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Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning

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[1] Analyses of sea surface height (SSH) records based on satellite altimeter data and hydrographic properties have suggested a considerable weakening of the North Atlantic subpolar gyre during the 1990s. Here we report hindcast simulations with high-resolution ocean circulation models that demonstrate a close correspondence of the SSH changes with the volume transport of the boundary current system in the Labrador Sea. The 1990s-decline, of about 15% of the long-term mean, appears as part of a decadal variability of the gyre transport driven by changes in both heat flux and wind stress associated with the North Atlantic Oscillation (NAO). The changes in the subpolar gyre, as manifested in the deep western boundary current off Labrador, reverberate in the strength of the meridional overturning circulation (MOC) in the subtropical North Atlantic, suggesting the potential of a subpolar transport index as an element of a MOC monitoring system. **Citation:** Böning, C. W., M. Scheinert, J. Dengg, A. Biastoch, and A. Funk (2006), Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning, *Geophys. Res. Lett.*, *33*, L21S01, doi:10.1029/2006GL026906.

1. Introduction

[2] The cyclonic circulation of the subpolar gyre in the North Atlantic (Figure 1) represents an important part of the global thermohaline circulation (THC). The eastern, northward flowing portion of the gyre includes various, vigorously eddying branches of the North Atlantic Current (NAC), supplying the northeastern Atlantic with warm, saline waters of subtropical origin. Subsequently cooled through surface heat loss in winter, the different return flows merge along the southeastern continental slope off Greenland, to form an intense boundary current system, with a volume transport of 40 to 50 Sv (1 Sv = 10^6 m^3s^{-1}), around the Labrador Sea [*Pickart et al.*, 2002; *Fischer et al.*, 2004] (Figure 2). About a third of this transport comprises the different constituents of the North Atlantic Deep Water (NADW) that feed the deep limb of the meridional overturning circulation (MOC) of the mid-latitude North Atlantic [*Lumpkin and Speer*, 2003]. The potential threat to the MOC and its related northward transport of heat due to anthropogenic climate change [*Gregory et al.*, 2005] has led to major efforts in designing a monitoring system able to detect changes in the MOC transport in the subtropical North Atlantic [*Hirschi et al.*, 2003] where ship-based transoceanic sections have provided repeated snapshots of the MOC [*Bryden et al.*, 2005]. The detectability of a potential (multi-)decadal MOC signal related to changes in subarctic deep water formation is impeded, however, due to contaminations by high-frequency fluctuations, particularly due to local wind forcing [*Baehr et al.*, 2006]. Here we demonstrate that decadal MOC signals of subarctic origin can be traced back to pronounced changes in the strength of the deep western boundary current of the subpolar gyre.

[3] It is well established that the hydrographic properties in the subpolar North Atlantic undergo pronounced variations on decadal-to-centennial time scales, primarily as a consequence of changes in the local atmospheric conditions associated with the NAO [*Curry et al.*, 1998]. These are particularly manifested in the properties of the Labrador Sea Water (LSW), the upper constituent of the deep MOC limb, generated by enhanced air-sea heat fluxes and subsequent, deep convective mixing events during wintertime storms. A prominent, well documented period of change occurred during the 1990s, where a phase of exceptionally intense convection related to the high NAO-index years of the early 1990s, was followed by a period of weak convection after 1994 [*Lazier et al.*, 2002].

[4] Recent studies based on satellite-tracked drifting buoys and satellite-altimeter data have added to this picture by also documenting evidence for changes in the gyre circulation during the 1990s. *Häkkinen and Rhines* [2004, hereinafter referred to as HR] used sea surface height (SSH) data based on altimeter records for 1992 to 2002 to propose a "gyre index" for the strength of the cyclonic circulation in the subpolar North Atlantic, and reported a substantial decline in this index after 1994. Their analysis suggested a link between the gyre strength and the cessation of deep convection in the Labrador Sea associated with the trend in the net heat fluxes, indicating a possible importance of the dynamical variability in the subpolar gyre for the evolution of the thermohaline circulation in the Atlantic. The evolution of the SSH pattern and the concomitant changes in the eastward extension of the gyre were reproduced with an Ocean General Circulation Model (OGCM) forced by atmospheric reanalyses [*Hátún et al.*, 2005]. In this study we examine the nature and role of the subpolar gyre variability by assessing the correspondence of a SSH-based "gyre index" with the actual volume transport of the gyre, by elucidating the forcing mechanisms contributing to this variability during the last decades, and by demonstrating its repercussion for the basin-scale MOC.

2. Model Experiments

[5] We use a sequence of OGCM simulations, with horizontal resolutions (longitude by latitude) of 1/12° by 1/12° cos (φ) and 1/3° by 1/3° cos (φ) (φ being latitude), forced by monthly flux anomalies derived from the NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996], utilizing a primitive equation model that has been developed for studying the

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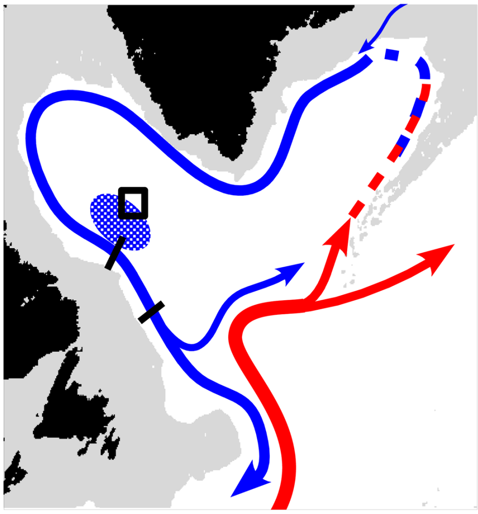

Figure 1. Schematic of the topography (water depths smaller than 1500 m are shaded grey) and circulation of the western subpolar North Atlantic, illustrating the import of warm water by the NAC (red), its recirculation and successive cooling in the Irminger Basin (red dashed), and the deep western boundary current (blue), by which the cold deep waters outflowing from the Nordic Seas (light blue) and formed by deep winter convection (shaded blue) are exported from the Labrador Sea. Indicated (black lines) are the sites (near 53°N and 56°N) of multi-year current measurements off the Labrador continental slope [*Fischer et al.*, 2004], and the area (black box) taken for the computation of the SSH variability in the central Labrador Sea (57°N, 52°W) following the definition of *Häkkinen and Rhines* [2004].

wind-driven and thermohaline circulation in the Atlantic Ocean (Family of Linked Atlantic Model Experiments, FLAME). The z-coordinate model is based on a modified version of the Modular Ocean Model (MOM2) [*Pacanowski*, 1995]. All model cases cover the Atlantic Ocean up to 70°N, using 45 levels in the vertical, isopycnal mixing schemes, and a bottom boundary layer formulation following *Beckmann and Döscher* [1997]. Our study builds on previous applications of the FLAME hierarchy (with 4/3°, 1/3°, and 1/12° resolutions) to issues of deep water formation [*Böning et al.*, 2003] and eddy variability [*Eden and Böning*, 2002] in the Labrador Sea, the mechanisms of decadal MOC variability [*Eden and Willebrand*, 2001, hereinafter referred to as EW], and the propagation of subarctic MOC anomaly signals to the tropics [*Getzlaff et al.*, 2005]. The model experiments simulate the ocean's response for 1958–2001 (in the 1/3°-case; following a 50-year climatological spin-up) and 1987–2004 (1/12°-case; 10-year spin-up) to interannual variations in wind stress and heat flux. The heat fluxes are computed with the linearized bulk formulation of EW. Sea surface salinity as well as the hydrographic conditions near the northern boundary are restored to climatological conditions on a time scale of 15 days, effectively eliminating possible effects of changing outflow conditions from the Nordic Seas.

3. Changes in the Subpolar Gyre Transport

[6] In the altimeter data analysis of HR, the interannual variation in the gyre circulation during 1992 to 2002 was depicted by the principal component of an empirical orthogonal function (EOF) analysis, as well as by the actual SSH anomalies in the central Labrador Sea; both indices showing a similar rise of about 8 cm after 1994. The 1/12°-model simulation is assessed in Figure 3a by inspecting the central-gyre SSH evolution in comparison to altimeter products. The monthly values are governed by strong intra-seasonal fluctuations and obviously lack correlation between model and data. (These fluctuations are much weaker in the 1/3-model and may thus partly reflect stochastic, eddy-related "noise".) The 2-year low-pass filtered SSH anomalies indicate a comparable behavior as observed, with a rise between 1994 and 1998 of about 10 cm.

[7] The relation of this SSH-based index to the actual volume transport of the subpolar gyre is inspected in Figure 3b. In the model the SSH-index covaries (r = 0.74) with the maximum cyclonic gyre transport (as defined by the minimum of the transport streamfunction at 57°–58°N): it declines by 7–8 Sv between 1994 and 1999, but rises again by 4–5 Sv until 2003. The latter feature is consistent with measurements in the deep Labrador Current which suggested an increased LSW transport between the late 90s and 2001–2005 (M. Dengler et al., The Deep Labrador Current and its variability in 1996–2005, submitted to *Geophysical Research Letters*, 2006, hereinafter referred to as Dengler et al., submitted manuscript, 2006). Comparison of the 1/12°- and 1/3°-simulations shows that the higher resolution, although essential for a realistic representation of the narrow boundary flows and the mesoscale eddies which govern the intra-seasonal variability in the subpolar gyre [*Eden and Böning*, 2002], is of little consequence for capturing the low-frequency variability of the gyre transport. The 1/3°-hindcast can hence usefully be applied to obtain a longer term perspective of the subpolar gyre intensity: it depicts the mid-

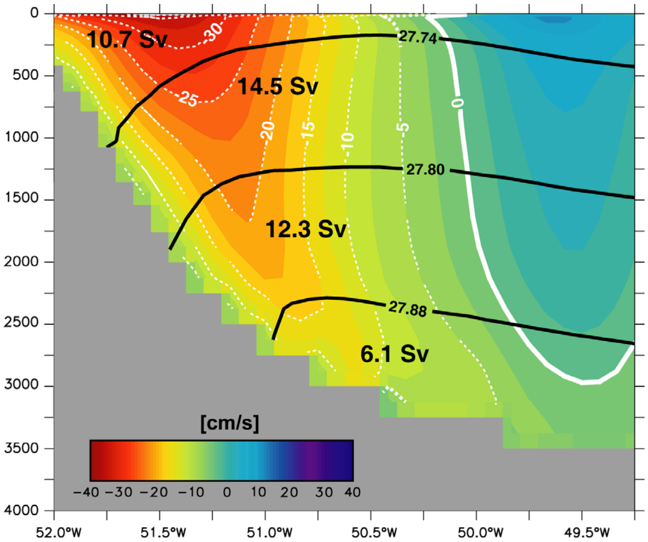

Figure 2. Cross-section of mean meridional velocity and (southward) volume transports (heavy black; in Sv) between potential density (σ_0) surfaces in the western boundary current of the Labrador Sea at 53°N in the 1/12°-model. The transports for the LSW (σ_0 = 27.74–27.80) and overflow water layers ($\sigma_0 > 27.8$) compare to measurements by *Fischer et al.* [2004] near 53°N of 11.4 Sv (σ_0 = 27.74–27.80) and 13.8 Sv ($\sigma_0 > 27.8$).

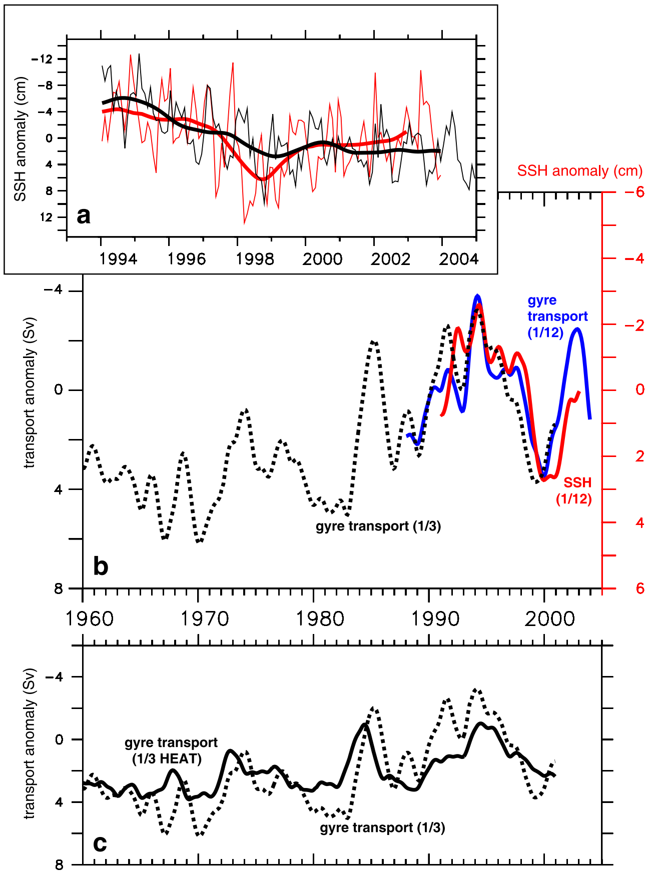

Figure 3. (a) SSH anomaly in the central Labrador Sea (57°N, 52°W) in the 1/12°-model simulation (in red; thin curve: monthly values, heavy curve: 2-yr. low-pass filtered) and altimeter data (black), based on merged products from TOPEX/POSEIDON, ERS-2, Geosat Follow-on, Jason-1 and Envisat. (b) Comparison of the central gyre SSH-index (red) with the gyre transport in the 1/12°-model (blue), and the 1/3°-hindcast (black dotted); negative transport and SSH anomalies indicating a stronger cyclonic circulation. (c) Subpolar gyre transport in the 1/3°-model forced by interannually-varying heat fluxes and wind stresses (as in Figure 3b), compared to 1/3°-HEAT forced by interannual heat fluxes and climatological (repeated annual cycle) wind stresses (heavy black curve). All time-series in Figures 3b and 3c are 2-year filtered.

1990s' decline as part of a decadal variability pattern, superimposed on a longer-term trend from a phase of minimum transports in the late 1960s, to a maximum during the early 1990s. This behavior appears consistent with the (fragmentary) observational evidence (as discussed, e.g., by HR) which suggested the early-to-mid 1990s to be unusually energetic.

[8] Insight into the causes of the transport variability is provided by a comparison of the 1/3°- and 1/12°-model hindcasts with a companion experiment (1/3°-HEAT) in which the interannual forcing variability is artificially restricted to the heat flux, while the wind stress is kept a climatological, repeating annual cycle (Figure 3c). In addition to the effect of the changing heat flux emphasized by HR (associated mainly with changes in wintertime wind intensity related to the NAO), and consistent with idealized response experiments by *Esselborn and Eden* [2001], the model results point to a substantial, additional effect of wind stress on the gyre variability; the early 1990s appear exceptional in that both forcing factors acted in concert to produce the prominent transport maximum in 1994.

4. Relation to MOC Changes

[9] Is there a repercussion of changes in the subpolar gyre for the large-scale meridional transports of mass and heat in the North Atlantic further south? A host of model studies has established the response of the mid- to low-latitude MOC to variations in subarctic deep water formation [e.g., EW; *Häkkinen*, 1999; *Bentsen et al.*, 2004; *Gulev et al.*, 2003; *Bailey et al.*, 2005]. Whereas models suggest longer-term MOC trends to be governed mainly by the Nordic Sea outflow conditions, changes in Labrador Sea convection appear as the prime cause of MOC variability on interannual-to-decadal time scales [*Schweckendiek and Willebrand*, 2006]. Since year-to-year changes in deep water formation rates are difficult to quantify observationally, it appears of interest to examine here whether an indirect, but potentially more accessible account of convection changes can be based on the transport changes in the subpolar gyre. Specifically, we seek a volume transport metric primarily governed by changes in air-sea heat flux, i.e., the primary control of convection variability (as discussed in the model studies cited above).

[10] Since the maximum gyre transport discussed above (Figure 3c), and thus the SSH-index (Figure 3b), involve a significant contribution from wind stress changes, we turn attention on the transport manifested at the western boundary of the southwestern Labrador Sea, a site (see Figures 1 and 2) well-accessible to long-term current measurements as demonstrated by *Fischer et al.* [2004] and Dengler et al. (submitted manuscript, 2006). The total, top-to-bottom WBC transport variability in the model basically parallels the maximum gyre transport examined in Figure 3 (not shown). The effect of the variable wind stress appears diminished, however, in the lower portion of the WBC, i.e., in the components eventually feeding the lower limb of the MOC: as demonstrated in Figure 4a, the deep WBC transport corresponds to the variability in convection intensity ($r = 0.78$ (0.73) for a lag of 1 year (2 years), convection leading), used here as a simple measure of Labrador Sea Water formation: stronger southward transport episodes are notably associated with the convection events in the mid-70s, mid-80s and, most prominently, early 90s. (Alternative use of a "formation rate" based on the wintertime increase in LSW volume leads to similar results; this rate varies between 0–2 Sv in weak and 6–8 Sv in strong convection years, with no significant differences between the 1/3°- and 1/3°-HEAT cases.)

[11] How is the decadal variability in the subarctic deep water formation reflected in the basin-scale MOC? As discussed by *Eden and Greatbatch* [2003], the dynamical signal at the exit of the subpolar basin near 45°N lags convection changes by about 2 years associated with the advective spreading of the newly formed water mass; south of that there is a rapid southward propagation of MOC signals via fast boundary wave processes [e.g., *Getzlaff et al.*, 2005]. This behavior can be seen in 1/3°-HEAT: Figure 4b depicts a

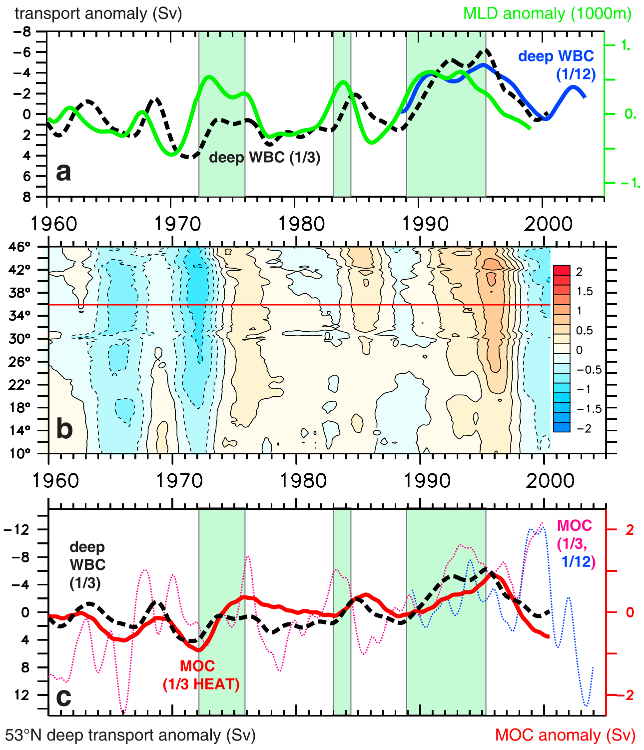

Figure 4. (a) Variability of the dense portion (LSW and deeper) of WBC transport at 53°N in the 1/3°- (dashed black) and 1/12°-models (blue), in relation to the convection intensity as given by the anomalies in the mean depth of the mixed layer in winter (in green; the anomalies represent the deviations from a time-mean depth of 1030 m, taken over the area of 56.5°–58.5°N, 55°–53°W; the green shading highlights strong convection episodes); all time series 2-year filtered. (b) Anomalies in the MOC transport (in Sv) as a function of latitude and time in 1/3°-HEAT, showing the rapid southward spreading of the dynamic response to the variation in LSW formation. (MOC anomalies are defined as the deviations from the time-mean MOC at each latitude; the maximum mean MOC transport is 18 Sv at about 40°N.) (c) Variability of the MOC transport at 36°N in the 1/3°- and 1/12°-models (thin purple and blue curves, respectively), and in 1/3°-HEAT (red), in relation to the deep WBC at 53°N in the 1/3°-model (dashed black; as in Figure 4a).

MOC variability clearly following convection events and rapidly communicated toward the tropical Atlantic. Note, however, that the MOC amplitude associated with the vigorous convection changes is only O(1–2 Sv) in mid-latitudes, and becomes even weaker in the subtropics. The possibility of detecting such thermohaline signals of subarctic origin is exacerbated further due to their superposition by vigorous wind-driven transport fluctuations [EW; *Jayne and Marotzke*, 2001; *Shaffray and Sutton*, 2004]. In Figure 4c this is exemplified for an arbitrary latitude (36°N): in the 1/3°- and 1/12°-hindcasts the decadal MOC-anomalies related to the subarctic buoyancy forcing (as given by 1/3°-HEAT) are effectively masked by a wind-driven signal of about twice the amplitude. Concerning the detectability of MOC changes of subarctic (thermohaline) origin, it is thus important to find this signal linked to the (rather pronounced) variability of the subpolar gyre: Figure 4c shows the contribution to the total MOC variability due to changes in the subarctic deep water formation (as seen in 1/3°-HEAT) co-varying with the dense fraction of the WBC transport off Labrador (as simulated in the 1/3°-hindcast which *includes* the wind-driven variability) (r = 0.71 (0.67) for 36°N, and 0.58 (0.56) at 26°N for lags of 0 (1) years).

5. Conclusions

[12] *Häkkinen and Rhines* [2004] noted a substantial decline in their SSH-based "gyre index" for the strength of the subpolar gyre after 1994, suggesting a link to the cessation of deep convection in the Labrador Sea and implications for the thermohaline circulation in the Atlantic. The model simulations discussed here put these observations into a multi-decadal context of transport changes in the subpolar gyre: while, as in the previous study using a different model (MICOM) by *Hátún et al.* [2005], the major decline in the SSH-index during the 1990s is reproduced in the present hindcast, the concomitant drop in the gyre transport (of 7–8 Sv, or about 15% of the long-term mean) appears as part of a decadal variability: it follows a strengthening trend of the gyre intensity since about 1970, and is followed by an increase during 1999–2003. Whereas the total, top-to-bottom transport variability appears forced by both heat flux and wind stress anomalies, the model results indicate that the deep fraction of the boundary current in the southwestern Labrador Sea represents a signal of primarily thermohaline origin: the decadal variability of the deep WBC basically follows, with a lag of 1–2 years, that of the intensity of deep winter convection. An important consequence of this behavior is that a transport anomaly in the deep WBC represents a harbinger of the basin-scale MOC response to changes in the subarctic thermohaline forcing.

[13] It has to be noted that the present model configuration, by imposing climatological conditions at the northern boundary (70°N), excludes changes in the outflows from the Nordic Seas and thereby a potential source of gyre transport and MOC variability. Whereas, according to analyses by *Latif et al.* [2006], variations in the outflows may have been of secondary importance compared to the effect of Labrador Sea convection variability during the past decades, the long-term evolution of the MOC, such as the possible weakening during the 21st century as projected in various climate models [*Gregory et al.*, 2005], is found to be governed primarily by changes in the density of the outflows [*Schweckendiek and Willebrand*, 2006]. It needs to be investigated whether a similar link between subpolar gyre and MOC transports, as in the case of the convection-related variability discussed here, also holds in an overflow-dominated climate change scenario: if established for that case, transport measurements in the Labrador Sea boundary current system could provide an important, complementary contribution to a monitoring system aiming at an early detection of potential anthropogenic changes in the Atlantic MOC.

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