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FRESHWATER TRANSPORT IN THE NORTH ATLANTIC OCEAN

by

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Abstract

Global conveyor belt ocean circulation compensates fresh water loss (0.3 Sverdrups) from the North Atlantic ocean to the atmosphere. The difference between the North Pacific and the North Atlantic mean steric level height (0-5000 dbar) is 0.94 m, 3/4 of this value is explained by salinity contrast.

The freshwater flux is determined with traditional formulation. Meridional freshwater flux (MFWF) is evaluated according to water balance method with correction using atmospheric water transport and evaporation minus precipitation over the land. To obtain the anomalies of the MFWF and heat transport in the oceans the World ocean flux is divided in accordance with the width of the basins. This values are subtracted from the real ones at the proper latitude. The analysis of the anomalies allows to conclude that the heat transport returns energy to the North Atlantic through the Indian ocean, while the equal parts of freshwater are driven to the North Atlantic from the Arctic ocean and from the Pacific ocean through the Drake Passage and the equator.

Anomalous direction of freshwater transport is explained using water mass transport inverse model with additional Ekman component and barotropic Sverdrup flux in western boundary currents. Parametric form of meridional velocity as a function of temperature assuming the sharp T(S) relation and kinetic energy minimum is used. The main component of the northward MFWF in the Tropical Atlantic is the Antarctic Intermediate water. The southward MFWF from the Arctic ocean penetrates to the North Atlantic in the upper layer in the western boundary current and sinks to the deep layer in the Polar Front Zone (PFZ). Climatic conditions in the PFZ region determine the intensity of this downwelling of freshwater and MFWF to 20°N.

Seasonal variability of freshwater transport reveals the existence of southward flux in all latitudes of the North Atlantic in May-July instead of presumably northward MFWF in other seasons. The interannual variability of freshwater transport is much less than the seasonal one.

Introduction

The North Atlantic is the unique region with extremely intensive energy exchange. Occupying only 11% of the World ocean's surface, this basin provides 21% of the sensible heat flux and 16% of the latent heat flux to the atmosphere (Lappo, Gulev, Rozdestvensky, 1990). In addition, the surface of the North Atlantic is a strong evaporative area with the negative fresh water balance of over 0.3 Sverdrups (Dobroliubov, 1991; Schmitt et al.,1989).

North Atlantic volume mean potential temperature and salinity (including the Arctic ocean and the other marginal basins) is 1.3°C and 0.5 psu higher than in the North Pacific. The difference between the North Pacific and the North Atlantic mean steric level height for the layer 0-5000 dbar is 0.94 m; 77% of this value is determined by the salinity contrast (Dobroliubov, 1987). According to so-called "global conveyor" hypothesis (Broecker, 1991), upper layer warm water flows in accordance with the sea-level inclination from the Pacific to the Atlantic ocean, downwells in the North Atlantic and moves back as a cold deep water. It is now apparent that variations in water balance do modulate thermohaline overturning cell and meridional heat transport in the northern part of the Atlantic ocean by decreasing deep water formation (Lazier, 1980; Dickson et al., 1988; Delworth et al.,1993). Thus conveyor disturbances on decadal to millennial time-scales should reflect variations in North Atlantic fresh water fluxes.

Our present understanding of fresh water cycle in the oceans is rather poor. The problem is explained mainly by limitations of ocean salinity and current velocity observations and difficulties in precipitation measurements. Numerous climate research programs such as GEWEX, WOCE, CLIVAR, JGOFS are aimed to assess the ocean fresh water budget and to reveal its interaction with heat flux. This paper provides some new results carried out as the contribution to the international programs. The main objectives of this research are:

- to obtain a reliable estimation of the annual mean meridional fresh water flux in the North Atlantic;
- to define main routes of heat and fresh water transport in the "global conveyor" between the North Pacific and North Atlantic;
- to determine main components (or water masses) transporting fresh water and heat in the oceans;
- to evaluate seasonal and interannual variability of the meridional fresh water fluxes in the North Atlantic.

Meridional freshwater fluxes

The **meridional transport of freshwater in the oceans F°** is determined with traditional formulation of fresh water flux (Stommel,1980; Fu,1987) as the divergence of water flux in a control volume with varying salinity on its boundaries. For the latitudinal section of the ocean meridional freshwater flux F° may be written as follows:

$$F^{o} = -\frac{\overline{S'\cdot(\rho\cdot v)'}}{\bar{\rho}\cdot\bar{S}} \qquad (1)$$

where ρ is the water density, **S** is the salinity, **v** is the meridional cross-sectional velocity, overbars represent the sectional averages and primes denote the deviations from sectional averages.

Another formulation $\mathbf{F^{o*}}$ was suggested by (Wiffels et al.,1992):

$$\mathbf{F^{o*}} = \rho(\bar{v} - \bar{v}\cdot\bar{S} - \overline{v'\cdot S'}) \qquad (2)$$

Equation (2) represents negative salt flux similar to (1) only in the case where ‾ =0. When we consider ocean basins with throughflows of order 1-10 Sverdrups (Indonesian seas, the Bering Strait) the effect of evaporation minus precipitation over the basins (less than 0.5 Sv) is absolutely neglected by total mass imbalance and its uncertainty. So meridional freshwater flux (MFWF) formulation according to (1) seems to be preferable in comparison with (2). In this case, of course, additional error originates from the reference salinity uncertainty, but the error is two orders less than in (2).

The evaluation of MFWF by the "direct method"(1) and oceanographic data along the latitudinal section produces large uncertainties (Rago, Rossby, 1987; Dobroliubov, 1991). Thus the more appropriate technique is "water balance method": F^o is evaluated in this case from the surface budget of the observed region (Stommel, 1980):

$$\text{div}F^o = (E^o - P^o - R^o) \qquad (3)$$

where E^o, P^o and R^o are the volumes of evaporation, precipitation and runoff, respectively.

In order to reduce errors in evaporation minus precipitation over the oceans the atmospheric water transport F^a and evaporation minus precipitation over the land $(E^L - P^L)$ in the appropriate latitude belt are used (Dobroliubov, 1981):

$$E^o - P^o = \text{div}\, F^a + P^L - E^L \qquad (4)$$

The data used to determine MFWF according to the equations (3) and (4) are mean values in latitudinal belts from different sources: precipitation and evaporation over the land are taken from (Baumgartner,Reichel,1975) and (World water balance...,1974), ocean precipitation is averaged from (Elliot, Reed, 1984; Bogdanova, 1986; Baubgartner, Reichel, 1975; World water balance, 1974), ocean evaporation is estimated from (Baubgartner, Reichel, 1975; World water balance, 1974; Isemer, Hasse, 1987;Strokina,1991). Runoff is calculated from (Baumgartner,Reichel,1975) and (World water balance...,1974). The meridional water vapour flux divergence is taken from (Peixoto, Oort, 1983).

The $(E^o - P^o)$ value for any latitudinal belt over the World ocean is estimated in two ways: as a simple difference between the evaporation and precipitation volumes and according to (4). The difference between the two values imply a corrections over the World ocean. This corrections do not exceed 30% of individual $(E^o - P^o)$ and are distributed over the certain ocean basins in proportion to the precipitation volume. Then the integration is carried out for every ocean to calculate MFWF from the northern boundary to the Antarctic coast.

MFWF at the northern boundary is determined from (1) according to interbasin flux characteristics. If we combine the North Atlantic with the Arctic basin, then the transport through the Bering Strait should be used as the starting value for the integration of (3) over the Atlantic. Volume fluxes of 0,8 Sv in the Bering Strait (Coachman, Aagaard,1988) and freshwater 13 Sv in the Indonesian passages (Dobroliubov, 1996) are used. Using salinity data from (Levitus, 1994), one can obtain the annual mean fresh water flux from the Pacific to the Arctic ocean of 0.06±0.01 Sv.

The integration errors accumulated on the South Pole are compensated according to the equation given in (Carissimo, Oort, Vonder Haar, 1985):

$$F^{o'}(\varphi) = F^o(\varphi) - F_{SP} \cdot [\frac{1}{2} - \frac{\varphi}{\pi} - \frac{\sin(2\varphi)}{2\pi}] \qquad (5)$$

where φ - latitude, $F^{o'}(\varphi)$ -corrected value of MFWF, $F^o(\varphi)$ - the flux computed during the first integration from the North Pole, F_{SP} - accumulated transport at the South Pole). Then the correction (5) for the World ocean is added to the MFWF in the individual oceans in proportion to their area to the north of the corresponding latitude φ.

The total uncertainty of MFWF in the ocean represents the r.m.s. sum of errors within the integrated latitudinal zones (70-90% of the total error explained by **(E-P)** uncertainty) and the interocean flux uncertainty. Finally the obtained meridional freshwater flux and corresponding errors for the Atlantic are presented on Fig. 1.

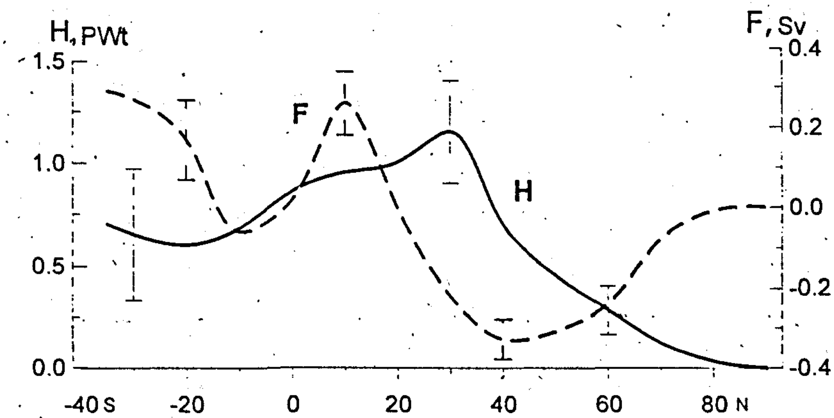

Fig. 1. Meridional heat and freshwater fluxes in the Atlantic ocean (positive - northhward).

Returning freshwater flux from the Pacific to the Atlantic through the Bering Strait is only 1/5 of the total Atlantic freshwater loss, 45% of freshwater reaches the Atlantic through the Southern ocean, the remainder flux originates from the Arctic basin. Similar results were reported by (Broecker et al., 1990). For the comparison the meridional heat transport (MHT) is also displayed. It is calculated as a mean value of 13 independent balance estimations given in (Gulev, Lappo, Rozdestvensky, 1990), error bars represent r.m.s. deviations of this mean at the corresponding latitude. It's interesting that maximum of MHT coincides with the region of freshwater convergence near the 25°N.

Anomalies of meridional transport and possible routes of fresh water and heat to the North Atlantic

In order to define possible routes of returning freshwater and heat transport to the Atlantic we determine meridional flux anomalies. The term "meridional flux direction anomaly" was first used in (Stommel, 1980). Stommel explained nortward direction of MHT in the South Atlantic and southward direction of MFWF in the South Pacific with the "global conveyor" hypothesis. But now it's obvious that MFWF contains two extremes in each hemisphere, so we need to revise this term.

To obtain the significant anomalies of the MFWF and heat transport in the oceans (not necessarily in direction) the following procedure is done. The World ocean flux is divided in accordance with the width of the three basins - Atlantic, Pacific and Indian oceans. This values are subtracted from the real ones (taking into account the interbasin exchanges) at the corresponding latitude. The resulting anomalies of heat and freshwater are presented on Fig. 2 and 3.

Significant MHT anomalies takes place in the Atlantic (northward) and in the South Indian ocean (southward), while MFWF contains anomalies in all the basins. The North Atlantic reveals additional southward freshwater flux in the mid- and high latitudes and northward anomaly in low latitudes.

The analysis of the presented anomalies allows to detect the role of interocean exchange in freshwater and heat redistribution. South Indian and Atlantic MHT anomalies confirm advection of heat from the Pacific to the Atlantic in the "global conveyor" through the Indonesian seas and the Agulhas current system (so-called "warm route"). On the contrary, southward anomaly of MFWF in the South Indian is replaced by northward one and the Atlantic ocean is filled with additional freshwater through the northern boundary and from the South Pacific (two different "cold routes"). Hence **"global conveyor" returned heat and freshwater to the North Atlantic by different ways!**

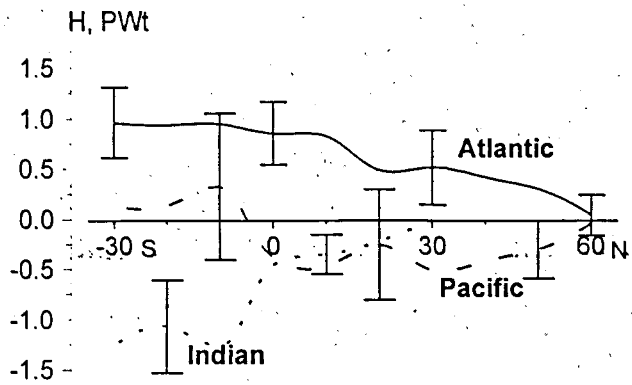

Fig. 2. Meridional heat flux anomaly in the individual oceans.

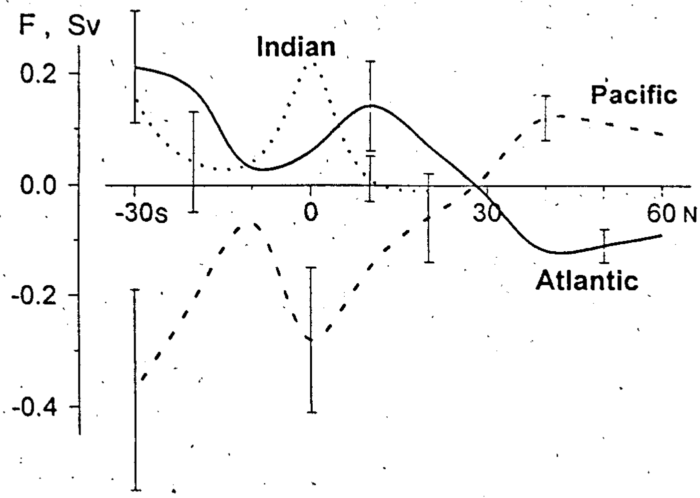

Fig.3. Meridional freshwater flux anomaly in the individual oceans.

Components of the meridional freshwater and heat transport in the North Atlantic

To determine main components transporting fresh water and heat in the oceans a simple water mass inverse model is used. The model was first proposed by Stommel and Csanady (1980) and allowed to evaluate fluxes within T,S-classes:

$$\begin{aligned} \iint m(S,T)dSdT &= \rho F \\ \iint Tm(S,T)dSdT &= H/c_p \\ \iint Sm(S,T)dSdT &= 0, \end{aligned} \tag{6}$$

where **S**- salinity, **T**- temperature, c_p - specific heat, ρ -density, **F** and **H** - meridional freshwater and heat flux accordingly, mass transport function **m(S,T)** defined as follows:

$$m(S,T) = \rho(S,T)\, a(S,T)\, v(S,T) \tag{7}$$

where **a(S,T)** - area-density function, **v(S,T)** - average northward velocity of water in proper **T,S**-class. Stommel and Csanady suggested to use parametric form of meridional velocity as a function of temperature assuming the sharp **T(S)** relation:

$$v(T) = b_0 + b_1 T + b_2 T^2 \tag{8}$$

In this case coefficients b_i are unknown, **a(S,T)**, **H** and **F** are defined from the annual mean distribution at the given latitude. Shortages of parametrization (6-8) are explained mainly by the assumption of only one MHT and MFWF component in the ocean - meridional overturning cell with one meridional velocity extreme. Really the situation, of course, more complicated. In order to improve the results it is proposed:

- to take into consideration additional components of meridional heat and freshwater fluxes such as Ekman flux, interbasin exchange and barotropic Sverdrup transport in the western boundary current

- to use the condition of kinetic energy minimum and to increase order of parametrization (8) by one. As a result the system (6-8) is written in a form:

$$\begin{aligned}
&b_0\int a dT + b_1\int T a dT + b_2\int T^2 a dT + b_3\int T^3 a dT = F - K_W - K_E - K_I \\
&b_0\int T a dT + b_1\int T^2 a dT + b_2\int T^3 a dT + b_3\int T^4 a dT = H\cdot(\rho c_p)^{-1} - K_W T_W - K_E T_E - K_I T_I \\
&b_0\int S a dT + b_1\int T S a dT + b_2\int T^2 S a dT + b_3\int T^3 S a dT = -K_W S_W - K_E S_E - K_I S_I \qquad (9) \\
&\int (b_0 + b_1\cdot T + b_2\cdot T^2 + b_3\cdot T^3)^2 dT = \min,
\end{aligned}$$

where $v=(b_0+b_1\cdot T+b_2\cdot T^2+b_3\cdot T^3)$, volume flux K_W is determined according to Sverdrup relation, K_E – Ekman transport, K_I - interbasin exchange (0.8 Sv in the Bering Strait), corresponding values of temperature and salinity T, T_E, S, S_E are determined from zonal mean values (Levitus et. al., 1994), T_W, S_W are calculated as areal means for the westernmost part (~150 km) of the latitudinal section. Wind characteristics are taken from (Hellerman, Rosenstein, 1983). After resolving the system (9) and determination we can evaluate MHT and MFWF in any layer of midocean area. The boundaries between the layers in the midocean part coincide with isopycnals 27.00 and 27.60; at 57.5N - with isopycnals 27.60 and 27.74.

The results of this estimation at different latitudes are presented at Table 1.

Table 1

Components of meridional volume (k, Sv), freshwater (F, 10^{-2} Sv) and heat fluxes (H, 10^{15}Wt) in the oceans

components		latitude					
		57,5N	27,5N	7,5N	7,5S	17,5S	32,5S
Ekman flux	k	-4	4	12	-16	-8	1
	F	-4	-17	-10	42	40	-1
	H	-0,1	0,4	1,3	-1,6	-0,8	0
Barotropic boundary current	k	-31	38	-5	7	-9	-32
	F	-12	-88	1	-2	4	9
	H	-0,5	3,0	-0,2	0,2	-0,3	-0,9
Midocean upper layer	k	35	-33	-4	27	24	20
	F	-7	100	19	-56	-46	-14
	H	0,8	-2,3	-0,6	2,0	1,5	0,9
Midocean intermediate layer	k	13	11	21	9	14	29
	F	-3	2	13	6	13	33
	H	0,2	0,2	0,6	0,2	0,3	0,6
Midocean deep layer	k	-13	-20	-24	-28	-20	-18
	F	-1	-18	-2	0	-2	0
	H	-0,1	-0,2	-0,2	-0,2	-0,2	-0,1

The main reason to use the models of this type is to verify the correspondence between the observed circulation and the evaluated total fluxes of heat and freshwater. From this point of view the situation is quite reliable. Volume transport in the deep layer looks reasonable - of order 20 Sv southward (including the deep part of the western boundary current). Usually the direction of upper and intermediate layer transport coincides well in the Atlantic, the total values (with Ekman and corresponding barotropic components) range from 5 to 20 Sv. According to the Table 1, the main components of MHT in the North Atlantic are: interaction of Ekman flux with upper layer transport in tropical regions ("shallow overturning cell"), western boundary current and upper midocean countercurrent in subtropical and subpolar regions ("gyre circulation").

Main components of the meridional freshwater flux in the North Atlantic are quite different. In subpolar regions the leading process is the freshening in southward flowing western boundary current, in subtropical regions the direction of freshwater flux is determined by transport of highly saline water in anticyclonic gyre (MFWF in the Gulf Stream is directed to the south, i.e. opposite to the volume flux). In the tropical region the direction of MFWF is determined by southward flowing upper layer and northward flow of the Antarctic Intermediate water.

If we combine the above mentioned six components into three layers - upper, intermediate and deep, then the role of zonal mean thermohaline circulation would be more pronounced. In this case it's clear that two-layer global conveyor is a good approximation for the heat transport in the oceans: upper and intermediate layer determine the direction of MHT, deep water produces "the flux of cold". But as for the freshwater transport, the situation is more complicated. Upper layer low-salinity water is responsible for the advection of freshening from the poles to the Polar Front zones in high latitudes of both hemispheres. This freshening includes both liquid part and ice movement. The Polar Front zones are the regions where the MFWF changes the layer - freshwater sinks to the intermediate layer and penetrates to the low latitudes as the Antarctic Intermediate water or the North Pacific Intermediate water. The North Atlantic Polar Front is the only zone with freshwater downwelling to the deep layer (if the Labrador sea water is really deep water). The MFWF converges near 20N in the North Atlantic: southward flux in the deep layer encounters with northward transport of Antarctic intermediate water.

Thus climatic variations near Polar Front zones can shift the sinking of freshening from one isopycnal interval to another. Finally the leading components of the freshwater transport in the World ocean and values of total MFWF are represented on Fig. 4.

Seasonal variability of the freshwater transport

Large uncertainties in annual mean freshwater transport, lack of available data and some inherent difficulties (impossibility of corrections such as (4) or (5)) cause to treat with suspicion to any estimates of seasonal MFWF. Nevertheless, such attempts are very important both for the determination real mechanisms of freshwater redistribution and for the detection of interannual signal.

Seasonal budget of freshwater contains additional component - changes of freshwater storage in the upper layer of the ocean $\frac{\partial F_i}{\partial t}$. This component is evaluated from seasonal salinity changes $\mathbf{S}^h$ (Levitus, 1986):

$$\frac{\partial F_i}{\partial t} = -\frac{1}{S_{ai}} \cdot \frac{\partial S_i^h}{\partial t} \qquad (10)$$

where $\mathbf{S}_{ai}$ – annual mean upper layer salinity in the corresponding latitudinal belt **I**. We use salt storage data from (Levitus, 1986) and accepted his seasons: February-April, May-July, August-October and November-January. After estimating freshwater storage change

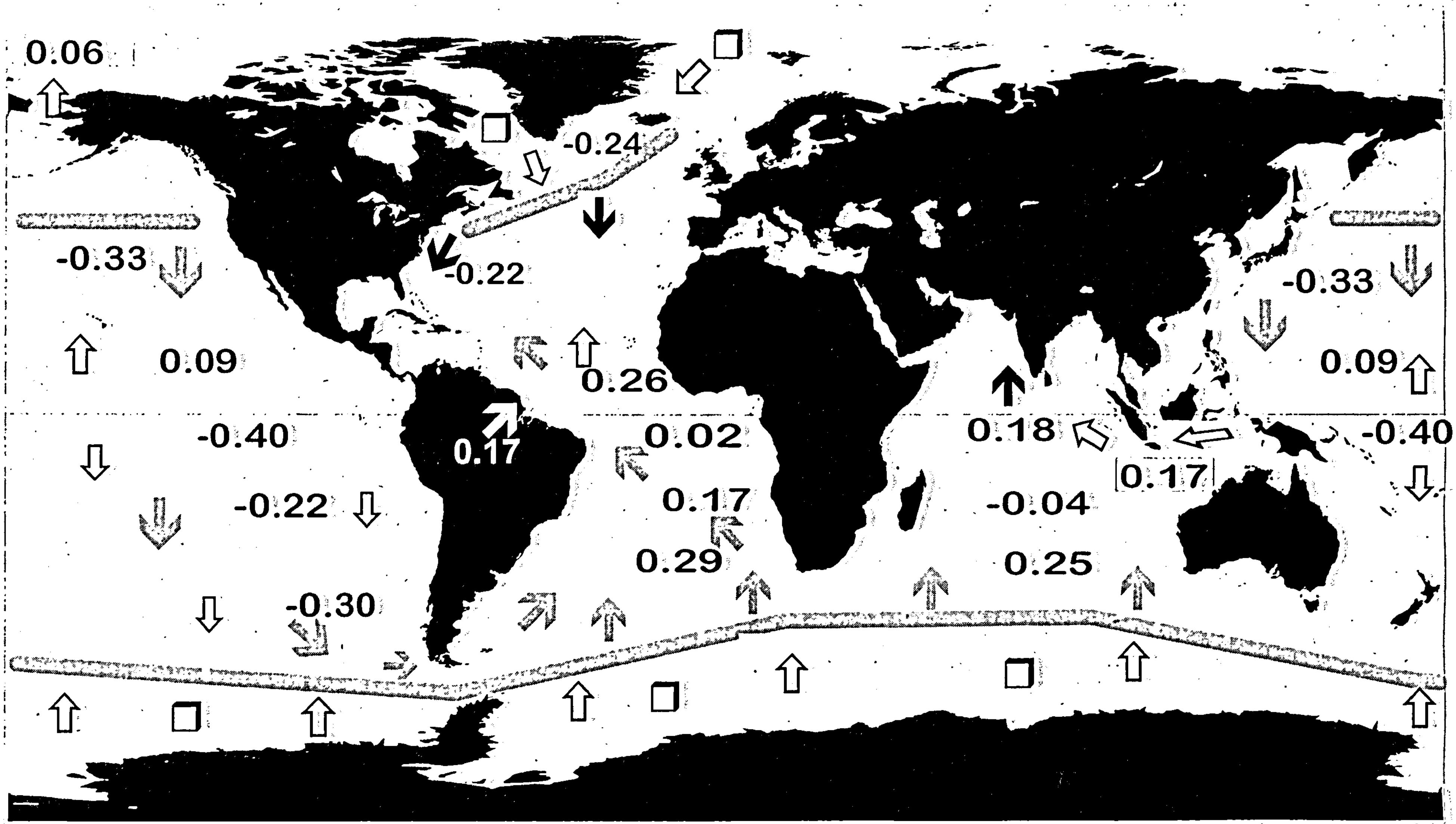

Fig.4. Main components of the freshwater flux in the oceans (Sv).
⇨ - upper layer, - intermediate layer, ➔ - deep layer, □ - transport by ice, Amazon runoff,
- Polar front zones ▭ - interbasin freshwater flux

between the seasons according to (10) we attribute $\frac{\partial F_i}{\partial t}$ to the centre of the seasons by central difference formula.

To obtain seasonal MFWF the characteristics of the North Atlantic evaporation are taken from (Icemer, Hasse, 1991), precipitation data - from (Bogdanova, 1986),runoff - from (World water balance..., 1974), ice transport - from (Lebedev, Uralov, 1981) and the Gibraltar Strait transport - from (Bryden et al., 1994). The Northern boundary of the North Atlantic is suggested to coincide with 65°N so freshwater balance of the North Polar ocean is evaluated separately: (E-P) data is derived from (Atlas..., 1980), river discharge - from (World water balance ...,1974), the Bering Strait variability - from (Coachman, Aagaard, 1988), salinity data - from (Levitus, 1994). Table 2 presents main components of the seasonal freshwater budget in the North Atlantic.

Table 2

Seasonal variability of the North Atlantic water budget (Sverdrups)

Months	Components: cross-boundary fluxes (positive-northward), 65° N*, fresh-water & ice	cross-boundary fluxes, 65° N*, ice	cross-boundary fluxes, 0°	surface water budget	fresh-water storage change	fluxes through the straits: Bering Strait	fluxes through the straits: Gibraltar Strait
February-April	-0.45	-0.08	1.18	-1.24	-0.32	0.03	-0.04
May –July	-0.69	-0.04	-1.20	0.07	0.47	0.06	-0.04
August-October	0.10	-0.01	1.07	-1.25	0.32	0.07	-0.04
November-January	0.18	-0.05	1.15	-0.46	-0.47	0.04	-0.04

* – including the Bering Strait freshwater transport.

Freshwater transport at 65° N is directed northward in August-January and southward in February-July, ice transport is only a small part of this value. Transequatorial transport is evaluated as a residual and is directed southward only in May-July. All other seasons reveal evaporative character of the basin. It's interesting that the annual Bering Strait freshwater transport equals to ice transport to the south at 65° N and in turn is compensated by freshwater sink through the Gibraltar Strait.

The combination of the equations (3) and (10) allows to estimate seasonal MFWF (Fig.5). No additional corrections such as (4) and (5) can be applied in this case. Uncertainties are of over 0.4 Sv, thus the presented fluxes are only a rough approximation. The most prominent feature is the southward freshening wave at all latitudes in May-July and significant variations of MFWF of order 2 Sv, i.e. 10 times more than Amazon runoff. To give the possibility of the seasonal analysis of amplitude-phase characteristics we present seasonal-phase diagrams of MHT and MFWF for the 25° N and 55° N in the North Atlantic (Fig. 6). MHT is taken from (Gulev, Lappo, Rozdestvensky , 1990) and freshwater transport

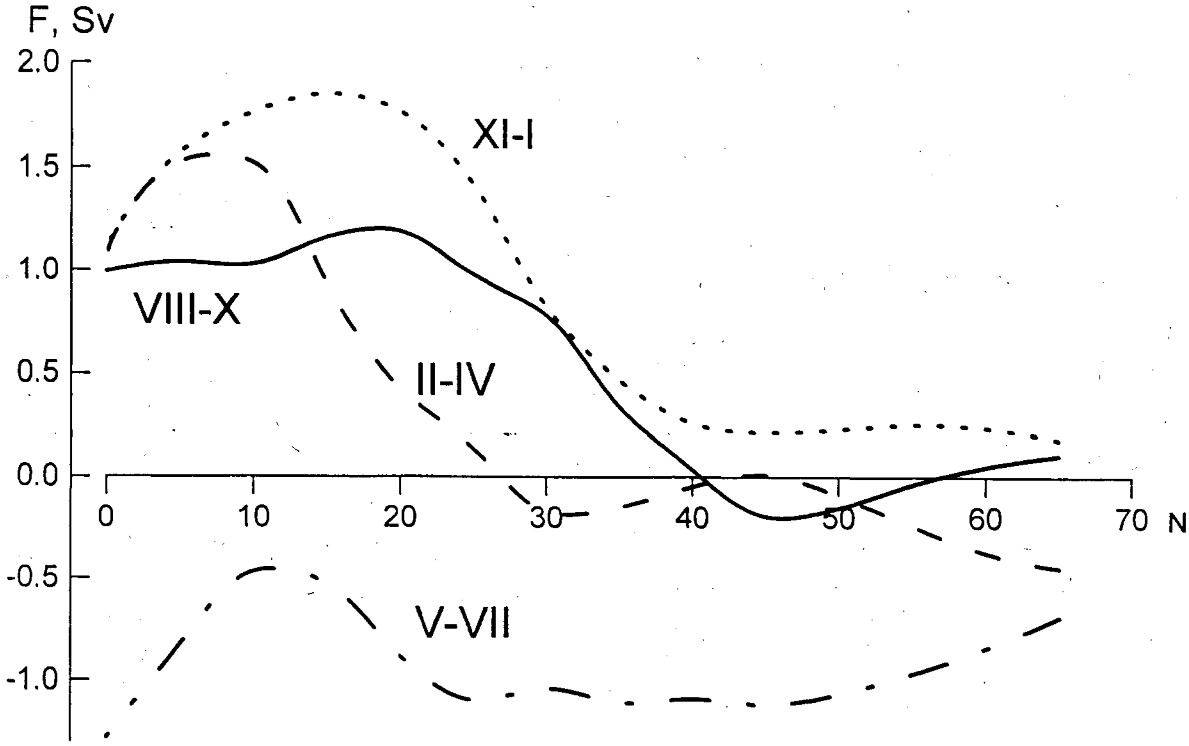

Fig.5. Seasonal variability of the meridional fresh water flux in the North Atlantic

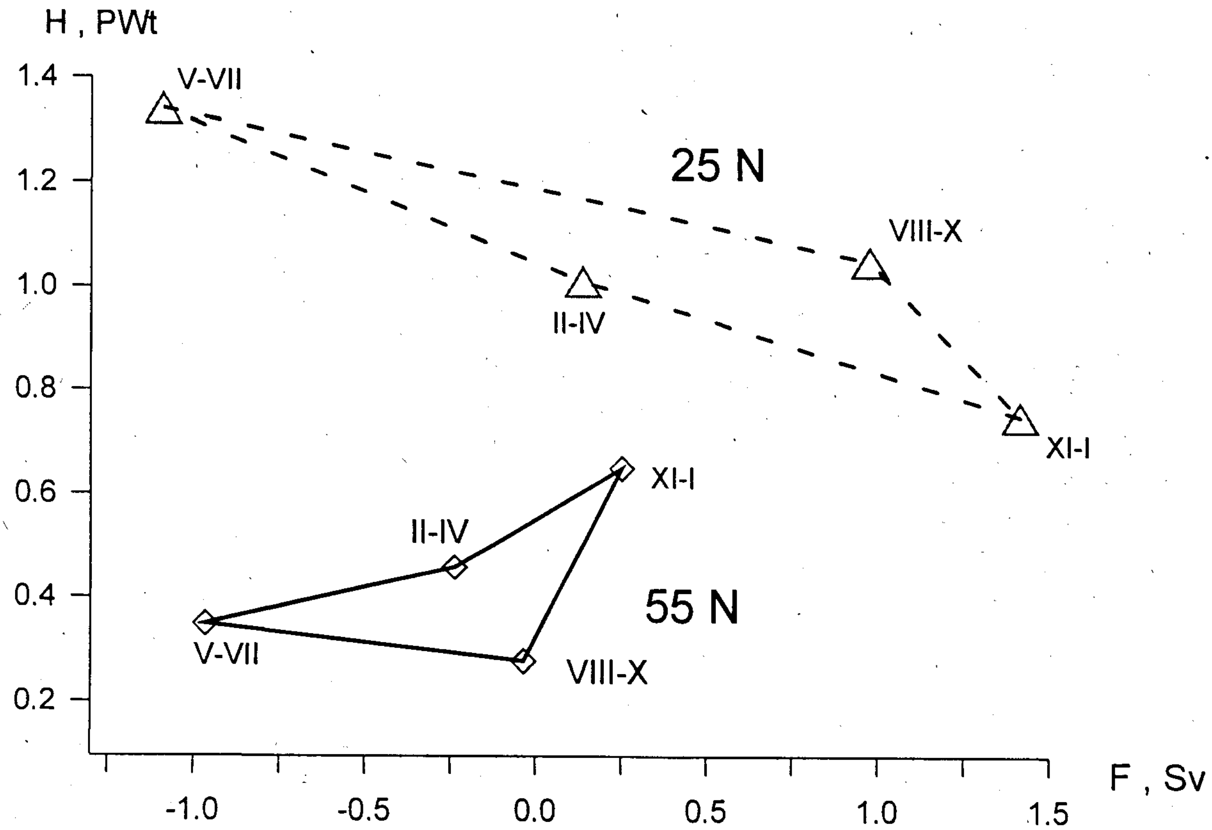

Fig.6. Seasonal phase diagrams of the meridional heat and fresh water transport in the North Atlantic

corresponds to Fig. 5. The diagrams reveal two different regimes of the interaction between heat and freshwater seasonal transport. According to Fig.6, MHT forestalls MFWF in the seasonal cycle 25° N and the reversal picture is situated at 55° N. More careful analysis of this diagrams will be promoted with monthly MFWF in future.

As for the interannual freshwater flux estimates, we can only conclude that huge seasonal changes make evaluation of long-term changes extremely difficult. For example, the detected salinity anomaly of 0.4 psu in the Labrador current with volume transport 5 Sv during the Great Salinity Anomaly (Dickson et al., 1988) corresponded to freshwater flux of only 0.06 Sv.

Direct measurements at 36° N allowed us to estimate MFWF of 0.48 Sv northward for the September-October 1993 and 0.31 Sv northward for the June-July 1981. The former coincides well with the values derived from water balance (Fig.5), but the latter differs with the corresponding balance estimates even in sign. The only way to obtain significant interannual variations is to improve the accuracy of the freshwater budget estimates not only in the North Atlantic, but also in the Arctic basin.

Conclusions

•Global ocean circulation compensates freshwater and heat loss (0.3 Sv and 0.8 PWt correspondingly) from the North Atlantic to the atmosphere. North Atlantic meridional freshwater flux directs southward in mid- and high latitudes and northward - in low latitudes.

• The analysis of meridional flux anomalies allows to conclude that the freshwater and heat revert to the basin by different ways. Returning FWF from the Pacific through the Bering Strait is only 1/5 of the total North Atlantic freshwater loss, the equal parts of FWF are driven to this region from the Arctic and from the South Pacific, Drake Passage and South Atlantic. In contrary, heat is transported to the North Atlantic through the Indonesian seas, Indian ocean and South Atlantic.

• The southward direction of MFWF in mid- and high latitudes is explained by gyre-type interaction of western boundary current and midocean returning transport with different salinities. Northward MFWF from the South Atlantic to the 20°N is imposed by penetration of the Antarctic Intermediate water.

• Polar Front zones are the regions where the MFWF changes the layer - freshwater sinks to the intermediate layer and penetrates to the low latitudes in intermediate waters. The North Atlantic Polar Front is the only zone with freshwater downwelling to the deep layer (if the Labrador sea water is really deep water). Thus climatic variations near Polar Front zones can shift the sinking of freshening from one isopycnal interval to another.

• The analysis of freshwater flux seasonal variations revealed southward freshening wave at all latitudes in May-July and significant MFWF range in low latitudes of order 2 Sv. Interannual variability of freshwater transport is within uncertainties of seasonal estimates.

Acknowledgements

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