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Impact of Panamanian Gateway Opening on the Global Ocean Circulation

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ABSTRACT

It is believed that Panamanian isthmus was opened during the early to middle Miocene, and the Pacific and the Atlantic Oceans were connected via Panamanian Gateway. Several papers using proxy data suggested that oceanic circulation and climate system in that period had been significantly different from the present state. Numerical studies, which used oceanic general circulation model (OGCM), also proposed various views concerning oceanic circulation patterns in that period. In this study, numerical results from an ocean-atmosphere coupled general circulation model are analyzed to investigate paleoceanic circulation during Miocene. We focused on the effects of the Panamanian gateway to create paleoceanic steady state and oceanic conveyor belt during Miocene. The results show that water transport from the North Atlantic to the North Pacific Oceans through the Panamanian Gateway was important in maintaining the ocean circulation and the climate state in the past.

Keywords: Oceanic conveyer belt, Coupled GCM, Panamanian gateway, Miocene

INTRODUCTION

The earth experienced three major tectonic events during Miocene and Pliocene, i.e., disconnection between the Tethys and the Indian Ocean, opening of the Drake Passage and emergence of the Panamanian isthmus. Opening or closing of such oceanic gateways had large impacts on oceanic circulation, climate system, and ecological system on the earth. In particular, closing of the Panamanian gateway was the most recent tectonic event, and resultant oceanic and climatic environmental changes are crucial to discuss extinction or evolution of flora and fauna leading to the present.

Paleoceanographic studies related to Miocene were mainly developed by various proxy data during the early stage of research. For example, several studies [1–4] discussed deep water properties and its circulation pattern in Miocene. Other studies [5–7], in particular, focused on evolution and closure of the Panamanian gateway and related oceanic circulation or environmental change in the region surrounding the Panamanian Gateway. As for impact on meridional overturning circulation (MOC) of the world ocean, it is suggested that the closure of the Panamanian gateway intensified the Gulf Stream and deep water formation in the North Atlantic Ocean by analysis of stable isotope and carbonate data [7]. Although implications from these studies are limited to specific regions, they provide a large body of significant paleoceanographic information on effects of the Panamanian gateway closure.

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Since the last decade, numerical studies also began to provide paleoceanographic insight from physical oceanographic or climatic viewpoint. Based on the Hamburg ocean model with present atmospheric boundary conditions, it has been suggested that the opening of the Panamanian gateway collapsed the formation of North Atlantic Deep Water (NADW) due to intrusion of low salinity water from the Pacific Ocean through the gateway [8, 9]. Another study [10], which also used the Hamburg ocean model with atmospheric energy balance model, obtained essentially the same results. In addition, the results [10] also showed that modest levels of the Panamanian through flow could maintain NADW formation. Similar experiments [11] also showed collapse of NADW formation by opening of the gateway. However, experimental results [12], employing Massachusetts Institute of Technology (MIT) ocean model, proposed that the Panamanian gateway opening did not collapse NADW formation, but reduced it slightly. The resultant oceanic circulation, however, had been quite different from the present one; Pacific shallow waters intruded the Atlantic Ocean through the gateway, while NADW passed through the gateway in opposite direction and joined Antarctic Circumpolar Current (ACC) via western boundary of the Southern Pacific Ocean. The contradicting results of the previous studies indicate the necessity of improved numerical models. Given the fact that the previous numerical models have general circulation models for ocean component but not for the atmosphere, the use of atmosphere-land-ocean coupled models for the influence of the Panamanian gateway should be considered. So far, only one recent numerical study [13] used an Atmosphere-Land-Ocean coupled model to address the Panamanian gateway. In this model, the opened gateway led to the collapse of NADW formation in the same way as proposed by the numerical studies made earlier. In addition, the meridional overturning in the Pacific Ocean exhibited interesting enhancement. The region where the deep water formation occurred in the Northern Hemisphere switched from the North Atlantic to the North Pacific by the Panamanian gateway opening [13].

In this study, paleoceanic circulation has been investigated by analyzing available numerical data [13] with focus on the conveyor belt, which transports heat and salt poleward and exerts strong influence on the formation of stratification in the ocean. Only the coupled model [13] includes land effects and atmospheric circulation explicitly.

NUMERICAL MODELING, DATA AND RESULTS

Numerical Data

We use numerical data given in Ref. [13], in which a coupled ocean-atmosphere-land surface model [14] developed at Geophysical Fluid Dynamics Laboratory (GFDL) is used. Physical processes of the model were described in detail in [13] and [14].

The atmospheric component of the model has 9 levels in the vertical direction, which is expressed by the spectral element method. Horizontal resolution of the atmospheric component is approximately 4 degree in the meridional direction and 8 degree in the zonal direction. The oceanic component of the model has 12 layers in the vertical direction, and its horizontal resolution is about 4×4 degree. The model topography is shown in Figure 1.

To obtain an equilibrium state of the ocean, integration was carried out for 10 thousand years with realistic topography. Then, additional integrations for 5 thousand years with two options were carried out: one with the opening of the Panamanian Gateway, and the other without opening (control run). The geographic difference between the two runs is shown in Fig. 1.

Equilibrium State of the Ocean

Let us compare oceanic steady state of the control run and that of the Panamanian gateway opening (hereafter PG) run. The most notable feature of the PG run is the collapse of NADW formation in the northern part of the North Atlantic [13]. Figure 2 shows histograms of the North Atlantic temperature and salinity. As discussed in [13], salinity of the North Atlantic decreased (Fig. 2) due to intrusion of fresh water from the Pacific Ocean through the gateway. This diluted surface water collapsed NADW formation in the northern part of the North Atlantic. In the control run, the MOC cell in the North Atlantic transports huge amount of heat poleward. Hence, the collapse of the MOC cell with the opened gateway lowers temperature in the North Atlantic (Fig. 2). It should be noted that larger masses for lower temperatures in the PG run are also due to the collapse of MOC cell. The South Atlantic (not shown) also experiences decrease in its temperature and salinity in the same way as the North Atlantic.

The histograms of temperature and salinity for the North Pacific, the Arctic Sea and the Southern Oceans are presented in Fig. 3. In the North Pacific

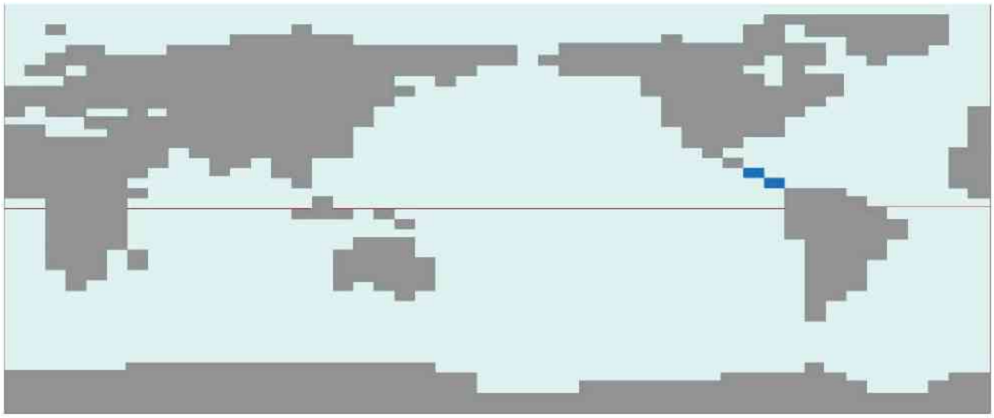

Fig. 1 Model topography [13]. Realistic topography is employed in the control run. After the opening of the Panamanian Gateway, the blue grid boxes are set to be ocean. The depth of the gateway is set to be approximately 2.5 km.

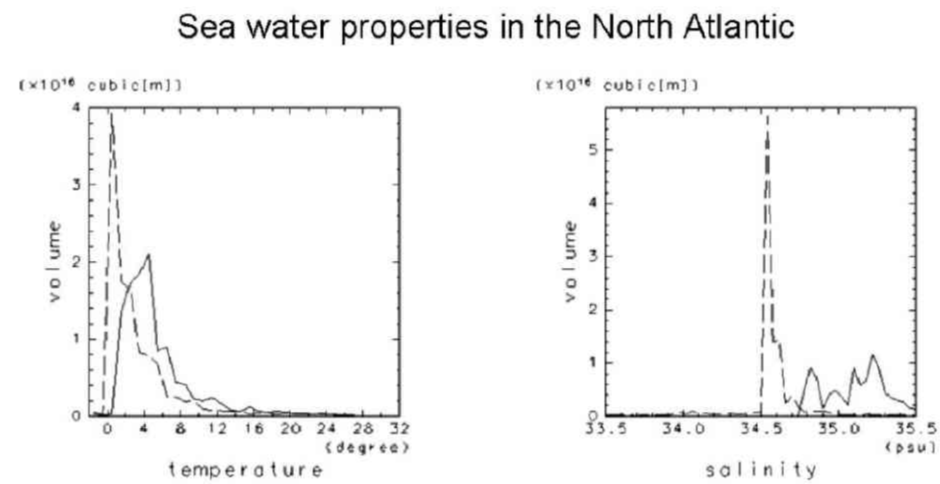

Fig. 2 Histograms of temperature (left) and salinity (right) in the North Atlantic. In both diagrams, solid and dashed lines depict control run with the closed Panamanian Gateway and another run with the opened gateway (PG run), respectively.

(Fig. 3a, b), maximum volume of water at 0.5°C decreases in the PG run compared with the control run. This is owing to switching of deep water formation region in the Northern Hemisphere, and the enhanced MOC cell in the North Pacific in the PG run [13]. Salinity difference between the two cases is relatively small. The oceanic environment in the Arctic Sea is significantly different between the two runs (Fig. 3c, d). In the PG run, collapse of the MOC cell in the North Atlantic shut off the supply of warm and saline water from the Atlantic Ocean to the Arctic Sea.

As a result, the steady state of the Arctic Sea in the PG run corresponds to low temperature and low salinity, which enhance sea-ice growth and climate cooling in the Arctic region. Seawater properties in high latitude of the Southern Hemisphere are almost the same between the two runs. (Fig. 3e, f) This implies that the environmental change by opening or closure of the Panamanian Gateway is relatively small in the Southern Oceans.

Volume Flux Between Oceans

To investigate the density weighted volume budget for each ocean, we calculate volume transport as a function of density at several sections shown in Figure 4. The volume transport across the equator of the Atlantic Ocean and the Pacific Ocean (corresponding to lines 5 and 4 in Fig. 4) is shown in Fig. 5. In the control run, the southward deep flow and the northward shallow flow are evident across the equator in the Atlantic Ocean, and correspond to southward flowing NADW and compensating northward flow. In the PG run, however, no

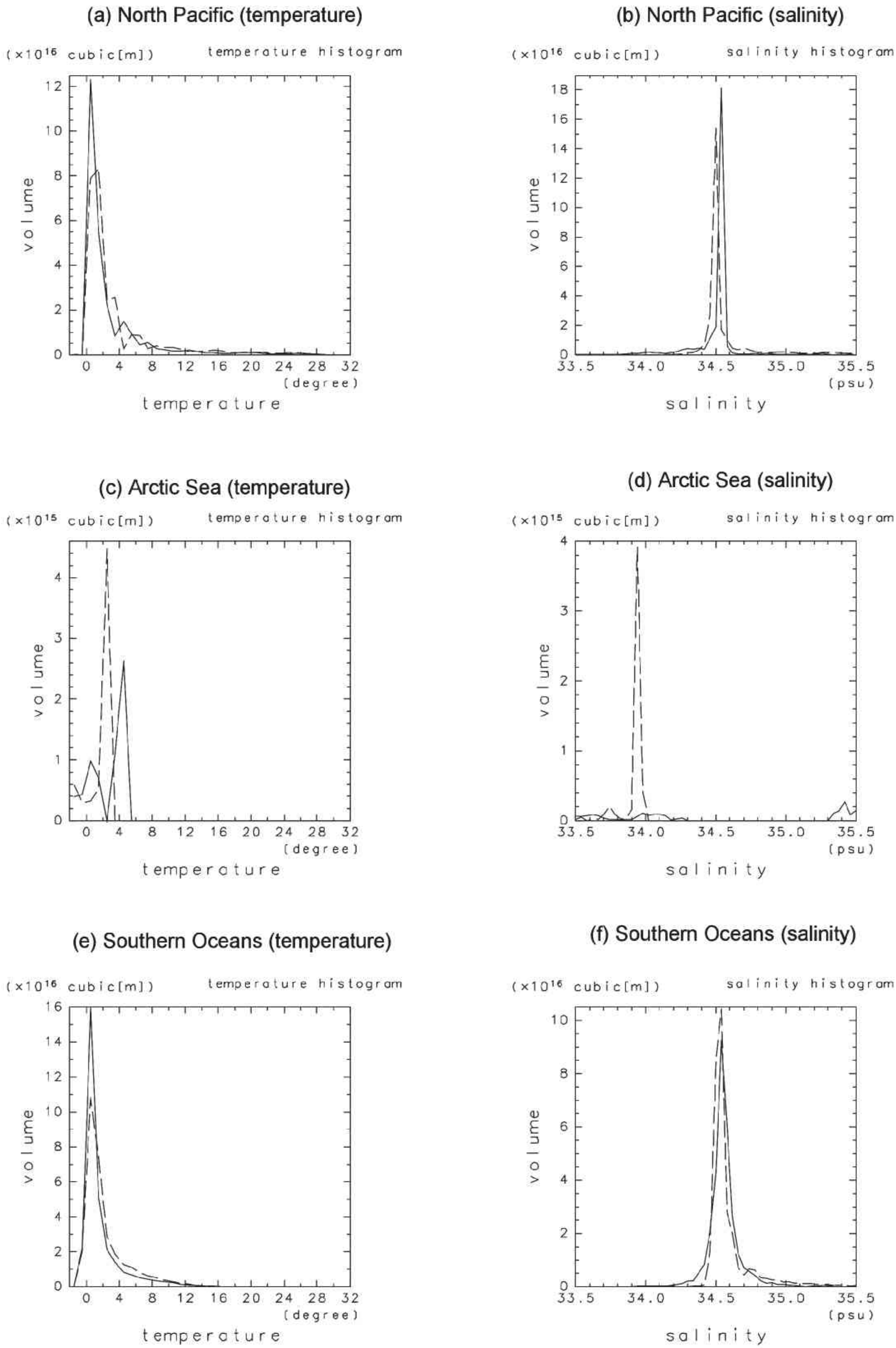

Fig. 3 Histograms of temperature (left) and salinity (right) for North Pacific (top), the Arctic Sea (middle) and the Southern Oceans (bottom), respectively. Solid and dashed lines in each panel depict control and PG runs, respectively.

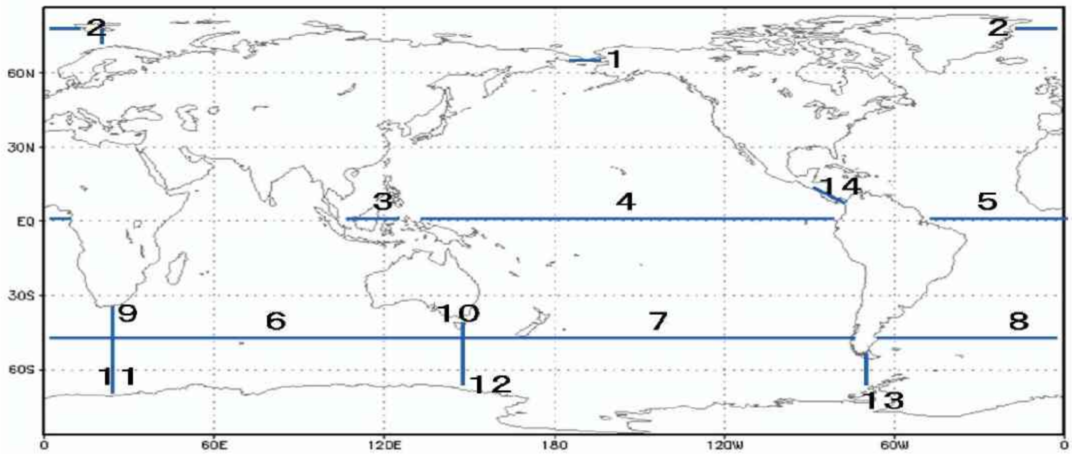

Fig. 4 Inter-ocean sections where density weighted volume transport is calculated. 1. Bering Strait, 2. Fram strait, 3. Indonesian Strait, 4. Equatorial Pacific, 5. Equatorial Atlantic, 6. Southern Indian Ocean, 7. Southern Pacific, 8. Southern Atlantic, 9. South of Africa, 10. South of Australia, 11. ACC south of Africa, 12. ACC south of Australia, 13. Drake Passage, 14. Panamanian Gateway.

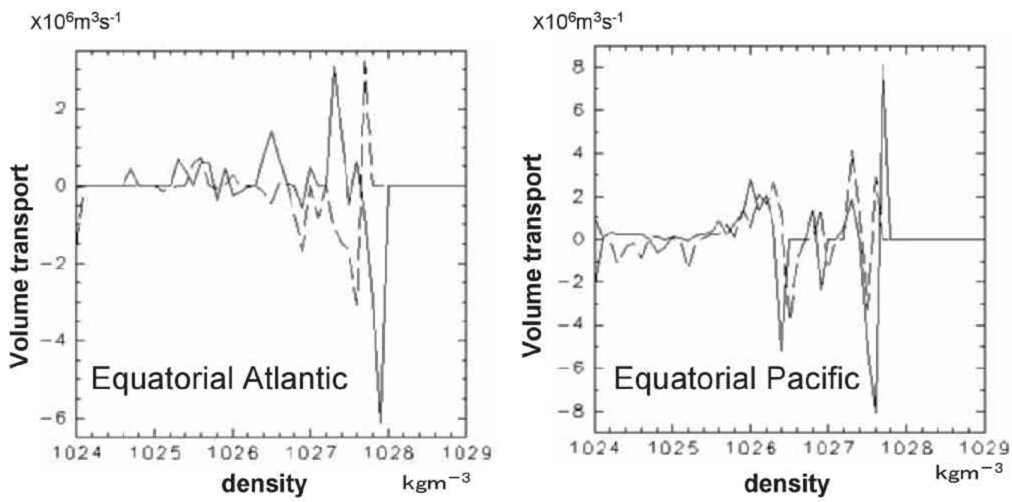

Fig. 5 Density weighted volume transport across the equator. Left: transport across the equator in the Atlantic Ocean (line 5 in Fig. 4); right: transport across the equator in the Pacific Ocean (line 4 in Fig. 4). Solid and dashed lines in each diagram depict the control and PG runs, respectively. Positive and negative values indicate transport northward and southward, respectively.

evidence for NADW, i.e., deep water transport in the Atlantic Ocean, is found.

For the equatorial Pacific Ocean, the transport pattern of the PG run is similar to that of the control run. No deep water formation occurred in the Pacific Ocean in both runs. In the Pacific Ocean, northward deep water transport in the PG run is small relative to the control run because of the enhanced Pacific MOC in the PG run [13].

Volume fluxes across the various gateways are shown in Fig. 6. Transport across the Bering Strait is limited in this model, as the meridional velocity is set to zero just north of the strait and only the diffusive process can exchange water masses between the Pacific Ocean and the Arctic Sea.

Hence, the enhanced Pacific MOC cell cannot compensate reduced flux through the Fram Strait and leads to the cooling of the Arctic region. In addition, we can see the evidence of no NADW formation in the PG run in the Southern Hemisphere. Zonal transport across the Drake Passage shows mass concentration around 1027.6 kg m^{-3} in the PG run. As shown in Fig. 5, the density of the North Pacific deep water in the PG run is not as heavy as

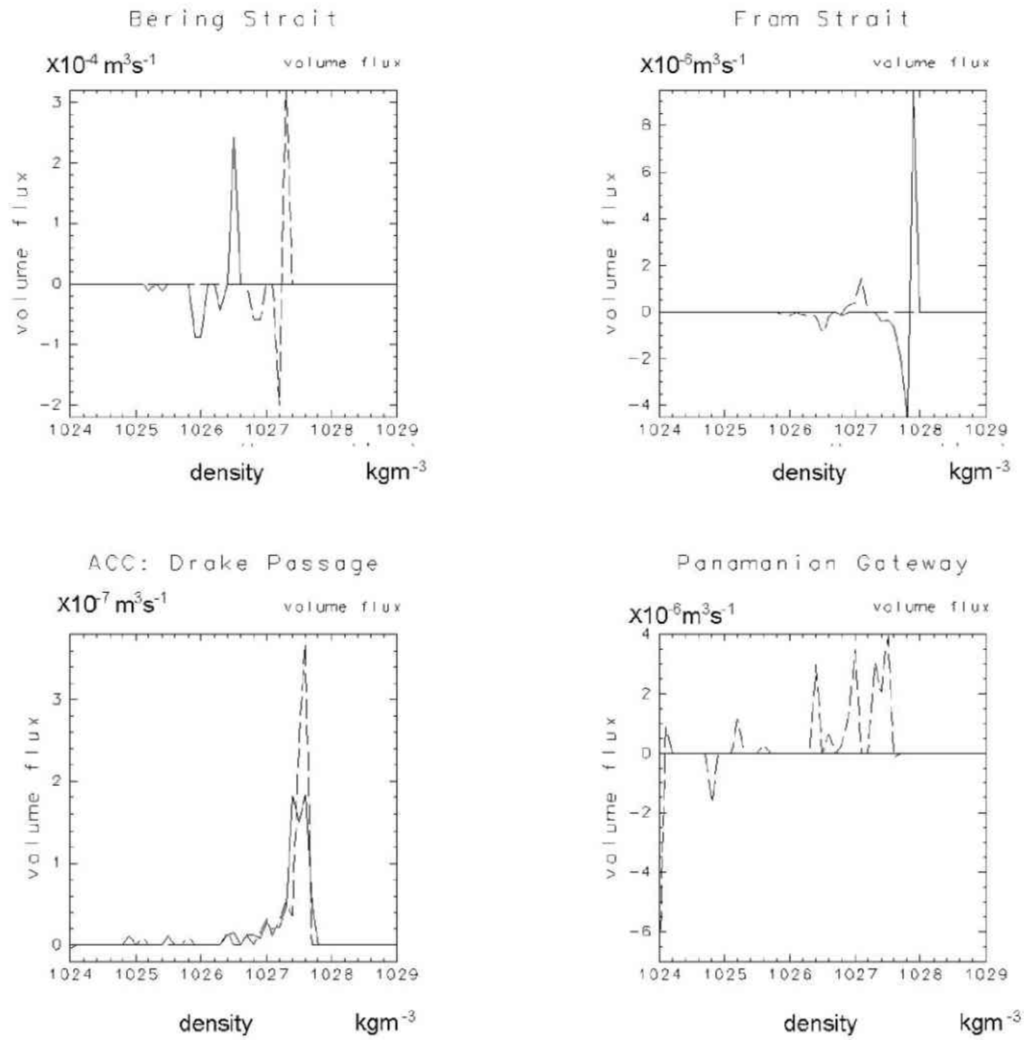

Fig. 6 Density weighted volume transport across the Bering Strait (Fig. 4 section 1), the Fram Strait (Fig. 4 section 2), the Drake Passage (Fig. 4 section 13) and the Panamanian Gateway (Fig. 4 section 14). Solid and dashed lines in each diagram depict the control and PG runs, respectively. Positive value in each figure indicates northward flow except for the Panamanian Gateway. For the Panamanian Gateway, positive value indicates north and eastward flow (flow from the North Pacific to the North Atlantic). Note that the unit of the volume flux is different in each diagram.

that of NADW in the control run. Hence the deep water originated from the Northern Hemisphere does not occupy the lower component of ACC. It should be noted that the flow through the Panamanian Gateway is unidirectional in the lower layer and its volume transports is larger than that across the equator in the Atlantic Ocean. Integrated volume flux through the Panamanian Gateway is from the North Pacific Ocean to the North Atlantic Ocean, and its amount reaches 10^7 m^3 s^{-1}.

Oceanic Conveyor Belt

To investigate oceanic conveyor belt, the water mass budget of each ocean is calculated. Firstly, oceanic mean density ρ_0 in both experiments is calculated to define reference density for the oceanic conveyor belt. We defined lower and upper layer by the depth of reference density ρ_0. Secondly, the sum of incoming lateral flows is calculated in the lower layer in each basin. During these calculations, the outgoing flows are assumed as negative incoming flows. If the sum is positive, there is upwelling in the basin. If the sum is negative, there is deep water formation in that basin. This calculation shows that there are two regions for deep water formation in the control run, i.e. the North Atlantic and the Southern Oceans. In the PG run, however, deep water formation takes place only in one region, i.e. the

Southern Oceans. The enhanced MOC cell in the Pacific Ocean, discussed in Ref. 13, does not penetrate to the lower layer defined by the mean density ρ_0. Finally, we calculate the sum of incoming flows and upwelling (downwelling) vertical flow in the upper layer. If the sum in the upper layer is positive, atmospheric forcing (evaporation-precipitation flux, hereafter EP flux) removes water from the upper layer. When the sum is negative, atmosphere (partially through the land) puts water into the upper layer.

Schematic diagrams of the conveyor belts based on the estimates described above are shown in Figure 7. The conveyor belt of the control run (Fig. 7a) reasonably matches the observed one proposed in [15, 16] except for Indonesian through flow.

The PG run, however, yields a substantially different view of the oceanic circulation (Fig. 7b). Notable difference from the present state is shown by the reduction of the deep water source, i.e. no source in the Northern Hemisphere. In the equatorial Pacific, integrated volume flux in the upper and the lower layers is northward; the flux in the lower layer maintains the North Pacific stratification, while the flux in the upper layer, partially modified in the North Pacific by the enhanced MOC, supplies eastward flux to the North Atlantic through the Panamanian Gateway. In the equatorial Atlantic, the northward flux is relatively small ($0.1 \times 10^6\ m^3\ s^{-1}$) compared with the southward flux in the upper layer ($8.2 \times 10^6\ m^3\ s^{-1}$), indicating the North Atlantic stratification is partially maintained by the flux through the Panama-

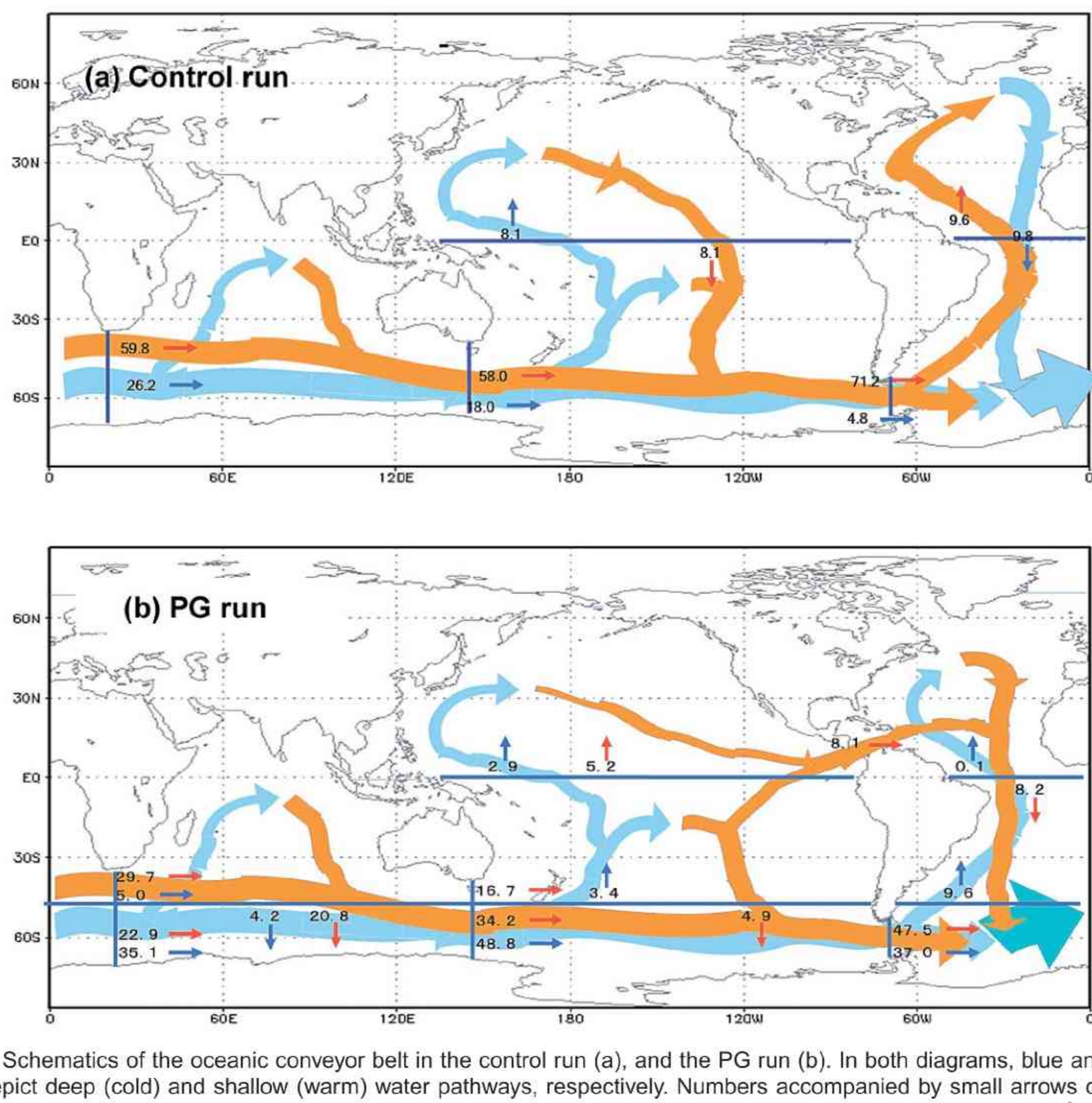

Fig. 7 Schematics of the oceanic conveyor belt in the control run (a), and the PG run (b). In both diagrams, blue and orange belts depict deep (cold) and shallow (warm) water pathways, respectively. Numbers accompanied by small arrows depict the volume transport in the upper (red arrow) or the lower (blue arrow) layer. The unit of the numbers is Sverdrup ($10^6\ m^3\ s^{-1}$).

nian Gateway. The net water flux between the ocean and the atmosphere in each basin is small relative to the lateral oceanic transport. However, it may affect density distribution in each basin.

SUMMARY AND DISCUSSION

We propose the formation of a paleoceanic steady state and a conveyor belt in the early to middle Miocene (when the Panamanian Gateway was opened) from the analysis of the numerical results of the atmosphere land-ocean coupled general circulation model. The seawater properties in the North and South Atlantic were quite different from today and this was mainly due to the collapse of NADW formation in the northern part of the North Atlantic. The paleoceanic conveyor belt also shows a circulation pattern that is quite different from the present one. There are no regions of deep water formation in the Northern Hemisphere, and the flux between the North Pacific and the North Atlantic through the Panamanian gateway is important in maintaining the paleoceanic equilibrium state.

The depth of the Panamanian Gateway may be critical to the resultant circulation. Chronology of the gateway closing is described in detail elsewhere [4, 5]. Before the final closure, the gateway shoals gradually throughout Miocene (23.7–5.3 Ma). Tectonic and biostratigraphic studies suggested that deep water connection between the Pacific Ocean and the Atlantic Ocean had been established throughout the early Miocene (23.7–16.6 Ma), while shallow and intermediate waters were connected in middle Miocene (16.6–11.2 Ma). In late Miocene (11.2–5.3 Ma), only shallow waters were connected or partially restricted. The Final closure of the Panamanian gateway was estimated at Pliocene (~3.5 Ma) as reported in Ref. 17. Hence, the present study concerns the period from the early to the middle Miocene (23.7–11.2 Ma). It should be noted here that the opening of the Drake Passage thought to be in early Miocene (24–20 Ma?). Therefore, our study treated the situation after the opening of the Drake Passage in early Miocene.

As mentioned in introduction, some studies [10, 12] suggested that the NADW formation started before the final closure of the Panamanian Gateway. Because the depth of the Gateway is critical to the patterns of the paleoceanic conveyor belt, numerical experiments with various gateway depths are needed to understand the whole history of oceanic circulation during Miocene to Pliocene times. We also have to compare the numerical results with the proxy data to examine the reliability of our numerical results in future.

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