Ocean-atmosphere dynamics in the Greenhouse world; Paleo perspectives

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Abstract

Understanding the dynamics of Earth's climate system during the extremely warm "greenhouse" period has been proposed as one of the major targets of the initial phase of the IODP. One of the most intriguing greenhouse periods is the mid-Cretaceous. During the past decades, intensive investigations of geological records obtained by ocean drilling have revealed the principle nature of the mid-Cretaceous greenhouse world; formations of large igneous provinces (LIPs), high production rate of oceanic crust, geomagnetic superchron, repeated occurrence of global oceanic anoxic events (OAEs), and low latitudinal gradient of sea surface temperature (SST). The importance of these unique features of mid-Cretaceous time has been addressed in the IODP's previous scientific plans. Key questions include: is there causal linkage between LIP formation and OAEs? What was the driving force to keep the high meridional heat transport, which resulted in the low latitudinal temperature gradient? However, detailed processes and causal mechanisms of these marked events have still been unanswered.

Most of paleoceanographic data have been obtained from the Atlantic Ocean, while little has been known about the Pacific Ocean. Drilling of mid-Cretaceous sequence from the Pacific would provide important knowledge for understanding ocean-atmosphere dynamics in the greenhouse world. Pacific Ocean should have played a major role on deep water formation and global seawater circulation. Therefore, in the next phase of the IODP, we aim to clarify the detailed processes and causal mechanisms of the environmental change in the Pacific at the interval of marked climatic transitions of the Cretaceous period on various time scales.

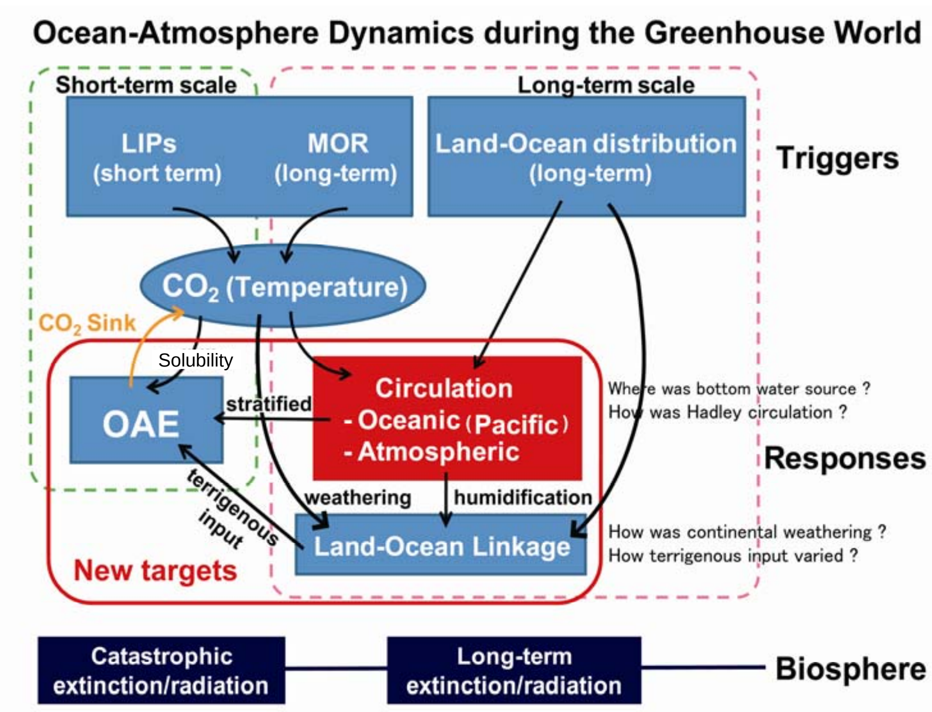

Fig. 1. Conceptual diagram of the relationships between forcing (triggers) and responses of ocean-atmosphere system with responses of biosphere in the greenhouse world.

1. Introduction

To understand the nature of Earth systems in the greenhouse world, here we summarize major achievements of previous studies, propose high-priority scientific objectives and relevant hypotheses that we think important to build our science. Then we discuss, from the viewpoint of "Forcing vs. Response" (**Fig. 1**), the importance of ocean drilling to reconstruct whole picture of the greenhouse Earth.

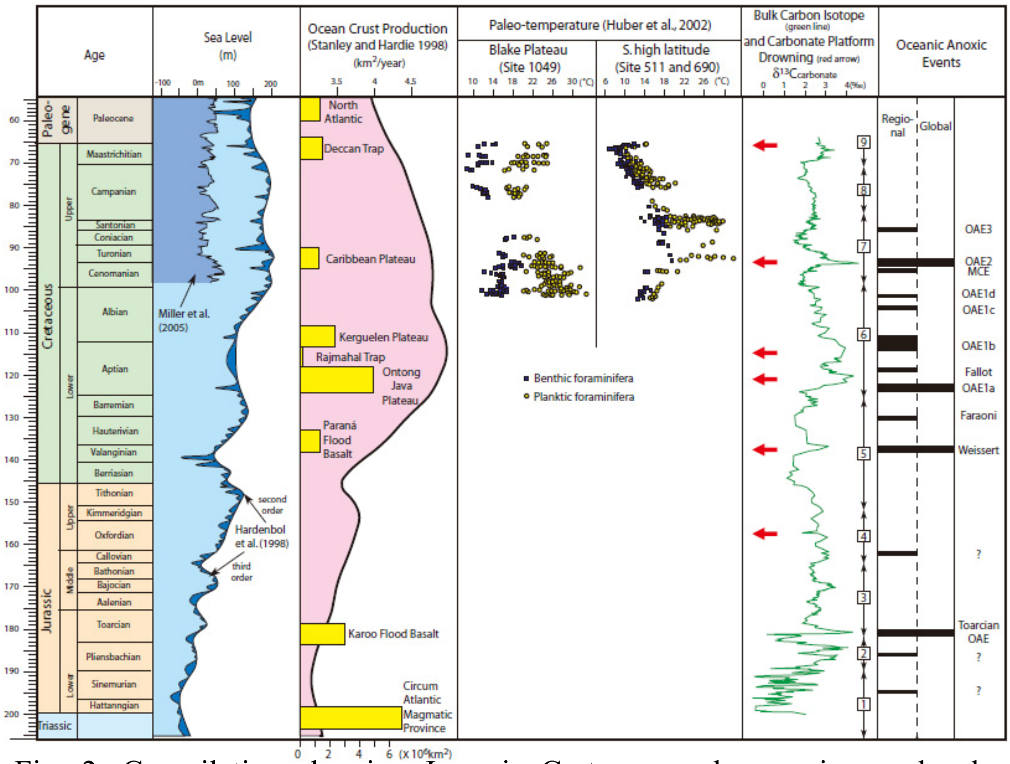

Fig. 2. Compilation showing Jurassic–Cretaceous changes in sea level, oceanic-crust production, LIP formation, SST, bulk carbonate $\delta^{13}C$ record, carbonate platform drowning events and OAEs (**Ref. 13**).

2. Research target: Forcing

2-1. Large Igneous Provinces (short-term). Emplacements of Large Igneous Provinces (LIPs)[1] are associated with high stand sea level characterize the mid-Cretaceous time (**Fig. 2**). Because the LIP volume exceeds 10^6 km^3 and is characterized by unexpectedly high magma flux, there is no analogous expression of these LIPs during the historical past. Emplacement of LIPs could have induced environmental change and biotic evolution by releasing trace metals (e.g., Fe) and volatiles (e.g., CO_2 and SO_2); the former may have stimulated primary productivity, whereas the latter may have induced global warming and ocean acidification. The elevated atmospheric pCO_2 could have accelerated chemical weathering of the continental crust. Nature of eruptions such as explosibility (explosive vs. quiescent), water depth (deep submarine vs. subaerial) and volatile contents may be crucial for its impact on global environments. In some LIPs such as Ontong Java Plateau (OJP), knowledge of these parameters has been increasing. Further drilling into these LIPs during the IODP Phase II will surely improve our understanding of these parameters (**Fig.3**).

Fig. 3. Schematic images of the LIP-OAE linkage (**Ref. 11**).

2-2. Mid-Ocean Ridge activity (long-term). Cretaceous time is characterized by high magma production rate at the mid ocean ridge (MOR) that resulted in elevation of pCO_2 levels, which could have contributed to SST change and have great impact on the oceanic and atmospheric circulation system. Higher MOR activity also resulted in the consequent global sea-level rise. These effects would have impacted on long-term variation (10^7 years) of atmosphere-ocean system.

2-3. Change in land-ocean distribution (long-term). Continental and oceanic arrangement had been significantly varied through the long interval (144–65 Ma) of the Cretaceous. Because South American and African continents were separated at the mid-Cretaceous, Equatorial Atlantic gateway had prevented the intermediate water connection between the north and south Atlantic until the Cenomanian (~90 Ma)[2]. Before the opening of the Equatorial Atlantic gateway, the Pacific was the exclusive and largest ocean on the Earth. The global oceanic circulation system must have been largely affected by the changes in the land-ocean distributions. Furthermore, due to the higher global sea-level, broad area of the epicontinental seaways and shallow water existed during the Cretaceous. It may also have affected the continental weathering rates and input of terrigenous nutrient to the ocean and thus primary productivity of the oceans.

3. Research target: Responses

3-1. Oceanic circulation. Numerical climate modeling predicts that southern high latitude in the Pacific Ocean is assumed to be a site for deep water formation site in the Cretaceous greenhouse period[3-4]. Some model experiments also predict that the sites of deep water formation switch to the northern Pacific high latitude with decreasing pCO_2. It suggests that pCO_2 decrease, hence cooling, in the several interval of the Cretaceous period could involve considerable changes in the global ocean circulation, both in shorter and longer time-scales[4]. Currently little proxy data are available for determining the inter-ocean mixing of deep-water masses during the Cretaceous, and thus uncertainty remains as to the importance of deep-water circulation in latitudinal heat transport and bottom-water oxygenation for that time. A solution potentially lies in exploiting geochemical water-mass tracers, such as Nd isotopic composition of seawater.

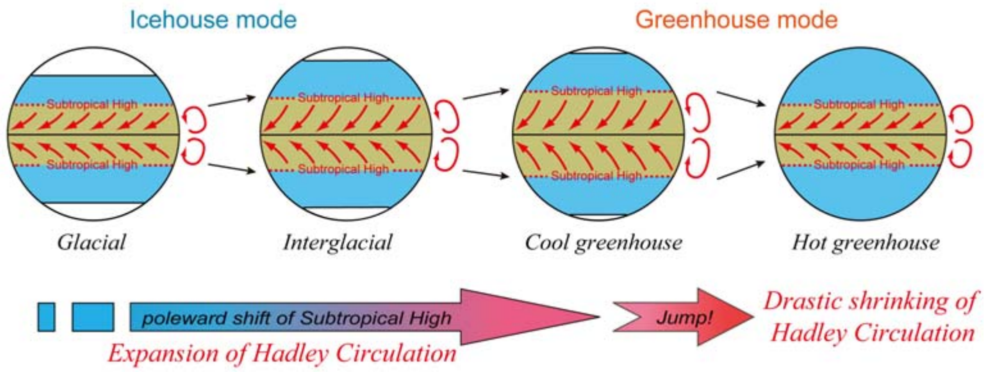

Fig. 4. Evolutionary trends of the changing atmospheric circulation pattern in response to climatic warming (from icehouse to greenhouse) (**Hasegawa et al., in review**).

3-2. Atmospheric circulation. Hasegawa et al. (submitted) reconstructed temporal changes in latitude of the subtropical high-pressure belt and its divergence axis during the Cretaceous. They found a poleward shift in the subtropical high-pressure belt during the early and late Cretaceous periods, indicating a poleward expansion of the Hadley circulation. In contrast, a rapid equatorward shift of the belt was found during the mid-Cretaceous extremely warm period, suggesting drastic shrinking of the Hadley circulation. On the basis of these geological evidences, they proposed a threshold in atmospheric CO_2 level or temperature beyond which the Hadley circulation shrinks drastically (**Fig. 4**). For assessing the drastic shrinking hypothesis of Hadley circulation during the extreme warm periods (e.g., mid-Cretaceous and Paleocene/Eocene Thermal Maximum: PETM), it is essential to reconstruct of the paleo-location of the subtropical high-pressure belt from the marine sedimentary records. For more details, see a white paper by H. Hasegawa & R. Tada.

3-3. Oceanic Anoxic Event. Mid-Cretaceous is characterized by a repeated occurrence of quasi-global deposition of organic-rich sediments (black shale) that is referred to as the Oceanic Anoxic Events (OAEs, **Fig. 2**)[5-7]. During the anoxic events, rapid and extreme warming and subsequent rapid cooling have been suggested by geochemical proxies[8]. Thus, an OAE is considered to be undertaken as a role of the thermostat in the greenhouse world through eliminating the carbon from atmosphere (i.e., CO_2) into the carbonaceous sediment as black shale[9] (**Fig.1**). Forcing of this climate transition is ascribed to massive eruption of LIPs and associated CO_2 input into the atmosphere[10-11]. Although the possible relationships between LIPs activities and OAEs have been described in the IODP Initial Science Plan, detailed processes and causal mechanisms of these marked events have still been controversial (**Fig. 3**). In the next phase of IODP, more detail reconstructions of the spatial and vertical profiles of the lithologic components of the oceanic sediments, seawater chemistry, bioproductivity, sea surface ecology, and deep circulation system are essential. Details are given in white papers by R. Takashima & H. Nishi, and J. Kuroda & N. Ohkouchi.

3-4. Evolution of seawater chemistry. Secular changes in global climate could be an ultimate manifestation of changes in elemental distribution on Earth. A number of processes are involved in controlling elemental distribution among atmosphere, hydrosphere, ocean, biosphere, and sediments. When considering distribution coefficient of a given element between seawater and sediments, pH and Eh of seawater should have been major parameters in most cases, since they control the transfer between dissolved and particulate phases for many elements in the ocean. One of the typical examples is redox change across the Cretaceous OAEs. Since each OAE continues as long as 1 Myr, chemistry of seawater, especially for relative abundances of redox-sensitive transition elements could have varied significantly during these periods. For example, organic-rich black shales deposited during the OAEs have elemental composition far different from normal deep-sea sediments, i.e., Fe, Mo, Cu, V and Zn are heavily concentrated in black shale. Thus the global deposition of black shales across the OAEs could have significantly changed the seawater chemistry. Such changes in chemical composition of seawater would have affected evolution speed or direction of marine biota. Some elements such as Fe, Mo, Cu, V, and Zn are both biologically essential elements and concentrated in black shales deposited during OAEs. Therefore, they are potentially key elements for connecting between seawater chemistry and marine biotic evolution.

3-5. Biotic response. Recent climate models predict that rapid increase of pCO_2 will cause acidification of sea surface water that could significantly affect marine ecosystems. The model predicts that ocean may absorb increasing amounts of fossil fuel CO_2 in the future, with the pH of surface waters decreasing by 0.5. The PETM has been suggested as an analogue for future climate change and ocean acidification[12] as the rate of carbon release is thought to be comparable to that of today. The Cretaceous ocean is characterized by the coincidence of sudden drowning of shallow-water carbonate platforms, negative carbon isotopic excursions, and the crisis of heavily calcified plankton groups in the pelagic sea (i.e., "Biocalcification crises")[9,13] (**Fig. 2**). The Biocalcification crises occurred 5 times during Cretaceous; the three of them coincided with OAEs and it is thought to be evidence of oceanic acidification, but the rest two are not accompanied by the major climatic turnover. Thus reconstruction of the changes in seawater chemistry and alkalinity at such interval might provide us important clue to understand the causal mechanism of ocean acidification and resulted impacts to marine ecosystems in the greenhouse world. Details are given in R. Takashima and H. Nishi.

Modern biological data based on controlled cultivation may also provide new insight into the biotic response to the climatic turnover such as OAEs. Changes in nutrient availability and upper water column structure across the OAEs would have caused the planktonic turnover[14]. For instance, largest and most heavily calcified plaktonic foraminifera were seriously affected by the ocean-climate changes associated with OAE-1b. On the other hand, the deep-dwelling planktonic foraminifers were eradicated during OAE-2 which was likely caused by an expanded oxygen minimum zone. Collaboration of ocean drilling science with biological cultivation (e.g., planktic foraminifers) becomes more important to understand biological responses against environmental changes such as temperature, food availability, and light intensity[15]. Experimental examination of biological responses of plankton to changes in dissolved oxygen, reflecting calcification under low DO level, would be one of the key targets to obtain a clue to understand paleoenvironments during the mid-Cretaceous world.

3-6. Development of ice-sheet. A long running debate in climatic transition concerns a timing of initial polar ice-sheet development after the greenhouse condition. Sedimentological evidences, such as ice-rafted debris and clay mineral composition, and physicochemical proxies like oxygen isotopes and Mg/Ca ratios of foraminifer shells indicate that a massive ice-sheet was first developed around the Eocene/Oligocene boundary (33.5 Ma). However, some studies questioned this view, arguing for earlier and/or larger polar ice sheets, and even bipolar glaciation in the Eocene. The Cretaceous greenhouse has now been not an exception of this heated dispute. Although some researchers indicate little possibility for a polar ice-sheet[16], multi-proxy analyses for temperature and oxygen isotopic composition of the mid-Cretaceous ocean imply that at least a short-lived ice-sheet had been developed in the greenhouse world[17]. Although these proxy records indicate a possible ice-sheet development in the mid-Cretaceous greenhouse period, timing and magnitude of the glaciations, and relationship between sea-level fluctuation and proxy record have still been unclear. If massive ice-sheet had been developed in the greenhouse period, signals of the glaciation, such as sea-level fluctuation, isotopic shift of marine water, etc., must be recorded in sediments deposited all over the world. However those putative glaciation signals are recovered only from the Atlantic regions so far. Therefore, analyses in the Pacific continental margin are key to understanding the glaciation in the greenhouse world.

3-7. Ore deposits as proxy of redox condition and hydrothermal activity. Origin of ore deposits have been analyzed in a few hydrothermal ore deposit during the DSDP/ODP (e.g. Juan de Fuca Ridge). Non-hydrothermal sedimentary deposit is out of scheme in the previous DSDP/ODP programs except some evaporites. But, in addition to common paleontological and geochemical studies for sediments, metallogeny and spatiotemporal distribution of sedimentary and hydrothermal ore deposits are important to understand comprehensive sedimentary environments. For example, shallow marine Mn deposits develop at the oxic-anoxic interface of a stratified basin. In addition to direct studies for anoxic sediments, spatial distribution of shallow marine Mn deposits surrounding anoxic basins could be a key to understand the degree of anoxic condition and vertical distribution of the oxygen minimum zone during the OAEs.

3-8. Methane hydrate explosion and its impact on climatic change. Release of huge amount of methane is hazardous to the global system. Seawater becomes anoxic after a massive dissociation of gas hydrates because of increased amount of methane that is strongly reductive, and may cause mass extinctions. There are some lines of evidence for catastrophic climate changes due to the gas hydrate dissociations. For example, a 1.1×10^{18} g of methane was releasing due to hydrate dissociation at PETM[18], resulting in a significant global warming and ocean acidification. More detailed assessments during the next IODP phase are required to reconstruct the history of hydrate dissociation and its linkage with climatic changes, particularly addressing how these hydrocarbons have been released, what was the trigger of hydrate dissociations (e.g., change in intermediate water temperature), and how these dissociations affected global changes in SST, pH of seawater and sea levels. Details are given in a white paper by H. Tomaru.

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