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Strengths and weaknesses of the global ocean conveyor: Inter-basin freshwater disparities as the major control

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Abstract

According to the current paradigm of modern climatology and oceanography, the global ocean thermohaline circulation works as the so-called "global ocean salinity conveyor belt" – a system of currents connecting different ocean basins and most notably – the northern North Atlantic and northern North Pacific Oceans – the most distant regions of the world ocean. It is shown here that a slight disparity in freshwater redistribution between the Atlantic and Pacific oceans can be sufficient for building up and maintaining a global conveyor-type ocean thermohaline circulation. On the other hand, relatively small changes in this disparity leading to change in sea surface salinity contrasts between and in the north-south within the northern parts of these two oceans can easily change the conveyor.

1. Introduction

There are very few scientific metaphors that took over the research masses in earth sciences as strikingly as the idea of a global ocean "salinity conveyor belt" did. The advent of the metaphor, originally put forward by (Broecker, 1991), was preceded by a number of studies of world ocean circulation as a global entity (e.g. Broecker and Denton, 1989; Cox, 1989; Gordon, 1986; Stommel, 1958; Stommel and Arons, 1960).

However, none of the results of these studies had ever been as popular as the metaphor conveyed in the form of an art drawing in Broecker (1991). In this drawing, the idea of the global "conveyor" is illustrated as a loop of currents connecting the two most distant parts of the world ocean – the northern North Atlantic and northern North Pacific (Fig. 1; after (Brasseur et al., 1999)). This first drawing and many redrawings of the original art from Broecker (1991) have found their way in numerous publications (see for example (Bigg, 1996)), including popular books and magazines. As a result, many believe that the ocean circulation does indeed form a coherent global water flow. The most striking part of the story is that this belief is not that far away from the way the world ocean is working, as could be expected based on the nature of most popularizations.

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Fig. 1. Art drawing of a loop of currents connecting two most distant parts of the world ocean – the northern North Atlantic and northern North Pacific (after (Brasseur et al., 1999)).

The image in Fig. 1 is a waste simplification of what is known in the professional circles as the ocean thermohaline circulation (THC). It just emphasizes that the basic feature of the deep ocean circulation, which is the cold deep branch of the conveyor belt in Fig. 1, is remarkably coherent in many sections of the deep flow. Jet-like (though slow) deep-ocean meridional flows, also known as western boundary currents, occur along eastern slopes of the continents, while the most of intense zonal oceanic flow concentrates in the Antarctic Circumpolar Current (ACC) (Stommel, 1958). There is also a slow spreading of deepwater away from the intensive boundary currents and ACC, and upwelling in different parts of the world ocean that is not seen in Fig. 1. However, the bottom line is that the metaphor does convey the correct message, at least regarding the deep-ocean conveyor leg – it is indeed the longest possible deepwater highway connecting the northern parts of the Atlantic and Pacific Oceans.

There are two key words in the name of the conveyor – the word "conveyor" itself, and the word "salinity". That is, the name already suggests that the conveyor depends on salinity distribution in the world ocean. In this respect, even a brief look at sea surface salinity (SSS) distribution in the world ocean shows how strikingly different the Atlantic and Pacific Oceans are. The sea surface is much saltier in the Atlantic than in the Pacific Ocean, especially in the Northern Hemisphere (e.g. Levitus and Boyer, 1994). The excess of salt in the upper layers in the North Atlantic is thought to be the most important peculiarity of the Earth's freshwater cycle in the atmosphere–cryosphere–ocean system responsible for the conveyor as we know it now.

There is still a great deal of dispute over how the global ocean THC really works (or even how it should be correctly defined; a useful recent discussion can be found in Wunsch (2002)). A number of abyssal circulation schemes have been designed during several past decades, of which two schemes are most widely cited. One scheme emphasizes the role of deep-ocean western boundary currents (Stommel, 1958) and is supported by the Stommel–Arons theory of abyssal circulation (Stommel and Arons, 1960). Another scheme endorses the inter-ocean salinity contrasts as the key control of the THC (e.g. Broecker, 1991; Gordon, 1996, 2001; Schmitz, 1995) and is pictured in the salinity conveyor belt logo (as in Fig. 1). Both schemes agree, however, that the global THC is driven by deepwater production in few high-latitudinal convection sites, although the exact nature of impacting this production is still debated (e.g. Nilsson and Walin, 2001).

The idea of high-latitudinal density control of THC received a lot of attention and has been thoroughly examined in various models (e.g. Bryan, 1986; Ganopolski et al., 1998; Hughes and Weaver, 1994; Manabe and Stouffer, 1988; Rahmstorf, 1996; Renssen et al., 2002; Schmittner and Clement, 2002; Wang and Mysak, 2002); see more references in Clark et al. (2002), Rahmstorf (2002), Haupt et al. (2001). However, the significance of inter-basin SSS contrasts, especially between Atlantic and Pacific Oceans, has never been disputed (though receiving less attention). The inter-basin SSS contrasts and the freshwater fluxes needed for maintaining these contrasts are our main focus in this work. Recent ocean and coupled modeling studies support the idea of an inter-basin freshwater disparity and resultant SSS asymmetry that is directly responsible for the THC asymmetry between the Atlantic and Pacific Oceans (Saenko et al., 2004; Seidov and Haupt, 2005).

Inter-basin SSS asymmetry can develop for a variety of reasons (see a review in Weaver et al. (1999)), of which we discuss only the disparity in ocean-atmosphere freshwater exchange between major ocean basins. Earlier, we have shown that SSS zonally averaged within individual basins, i.e. retaining only basin-scale inter-basin SSS contrasts, can yield reasonable global THC (Seidov and Haupt, 2002). Building on those results, a stronger hypothesis has been introduced that inter-basin SSS gradients, regardless of their genesis

Table 1
Freshwater fluxes in different ocean basins

Exp.	Fresh water removal rate in NA [Sv][a]	Fresh water removal rate in NNA and GIN [Sv][a]	Fresh water removal rate in NP [Sv][a]	Fresh water removal rate in NNP [Sv][a]
1	Control experiment (see text)			
2	Homogeneous salinity everywhere (34.25; see text)			
3	−0.035	–	+0.01	
4	−0.035	+0.007	−0.03	–
5	−0.035	+0.007	−0.03	+0.015

[a] Removed/added water is redistributed/removed over/from the entire sea surface to conserve water balance in the World Ocean. Minus means removal of freshwater (more saltier surface water), and plus means added freshwater (fresher surface water). The rates are in Sv. NA – the North Atlantic Ocean; NNA – the northern NA; NP – the North Pacific Ocean; NNP – the northern NP; GIN – the Greenland–Iceland–Norwegian Seas.

and without detailed latitudinal distributions of SSS in different basins, can be held accountable for the global THC structure (Seidov and Haupt, 2003a).

Here, we also look into the genesis of SSS contrast and how the global ocean conveyor may depend on rather small changes in water balance in different basins. Based on the results in Seidov and Haupt (2003a,b), our working hypothesis is that the global conveyor may function only if there is a freshwater redistribution between major parts of the world ocean sufficient for maintaining the observed large-scale SSS pattern, and that the basin-scale details of this redistribution are not important.

In order to test this hypothesis, we conducted a new series of numerical simulations using an ocean circulation model. As in Seidov and Haupt (2003a), we use MOM version 2 oceanic model (Pacanowski, 1996) with relatively coarse resolution of $4^\circ \times 4^\circ$ with 16 layers. The physics of the model and model parameters are all the same as in our recent work (e.g. Seidov et al., 2001; Seidov and Haupt, 2003a). There are five new freshwater experiments that are summarized in Table 1 and Fig. 3 (the experiment setups are described in respective sections).

Saenko et al. (2004) have conducted similar research using the UVIC climate model of intermediate complexity, which is also indicates that Atlantic-Pacific SSS contrast may be critical for the global THC structure. They suggested that a kind of "Atlantic-Pacific seesaw" may develop because of redistribution of the freshwater between the two oceans.

The differences between the previous experiments published in Seidov and Haupt (2003a,b) and between our new experiments and the simulation in Saenko et al. (2004) can be summarized as follows. In Seidov and Haupt (2003a) the role of the SSS contrasts between the NA and NP and also between other major ocean basins have been addressed using prescribed SSS, with the salinity in the upper ocean layer adjusting to the specified SSS; the full set of parameters of sea surface conditions in that publication was wind stress, sea surface temperature (SST), and SSS. Thus, the origins of inter-basin SSS contrasts were left out of consideration, and the focus was on how the THC would respond to changes in known and prescribed SSS distributions.

Here, we expand the presentation of the follow-up publication (Seidov and Haupt, 2005) that has revisited the results of Seidov and Haupt (2003a). We analyze more advanced simulations where the SSS contrasts arise due to specified freshwater redistribution between the ocean basins, and thus focusing on both THC response to the SSS irregularities and how these irregularities may arise due to regionally unbalanced evaporation and precipitation regimes. The set of boundary conditions at the sea surface are wind stress, sea surface temperature, and highly idealized freshwater fluxes across the sea surface.

Regarding the work by Saenko et al. (2004), their work targets the response of ocean-atmosphere system to perturbation of the water balance, rather than focusing on emergence of different regimes due to structural changes in this balance.

2. Ocean conveyor and sea surface salinity

We begin by summarizing the experiments with specified SSS from Seidov and Haupt (2003a). Since no assumption on the genesis of SSS spatial distribution has been made, these runs are phenomenological in nature. We do not know and do not presume any structure of the freshwater redistribution regime that caused the observed SSS distribution. One can argue that the evaporation minus precipitation (E−P) pattern (and a lesser

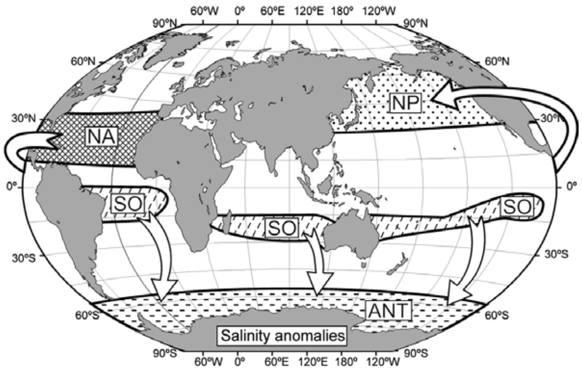

Fig. 2. A conceptual model in simulations with specified SSS anomalies (Seidov and Haupt, 2003a). Areas where SSS has been changed (see text).

important river runoff) are such that the final SSS pattern is as we see it on ocean climatology maps (e.g. Levitus and Boyer, 1994). Inter-basin SSS contrasts in experiments 3–5 are simulated by increasing SSS in the subtropical NA, and decreasing SSS in the NP in the areas shown in Fig. 2 and keeping SSS = 34.25 everywhere else.

In the second part of the paper we will show how small disparities of E−P over the world ocean can cause substantial THC change. For now, we specify a very generalized pattern of SSS that would match a very general view of salinity contrasts between major ocean basins and THC response to small changes in this idealized picture, as described in Seidov and Haupt (2003a).

The six sensitivity experiments in Seidov and Haupt (2003a) are the following: (i) the control run with annual mean sea surface SST and SSS from the Levitus and others' World Ocean Atlas and Hellerman-Rosenstein wind stress (see all appropriate references in Seidov and Haupt, 2002); (ii) the experiment with constant SSS = 34.25 psu everywhere; (iii) three experiments with idealized SSS contrasts between the NA and the NP with (a) low (about 50% smaller than observed), (b) moderate (matching observations), and (c) strong (about 50% larger than observed).

An analogy of a ‘‘freshwater air teleconnection'' or ‘‘effective salt teleconnection'' was invoked to illustrate the build-up of the Atlantic-Pacific SSS asymmetry, as shown in Fig. 2. The cartoon in Fig. 2 does not depict actual fluxes of water vapor; it just indicates that freshwater redistribution between major ocean basins leads, at least partially, to the build-up of inter-basin SSS contrasts.

As the results of these experiments with restoring to specified and highly-idealized SSS are described in the cited publications (Seidov and Haupt, 2003a), we only summarize the major inferences, without going into too much detail.

Despite only rudimentary NA-NP SSS contrasts are prescribed in these experiments, the computations tend to return a more realistic mode of the conveyor in experiment with those contrasts increase and is over a threshold of about 2.5 psu. If the amplitude of the NA-NP SSS is too small, the global conveyor and observed salinity structure cannot develop. However, if this amplitude is too large, an exaggerated overturning and vertical salinity structure develops in the Atlantic Ocean.

The bottom line is that even a moderate and rudimentary NA-NP SSS asymmetry may be sufficient for running a NADW-driven global ocean conveyor. A decrease or increase of this asymmetry can slow down or speed up the conveyor. A threshold in NA-NP SSS difference, after which a true global conveyor emerges, is less than 50% of the observed NA-NP SSS amplitude. A relatively small leveling of the NA-NP asymmetry below that threshold can even allow a competitive NP overturning.

The role of THC in sustaining inter-basin salinity contrasts is not yet completely understood. Some studies imply that the conveyor ‘‘on'' and ‘‘off'' regimes depend on NA-NP water vapor exchange (e.g. Wang and Birchfield, 1992). On the other hand, Manabe and Stouffer suggest that the conveyor itself, if started, can sustain the NA-NP SSS contrast (Manabe and Stouffer, 1988) (see also Stouffer and Manabe, 1999). Our experiments represent a different line of work, and cannot prove, or disprove results of coupled ocean-atmosphere models. Yet, we show below that they suggest that these opinions may, in fact, converge.

To comment on the conveyor capacity to sustain inter-basin SSS contrasts, we analyzed meridional salinity transport by ocean currents. In the Atlantic Ocean (Table 1) a stronger conveyor transports salinity into the northern NA, thus effectively removing freshwater from the middle latitudes, rather than compensating for its catchments. Quite opposite, a weaker conveyor fails to transport salt northward into the northern NA and Nordic Seas, and a negative feedback may establish that would further hamper the conveyor operation. This agrees well with Rahmstorf (1996) (see above) and with the results in Manabe and Stouffer (1988). However, a northward compensatory freshwater influx (i.e., negative salt transport) occurs in the South Atlantic, rather than a southward outflux suggested in Rahmstorf (1996). There is a negative northward salt transport (or effectively northward freshwater transport) across 30°S in the Atlantic, which is in agreement with recent results in Saenko et al. (2002). It is also worthwhile to mention how well salt transports in experiments 4 and 6 agree with those in experiment 1 (Table 1).

Based on these experiments, we have concluded in Seidov and Haupt (2003a) that high-latitudinal freshwater impacts, as a mechanism of altering global THC, may be less effective than inter-basin freshwater communications. These simulations suggested that exact knowledge of the spatial distribution of sea surface salinity may not be critical for THC sensitivity studies, as long as the basin-wide inter-basin SSS contrasts can be specified.

3. Freshwater disparity experiments

As has been emphasized above, rather small changes in the SSS contrast between the Atlantic and Pacific Oceans may cause substantial alteration in THC dynamics. Consequently, one may conclude that a small variation in the freshwater redistribution between ocean basins can, by altering SSS, either slow down or even terminate the conveyor, or, alternatively, considerably increase its intensity.

What should then be regarded as a ‘‘considerable change’’? If the conveyor metaphor is essentially to bring into focus the identity of the THC running in a conveyor-type mode, then we may question how much, or how little of additional rainfall or evaporation would be enough to wipe out this identity? In other words, how can we recognize the conveyor as a structured pattern? Can this pattern be already predicted given an SSS pattern, especially the inter-basin or intra-basin SSS contrasts? If yes, what are the thresholds in such contrasts beyond which the prodigious conveyor loop emerges, or at least becomes recognizable as the THC major character? Alternatively, what should the scheme of global freshwater redistribution and corresponding SSS be to make the conveyor clearly visible in the world ocean circulation pattern? In fact, all these questions presume that we are capable of recognizing different conveyor modes based on the totality of observational and computational indicators of THC (e.g., meridional overturning in the Atlantic and Pacific Oceans, vertical salinity sections, etc.).

The numerical simulations with idealized SSS contrasts described in the previous section imply that such a conveyor-related threshold in sea surface conditions may be not that high at all. In this section, we reverse the approach in order to find what changes in freshwater balance at the sea surface make the THC a global conveyor. In a way, this is a search for a ‘‘minimalist's conveyor,’’ that is, the conveyor emerging in response to small structural changes in very generalized surface salinity distribution.

We are not trying to assess the details of realistic shape, speed, or behavior of the real-world ocean THC (although, as we will show, the main character of the THC can be reproduced surprisingly well in view of the smallness of additional information). Our goal is to determine the most important structural elements of the E−P disparity that may cause the global conveyor connecting different parts of the world ocean.

Here, we simplify the entire hydrological cycle to E−P because only these two components are responsible for the large-scale sea surface salinity distributions off the high latitudes and for the utmost important generalized Atlantic-Pacific salinity contrast similar to those shown in the previous section, although river runoff and ice melting or forming are important local factors.

To address this problem, we conducted a series of very simple computer simulations of the ocean circulation driven by realistic wind and thermal forcing from the atmosphere, but with either none or simplified freshwater fluxes that may or may not bring up the conveyor character to THC. In fact, these experiments were designed to match the earlier SSS idealized specifications described in the previous section.

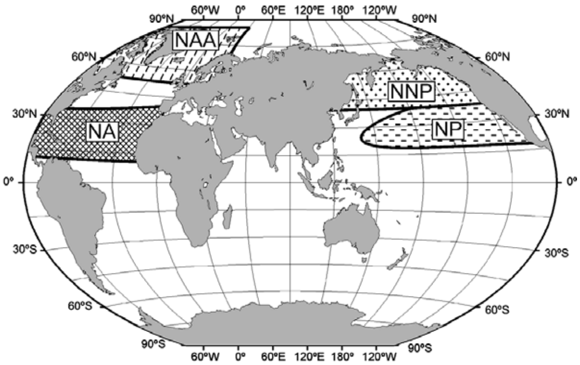

Fig. 3. Graphical information for cognition of structured patterns. There are four experiments that are summarized in Table 1 and Fig. 3.

There are five experiments that are summarized in Table 1 and Fig. 3. All runs start from an initially homogeneous ocean state with a temperature of 4 °C and a salinity of 34.25 psu (practical salinity unit) everywhere and continue for two thousand years in the upper ocean (effectively to 10,000 years in deep-ocean model time; we use accelerating technique with two different time scales in the upper and deep layers (Pacanowski, 1996; see also Bryan, 1984)). In all experiments, the temperature of the upper ocean layer relaxes to the annually mean observed sea surface temperature (Levitus et al., 1994). Wind stress is specified from Hellerman and Rosenstein (1983). Thus, the only difference in the experimental setups is in the freshwater fluxes across the sea surface.

First, we show two sets of figures. The SSS at the end of each run is shown in Fig. 4 (except for experiment 2, which unsurprisingly yielded a homogeneous SSS unchanged and equal 34.25 psu everywhere), and the meridional overturning in the Atlantic and Pacific Oceans in all five experiments in Fig. 5.

Experiment 1 (Table 1) is, conventionally, the control run, and all three forcing fields – wind stress, SST, and SSS – are annually mean observed values from Hellerman and Rosenstein (1983), Levitus et al. (1994) and Levitus and Boyer (1994). The results of experiment 1 are the same as those shown in Seidov et al. (2001),

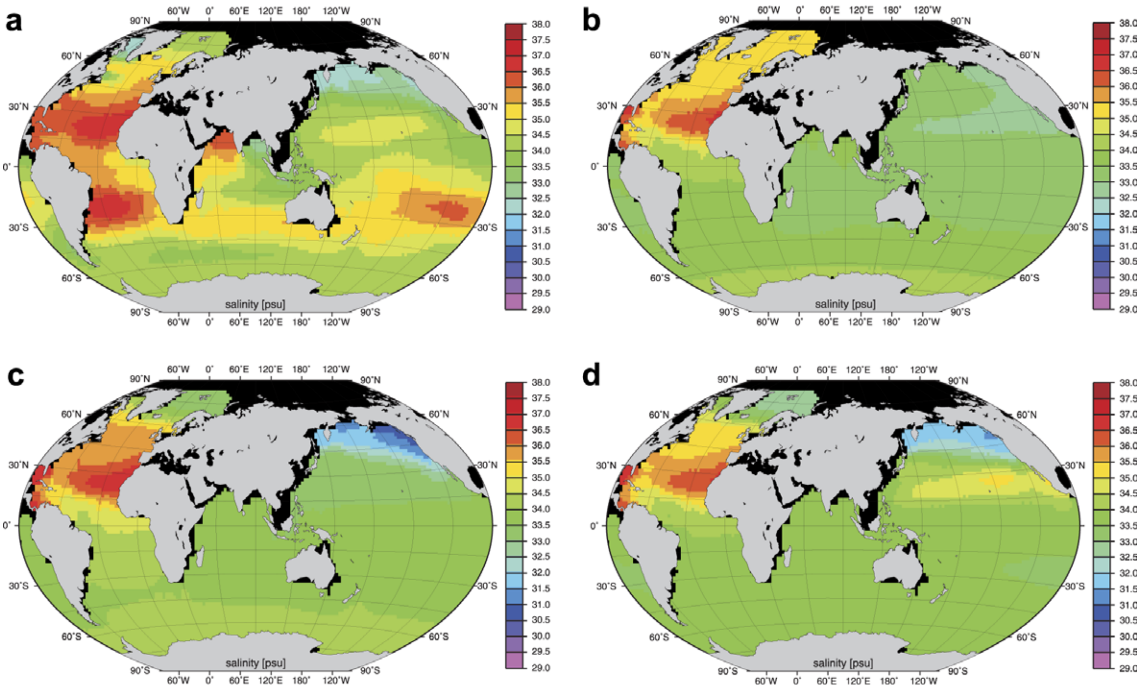

Fig. 4. Sea surface salinity in psu: (a) experiment 1, (b) experiment 3, (c) experiment 4, and (d) experiment 5.

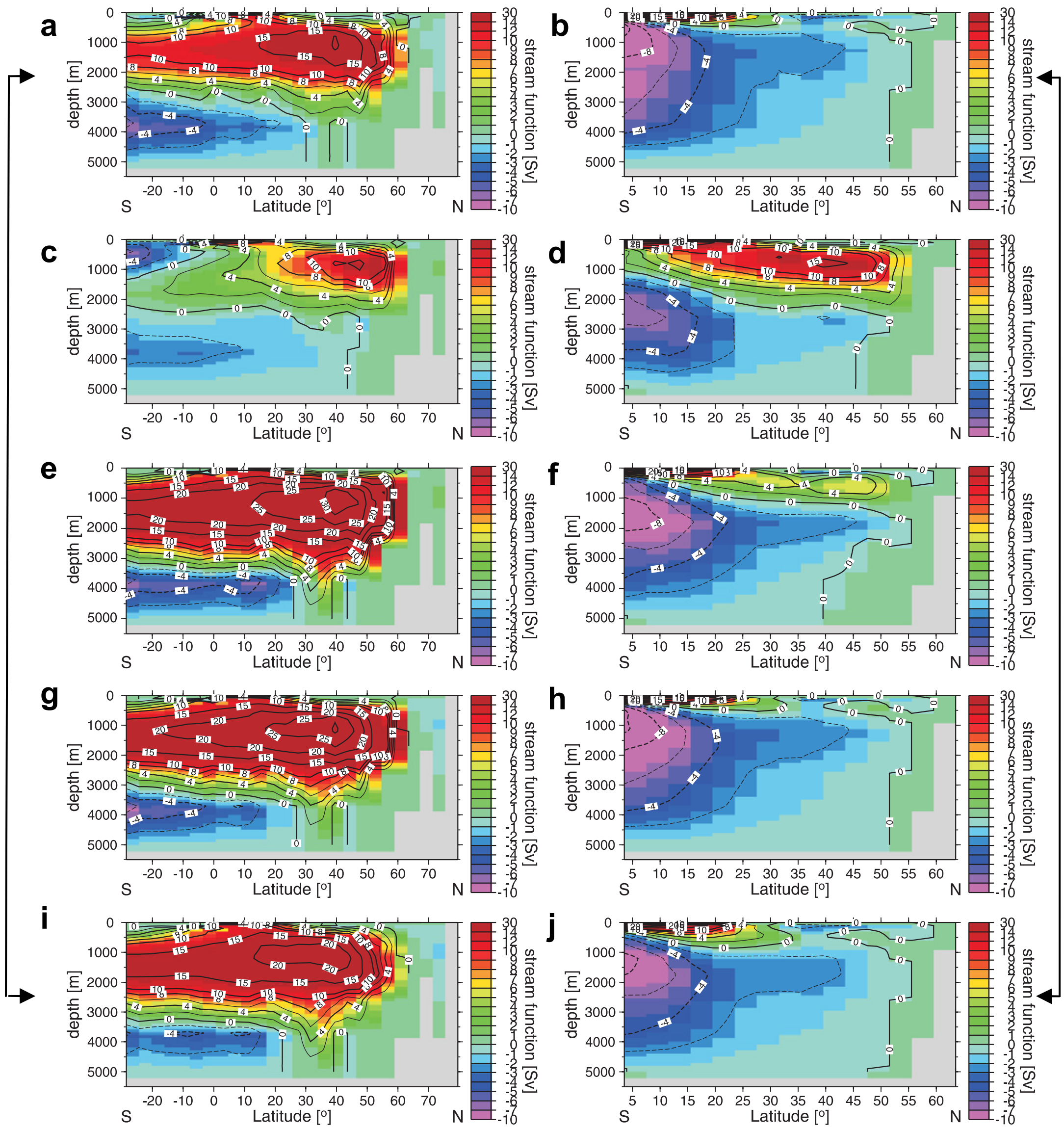

Fig. 5. Meridional overturning in the Atlantic Ocean (left panel) and in the Pacific Ocean (right panel) in experiments 1–5 (from top to bottom; see Table 1). The overturning is shown in Sv (1 Sv = 106 m^3/s). Note transformation of the NP overturning cell from a non-conveyor, to a global conveyor pattern (two connecting lines with arrows emphasize the similarity of the control run (experiment 1) and experiment 5).

Seidov and Haupt (2003b) and Seidov and Haupt (2003a). A reasonable global ocean conveyor has repeatedly emerged in all control experiments, restoring to the observed SST and SSS values. The goal of this new series is to find the basic patterns of freshwater fluxes that would be sufficient for running a global conveyor.

To simulate a hypothetical world ocean without water cycle (or a water cycle with E−P totally balanced locally), another reference run, additional to the traditional control experiment, has been conducted. In this run initial salinity was set constant everywhere, including the sea surface, and the freshwater fluxes across the sea surface were set to zero everywhere over the world ocean (experiment 2 in Table 1). In this experiment, the sea surface salinity cannot change and remains constant (34.25 psu) everywhere. The THC in experiment 2 is entirely different from experiment 1: The North Atlantic and North Pacific Oceans are not connected by a deep ocean THC, and deepwater production occurs in both oceans – a complete contradiction to the known fact that no deepwater is produced in the North Pacific Ocean.

This result taken out of a context is trivial – it is well known that salinity is responsible for the global THC as observed in the ocean (therefore the "salinity conveyor belt" in the original paper (Broecker, 1991)). However, here we use this extreme case as the starting point in our simplified freshwater-driven experiments to find out at what point the THC bifurcates and familiar features of the global conveyor come into view. Both, experiments 1 and 2 are described in detail in recent publications (Seidov and Haupt, 2003a,b) and summarized in the previous section, so we skip a further discussion here.

Experiments 1 and 3–5 are illustrated in Figs. 4 and 5. The SSS distribution built by the combined forces of freshwater fluxes and advection by ocean currents is shown for these three experiments, while the control run is restored to the observed SSS. Fig. 4 shows the Atlantic (left) and Pacific (right) overturning in all five experiments (including the experiment 2, which is the run with "zero" hydrological cycle).

Experiment 3 in Table 1 is the first in the series and the simplest possible inter-ocean freshwater redistribution, which is the removal of freshwater in the North Atlantic Ocean and re-depositing it in the North Pacific. That is, in this setup, the removal of freshwater creates a positive SSS anomaly in the central North Atlantic and a negative anomaly in the North Pacific, that is, in the areas NP and NNP in Fig. 3 combined (in Table 1 we denote freshwater removal as negative and freshwater adding as positive values to emphasize SSS change induced by these fluxes). The setups of experiments 4 and 5 are slightly different from the one in experiment 3 (see below).

In experiments 3–5, the freshwater fluxes are small (varying from 0.035 Sv (1 Sv = 10^6 m^3/s) in the central North Atlantic to even smaller numbers in other parts of the world ocean). Although, they follow observed or modeled patterns (e.g. Gent et al., 1998; Stammer et al., 2004; Tziperman and Bryan, 1993; Wijffels, 2001), these fluxes have very generalized spatial distributions (see Fig. 2), without the fine details of observed evaporation and precipitation patterns. The hope is that despite the lack of many details in hydrological cycle a schematic global ocean conveyor may nonetheless emerge. It turned out that the THC structure we were looking for – deepwater formation in the northern NA (NNA) and upwelling in the northern NP (NNP) – did not emerge in this run and, thus, a global conveyor did not materialize. Therefore, we continued to tune the most basic E−P pattern of experiment 3 by adding new elements in experiments 4 and 5.

Although, the E−P anomalies lack realistic spatial distribution, the magnitude of the inter-basin water balance disparities is quite realistic. For example, Stammer et al. (2003) suggests that the removal rate in the Atlantic Ocean is about 0.05 Sv at 10°N and 0.025 Sv at 37°N. Our median number 0.035 Sv matches these estimates quite well.

To add a little more realism to the Northern Hemisphere water balance, some additional evaporation was assigned to the central NA in experiment 4, with part of the evaporated water precipitating in the NNA, while the rest of the added freshwater precipitating evenly around the world ocean. Evaporation in NP is introduced to make surface water slightly saltier in the NP area (Fig. 3), and the removed freshwater is also redistributed evenly around the globe, so the water balance is always maintained globally. The freshwater flux is globally balanced and designed just to mimic the large-scale SSS distribution in the North Atlantic and North Pacific (experiment 4), with a secondary freshwater flux added in experiment 5 to reproduce the fresher surface water pattern in the NNP. The basic freshwater flux of experiment 4 still maintains the main Atlantic-Pacific SSS contrast achieved in experiment 3. Yet, it introduces a new element of meridional contrast in the North Atlantic Ocean that mimics freshwater redistribution within the NA to keep the Nordic Seas and some portion of the NNA substantially fresher than the subtropical waters. A global conveyor comes into sight already in experiment 4. It can be now unambiguously recognized as a global conveyor-like THC pattern. Indeed, the overturning cell in the northern Pacific is greatly reduced, with the northward incursion of AABW and AIW noticeably increased.

Still, the intensity and the structure of the THC do not match the observed conveyor close enough. Obviously, the overturning in the Atlantic Ocean is too strong and there is still some deepwater formed in the North Pacific, although the whole picture is qualitatively different from experiment 3. The last and the most "realistic" in the series, experiment 5 is even more successful in depicting the conveyor. Importantly, this substantial improvement of experiment 5 over experiment 4 is due to a very small freshwater outflow added to the "zeroed" freshwater fluxes over subtropical NP (Table 1), with part of this freshwater removal precipitating in the NNP and the residual distributed over the world ocean (as described above for experiment 3). However, this additional small freshening in the NNP in experiment 5 leads to cardinal improvement in the Pacific over-

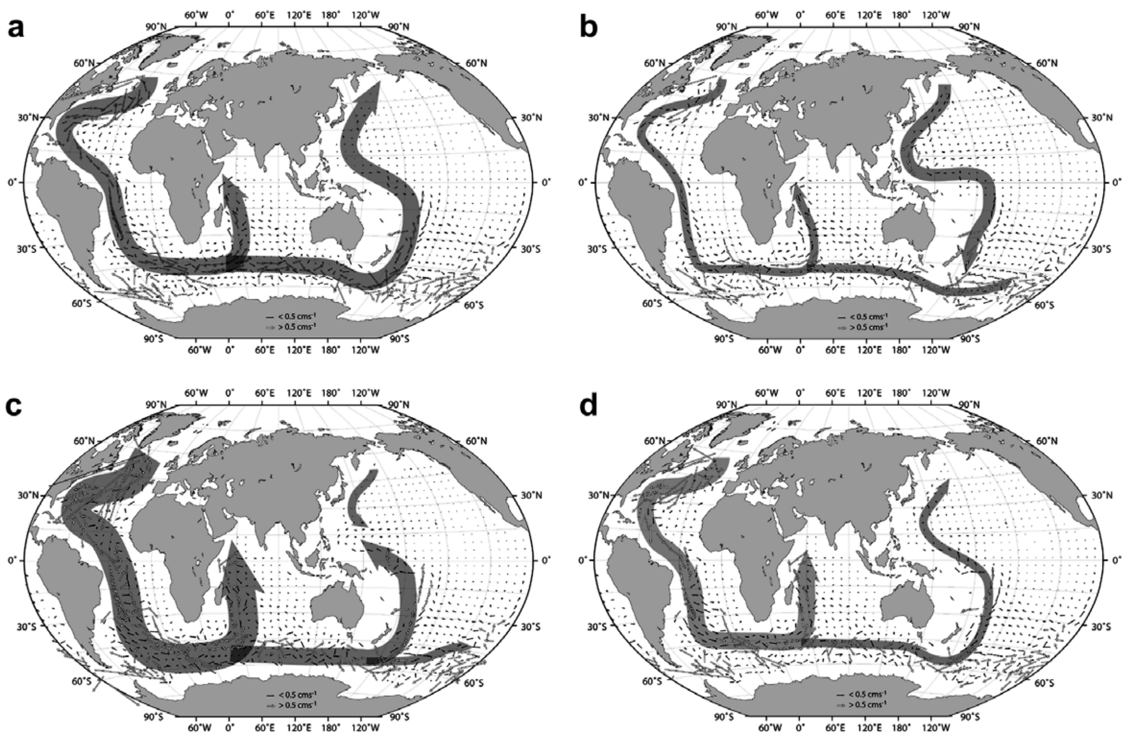

Fig. 6. Velocity vectors at 2.5 km depth from four experiments: (a) experiment 1, (b) experiment 2, (c) experiment 3, and (d) experiment 5. The NADW transport in the deep-ocean is schematically shown to emphasize the difference in the deep-ocean branches of the global THC in four different patterns of freshwater fluxes across the sea surface (see text, Table 1, and Fig. 3).

turning and, eventually, to emergence of the fully-developed global conveyor very similar to the one observed today and seen in the control simulations.

It is easy to understand that the increase of north-south SSS contrast caused by additional precipitation and thus freshening of the NNA and Nordic Seas can reduce the strength of the Atlantic THC. However, it is less obvious that this additional freshening in the Atlantic may have any effect on the overturning cell in the northern Pacific. Weakening of the overturning in the NNA, and thus making the THC there more compliant with observation, is exactly the consequence of increased ‘‘globality’’ of THC, that is, a stronger upwelling of transformed NADW reaching out into the NNP. Stronger upwelling increases density stratification and causes lessened overturning.

The maps of deep-ocean currents at 2.5 km are shown in Fig. 6. The schematic deep ocean flow represents the travel of NADW from its origin in the NNA and the Nordic Seas around the globe. The global conveyor mode of present-day observed THC in Fig. 6a is in striking contrast with a ‘‘broken’’ conveyor in the case of absent freshwater flux across the sea surface in experiment 2 (Fig. 6b). As the conveyor regains its global character in subsequent experiments experiments 3–5, we show only experiment 3 with the Atlantic overturning overshoot (Fig. 6c) and our final experiment 5 (Fig. 6d). Although sea surface freshwater flux is still very schematic, the structure of the conveyor, especially its global character, is markedly similar in Fig. 6a and b.

4. Discussion and conclusions

A small structural element (here an additional meridional variability of freshwater balance in the Pacific Ocean) appeared to be crucial to the fate of the THC as a globally structured entity. What further speculation can be drawn? Based on these simple simulations, it is tempting to consider combined effect of salinizing of the central NA and freshening of the NNP, rather than formation of NADW alone as the crucial element of the THC dynamics observed today. There are two possibilities for the NNP to connect to the abyss – either through upwelling of the NADW (modified in the Southern Ocean) or deepwater production, thus cutting off NADW northward incursion. Thus, one might hypothesize that short circuiting of freshwater within the NP could be sufficient for suppressing deepwater production and thus giving way for the fully-functional global conveyor.

As tempting as it is, this hypothesis can only be tested in a more advanced coupled model and proxy data analysis of past THC structures, with different freshwater partitions between major ocean basins. Our simple experiments with an ocean-only model driven by very simplified freshwater fluxes cannot definitively answer the questions about the THC dependence on ocean-atmosphere interactions. These questions can only be fully stated and answered in a coupled climate model with advanced hydrological cycle. However, our experiments shed some light on how the THC may depend on freshwater disparity between the major ocean basins. They demonstrate that the freshwater fluxes that help building NA-NP contrast are necessary but not sufficient for running the observed global THC, even in a minimalist's setup. Another key element is needed – the meridional contrast between subtropical and polar regions in both oceans.

It should be kept in mind that THC is indeed not only a heat but also a "salt" machine. In our simple experiments, it would grow unrestrictedly if the build-up of salt concentration in the central NA by THC would not be constantly removed by THC. After 2000 years of the build-up, SSS in the NA without THC control would have reached absolutely unrealistic values.

Basically, our calculations suggest that the Atlantic-Pacific freshwater disparity speeds up the conveyor, whereas the subtropical-polar disparity puts the brakes on the overturn (specifically, the conveyor in the Atlantic Ocean is too fast in experiment 3, and slows down in experiments 4 and 5). And, last, but not least, it looks as though the meridional freshwater redistribution bending salinity southward in the NP is responsible for the Atlantic-Pacific deep-ocean interconnection, and eventually for the global conveyor itself.

It makes sense to note that the surface distribution of SSS resembles the observed pattern in the Northern Hemisphere. In additional experiments (not shown), we were able to reverse the global conveyor by modifying the three major elements of the idealized hydrological setup described above. As soon as the north-south gradient in the North Pacific reached the magnitude characteristic to the NA, and vice versa, a fully reversed conveyor developed. Additionally, introduction of similarly idealized freshwater redistribution in the Southern Hemisphere (small freshwater outflow from the ocean in the southern subtropics, and small influx in the Southern Ocean) further improved the overall conveyor functionality by increasing AABW and facilitating northward cross-equatorial salt transport in the tropical Atlantic.

The following important conclusion can be drawn: the very nature of the global salinity conveyor depends critically on only one parameter, namely the salinity difference between the Atlantic and Pacific Oceans. If there is no sufficient SSS contrast of this nature, the global conveyor cannot develop. Thus, freshening of the Atlantic Ocean found in new analyses of salinity observations (e.g. Curry et al., 2003) can potentially be a factor in the overall global conveyor functionality as it affects the Atlantic-Pacific SSS contrast.

However, this is only a necessary but not a sufficient condition for running even a "minimalist's" global conveyor. (Throughout this paper we consider a THC structure as a "minimalist's conveyor" when a global conveyor emerges possessing major features of the observed THC but not its finer details; we also ignored the feedbacks between the SST and freshwater transports in the atmosphere, e.g. Tziperman and Gildor (2002)) The SSS contrasts between mid-latitudinal relatively salty waters and high-latitudinal fresher waters in the NA (and to a lesser extent, in the NP) is another critical element of the "minimalist's global conveyor" matching the major recognized pattern of a global conveyor versus disconnected local-basin circulation systems.

Another important conclusion is that AABW, in contrast to NADW, is largely thermally driven, as its dominance over the deep ocean was secured without any additional freshwater redistribution over the Southern Ocean. Moreover, the freshwater fluxes in the Southern Hemisphere are not as critical to the fate of the global conveyor as they are in the Northern Hemisphere (see above).

A more general hypothesis can thus be put forward that the whole complex of the ocean-atmosphere-ice interactions needs to yield an astonishingly simple main pattern of water cycle responsible for the global salinity conveyor belt. The simplicity of this pattern may contribute to stability of the observed climate, as minor details seems unimportant for maintaining the global conveyor – the key element of the climate system in the long run. In our simple experimental ocean-only approach we cannot prove this hypothesis; we hope, however, that fully coupled climate models can prove its viability.

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