Multi-spatial variability modes of the Atlantic Meridional Overturning Circulation

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Abstract The multi-spatial variability modes of the Atlantic Meridional Overturning Circulation (MOC) are identified in the natural coupled simulation of two climate models, the MOC either oscillates at decadal scales with strong cross-equatorial flow or fluctuates locally at interannual scales with weaker cross-equatorial flow. Former studies mainly emphasize the paleo-environmental and paleo-climatic impacts of the meridional overturning states transition; this analysis indicates the existence of the multi-spatial variability modes of the MOC at interannual to decadal scales. Further analysis indicates that the conventionally used MOC index, which is defined as the maximum zonal mean meridional stream-function of the North Atlantic, cannot properly describe the multi-spatial variability characteristics of the MOC.

Keywords: Atlantic Meridional Overturning Circulation, basin scale, local scale.

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One of the major elements of today’s ocean system is a conveyor-like Atlantic Meridional Overturning Circulation (MOC) that includes the northward transport of the warm, salty tropical and subtropical surface water and the southward transport of the cold North Atlantic Deep Water. This circulation system delivers an enormous amount of tropical heat to the northern Atlantic. This circulation system delivers an enormous amount of tropical heat to the northern Atlantic. For example, one famous case is the so-called “Younger Dray Event”, which occurred about ca. 12 kaBP and appeared as the sudden re-cycling of the European continent during the time of gradually warming after the last glacial period. There is evidence indicating that this event might be caused by the sudden shutdown of the Atlantic MOC and the associated weakening poleward heat transport. Signals of this event can be found worldwide, and the variability of the MOC is thus considered as one of the major challenges in climate change.

The short duration in time and sparse geographic coverage of direct measurements in the ocean make studies on the variability of MOC rely heavily on the numerical simulations. Previous studies have mainly focused on the low-frequency variability of the entire Atlantic meridional basin-wide MOC oscillation and its response to global warming. Less attention has been paid to the multi-spatial variability modes of the MOC. In this paper, one basin-scale and one more local-size oscillation modes of the MOC are identified in the long-term natural integration of two global air-sea coupled climate models. The MOC either oscillates in the basin wide at decadal scale or locally at interannual scale. The climate impacts of the different variability modes are emphasized.

1 Model description

Two global air-sea coupled models are used. The first is the so-called BCM, which consists of the MICOM OGCM, the ARPEGE/IFS AGCM and a thermo-dynamical sea-ice model. The AGCM is global with a horizontal resolution of T42 on a reduced Gaussian grid and has 31 layers in the vertical. The OGCM employs the stretched grid system with one pole over Siberia and the other over the South Pole. The horizontal grid has a resolution of 2.4° along the equator. The grid cells are approximately square and consequently scales with the cosine of the latitude except in a band along the equator where the meridional grid spacing is gradually increased to 0.8°. The OGCM has 24 layers in the vertical, of which the uppermost mixed layer has a temporal and spatial varying density. The coupled model has recently finished a 328-years simulation, the final 300 years output forms the data for the analysis presented here.

The second model is the IAP/LASG GOALS model. The atmospheric component of GOALS is a global spectral AGCM, which is rhomboidally truncated at zonal wave number 15 (R15). There are nine unevenly spaced levels in the vertical σ coordinate. To get more insight into the impacts of land surface processes on climate, a simplified biosphere model is implemented into the AGCM. The oceanic component of GOALS is an OGCM with 20 unevenly spaced layers in the vertical η coordinate. The horizontal resolution is 4° in latitude by 5° in longitude on B-grid. A simple thermodynamic sea-ice model is incorporated into the ocean model. Flux correction technique is used in the ocean-atmosphere coupling process. The GOALS model version 4 has been integrated for 200 years, and the final 120 years output is used in the following analyses.

2 The basin scale and local scale MOC oscillations

The meridional overturning stream-function is extensively used in describing the MOC. In comparison with the velocity vector field, it is better in representing the meridional mass transport of the ocean circulation. The definition of the meridional stream-function is as follows.

Consider the continuity equation of the sea water in spherical coordinate,
The vortex of the non-divergent movement can be expressed in terms of the stream-function as the following way:

$$\nabla^2 \psi = \frac{\partial}{\partial \lambda} \left( \int_{\lambda_w}^{\lambda_e} w \cdot a \cdot \sin \theta d\lambda \right) - \frac{\partial}{\partial \theta} \left( \int_{\lambda_w}^{\lambda_e} v \cdot \sin \theta d\lambda \right).$$  (5)

The stream-function can be calculated by solving the Poisson equation. If the zonal integration is performed across the global ocean, the meridional stream-function then corresponds to the total global ocean meridional transport. If the zonal integration is performed across one specific basin, for example the Atlantic Ocean, the resulted stream-function corresponds to the Atlantic meridional transport.

Applying an Empirical Orthogonal Function (EOF) analysis to the annual mean Atlantic meridional overturning stream-function anomalies identifies the multi-spatial oscillations of the MOC. Fig. 1 displays the spatial pattern

![Image](image.png)
and the principal component (PC) for the first leading EOF mode of the BCM, which explains 52.1% of the total variance. It shows a pattern of basin-scale anomaly with substantial cross-equator transport, so it is a loop oscillation with the whole Atlantic “conveyor belt” accelerating or decelerating. Associated with this mode is the period of the oscillation at decadal scales, a Morlet wavelet analysis indicates a dominant period of 22a (figure omitted).

The second EOF mode and the associated PC are depicted in Fig. 2. It accounts for 14.2% of the total variance and appears as a dipole mode, with positive anomalies dominating north of 30°N of the North Atlantic Ocean and weaker negative anomalies dominating the tropical and southern Atlantic Ocean. This mode reveals mainly a local-size adjustment of the meridional overturning with weak cross-equatorial flow. The corresponding PC reveals mainly an interannual scale oscillation. A wavelet analysis reveals a dominant timescale around 3 years (figure omitted). Comparison of Fig. 1(a) with Fig. 2(a) reveals the spatial difference of the basin-wide and the local-size variability of the MOC.

Further analysis indicates that this kind of multi-spatial scale MOC variability is not model-dependent, similar results can be found in IAP/LASG GOALS model. The first leading mode of the GOALS model is shown in Fig. 3(a), which accounts for 28.7% of the total variance. The mode also appears as a basin-scale anomaly with substantial cross-equator transport, indicating a whole Atlantic “conveyor belt” oscillation. It also should be noted that the center of the anomaly field is shallower in depth and shifts equator-ward in comparison with the climate mean states. The corresponding PC oscillates at decadal scale, wavelet analysis indicates a 30a dominant period (figure omitted). Corresponding to Fig. 2, the situation of GOALS is indicated in Fig. 4, which is the third EOF mode and explains 15.4% of the total variance, wavelet analysis reveals a dominant period of 8—10a (figure omitted). The cross-equator flow of this mode is very weak and thus

Fig. 2. Same as in Fig. 1 except for the second leading mode. (a) EOF2 20.1%; (b) PC2.
indicates mainly a local size MOC variation. In addition, the second EOF mode of the GOALS appears as a local size MOC adjustment around the Nordic Sea, the cross-equator flow is also extremely weak (figure omitted).

3 Discussion

Above analyses based on two global air-sea coupled models indicate that the MOC exhibits multi-spatial scale oscillations under the situation of natural coupled simulation without any anomalous external forcing. Similar situations have also been reported in other models, for example, the decadal scale MOC oscillation in ECHAM1/LSG coupled model appears mainly as local scale advection mode rather than the whole conveyor oscillation[15]; the decadal scale MOC oscillation in GFDL model is located mainly in the northern part of the North Atlantic basin[16]. This reminds us that in the research regarding the MOC variability, while great attention has been paid to the change of the MOC intensity, spatial features of the MOC variation should also be noticed.

Previous studies on the MOC variability by using air-sea coupled models usually define a MOC intensity index as the maximum value of the North Atlantic meridional stream-function (hereafter referred to as THC$_{\text{max}}$). From the analyses presented above, we can find that this kind of definition has shortcomings, since the THC$_{\text{max}}$ variation might occur either at the basin scale indicating the whole conveyor accelerating/decelerating or at local size indicating partial variation of the conveyor. In view of climate impact, the whole conveyor variation is obviously more important. For quantitative analysis, we calculate the correlation of THC$_{\text{max}}$ series of BCM with PC1 and PC2 shown in Figs. 1(b) and 2(b) respectively, the absolute value of the corresponding correlation coefficient is 0.63.
and 0.34 respectively, indicating that the THC$_{\text{max}}$ can explain 40.1% of the basin-scale MOC variation and 11.8% of the local size MOC variation. Similar calculations are conducted for the THC$_{\text{max}}$ series of the GOALS and PC1, PC3 shown in Fig. 3(b) and 4(b), the resulted absolute value of correlation coefficient is 0.36 and 0.29 respectively, indicating that the THC$_{\text{max}}$ can explain 13.0% of the basin scale MOC variation and 8.4% of the local size MOC variation. In addition, the correlation between THC$_{\text{max}}$ and PC2 of GOALS is nearly zero, this is understandable, since EOF2 reveals mainly the local adjustment of the MOC around the Nordic Sea, this also indicates the deficiency of the THC$_{\text{max}}$ definition.

The extensively used THC$_{\text{max}}$ index only partially explains the basin scale or local size MOC variation, however, the climate impact of these two modes is obviously different. This might explain the question of why the climate signals associated with THC$_{\text{max}}$ are model dependent\cite{13-5171}. Among different models, the THC$_{\text{max}}$ explains either mainly the basin-scale MOC variation or mainly the local size MOC variation, the corresponding climate signals shown in oceanic or atmospheric physical variables would accordingly be different.

In fact, modes of North Atlantic deep water formation has already been noticed in the paleoclimate research community. Data and models suggest that the North Atlantic Ocean usually operates in one of three distinct modes or bands of circulation\cite{118}. The first mode is characterized by deep-water formation in both the Nordic Seas and farther south in the North Atlantic. This modern mode of circulation is associated with warm times in the North Atlantic. In the second mode, deep-water formation largely stopped in the Nordic Seas but with continued vigorous deep-intermediate water formation farther south in the North Atlantic. This mode is reached at glacial maximum and during the cold or stadial times of the 1500-year Dansgaard/Oeschger (D/O) oscillation\cite{119}. In the third mode, the deep-intermediate water formation is greatly reduced in both locations. This mode is achieved during especially large melt-water inputs, such as are as-
associated with some Heinrich events. These kinds of modes transition are mainly emphasized in paleo-climate studies. The analyses presented above remind us that even under the condition of modern climate, MOC might also have basin or local size strength oscillation occurring at decadal scales. Thus attention should also be paid to the spatial feature of the MOC variability in addressing the current climate effect of the MOC. In view of observation, though the global ocean observing system cannot provide enough instrumental data to describe the whole picture of the MOC, finite observation evidence still indicate the existence of local adjustment of the MOC at decadal scales, corresponding signals can be found in the marginal sea convection activity, the change of deepwater formation resulted from the polar-ice melt-water advection, the southward transport of the great salinity anomaly, etc. Nevertheless, the shortage of observation data indeed limits our detection on the variation of the whole MOC structure, to overcome the difficulty, long-term continuous observation efforts are needed.

4 Concluding remarks

Based on the outputs of two global air-sea coupled model simulation, the multi-spatial variability modes of the Atlantic MOC are identified, the MOC either oscillates at decadal scales with strong cross-equatorial flow or fluctuates locally at inter-annual scales with weaker cross-equatorial flow. Former studies mainly emphasize the paleo-environmental and paleo-climatic effects of the MOC states transition; this analysis indicates the existence of mode pattern variation of the MOC at shorter time scales, from inter-annual to decadal. The spatial features of the MOC variation should be noticed in modern climate variability research.

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References


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