Evidence of strong ocean heating during glacial periods.

Causes of ocean heating.

Part 2.

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Abstract

We have developed the model of World Ocean thermo-haline circulation which shows that Pleistocene glacial-interglacial cycles are connected with change in interior ocean temperature. During glaciations haline circulation dominated – warm and salty isotopically heavy water from Red sea filled the ocean interior, which led to strong freshening of ocean surface and its stratification. Additionally, interior ocean water was heated by geothermal heat flux and heat released at decomposition of organic rain. Due to increased temperature, density of water on the ocean floor declined and strong thermo circulation started. This resulted in new interglacial period. Ocean quickly released heat accumulated during the glaciation.

Text

Numerous hypotheses have addressed glacial-interglacial climatic dynamics, but non of them explain the sharp 25^{0}C temperature increase in Greenland in the last deglaciation (1,2). These robust data were obtained through analyzing temperature profile in the Greenland ice sheet where cold from the last glaciation is preserved (1,2). Approximately same temperature rise show data about extent of vast Pleistocene ice wedges on the plains of western Europe (3). Today such large ice wedges occur only in the extremely cold environments where average annual temperature is below -12^{0}C (3). Planet orbit oscillations, change in global albedo, increase in greenhouse gas concentrations, are all processes with relatively slow effect on atmospheric temperature. However the Greenland data indicate that climate changed instantly. In Greenland ice cores reveal that until ~14650 years ago, there were no substantial fluctuations in climate (4). Annual accumulation of ~100mm snow contained relatively stable isotopic content. This signal sharply changed along with the extreme temperature perturbation. Thickness of annual ice layers doubled as well (4). Then, during Younger Dryas climate changed back to glacial conditions, but ~11700 years ago a new shift in climate occurred (4). It can be supposed that because of glacier retreat, change in albedo and increased emission of greenhouse gases, temperature in northern latitudes should grow with the course of deglaciation. But data of temperature profile in the Greenland ice sheet clearly show that air temperature on the surface of the ice sheet have in contrast declined by 2.5^{0}C (2). Therefore this huge shift occurred instantly. Ocean surface circulation can change in one year, but that would only cause redistributions of energy. To increase air (and ocean) temperature in northern Atlantic by 25^{0}C then central Atlantic temperature should drop respectively.

25^{0}C is a huge change, analogous to the difference in average annual air temperatures between arctic and tropics. Such an increase is impossible to explain in the frames of existing knowledge about earth climate system. There are many natural phenomena which display asymmetric cycles, most frequently they are based on slow energy accumulation and consequent quick release (5).

During glaciations ocean circulation (ventilation) is dampened (6). We suggest that during glaciations interior ocean water have heated up to ~20-30^{0}C and during deglaciation this energy is released. This is supported by all temperature profiles in the deep boreholes of the open ocean (see the first manuscript). Here we consider reasons and mechanism of the phenomenon.

One of the possible reasons for ocean interior waters to warm is geothermal heat flux. Energy of 50mW/m^2 is sufficient to warm entire ocean water column (4km) during one glacial cycle (100 thousands of years) by 10^{0}C (6). Another mechanism is biological heating. About 11

Pg (10^{15} g) of organic matter (representing about one quarter of the ocean bio productivity) is descending annually to the ocean interior and the bottom (8). Only 2% of the value is buried in the bottom sediments (8). Taking into account the ocean area 0.361 x $10^{15}m^2$, on average, about 30 g of carbon (or ~60 g of organic matter) is oxidized on each square meter of the ocean floor annually. Heat flow of 40 mW/m^2 is computed using an average 5 kcal/g (21 kJ/g) energy content of 'sea food'.

Another mechanism is pumping of warm surface waters into the ocean bottom. Currently ocean is filled with cold and therefore heavy (1027.8 kg/m^3) water from high latitude seas (9). But that is a rather rare scenario in the history of ocean. In the past, in warmer climates ocean was filled with heavy but warm water from seas with high evaporation (9). Today there are two such seas (plus Persian Gulf). Mediterranean Sea, because of difference in evaporation and precipitation where every year on average lose 850 mm of water. Through Gibraltar surface 42320 km^3/yr of ocean water entering the Mediterranean while 40800 km^3/yr bottom flow leaves this sea with 38.4-38.7$^0/_{00}$ salinity, and 12.5^{0}C temperature (9,10). Annual evaporation from the Red Sea is 3500mm water. From it 9400-12600 km^3/yr of water with salinity 41.5$^0/_{00}$ and temperature of 22.5^{0}C is flowing down to abyssal depths of Indian ocean (9, 10). This stream would fill the whole of the world ocean volume in 100 thousand of years. The most dense water of the world ocean (1028-1029 g/m^3) is flowing out of these seas (9).Both Red and Mediterranean seas are very deep, they are like small oceans, and they represent model of warm ocean (9). On the bottom of these seas, temperature is 12.6-13.4^{0}C and 22.5^{0}C (9, 10). Today total flow from these salty seas into the ocean interior is only several percent of flow from high latitude cold seas (9). Therefore their effect on ocean interior temperatures is minor, because of their influence ocean bottom temperatures are not 0^{0}C but +2^{0}C (9). If one imagines these seas as water pumps, then these pumps have low power (debit). But haline pumps give stronger pressure (density of water), therefore they are stronger then thermo pumps.

One very important phenomenon is connected with the function of such haline pumps: they reduce salinity of ocean surface and compete with thermal pumps. They pump salt down to the ocean bottom and fresh water evaporated from these seas come back to the ocean surface. They pump down the ocean bottom water with high salinity and instead somewhere in the World Ocean appear a compensating flow to the surface with $34.7^{0}/_{00}$ salinity. While thermal pumps strongly mix the ocean, this process is barely noticed, but if thermo pumps would weaken an irreversible freshening of surface waters would begin. One possible trigger for this can be, for example, melting of glaciers and short term freshening of ocean surface. Density of this water will reduce and down flow of cold water will stop (9), thereafter, haline pumps would quickly make surface water even fresher. Water from cold seas become lighter and would not be already able to submerge. Ocean will become strongly stratified; wind and tides would not be able to mix this water with heavy bottom waters. As a result haline pumps will pump warm and salty water into the ocean floor without interferences. In a few centuries salinity of surface waters would strongly reduce. Because of that salinity of water flowing out from salty seas would reduce also and would not be able to flow all the way down to ocean bottom, and will spread along the lower horizon of the surface waters, i.e. haline pumps would be “idling”. However, with time, water on the ocean bottom would slightly warm up with geothermal and biological heat and will become less heavy. This enables the strongest haline pump to start working again (below we will show that in Pleistocene it was the Red sea). This pump would quickly reduce surface salinity and will start idling again. Then ocean would warm up again, and so on.

Glaciers have a large influence on haline pumps. Glaciers lead to increased salinity in surface ocean, and consequently increased salinity and density of water in haline pumps. Therefore as long as ice accumulates haline pumps will rarely idle. From the other side, if glaciers retreat, that decrease surface salinity and haline pumps would idle, until interior waters are heated.

Ocean heating can't last forever. When at some point density of water in the ocean depth will become less that in the cold sea, then thermo pumps would turn on and in cold seas very strong downwelling will occur. It would continue until ocean would not release all accumulated heat. But if on the surface of cold sea and on land surrounding it there is lots of ice then its quick melting will decrease salinity and water density in cold seas and thermo pump would stop, and release of interior ocean heat would stop.

If owing to tectonics, or ocean regression, a straight which connects haline sea with ocean become narrower or/and shallower, then regardless of ocean surface salinity, salinity of down flow from haline pump will be high, and decline in salinity of the ocean surface would continue. In extreme case a straight can become so shallow that outflow from it would stop, and evaporate basin will occur. Salty water would still flow into the basin, and fresh water would return with precipitation. Such a basin if the same size as Red or Mediterranean sea can evaporate from ocean surface almost all salt, and ocean will become ultra stratified – water exchange between surface and interior ocean would be very low. To imagine an idealized extreme case: density of surface water is close to 1000 kg/m^3, interior ocean water salinity is $35^0/_{00}$ and diffusion exchange of salt and heat between surface and interior absent, then to take ocean out of this stable state it would require to heat interior water up to 77^0C. Only at that temperature density of deep water would drop to 1 g/cm^3 and convection will start.

In reality as ocean warms up, diffusion heat exchange with surface waters would increase and become equal to deep heat flux, and after that ocean temperature rise will attenuate, A stable state can then occur: fresh light water lay above heavier but warmer water, i.e. because of diffusive heat losses bottom waters won't be able to heat to the point of overturning. This condition will be stable until haline pump will significantly desalinate the entire ocean. Such scenario likely didn't occur in Pleistocene, but it could be in other geological epochs when big evaporate basins were formed.

To illustrate these features of thermohaline circulation we present simple 4 block model of the ocean. In this model we have combine all cold seas into one with an area of $10.8*10^6$ km^2, which is 8 times bigger then the area of the Norway sea. Thickness of the top, well ventilated layer in this sea and ocean is accepted 200 meters. Salty sea area is accepted to be $0.45*10^6$ km^2 and average depth of 550 meters. These values are same as for Red sea. Thus, we consider a situation, when only one haline pump against all thermo pumps. Energy supplied to high latitude sea from the sun and atmosphere is accepted to be $65*10^8$ J/m^{2}yr; to the salty sea is $220*10^8$ J/m^{2}yr; to block of the ocean surface is $130*10^8$ J/m^{2}yr (11). Surface of each of these blocks emit energy into the space, in dependence from temperature of water in this block, by Stephen-Boltzmann law (11). Part of energy in salty sea is spent on evaporation of 3.3 meters of water annually. This water and energy of phase change is transported to the surface of the open ocean. Deep ocean block is receiving additional energy of 75 mW/m^2 from geothermal and biological heat flux. Density of water in each block is calculated using a known formula through salinity and temperature. We have accepted that exchange of water between blocks is proportional to difference in water density in these blocks, i.e. we are considering only thermo-haline circulation. Coefficient of water exchange between salty sea and ocean surface is accepted to be $0.003*10^{15}$ m^6/kg*yr. At this coefficient, salinity, temperature and water exchange in this sea will be the same as in Red Sea. As long as water density in these blocks is low they exchange water only from ocean surface block, but as soon as their density becomes more than in bottom reservoir, all water flowed out from salt sea drops down to the depth.

Coefficient of water exchange between cold sea and the ocean surface block is accepted equal to $0.15*10^{15}$ m^6/kg*yr. As soon as water density in the cold sea become higher than in depth reservoir water starts to sink down. For this flow, we accepted the coefficient equal to $5*10^{15}$ m^6/kg*yr. These coefficients are selected so that the temperature in the cold sea at the present conditions is close to 0^0C and flux to the bottom is close to $0.6*10^6$ km^3/yr (~20 Sv). At appearance of flow from the cold sea to the bottom additional (compensative) flow appears from the ocean surface to the cold sea and from depth to the ocean surface. If in surface ocean block density of water would become more then in the ocean bottom then there also would occur downwelling. For it we took same coefficient as for the cold sea. As soon as water density in one of the surface blocks become less than water density in bottom reservoir, down flows from this block stop.

All these currents redistribute salt and heat in-between blocks. As a result for each block we have budget equations for water, salt and heat. We have added the ice accumulation into the equations for cold sea. As soon as average temperature of cold sea drop below 0^0C, accumulation of fresh ice starts. Salinity in this block consequently increases, and additional source of heat appear (80 calories per gram of frozen water). On the other hand as soon as temperature of water in this sea increases above 0^0C, ice which has accumulated on the coast and floating in the sea melts, consuming energy and declining salinity. We have accepted that ice build up and melting is proportional to change between 0^0C and temperature of water in cold sea. Coefficients are such that a temperature of -1^0C in thousand years accumulates $4.86*10^{15}$ m^3 of ice. We also accepted that ice accumulation rate decrease linearly as its volume increase (larger glaciers have greater diffluence and ablation). We accepted such coefficient of proportionality that ice volume could not exceed a value equivalent to 150 m layer of ocean water. We have accepted that change in ice volume doesn't influence area and depth of seas, only deep reservoir volume change.

More salty water is less compressible, thus harder to submerge it to the bottom. To describe this thermobaric effect and model related to it short-period cyclicity (7) we have restricted haline pump – water from this pump reaches a bottom reservoir only if its density will be 0.25 kg/m^3 more then current density in bottom reservoir. Initial parameters were set at 25^0C water temperature and $34.7^0/_{00}$ salinity in all blocks.

The dynamic of modeled ocean parameters based on solutions of set of all budget equations described above appears in Figure 1. We see that our model ocean has lost all initial heat in 16000 years. Temperature in the depth decreased to 1.6^0C. At that point a noticeable decline in salinity of surface waters was observed and haline pump, quickly turned off thermal circulation – a glacial period has started. During the glaciation, haline pump was idling often and worked permanently only at the end of the glaciation period. Over the course of 112 000 years ice accumulation was equivalent to 149.5 meter of water in world ocean and salinity on ocean surface has declined to $31^0/_{00}$. Temperature of water in the depth reservoir have increased to 23.4^0C and water density have dropped to 1024.9 kg/m^3 and became same as in the cold sea. After that, active downwelling have appeared in the cold sea. Owing to the sea warming all ice quickly melted. In 14600 years the ocean has again lost all accumulated heat and new glaciation period have started.

We see that the simple model of thermohaline circulation at stable external conditions shows cycles which looks like glacial cycles. In the model we have even received a short cooling somewhat similar to a Younger Dryas.

Testing the model we have substantially changed initial parameters, have increased the number of blocks in the model, but if depth heat flux is small and if "pressure" of haline pumps is stronger than cold pumps, then in all cases we obtain ocean heating. Glacial cycles get shorter if bottom heating is increased. If the haline pump is further restricted this would cause occasional turning on of cold pump – Dansgaard/Oeschger warm events appear (6). If we take glaciers away from the model, haline pump will be often idling and glacial cycles will be longer. But if deep heat flux is removed then thermal circulation in the ocean would stop, and soon haline pumps would idle and thermohaline circulation will stop forever.

Many researchers note that geothermal heat flow is important for oceanic circulation (see refs. in 7). We especially note that with no heating from below, thermal haline circulation is impossible. The ocean water could be mixed by wind, but this is not thermohaline circulation. Thermohaline circulation appears only under buoyancy forces, i.e. upwelling water must be lighter than downwelling water. Rayleigh's formula describes conditions for thermal convection. In this formula, thickness of liquid layer is in a power of 3. For instance, in shallow lakes convection appears at several degrees of temperature difference between surface and bottom, convection in the non stratified ocean which is 1000 times thicker appears at a billion times less temperature difference. An energy value of 50 mW/m^2 is a tremendous sum, enough even for convection in the hard mantle. If all the energy converts into kinetic energy of ocean currents then all ocean water could reach speed of 0.7 m/sec in one year. Parameterization coefficients are not necessary in models of the deep ocean circulation. In order to mix deep waters it is enough to add depth heating to the models.

Here we want to note that if to develop a more detailed model it should be considered that main ocean heating from the bottom occurs in the rift zones, on the depths of 2-3 km, and on big depths water penetrating from Red sea in the beginning of glaciation would not warm but instead cool, heating up the cold floor.

To prove the described dynamic we present the following facts.

Analyses of $\delta^{18}O$ of benthic foraminifera showed that on the warm bottom of Red sea in LGM $\delta^{18}O$ was +(4.7-5.5)‰, the same as on the surface of the northern part of Red Sea where deep water forms and the same as in the bottom of all other oceans (12-15). This confirms that water from Red sea had spread along the bottom of all oceans.

The most exact data of surface ocean salinity in the last glaciation are obtained through analyzing plankton fauna in deep boreholes of north-western Atlantic and numerous samples obtained for recent complexes of these species for different basins in northern Atlantic and Arctic (16). Before the peak of glaciation, huge masses of fresh ice were accumulating on land and on sea surfaces, and water salinity should have expected to rise at that time. However on the north-west Atlantic both before and during LGM it was 30-32‰ (16). It is an open ocean, from this follows that on entire ocean surface in LGM salinity was ~3-5‰ lower than today. We have received in our model the same value.

If temperature and salinity of water on the ocean bottom in the past often and strongly changed, then benthic organisms should be resistant to these changes. And distribution of foraminifera on the ocean floor indeed depends on food supply and is not connected with temperature and salinity (17). The same species now may be found both in Red and Norwegian seas (15).

Main and most reliable proof of a warm ocean during glaciation is data about temperature profiles in the ocean deep boreholes (see first manuscript). Profile of bottom temperatures are a very simple and reliable paleothermometer (it is not more complicated than a mercury thermometer). It is based on a single physical principle, and to obtain paleotemperatures only heat conductivity profile of sediments must be known. Therefore we consider these paleo thermometer data robust. Other paleothermometers are more complicated and less reliable. For example, the Mg/Ca paleothermometer depends on many parameters, and often show either high temperatures on the ocean interior in LGM (18) or a complete disconnect with temperature (18-19). $\delta^{18}O$ paleothermometer also demands a correction. Its results are dependent on volume of both terrestrial and ocean ice, from its isotopic content, and additionally (as now noted) from conditions of fractionation of oxygen isotopes in Red sea. If $\delta^{18}O$ on the warm bottom of the Red Sea in LGM was the same as it is on the cold (as is supposed) bottom of ocean, then either this paleo thermometer in not correct or in both reservoirs bottoms were warm.

Based on temperature data from deep boreholes and modeling results we can make some conclusions.

If weak sources warm up the ocean, this means that ocean mixing by wind, tides and thermal pumps were negligible.

Average $\delta^{18}O$ of Pleistocene glaciers was probably lower than it was previously assumed. The volume of floating ice at high latitudes was high. If temperature in Greenland was 25^0C colder than today (2), then Arctic ocean surface were frozen and did not melt (20). On the surface of the ice, snow was accumulating, and there must have been floating sea glaciers, with very low ice $\delta^{18}O$. These glaciers were mostly submerged and only 10% of their volume was above the water surface, therefore it could not flow into the land or penetrate through shallow straights. At an ice accumulation rate of 8 cm/yr Arctic Ocean could be twice filled with ice during glacial periods.

If water temperature on the ocean bottom have changed significantly, then the most part of gas clathrates of World Ocean in Pleistocene have several times melted and frozen again. Methane content in depth sediments is 10000-20000 Pg (21). Today it is stable, but gas clathrates melted during glacial periods. Water level and pressure were lower and this accompanied the emission of hundreds of pentagrams of methane from bottom sediments, dissolution of methane in the water and further oxidation. $\delta^{13}C$ of gas clathrates is very low (-65‰) (21), therefore $\delta^{13}C$ content of ocean water in glaciations was reduced. An emission of 170 Pg C equivalent of this methane (this is only 1-2% of global storage) will have the same effect on $\delta^{13}C$ of oceanic water as an emission of 500 Pg C from terrestrial or oceanic organic reservoirs. Actual data is in agreement with this (22).

Because of low circulation in glaciation, nutrition flow from ocean bottom to the surface was strongly depleted and productivity of open ocean was low. During the last glaciation, as indicated by numerous boreholes, bioproductivity was reduced in all oceans ubiquitously (23). Only at the end of glaciation when ocean has substantially heated and circulation have slightly increased (see Fig. 1) productivity increased in the Atlantic (23, 24) Furthermore, when cold pumps started working, productivity have sharply increased (about tenfold in the Southern Ocean (25)). At the beginning of Holocene overturning circulation was in several times stronger than today (Fig. 1). Thus, nutrition input to the ocean surface and bioproductivity was correspondingly higher.

Areas of deep upwelling are the most productive in the ocean (25). In these areas, there is strong organic matter flux to the bottom indicating strong biological heating of bottom water. Thus this process in some cases provides positive feedback to upwelling.

At low circulation in glacial periods oxygen input to the bottom decreases, but at the same time biological pump was reduced as well. Therefore there were few anoxic conditions on the ocean floor. Additionally bottom water was heated by geothermal and biological heat, therefore despite low content of dissolved gases, their partial pressure was increasing. If such warm gas saturated water would eventually emerge on the ocean surface, it would first emit gases into the atmosphere, and only after cooling would strongly absorb them.

During the glaciation CO2 concentration in the atmosphere was declining, it was loosing ~200 Pg of carbon. Carbon content in forests was reduced by 500 Pg of carbon. It is thought that this carbon was absorbed by the ocean and in deglacial periods this carbon returned to the atmosphere and to the land (22). However mechanisms for this is still unclear (22, 23). On the contrary, there are several data which give evidence of decreased carbon storage in glacial ocean: i) Storage of organic carbon in the ocean is of comparable size with terrestrial organic carbon reservoir (their $\delta^{13}C$ signatures is same) (26). Ocean productivity in glacial decreased significantly (23, 25), therefore organic carbon content in the ocean's water and at the bottom should be lower correspondingly; ii) Salinity of the glacial ocean increased (because of glacier growth), CO2 solubility capacity decreased correspondingly (22); iii) An attempt to find the proof of 700 Pg deglaciaition emission from the ocean to the atmosphere was made in the work of Yu et. al., (27). The data indicated that the deep ocean's carbonate ion concentration during deglaciation increased only by 10 mmol/kg and only in the deepest part of ocean it is equal to a 100 Pg C loss from the deep reservoir (27). But in the other 70% of the ocean volume the carbonate ion concentration strongly decreased during deglaciation (27, 28) (at the ocean's surface by 60 mmol/kg (27)). If all these data are interpolated, the entire ocean's carbonate ion content decreased by 20-25 mmol/kg and the ocean absorbed as minimum as 700 Pg inorganic carbon during deglaciation.

CO2 dissolution in water is strongly dependent on water temperature (22), therefore one third of atmospheric CO2 decline in glaciation was explained by slight (2-3^0C) cooling of the ocean (22). But all deep boreholes show strong ocean warming. Ocean was "to half" filled with warm (much CO_2 depleted) water from Red sea and carbon content of ocean water during the glaciations must have been very strongly reduced because of that. Accounting for all stated carbon storage in LGM ocean was reduced by at least 1500 Pg C. From all known carbon reservoirs, only permafrost and soils of mammoth steppe biome could absorb such amounts of carbon. Only these soils are capable of accumulating hundreds of kilograms of carbon per square meter (24, 29). Today permafrost is the largest reservoir of organic carbon (1670 Pg C (30)), and at the LGM it was at least twice higher. The mammoth-steppe biome pumped over light carbon from other reservoirs into its frozen soils.

Uniqueness of variable Pleistocene climate is likely connected with the fact that on our planet appeared at the same time very cold and very salty seas and frozen soils which could accumulate big amounts of carbon. From the presented analyses it follows that glaciations are epochs when haline circulation dominated– the ocean was taking up warm water from the surface and accumulating heat. On land, polar oceans and permafrost ice was accumulating and ocean bottom ice (gas clathrates) were melting. Interglacials are epochs when in ocean dominated thermo circulation – ocean absorbs the coldest water and released its heat. In the ocean bottom water and methane was crystallizing while on the land glaciers and permafrost were thawing. Microbes turned into CO_2 and CH_4 organic, which was accumulated in the permafrost and cold soils.

Presently, the ocean has already released most of the accumulated heat from the last glaciation. Bottom sediments have cooled also, so thermo circulation has decreased. Soon it can be expected that salty seas will stop thermo circulation (see Fig. 1).

By artificially regulating water exchange in narrow straights which connect salty seas with the ocean we may have the capacity to change salinity and density of outflowing water. By increasing water exchange we might stop the freshening of surface water and may prolong life of cold pumps. In contrast if we could reduce the water exchange, the thermo circulation may slow more quickly and would hasten the beginning of next glacial cycle. This, to some extent, can compensate warming caused by increased greenhouse gases concentrations in the atmosphere. But results of this experiment are doubtful. Today, the ocean absorbs half of all anthropogenic emission of CO2. But if thermo circulation will be replaced by haline circulation, then the ocean interior would start warming and will start releasing CO2 in addition to anthropogenic emission. In the past, this emission compensated for by permafrost and mammoth steppes expansion. But with the anthropogenic rise in atmospheric CO2 concentrations, new permafrost won't be formed, and northern steppes won't expand in Europe. As a result, by changing thermo circulation to haline circulation we would cause doubled increase rate of atmospheric CO2 plus strong decline in ocean productivity.

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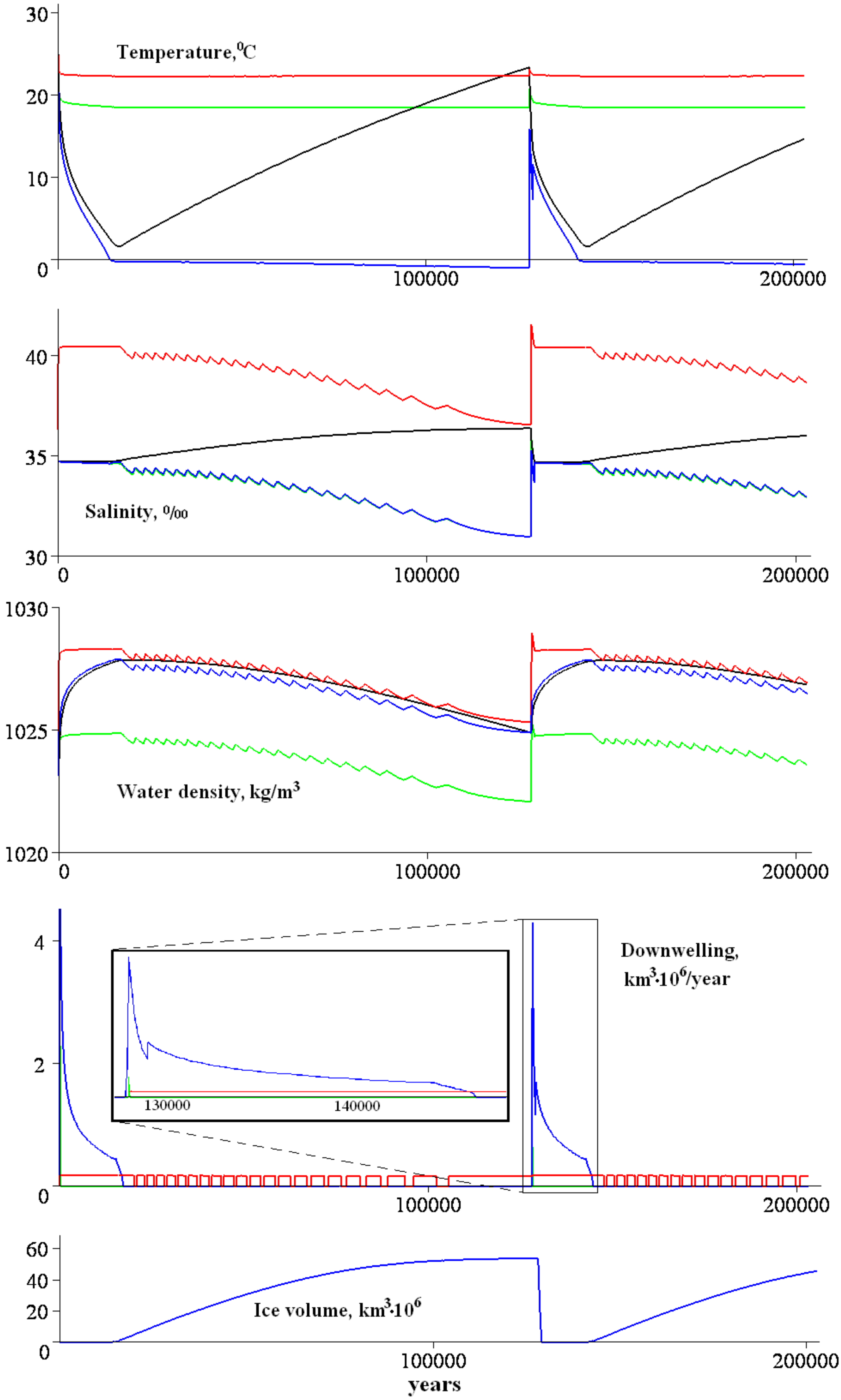
Figure captions

Figure 1. Results of model of thermo-haline circulation in the World Ocean. Red line – Red sea; Blue line – high latitude seas; Green line – Ocean surface; Black line – Ocean interior.

Fig 1.



Temperature,⁰C
30
20
10
0
100000
200000
40
35
30
Salinity, ⁰/₀₀
0
100000
200000
1030
1025
1020
Water density, kg/m³
0
100000
200000
4
2
0
130000
140000
Downwelling, km³·10⁶/year
100000
200000
60
40
20
0
Ice volume, km³·10⁶
100000
200000
years