [Park et al., 2000; Pletnev, 2012], there was no interruption in water mass influx to affect a lag in the course of transgression since the Sea of Japan never became isolated from the World Ocean even during the last glaciation maximum.

In order to reveal the factors affecting the course of marine transgression, a computer simulation of sea level changes as a result of glaciers melting in dependence on rheological parameters of the mantle layers was carried out. Performed using the SELEN 2.9 and SELEN 4.0 software suites, developed by a collective of authors under the guidance of G. Spada [Spada, Stocchi, 2006; Spada, Stocchi, 2007; Spada et al., 2012; Spada, Melini, 2019], the simulation set out to examine the influence of hydroisostasy on the course of marine coastline transgression.

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When analysing the literature data on sea level changes carried out by the methods of micropaleontological analysis and confirmed by means of absolute age determinations in the course of field researches, we took the altitude and age reconstructions of the traces of ancient coastlines into account. The quality of the data is sufficient to permit their use as reference marks for simulation of the curve of postglacial marine transgression and assessments of the relative contributions of eustatic transgression and tectonic movements.

Sea level change in the Primorye according to the results of field research

Korotkiy and co-authors [Korotkiy et al., 1980] note that achieving accurate determination of the Pleistocene stages of the shore development is extremely challenging due to the Cenozoic submergence of the Primorye coast and destruction of ancient coastlines. Although several abrasion terraces have been revealed on the Primorye shelf at depths of 20, 30–40, 100–120 m, their age is unknown. On the one hand, they may be tentatively dated to the Early, Middle or Late Pleistocene, but on the other, it is possible that they mark stages of postglacial transgression.

In any case, it should not be doubted that shelf transgression and regression regimes on the Primorye coastline changed more than once during the Pleistocene epoch. Although transgression and regression are apparently synchronous with planet-wide glacioeustatic oscillations of the World Ocean level, an accurate record of these sea level changes has yet to be practically revealed. On the shelf they have probably been eroded, since, when boring under coastal-marine layers of the Holocene and Upper Pleistocene sediments, it is typically sediments from the Neogene and later periods that are uncovered.

No traces of interglacial transgressions have been discovered apart from marine sediments revealed in several bays at levels close to the contemporary coastline. These traces are presented by littoral and lagoonal deposits having complexes of sublittoral and lagoonal diatoms along with the pollen of thermophilic plants. The authors [Korotkiy et al., 1980] do not even tentatively specify the age of these sediments.

At the beginning of the Holocene, the behaviour of the sea level curve is characterised as follows: “During the Amur (Preboreal) phase, the coastline of the Sea of Japan is located at around the –50 to –70 m marks. Sediments corresponding to the penetration of sea water into the valleys of the Tumannaya, Razdolnaya and Kievka rivers have been uncovered at the depths of (–48.7) and (–43) m. The most reliable position of the sea level during the Preboreal is determined in the well 2 in the Amur Bay, where the facies contour, separating continental sediments from marine, passes at the (–42.9) mark” [Korotkiy et al., 1980, p. 183]. Thus, at the beginning of the Holocene, notable lags from the sea level transgression, typical for eustatic curve, were not yet noted.

However, following the completion of the Younger Dryas period, within the period of melt water flow pulse MWP-1B (melt water pulse 1-B) [Peltier, Fairbanks, 2006; Tanabe et al., 2010], which accelerated the process of postglacial transgression, the resultant lags in the course of transgression are already being marked on the Primorye shelf.

Thus, despite the rare occurrence of the Holocene and Upper Pleistocene sediments on the middle Primorye shelf, Kuz’mina et al. [1987] describe such a section revealed by drilling on the shelf in the Kievka bay at a sea depth of 16–35 m, proposing to adopt it as the Holocene stratotype of the Primorye marine sediments. Although the authors suppose the location of bore to be relatively tectonically stable, as described by Kulakov [1973], they show that this area corresponds to the Central Sikhote-Alin geosuture. Continuous sedimentation taking place since the Sartan glaciation is recorded in the section with a sediments time interval of 20–25 ka BP. The section is paleontologically characterised and dated by the radiocarbon method.

In the borehole no. 132, drilled on the coastal shelf at the depth of 20 m, coastal sediments dated to 9660 ± 160 (MGU-822) were obtained, which, according to Kuz’mina et al. [1987], were formed a little lower than 48–49 m from the contemporary sea level, with their facies composition comprising evidence of the sea level position at that time.

According to the results of pollen analysis, the dated layer is characterised by abrupt climatic warming, providing evidence of a melt water influx pulse MWP-1B – the event following the Younger Dryas, as it has been shown on the Island of Barbados [Peltier, Fairbanks, 2006; Tanabe et al., 2010]. The layer was being formed under conditions of an oxidising and active hydrodynamic regime [Kuz'mina et al., 1987].

Analysing the results of works of the laboratory of recent sediments and Pleistocene paleogeography of MSU in the Sea of Japan and generalising existing literature data, P.A. Kaplin [Kaplin, 1978] concludes that three complexes of the ancient coastlines traces are revealed on the Primorye shelf. Two of these are represented with cumulative forms at depths of 45–50 and 35–40 m respectively, having an age more than 40 ka BP, while the third occurs at a depth of 20–25 m and is dated to 7–8 ka BP.

Ancient coastline traces dated to 7–8 ka BP also occur at depths of 20–25 m, while on other coasts, including Okinawa Island, coastline traces from this age are identified at depths of 10–15 m [Evelpidou et al., 2019]. This also confirms a lag in the postglacial transgression occurring on the Primorye shelf.

Another feature of postglacial transgression on the Primorye coast can be seen in the change of the contemporary sea level relative to the Holocene optimum. Accumulative landforms of the Holocene age, located higher than the contemporary sea level, often consist of several generations of the beach ridges.

For example, in the Rudnaya Bay three such generations are distinguished extending into the land and having a height above the coast of 2, 3–4 and 5–6 m respectively. These are separated from swamped depressions comprising former lagoons. Accumulative forms consist of a series of sand and gravel deposits, which include sand-silt lenses. A large number of radiocarbon dates were obtained from the deposits of accumulative formswithin the interval from 5.5 to 1 ka BP [Ignatov, 2004].

Kuz'mina et al. [1982] identify a raised sea level of 2–3 m during the Atlantic period as compared to the contemporary sea level. They observe the apparent appearance of a (2.5–3)-metre marine terrace during this time to form the base of a 3.5-metre lagoonal coastal terrace. Later, at the beginning of the Subboreal period, a slight regression of the sea occurred, confirmed in the finds of archaeological sites: the sites are revealed on abrasion surface at a height of 4.5 m above its outcrop from the surf zone.

For the Middle Holocene period (Atlantic), Korotkiy et al. [1980] identify a raised Holocene terrace covering practically the entire coast of the Sea of Japan. At the southwestern Primorye it is represented with an extensive low-lying plain of the Khasan seaside, that is observed onwards towards the north-east in the rivers' mouths and bays heads. Its height ranges within 4–8 m. There is an alluvial-lagoonal terrace with a height of 3–4 m behind a zone of ancient storm walls. The amplitude of relative raises of a coastal land is ambiguously estimated: 2–3, 5–8 and 11–13 m. Therefore Korotkiy et al. [1980] propose to use height marks of the lagoonal layers roof in a section of 3–4-metre terrace as a benchmark against which to calibrate the extreme sea level oscillations of the Sea of Japan during the Middle Holocene.

The age of the lagoonal deposition in a section of 3–4-metre terrace ranges from 736 ± 160 years (MGU-IOAN-229) in the mouth of Barabashevka river and to 4500–5000 years in the mouth of Chernaya river. These lagoonal sediments correlate well with accumulations of beach sediments in a section of 5-metre marine terrace with the following radiocarbon datings: 5530 ± 110 years (GIN-738), 5630 ± 110 years (GIN-739a), 6000 ± 130 years (GIN-739b) [Korotkiy et al., 1980].

Further, within the Ambin (Subboreal) phase, a depression is observed relative to the maximum of the Atlantic for 2.5–3.0 m [Korotkiy et al., 1980].

During the second half of the Subboreal, at a period of climatic warming, an observed increase in the sea level was confirmed with the settlements of ancient people at the structural-denudation surfaces at a height of 20–40 m [Selivanov, Stepanov, 1982].

During the present Subatlantic age, a regression in the sea level has place too. Evidence of ancient human settlements (Yankovskaya culture 2500–2000 years ago) appears not only at the height of 4–5 m, but also at the contemporary sea level. In the Subatlantic-2 (SAT2) on the 2.5-metre marine accumulative terrace, molluscs 1420 ± 18 years (MGU-758) and 1400 ± 200 years (MGU-810) have been dated to demonstrate a transgression of the Sea of Japan. Archaeological data comprises evidence of the burial of the Yankovskaya culture artefacts within beach sand and pebble of coastal walls at a height of 4.2 m [Selivanov, Stepanov, 1982].

Thus, a common feature of the postglacial transgression course in the Primorye at the Holocene beginning, following the Younger Dryas cold stadial consists of a lag behind the eustatic transgression [Kaplin, 1978; Korotkiy et al., 1980; Kuz'mina et al., 1987]. Here, a lag of the sea level rise was continuing even following an increase in the rate of melt water influx.

The other characteristic feature of postglacial transgression in the Primorye is an increased sea level at the Atlantic period, followed by a smooth decline, accompanied with oscillations of regressions and transgressions with an amplitude of a few metres.

The character of the transgression/ingression course of the Sea of Japan on river valleys and rias typical of the Prymorye coast confirm the dominance of negative tectonic vertical movements in this region. Conversely, the general spreading of the raised coastlines of the Atlantic period comprises evidence of alternation of descending tectonic movements with rises.

The conclusion concerning abrupt, pulsed tectonic movements typical for the region as a whole, does not contradict the results of seismic sections analysis [Antipov, 1987], which shows that the deep-water basin of the Sea of Japan has been formed by two pulses of differentiated short-term descents: the Pre-middle Miocene and Late Quaternary. For the rims of the Sea of Japan, "flexural-fault" zones [Antipov, 1987], with which tectonic movements are associated, are typical.

Simulation of the postglacial curve of the sea level change for the Primorye

Using the SELEN 2.9 open code software, computations have been carried out in the work with the aim of obtaining the curves of postglacial change of the sea level for the area of the Primorye coast.

The SELEN 2.9 software suite is intended for so-called sea level equation (SLE) solving [Spada, Stocchi, 2006]. The solution of the "sea level equation" lies in the range of values of spatio-temporal variability of the World Ocean's floor structure by keeping gravity potential of the sea surface, constant for a specific melting scenario of the Ice Age sheet glaciers and viscoelastic model of the Earth [Wu, Peltier, 1983]. The software suite realises the fundamental principles proposed by Farrel and Clark [1976] to calculate the sea level changes following the redistribution of meltwater over the surface of a viscoelastic model of the Earth.

The computations were made for different rheological characteristics of the Earth mantle layers and under different glacial melting scenarios. In addition, within the test mode, we have conducted a simulation with help of the latest version of the SELEN 4.0 software [Spada, Meline, 2019]. New software version differs from the previous SELEN 2.9 with such updates as consideration of the Earth rotation, changes of the land and ocean configuration as the World Ocean level increases because of the Late Pleistocene glaciers melting, pole shift as glaciers degradation. The updated version of the ICE6gC model of the Late Pleistocene glaciation with the VM5a rheological model of a mantle [Peltier et al., 2015] is used to simulate glaciers melting in the SELEN 4.0. Only one computation is given here due to the failure to obtain stable results in the SELEN 4.0 software.

The values of viscosity of the mantle layers, used by Nakada et al. [1991] for estimation of mantle rheology of the Japan Archipelago and taken by us for computations, are given in the table below. He proposes three types of the viscous characteristic of the Earth mantle layers: A, B and C. We have added the fourth type D with viscosity values, ultimate for the

Table. **Viscous characteristics of the mantle layers, Pa·s**

Layer	Model						
	ICE3gD	ICE3gB	ICE5gA	ICE5gB	ICE5gC	ICE5gD	SELEN 4
Lithosphere, viscosity and thickness, km	∞, 55	∞, 30	∞, 50	∞, 30	∞, 30	∞, 55	∞, 90
Upper mantle layer 1	10^{22}	$2\cdot10^{20}$	$2\cdot10^{20}$	$2\cdot10^{20}$	$2\cdot10^{19}$	10^{22}	$5\cdot10^{20}$
layer 2	10^{22}				$2\cdot10^{20}$	10^{22}	$5\cdot10^{20}$
Transition layer, 400–670 km	10^{22}				$2\cdot10^{20}$	10^{22}	$5\cdot10^{20}$
Lower mantle layer 1	10^{23}	10^{22}	10^{22}	10^{22}	10^{22}	10^{23}	$1.5\cdot10^{21}$
layer 2	10^{23}				10^{22}	10^{23}	$3.2\cdot10^{21}$
layer 3	10^{23}				10^{22}	10^{23}	$3.2\cdot10^{21}$
layer 4	10^{23}				10^{22}	10^{23}	$3.2\cdot10^{21}$
layer 5							$3.2\cdot10^{21}$
layer 6							$3.2\cdot10^{21}$
Core	∞	∞	∞	∞	∞	∞	∞

Note. The explanation of models' designation is given in the text.

mantle layers, as "the most viscous" [Bulgakov et al., 2020]. Models names in the table consist of a designation of a model of the postglaciation melting scenario – ICE3g [Tushingham, Peltier, 1991] and ICE5g [Peltier, 2004] with the addition of a symbol that represents the type of viscous characteristic of the Earth mantle layers.

Thus, for example, the ICE5gA designation stands for the computation of the ICE5g glaciers melting model on [Peltier, 2004] with a viscous model of A type on [Nakada et al., 1991].

As a result of computations, the curves of the sea level change in the postglacial period have been obtained for all the listed viscous characteristics and models of scenarios of melting of the glaciers of last glaciation. The obtained curves for the location point of Nahodka city are presented in Fig. 1. The curves designations match the models' names in the table.

Similar computation results of the course of postglacial transgression of the Primorye were obtained [Evelpidou et al., 2019] in the SELEN software for the ICE6g and VM5a models for the Okinawa Island of the Ryukyu Archipelago located comparatively nearby to the Primorye region. The computations results used when clarifying of the field data show the excess of the sea level at the Holocene optimum in the area of Ryukyu Archipelago.

Discussion

In comparing the results of numerical simulation of the Holocene transgression carried out by different authors for several models of the course of glaciers melting with data of the field observations in the Mediterranean Sea, P. Pirazzoli [2005] concluded that in some cases the computations results exceed and forestall the estimations obtained by the field observations at the coasts, while in the other cases they lag them. The analysis made by Pirazzoli [2005] shows that the numerical methods cannot precisely reconstruct the course of transgression in the all areas of the World Ocean.

It is necessary to point out that this situation continues despite the significant enhancement of both the computation methods and glacial melt models. In the present work, the computations are applied primarily in order to estimate the tendencies rather than to compute accurate height values for the marine paleolevels.

From the results of the field works presented above, the estimation of the level of the Sea of Japan seems the most reliable. This has been determined from the borehole no. 132 with an age of 9.6 ka BP at the depths about –48…–49 m [Kuz'mina et al., 1987], providing evidence of the extremely low sea level at this pe-

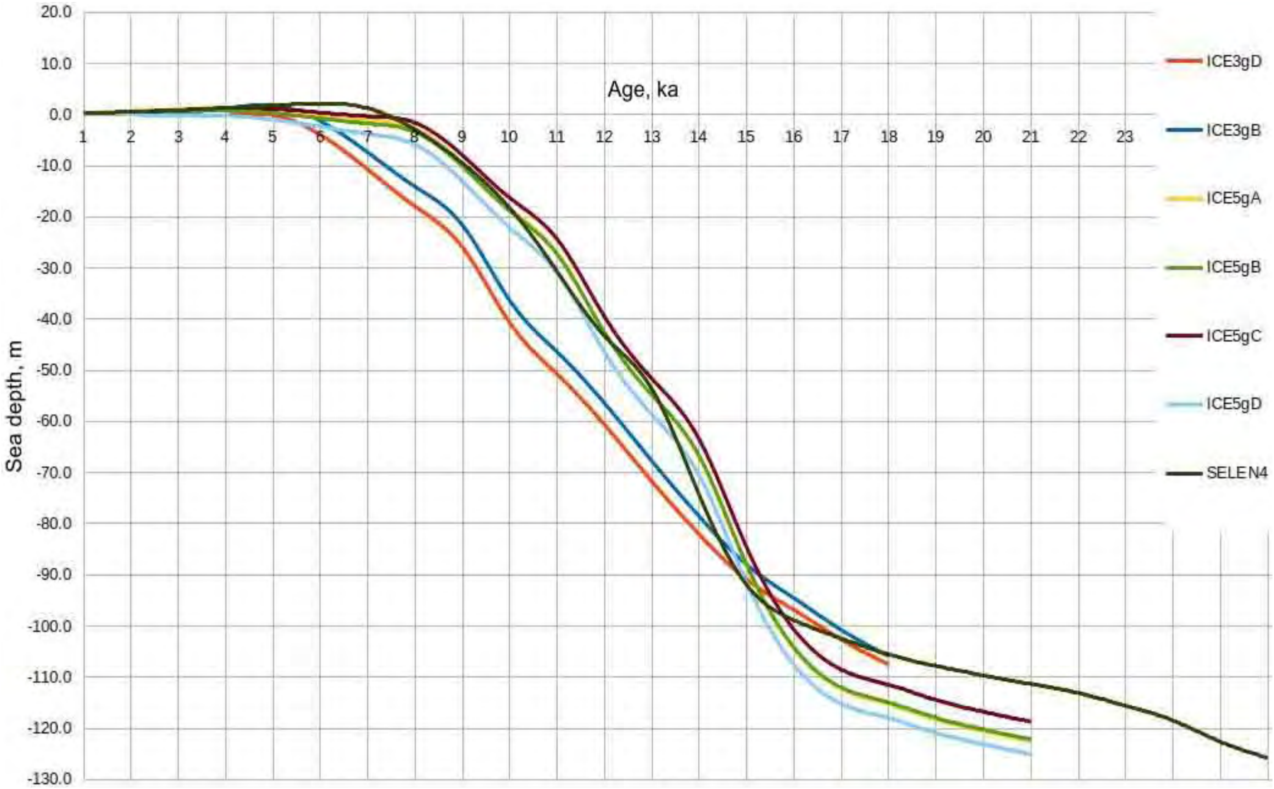

Figure 1. Postglacial transgression curves in the vicinity of Nakhodka.

riod. The assessment for chronologically subsequent position of the Sea of Japan level at depths of 20–25 m within the time interval of 7–8 ka BP [Kaplin, 1978] confirms the conclusion about the slowdown of transgression and expands the time interval in which this slowdown is marked.

A comparison of the value of the sea level of 9.6 ka BP (Fig. 1) with the sea level obtained by the results of no.132 borehole observation shows that the ICE3gD curve (the orange line), for which the sea level is about –37 m, is closest to these results. The same tendency – the closest proximity to the observed values – is clear for the time interval of 7–8 ka BP, when, according to observations, the sea level has been located at the 20–25 m depth, while on the ICE3gD curve, the depth is 10–19 m.

For the ICE3gD model, as shown in its designation, the ICE3g model of postglacial melting was used when perform computations. The equivalent curve of the sea level changes for this model is shown in Fig. 2. According to this curve, the total volume of the water that flowed into the ocean for 22 ka BP is equivalent to a sea level rise of 113.49 m, which is lower than the value of 127.11 m calculated for the same period for the corrected ICE5g model. The difference between these two models' curves is especially important for the time period from 6 to 22 ka BP. Rather than try to explain why this occurred, we will simply note that the transgression rate within the time period from 6 to 22 ka BP on the curve of ICE3g model is lower than on the successive ICE5g version.

Although, on the one hand, the transgression rate has decreased due to water influx in the Primorye area, on many coasts at this time a pulse of accelerated water influx from the glacial melting has been observed – MWP-1B [Lambeck et al., 2014]. Here it is necessary to consider that, since the Sea of Japan was not isolated from the World Ocean, no interruptions were observed in water mass flow into the Sea of Japan; therefore, these could not have affected the transgression course by the data of [Park et al., 2000; Pletnev, 2012].

On the other hand, the D type of viscous characteristic of the mantle layers has the highest viscosity values (see table), at which obtained calculated curves of the sea level change demonstrates the greatest transgression lag.

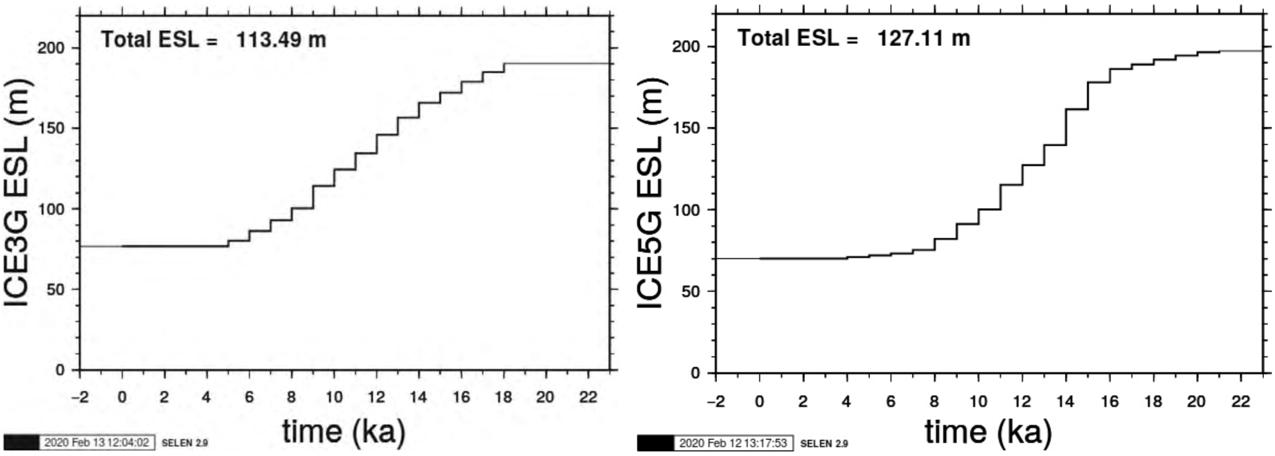

Figure 2. Equivalent sea level (ESL) curves for ICE3g (a) and for ICE5g (b).

When analysing the curves by the other computation models, a general trend can be distinguished: the higher the “viscosity” of the mantle layers of model, the slower the transgression and the lower the even-aged sea levels. This is typical for both glacial melting models.

On the models with low viscosity values, such as ICE5gC, the transgression rate is the highest and the Middle Holocene excesses are the most significant. We note that the greatest excesses in the middle of the Holocene were obtained on the SELEN 4 curve, which was carried out by the advanced IVE6g scenario of the glaciers melting and the mantle model with low viscosity values.

Concerning the Middle Holocene transgression, which coincides with the climatic optimum and is noted on many coasts of the World Ocean, it is necessary to pay attention to the fact that the climatic oscillations, which are registered everywhere both by biostratigraphic methods and by the change of oxygen isotopes ratio, are not considered in models of glacial melting (Fig. 2 a, b) [Kaplin, 1978]. That is, an additional volume of melting water from the glaciers is not necessary to explain the observed traces of excesses of the contemporary sea level during the Atlantic climatic optimum of the Holocene, since the lithospheric and mantle relaxation following hydroisostatic load is sufficient for this purpose [Lambeck et al., 2014].

If this mechanism explains the Middle Holocene excess of the contemporary level, then it will also be reasonable not to exclude such a contribution made by hydroisostatic relaxation in respect of additional oscillations of the sea level observed on the Primorye coasts, including the regression in the Subboreal (4 ka BP), the small-scale transgression in the Subatlantic (2–2.5 ka BP) and the transgression in the Subatlantic-2 (1–4 ka BP).

On Honshu Island, the even-aged level of the Middle Holocene excess of the sea level in the various points of the island changes from total absence to several metres higher than the contemporary sea level [Nakada et al., 1991], which could not be explained in terms of oscillating melt water. These results may be given in support of the idea about the leading role of vertical movements of the Earth’s crust in the result of hydroisostatic relaxation in the oscillations of the sea level following glacial melting.

We leave the question of whether the hydroisostatic load of the Sea of Japan basin with melt water from the glaciers of last sheet glaciation acted as an amplifier and accelerator of descending tectonic movements typical for the Primorye throughout the Cenozoic as a topic for a separate study, since it is beyond the scope of the present article.

Among viscosity models of A, B, C types borrowed from those applied for the Japanese Archipelago [Nakada et al., 1991], the highest Middle Holocene sea level excess was obtained when calculating for the models of C type with reduced viscosity, in which the contemporary level has been reached about 8 ka BP. Conversely, the models of D type with the highest viscosity values do not show the Middle Holocene sea level excess.

The most likely rheological characteristics of the mantle layers in the Primorye area are closer to the models of the A and B types. Here, although the transgression rate on the model of B type is not as high as that seen in C-type model, some increase relative to the contemporary level during the middle of Holocene is nevertheless noted. The curve obtained on the model of the A type is very similar to the curve of the B type; nevertheless, the lithosphere thickness of 50 km is closer to the data received using geophysical methods [Rodnikov et al., 2005]. The incomplete correspondence to the field observations is explained with an imperfection of the models of the course of glacial melting.

The peculiarities of sea level behaviour during the postglacial transgression obtained from the curves imply that the mantle layers in the Primorye area are more “viscous” in comparison with the area of Japanese Archipelago.

On the Echigo plain of Honshu Island at the eastern rim of the Sea of Japan, it was determined from core samples that the transgression accelerated within a time interval of 9.9–9.7 ka BP [Tanabe et al., 2010]. This is described as unique phenomena inherent only to this part of the coast of the Sea of Japan and did not occur in the other regions of the World Ocean. This acceleration is associated with coseismic tectonic submergences along the active fault, bounding the Echigo plain from the west. Here, the sea level after taking into account the contribution of seismotectonics is estimated at the level of –33.5 m for the age of 9.6 ka BP [Tanabe et al., 2010] (by comparison, in the Primorye it is just higher at between –48 and –49 m).

Taking into consideration that the simulation results approximate to the marks obtained by field observations for the Primorye region, but nevertheless are not identical with them, we may suppose, that coseismic tectonic submergences of the coast and shelf of the Primorye have contributed by analogy with Honshu Island. Although no active Holocene faults were revealed, the seismotectonic subsidences of the coast and shelf of the Primorye coast could occur along the “flexural-fault” zones [Antipov, 1987].

Conclusion

The results of the postglacial simulations in the Primorye area show that, under certain conditions, the course of postglacial transgression approximates to the marks of the Sea of Japan level registered by the field observations in the area of the Primorye coast.

The lag of postglacial transgression from eustasis in this area may be fully explained only by the presence of intermittent seismotectonic submergences of the shelf at the first half of the Holocene.

In comparison with viscous characteristics of the mantle layers of the Japanese Archipelago area, the effect of higher viscosity values of the mantle layers in the Primorye area seem to be more justified. The Japanese Archipelago is located directly above the contemporary subduction zone and is influenced with this process, while the interaction of plates affects the Primorye area to a significantly lesser extent.

Excesses of the contemporary sea level at the Atlantic optimum of the Holocene (about 5–6 ka BP) noted on the Primorye coasts may be explained by the reaction to hydroisostatic submergence of the coastline owing to a relatively rapid increase of the water load under which effect the common trend of descending movements has intensified on the shelf. Following the completion of glacial melt water influx, the descending trend has been interrupted and the shelf has returned to its balanced level due to viscoelastic properties of the mantle layers.

Coupled with an increase of the tendency of descending movements, the tectonic factors might make a significant contribution in the sea level oscillations following the attainment of the Middle Holocene maximum, i.e. the regression at the Subboreal about 4 ka BP and at the beginning of Subatlantic 2–2.5 ka BP. This raises the question about a special study on the contribution of climate fluctuations in the sea level oscillations following the Holocene climatic optimum, taking the completion of the Antarctica ice cap degradation at 4–6 ka BP into account.

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