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Subpolar Gyre Index and the North Atlantic Meridional Overturning Circulation in a Coupled Climate Model

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Abstract The subpolar gyre index (SPG), derived from the analysis of sea surface height (SSH), is proposed to be a potential indicator for the North Atlantic Meridional Overturning Circulation (AMOC) based on observation as well as the Ocean General Circulation Model (OGCM). We investigated the correspondence between the SPG and the AMOC in a coupled climate model. Our results confirm that the SPG can be used as an early indicator for the AMOC in the subtropical North Atlantic. Changes in the SPG are closely related to variations in the air-sea heat exchange in the Labrador Sea, and variations in deep water formation and southward dense water transport with the deep western boundary current (DWBC) in the North Atlantic.

Keywords: subpolar gyre index, North Atlantic meridional overturning circulation, indicator

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1 Introduction

The North Atlantic Meridional Overturning Circulation (AMOC) is an important and active component of the climate system (Rahmstorf, 2003). The warm, saline surface and near-surface water that flows from the subtropics northward with the North Atlantic Current (NAC) forming the upper branch of the AMOC transports large amounts of heat and salt towards the poles. A large part of the transported heat is released into the atmosphere at high northern latitudes, particularly during the winter, contributing to anomalous (high) temperatures in north Western Europe (Rahmstorf and Ganopolski, 1999). Likewise, the transported salt is critical for dense water formation in the Labrador and the Nordic Seas (Greenland-Iceland-Norwegian Sea, GIN) (Furevik et al., 2002). The dense water formed in the northern Atlantic flowing southward with the deep western boundary current (DWBC) forms the lower branch of the AMOC. As suggested by paleorecords (Broecker, 1997; Clark et al., 2002) and demonstrated by numerical studies (Manabe and Stouffer, 1999; Eden and Willebrand, 2001; Bentsen et al., 2004), the AMOC is closely related to climate state and vice versa. A potential reduction in the AMOC and in AMOC-related northward heat transport due to global warming has prompted sizeable efforts geared towards the development of a monitoring system that can detect early changes in the AMOC in the subtropical North Atlantic (Hirschi et al., 2003), where many observations have been made previously (Bryden et al., 2005).

One of the main elements of the lower branch of the AMOC is a water mass that is formed in the Labrador Sea, known as Labrador Sea Water (LSW; Pickart et al., 1996). LSW is generated during the winter due to enhanced heat loss to the atmosphere and subsequent deep mixing. Recently, Häkkinen and Rhines (2004) (hereinafter referred to as HR) analyzed satellite-derived sea surface height (SSH) from 1992 to 2002 and proposed the subpolar gyre index (SPG) as an indicator of the intensity of subpolar North Atlantic cyclonic circulation. Furthermore, HR suggested that the SPG is linked to deep convection in the Labrador Sea, implying the possible importance of subpolar gyre variability in the AMOC. The evolution of the SSH pattern and the corresponding changes in the eastward extension of the subpolar gyre were reproduced with an Ocean General Circulation Model (OGCM) forced by atmospheric reanalyses (Hátún et al., 2005). With a high resolution of OGCM, Böning et al. (2006) demonstrated that the SPG is closely linked to the volume transport of the boundary current system in the Labrador Sea, and they suggested that the SPG can be a potential predictor for the AMOC in the subtropical North Atlantic. It remains to be tested whether the relationship between the SPG and the AMOC, as indicated by an OGCM study of Böning et al. (2006), is simply model-dependent or also valid in a coupled climate system. In this study, we examined subpolar gyre variability by assessing the correspondence between the SPG and the AMOC, deepwater formation, and the volume transport of the DWBC in the North Atlantic in a coupled climate model.

2 Model description and experiment

A detailed description of the Bergen Climate Model (BCM) can be found in Furevik et al. (2003); this paper provides a brief introduction to the BCM.

The atmospheric component of the BCM is the spectral general circulation model ARPEGE/IFS from Météo-France (Déqué et al., 1994). The oceanic component of the BCM is the Miami Isopycnic Coordinate Ocean Model (MICOM; Bleck et al., 1992). The horizontal grid has a resolution of 2.4° along the equator, with one pole

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over Siberia and the other over the South Pole. There are 24 vertical layers, of which the uppermost Mixed Layer (ML) has varying spatial and temporal density, and 23 isopycnal layers below ML have a prescribed potential density ranging from $\sigma_0 = 24.12$ to $\sigma_0 = 28.10$.

The data used in this study are from a 300-year modern state simulation with the BCM [hereinafter refer to as (Control: CTRL)] (Furevik et al., 2003) and a freshwater perturbation experiment (FW) starting at year 100 of the CTRL, with a continuous threefold increase in river run-off to the high northern latitudes, which was thereafter integrated for another 150 years. For further details, please refer to Otterå et al. (2004).

3 Results

Figure 1 shows the time series of the normalized SPG and the AMOC in the subtropical North Atlantic in CTRL and FW. It followed that variations of the SPG were closely correlated to variations in the AMOC (correlation coefficient was 0.54 for CTRL and 0.53 for FW) on the inter-annual and the decadal time scales, with the SPG leading 5 years to the AMOC in both the CTRL and the FW. It should be mentioned in particular that the AMOC, following the SPG, showed an initial drop-down over the first 50-year integration and was followed by a gradual recovery over the last 100-year integration in FW (Otterå et al., 2004).

To explore the correspondence between the SPG and the AMOC, we investigated the relationships between the time series of the SPG, the deep convection (denoted by the ML depth) and heat flux of the Labrador Sea in the CTRL, and the FW, as shown in Fig. 2. It was indicated that stronger cyclonic circulation (high SPG) was linked to stronger deep convection and stronger heat release from the ocean to the atmosphere, leading to increased dense water formation in the Labrador Sea. The dense water formed in the Labrador Sea mainly spreads southward with the DWBC, as seen by both observations (Dickson and Brown, 1994) as well as simulations (Figure not shown). Consequently, the southward volume transport of the dense water in the North Atlantic and the SPG was investigated (Fig. 3). It was clearly shown that the SPG was correlated with the southward volume transport of dense water in the experiments; the SPG showed a 5-year lead to the dense water transport in the subtropical North Atlantic (24°N).

4 Discussion and Conclusion

The subpolar gyre index, derived from the satellite-based SSH, has been suggested to be linked to the activity of deep convection in the Labrador Sea and, therefore, to the AMOC (Häkkinen and Rhines, 2004).

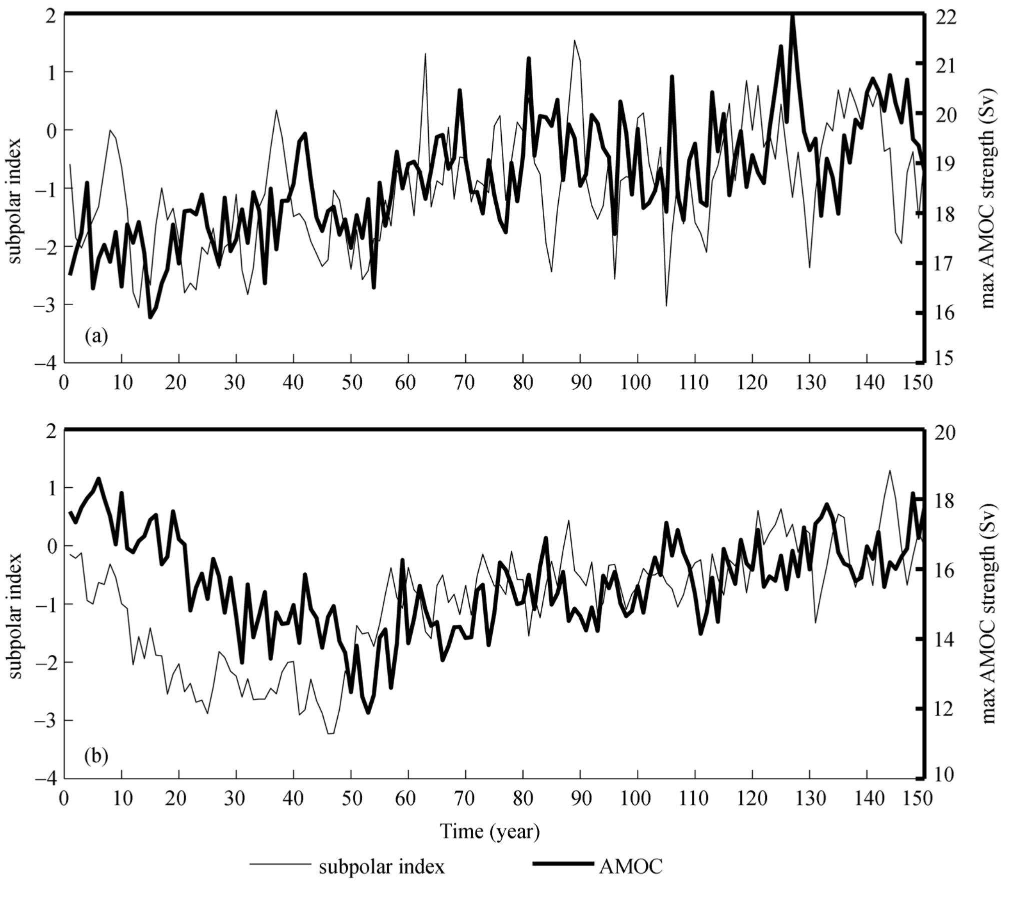

Figure 1 Normalized SPG and the AMOC in the (a) CTRL and (b) FW

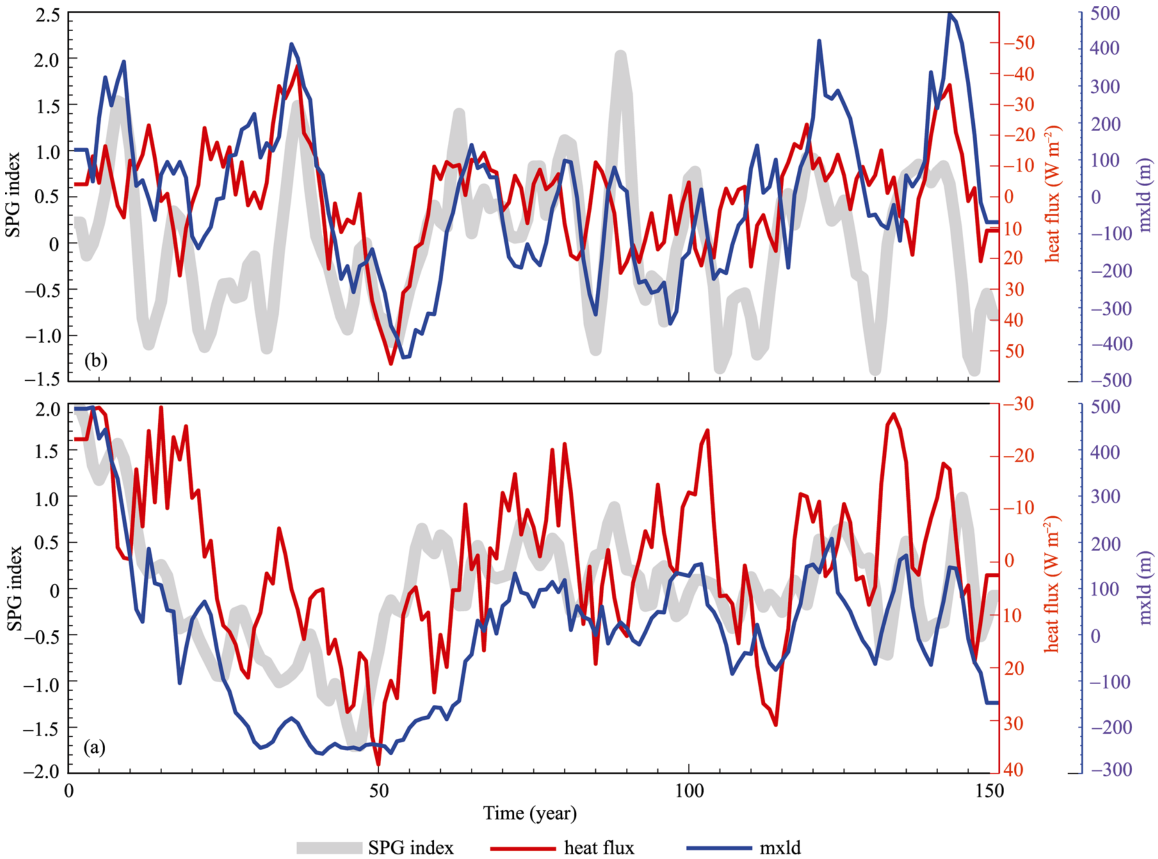

Figure 2 Time series of the SPG and anomalies of heat flux and the ML depth of the Labrador Sea in the (a) CTRL and (b) FW

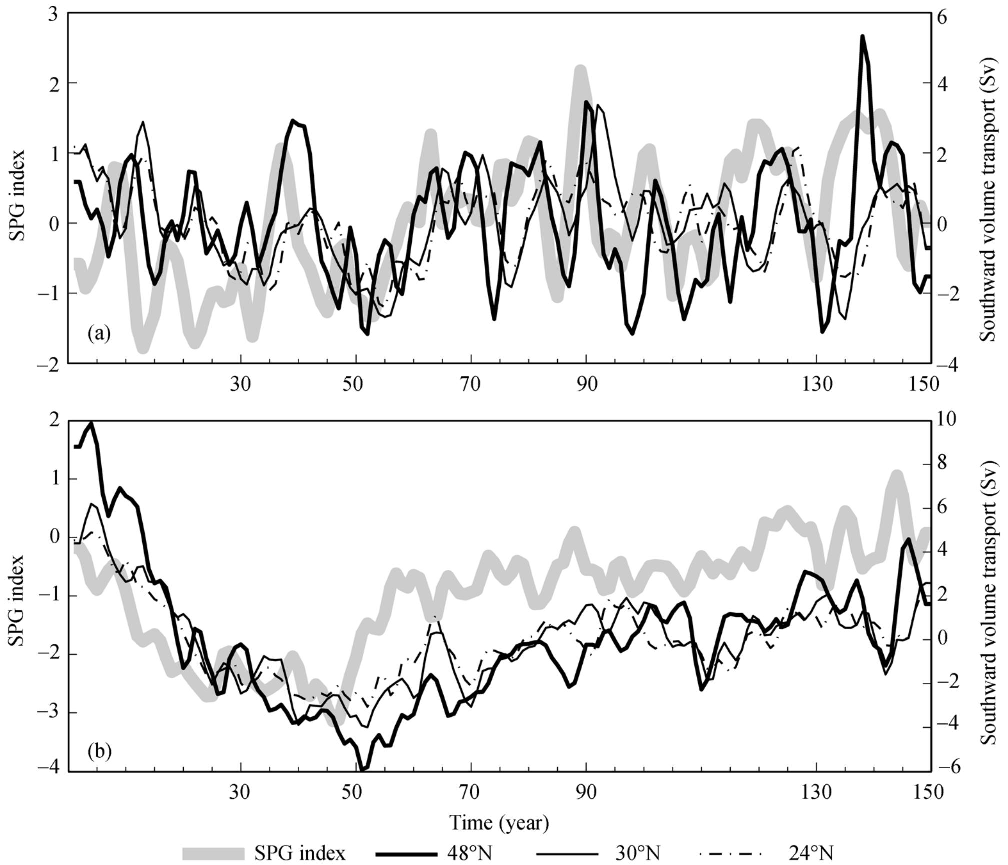

Figure 3 Time series of the SPG and anomalies in southward dense water transport in the (a) CTRL and (b) FW.

The OGCM simulation (Böning et al., 2006) has demonstrated that the subpolar gyre index is closely related to the volume transport of the DWBC from the Labrador Sea and, consequently, to the AMOC in the subtropical North Atlantic. In this study, we investigated the correspondence between the subpolar gyre index, deep-water formation, and deep-water transport of the DWBC in the subtropical North Atlantic in a coupled climate model. Our results support and confirm that the subpolar gyre index is highly correlated with deep-water formation in the Labrador Sea and with southward deep-water transport in the subtropical North Atlantic, with the subpolar gyre index leading 5 years. Consequently, the subpolar gyre index can potentially be used as an indicator of the variability of the AMOC on the interannual to decadal time scale. It also should be noted, as shown by our results, that the variability of the subpolar gyre index appears to be linked to heat exchange in the Labrador Sea.

It should be acknowledged that our SSH analysis, as in the case of Böning et al. (2006), does not include what takes place in the Nordic Seas. Therefore, a potential source of gyre transport and AMOC variability may have been neglected. Latif et al. (2006) suggested that the variations in the outflow of the Nordic Seas are likely less important than the variations in deep convection in the Labrador Sea over the past decades. However, the century scale evolution of the AMOC under global warming, as projected by numerical models, appears to be governed mainly by outflows from the Nordic Seas (Schweckendiek and Willebrand, 2006). It would be of interest to test whether the subpolar gyre index is also highly correlated with AMOC transport when the outflow from the Nordic Seas dominates the long-term evolution of the AMOC due to the climate change.

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