Earth's Long-term Sea-level Change and Surface Heat Flux from a Theoretical Model of Mantle Convection with the Supercontinent Cycle

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1. Introduction

The longest-term (first-order) sea-level change is within ~200–300 million years (Myr), which is roughly half or less of the period of the supercontinent cycle of ~500–700 Myr. It is recognized that the assembly of supercontinents involves either the closure of the "interior ocean" that resulted from the breakup of the supercontinent or the closure of the "exterior ocean" that surrounded the supercontinent. The former process is termed "extroversion," while the latter is termed "introversion," that is an end-member scenario of the supercontinent cycle. A "combination" process is also proposed to explain the complex behavior of continental drift on the actual Earth.

In this study, a theoretical model of mantle convection with various supercontinent cycle processes was constructed, and the effects of the supercontinent cycle on the longest-term sea-level change and surface heat flux were addressed. The sea-level change is estimated from bathymetry over the oceanic plates under different free parameters that control the fluctuation of the sea-level change.

This report summarized the results of previous papers [1, 2]. For more details, please refer to these papers.

2. Theoretical model

Figure 1 shows a cartography of the supercontinent cycle with three processes: extroversion, introversion, and a combination of the two. The separated continental plates were assumed to move 90° along the Earth's surface arc. The elapsed time t was set at 0 Myr when the supercontinent started to break up. After supercontinental breakup, the separated continental plates move to the length of $\pi R_e(1-\Gamma)$ and aggregate to form a new supercontinent, where R_e is the Earth's radius and Γ is the area ratio of the supercontinent or the separated continents to the entire surface.

The velocity of the continental plates, V_{con}, is related to the time interval from the breakup of the previous supercontinent to the formation of the next supercontinent, Δt_{sc}. Here, Δt_{sc} was set to 400 Myr. When Γ is 0.4, V_{con}, is estimated as ~3.0 cm yr^{-1}. In the present study, it was assumed that the elapsed time starts at a_0 = 200 Ma (i.e., 200 million years ago), considering the Pangea breakup of Earth, and ends at −200 Ma (i.e., 200 million years after the present; here, the minus indicates the future) after the formation of the next supercontinent. It should be noted that the time interval from the breakup of the previous supercontinent to the formation of the next supercontinent is 1.5 times longer for the combined process than that for extroversion and introversion individually (i.e., $1.5\Delta t_{sc}$ = 600 Myr), assuming that V_{con}, in the combined process is the same as that of the other two processes.

In the present model, plate flattening was considered for oceanic plates. The velocity of the oceanic plate in the "exterior oceans" is a constant and fixed at V_{oce} = 7 cm yr^{-1}, but varied from 6 to 8 cm yr^{-1} for some models, to examine the differences in V_{oce} on the results. In contrast, the oceanic plate in the "interior oceans" was assumed to move with a constant velocity, V_{con}, considering that they do not subduct into the mantle, or move increasingly with time to a specified speed, because they start to subduct into the mantle. In this study, three scenarios were considered for the speed of movement of an oceanic plate in the interior oceans. In one case, it was assumed that the oceanic plate

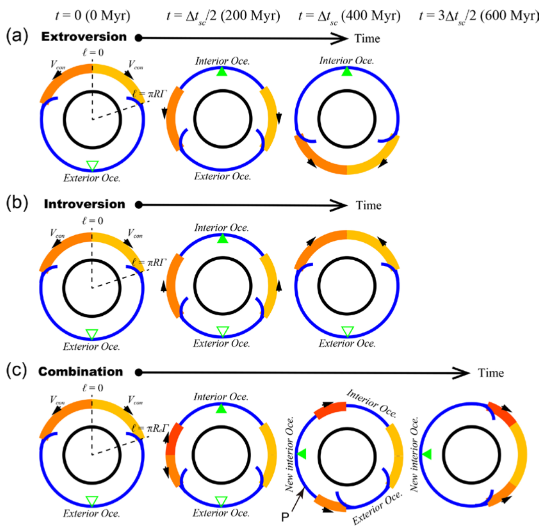

Figure 1. Cartoon of the present theoretical models with mantle convection with the supercontinent cycle. (a) extroversion, (b) introversion, and (c) combined processes. The thick orange and thin blue arcs indicate the continental and oceanic plates, respectively. Taken from Yoshida (2025) [2].

of the interior oceans did not subduct, even after a sufficiently long time and was temporally constant. Other cases assumed that these oceanic plates began to subduct and the speed increased linearly or gradually with time under an initial velocity of V_{con}.

3. Results

Figure 2 shows temporal changes in sea level and surface heat flux for each case study of the combination process. The observed sea level curves from 200 Ma were superimposed for comparison with those from the conceptual model (gray and black solid lines in each upper panel). The velocity of the oceanic plate in the exterior ocean was fixed at V_{oce} = 7 cm yr^{-1}. When the plate speed of the interior oceans (V_{in_oce}) was constant, sea level and surface heat flux decreased significantly during the last stage of the supercontinent cycle (arrows "P" in Fig. 2a), which largely depended on the age limit of plate flattening in the interior ocean ($t_{\max}$). This trend was significantly improved when V_{in_oce} increased linearly and gradually (arrows "Q" in Figs. 2b and c) and the sea level at the present time in the model was similar to current-day observations when V_{in_oce} increased gradually (arrows "R" in Fig. 2c).

Global sea levels have fluctuated throughout the history of the supercontinent cycle in response to changes in both the volume of ocean basins and the absolute volume of seawater. Here, the effect of water flux recycled into the mantle due to plate subduction on sea level change was considered. The result demonstrates that the present sea level was comparable to that at 200 Ma (arrows "S" in the upper panel of Fig. 2d).

Because surface heat flux is not related to absolute changes in water volume and sea level, surface heat flux shown in Fig. 2d is identical to that in Fig. 2c. Surface heat flux varied between approximately −5% and +30% during the supercontinental cycle (arrows "T" in Fig. 2c). The increase in surface heat flux and sea level from 0 Ma to about −200 Ma (200 million years into the future) were caused by new oceanic seafloors involved in the model of combined processes (Fig. 2c). Thus, the generation of new interior oceans due to the continental breakup leads to the increase in bathymetry, and hence, an elevated sea level, and an increase in surface heat flux during this period.

4. Future directions

The present analytical results suggest that in the combination process, asymptotic bathymetry due to the plate flattening effect of oceanic plates in the exterior and interior oceans is important to recover the realistic magnitude of sea-level fluctuations that is comparable to the sea-level curve of the past Earth.

Despite recent advances in numerical simulation studies of 3-D spherical mantle convection, some difficulties remain in the implementation of plate tectonics and continental drift, not only because of numerical resolution limitations, but also because of insufficient knowledge of mantle rheology. In the future, by using numerical simulation models that allow for realistic continental drift [e.g., 3] and plate subduction [e.g., 4], it will be necessary to test whether the results obtained in this study can also be confirmed for mantle convection with a strong time dependence, and to investigate in more detail the effects of supercontinent cycles on the long-term sea-level change and surface heat flow.

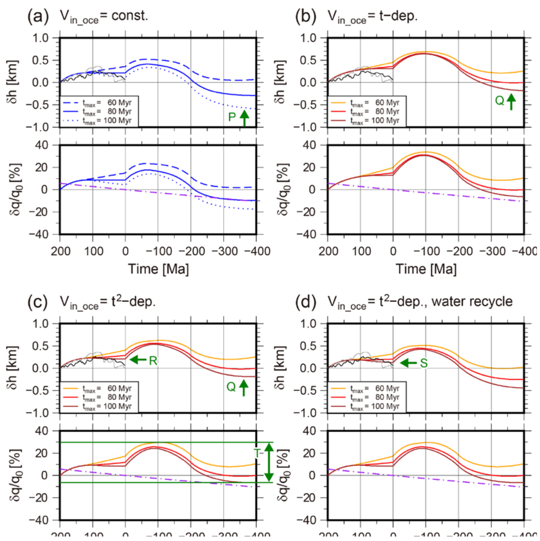

Figure 2. Relative sea-level changes (upper panels) and surface heat flux (lower panels) in the various scenarios of the combination process predicted from the present conceptual model. (a) The velocity of oceanic plates in the interior oceans, V_{in_oce}, was temporally constant. (b-d) V_{in_oce} was (b) linearly and (c and d) gradually time-dependent. (d) The absolute decrease of seawater was considered, and the fraction of volume decrease of seawater was fixed at 3%. The change in the surface heat flux due to Earth's secular cooling predicted from the parameterized convection theory is shown by the purple chained lines in each lower panel. Taken from Yoshida (2025) [2].

Acknowledgement

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