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Climate variations in the Northern Hemisphere based on the use of an atmosphere-ocean IPCC model

E. M. Volodin(1), N. A. Diansky(1), P. Lanucara(2), R. Purini(3) and C. Transerici(3)

(1) *INM, RAS - Moscow, Russia*
(2) *CASPUR - Rome, Italy*
(3) *ISAC-CNR - Rome, Italy*

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Summary. — Forced and natural variability of modelled and observed Atlantic Ocean temperature and Atlantic Meridional Overturning Circulation (AMOC) is studied. In the observations and in a forced climate model run, we find increasing temperature at 1000 m in the Atlantic (20N). SVD analysis shows that, for both model data and observations, a high index of North Atlantic Oscillation (NAO) corresponds to negative temperature anomaly at 1000 m to the north of 55N, although geographical details of temperature anomaly distribution are different for the model and observations. Particular attention has been paid to the influence of the fresh water flux due to the present global warning on the slowing down of the AMOC. It is shown that fresh water flux change is only a secondary cause of reduced AMOC in global warming conditions, while heat flux change is probably the main reason. Finally, it is shown that internal model AMOC variability is positively correlated with the near-surface air temperature in Atlantic-European Arctic sector on a 10-year time scale.

PACS 92.10.af – Thermohaline convection.
PACS 92.70.Gt – Climate dynamics.
PACS 92.70.Np – Global climate modeling.

1. – Introduction

The North Atlantic Current (NAC), an extension of the Gulf Stream, transports heat northward, and therefore is responsible for the mild climate of the northern and northwestern Europe, rendering this area much warmer (approximately 10 °C) than the average for these latitudes. This NAC is associated with the Atlantic Meridional Overturning Circulation (AMOC) that is the zonally integrated mass transport in the Atlantic Ocean, consisting of a northward surface flow (less than 1 km deep) above a southward flowing water (North Atlantic Deep Water—NADW). This "estuarine like" circulation is part of the global ocean circulation named Thermohaline Circulation (THC). In the 1980s of the last century, evidence from paleoceanographic data showed that during the Last Glacial

Maximum (LGM), a time interval centered approximately 21000 years ago and spanning few millennia, the AMOC was quite different from the present circulation. Therefore, an understanding of the basic mechanisms that govern this fundamental component of the general ocean circulation is important and will foster a better understanding of the impact of the anthropogenic increase of the greenhouse gases on the Earth' climate. In this context, it is worth mentioning that present climate models show the slowdown of the AMOC in the twenty-first century dampens the temperature rise due to the emission of the greenhouse gases. Parallely, recent papers show that the deep ocean temperatures have increased since 1950 [1, 2]. Moreover, global warming is changing the hydrological balance of the Arctic rivers and melting the Greenland ice cover. Taking into account these facts, the main aims of the present paper are: in the first section, to compare the observed temperature variation of the mid-depth North Atlantic with numerical results obtained by the INM RAS model [3, 4]; in the second section, to simulate the effect of the above increase of the fresh water input; and in the third section, to study model variability of AMOC and the ocean surface temperature (SST).

2. – Detection and simulation of the North Atlantic (NA) mid-depth ocean temperature (TT) variations

In a previous study Volodin and Diansky [4] have presented some results of a coupled atmosphere-ocean general circulation numerical model used to investigate possible climatic changes in the 21st-22nd centuries according to the IPCC scenarios. It is a full atmosphere and ocean general circulation model. Resolution in the atmosphere is 5×4 degrees in longitude and latitude, and 21 sigma levels from the earth surface to 10 hPa. In the ocean, model resolution is 2.5×2 degrees in longitude and latitude, and 33 sigma levels in vertical.

One of most striking aspects of the anthropogenic warming of the Earth's system is large-scale increase in the heat content of the world ocean over the last few decades [1,2,5]. However, while this warming is clearly detectable for the NA approximately until the mid 1990s, in the last ten years the deep temperature of the NA seems to decrease. To focus on this point, we have compared the simulated temperature variations with the observed data provided by the NCEP Global Ocean Data Assimilation System (GODAS) at the same (approximately), depth (1000 m for he model and 949 m for CODAS data) and latitude (20N). The temporal scale spans from 1979 to 2000 for the simulation and from 1980-2001 for the data.

Figures 1 and 2 show the simulated and observed temperature behaviour for the above period.

Considering the simulated results in fig. 1, we can ignore the initial bias (approximately 0.6 °C) and focus on the trends. The model results show first an increase of temperature at a rate almost double that in the long-term secular trend shown in fig. 3. This is followed by a decrease that starts at the beginning of the 1990s. It is worth mentioning that the same trends appear in the observed data even if the maximum is shifted by approximately a decade.

Please note that for both plots the increase of temperature before its decrease is approximately 0.2 °C, *i.e.* of the same order of magnitude presented in previous studies [2].

Moreover, fig. 3 shows that the increase of temperature is of the same order of magnitude (approximately 0.1 °C) for the two temporal intervals 1960-1974 and 1970-1992 [5], *i.e.* the trend of temperature increase is approximately linear till the end of the 1990s.

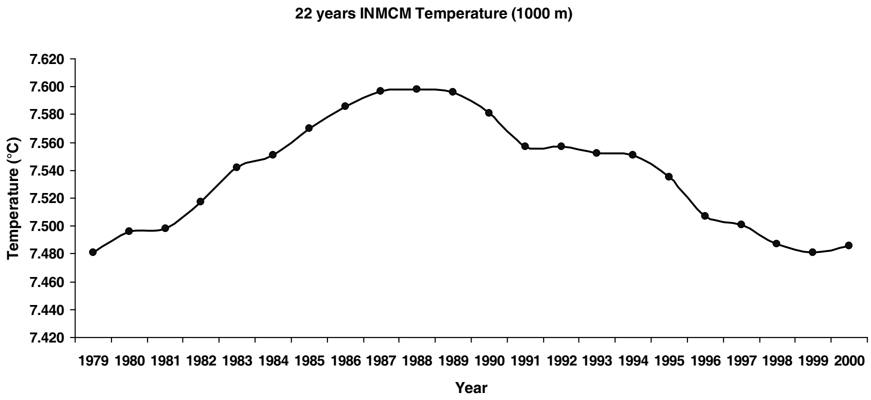

Fig. 1. – The ocean mean temperature at 20N for the period 1979-2000 as simulated by the INMCM model at the depth of 1000 m.

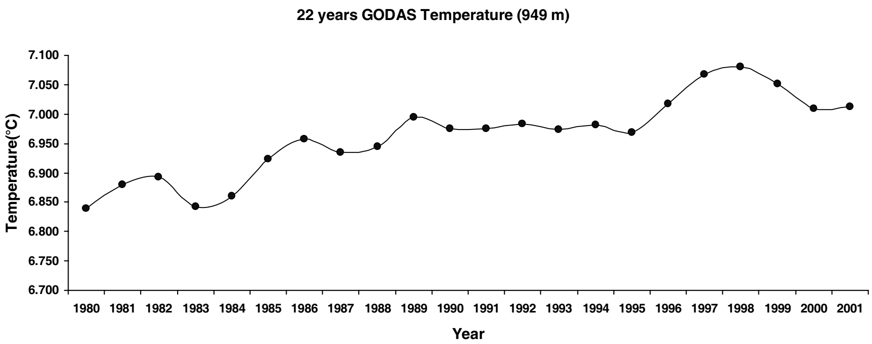

Fig. 2. – The ocean mean temperature at 20N for the period 1980-2000 as resulting for the observational data (GODAS) at the depth of 949 m.

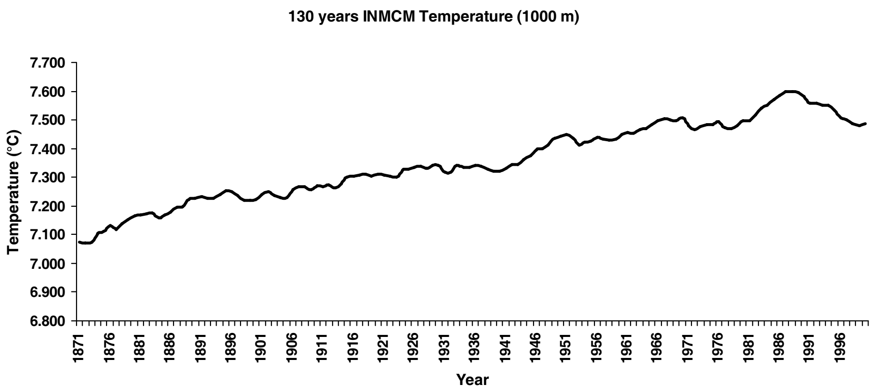

Fig. 3. – As fig. 1, for the whole simulation period 1871-2000.

To evaluate the links between the ocean and the atmospheric forcing, in the present study the Sea Level Pressure (SLP), the SVD (Singular Value Decomposition) method has been applied to the ocean temperature at the above depths (for simulation and observed data provided by GODAS) and to the SLP (for simulation and observed data provided by the ECMWF ERA40). We remind the reader that this technique is usually applied in geophysics to two related fields and it can be thought of as a generalization to rectangular matrices of the diagonalization of a square symmetric matrix (like in the EOF analysis). A climatic application of such a method was given first by Bretherton *et al.* [6] and it is now used to isolate spatial patterns in two fields that tend to be synchronized with one another.

a) The SVD analysis: TT and SLP for INMCM (22 years)

Figure 4 illustrates the first component of both TT and SLP for the model. In particular, fig. 4a shows negative value in the Atlantic with marked peaks in its northern areas where a positive value patch appears northward to the Scandinavian Peninsula. Figure 4b represents the North Atlantic Oscillation (NAO).

b) The SVD analysis: TT and SLP for GODAS and ECMWF ERA40 Data

Figure 5a presents the first component of the SVD for the GODAS temperature. Positive NAO index is correlated with positive temperature anomaly in Gulf Stream region and negative temperature anomaly to the north of 55N, especially to the east of Iceland. So cooling of significant part of North-East Atlantic water during high NAO index is a common feature of both observations and model results, although regional details differ somewhat.

The first SVDs of SLP and TT for the model are relatively stable. Calculation of SVD for 130 model years shows SVD structure similar to that for a 22 year span (not shown).

3. – The response of global warming to change of Arctic runoff and Greenland melting

The AMOC and its associated northward heat and salt transports have been the focus of many scientific papers because of the claims that its "shutdown" triggered the so-called Dansgaard-Oescher (D-O) event—*i.e.* abrupt climate change in the Northern Hemisphere—and that the present anthropogenic emission of carbon dioxide in the atmosphere will induce a shutdown of the AMOC and then a new D-O event [7-9]. To test this, we simulated possible effects on climate change of the change of Arctic runoff and Greenland melting in 20-21 centuries.

We performed model run (RUN0) for years 1860-2000 with prescribed observed emissions of greenhouse and other gases. The model results for the fresh water flux from Greenland ice melting and Arctic river runoff for 1860-1899 was saved.

Then, we continued the run for 2001-2100 with emission scenario A1B (RUN1). Another run (RUN2) was also performed for 2001-2100. This latter run was identical to RUN1 but with fresh water flux from Arctic rivers and Greenland melting prescribed to be that one from years 1860-1899 of RUN0. In RUN2, runoff was artificially fixed so that mean annual cycle of runoff of 1860-1899 was repeated year by year. The response of the model to different runoff levels was studied.

Total present-day model Arctic river runoff is about $4500\,\mathrm{km}^3$/year, while runoff from Greenland ice melting is about $1500\,\mathrm{km}^3$/year. In years 2081-2100 of the model run,

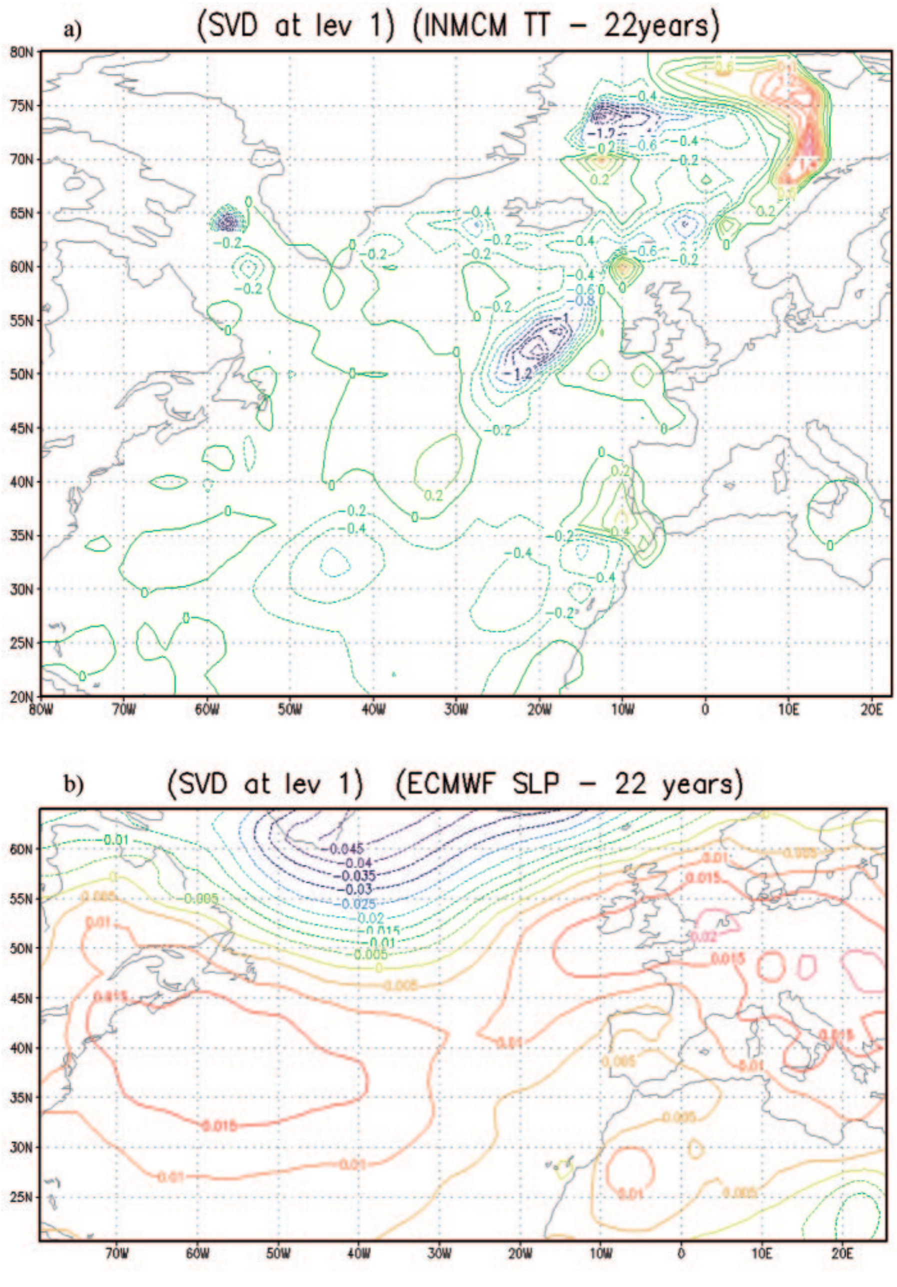

Fig. 4. – a) The first component of the SVD for the modelled temperature (1979-2000) at 1000 m. b) As a), for the SLP.

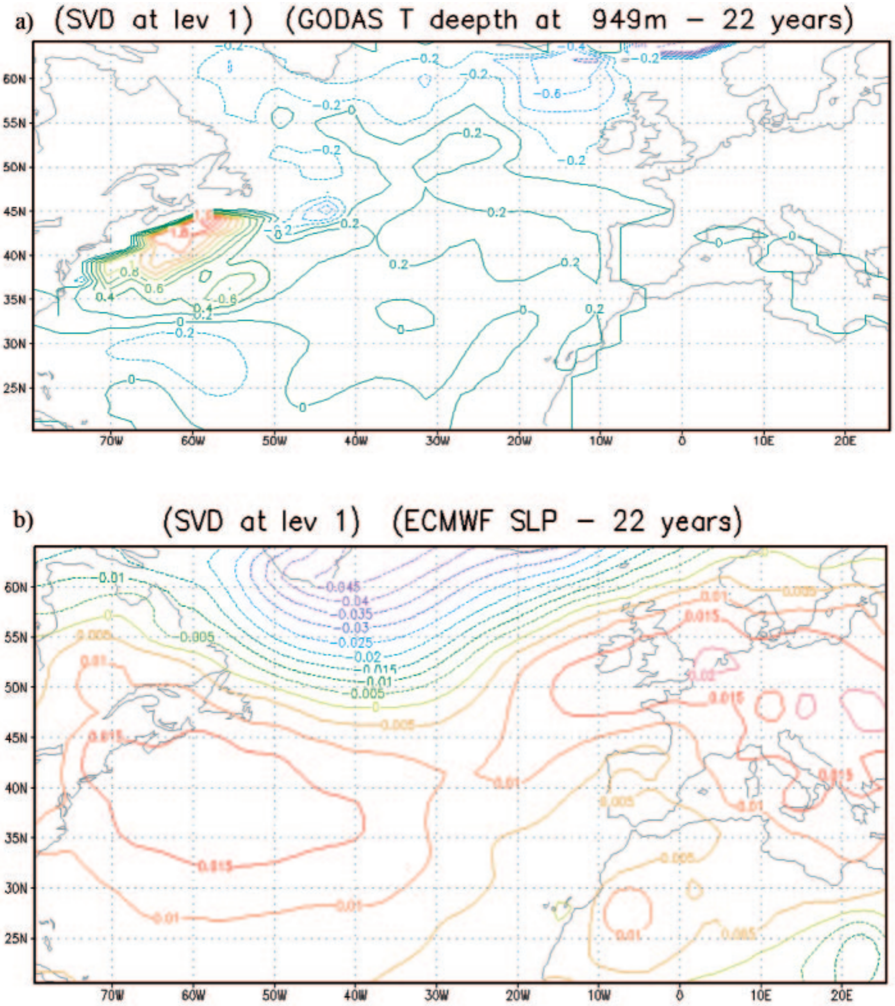

Fig. 5. – a) As for the observational data (GODAS). b) As fig. 4b SLP for the observational data (ECMWF).

Arctic river runoff increased up to 5500 km^3/year, while Greenland runoff was about 2100 km^3/year.

Figure 6 shows the near-surface temperature difference for 2081-2100 (RUN1) and 1860-1899 (RUN0).

The present model results show typical global warming structures: maximum warming appears in Arctic and some Antarctic regions (above 5–7 °C). In most of the tropics, the warming is smaller (2–4 °C).

The difference of surface temperature in 2081-2100 for RUN1 and RUN2, *i.e.* temperature response to increased rather than fixed pre-industrial Arctic river and Greenland runoff, is shown in fig. 7. The response is small relative to global warming. Increasing of fresh water flux leads to cooling in most of the North Atlantic by 0.5 °C, but in the Labrador sea by about 1 °C, and in the Barentz sea by 1–1.5 °C.

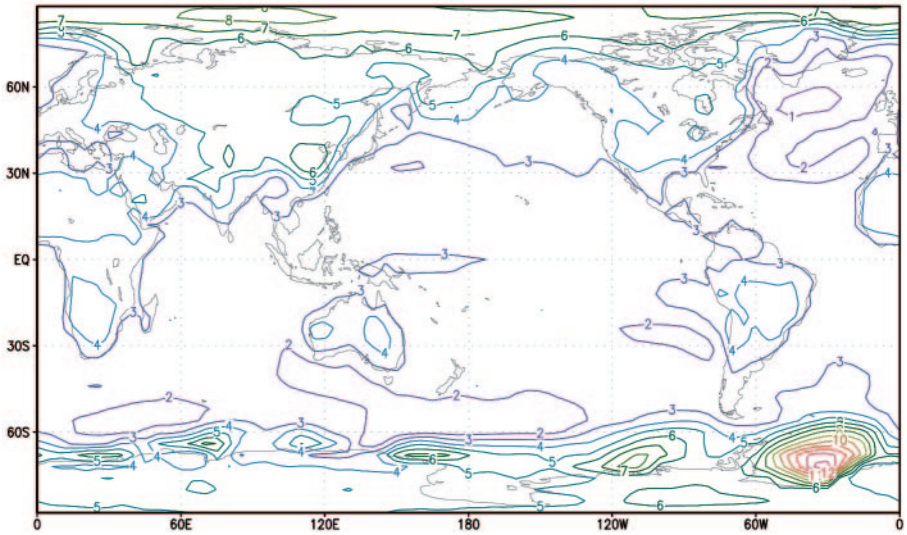

Fig. 6. – Near-surface temperature difference for 2081-2100 (RUN1) and 1860-1899 (RUN0).

To compare model response in AMOC, we present the time mean of the currents present model AMOC for 1960-1999 (fig. 8a). In the northern Atlantic the maximum is slightly overestimated by the model—15–20 Sv at 30N in the observations [10] and 25 Sv in the model. The model shows northward mass flux at 35S-60N in the upper layers and southward mass flux from 1000 m to the bottom. In global warming conditions (fig. 8b), there is a reduction of the AMOC by 5–10 Sv. The greatest reduction occurs near 25N, but negative AMOC changes appear almost everywhere in Atlantic. This is typical for the results of other models (*e.g.*, [11]) that show reduction of the AMOC

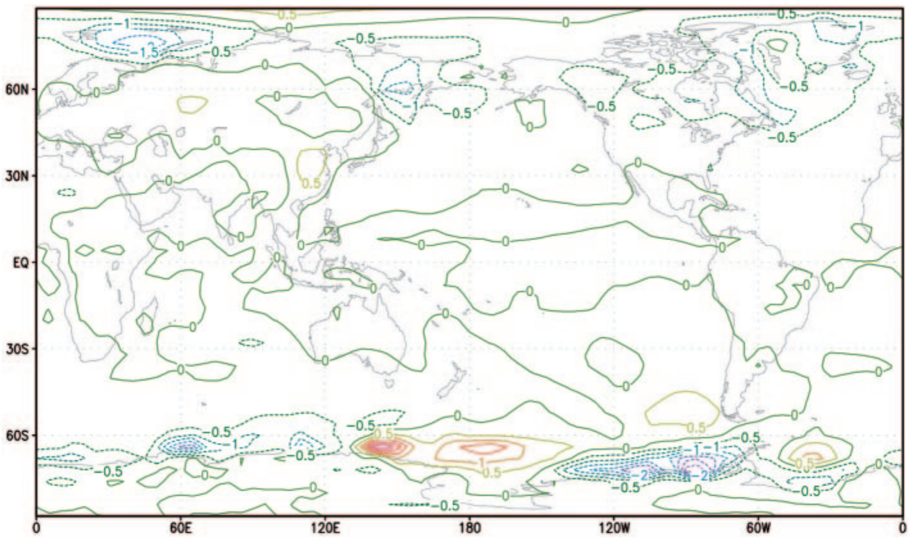

Fig. 7. – The difference of near-surface temperature for 2081-2100 in RUN1 and RUN2.

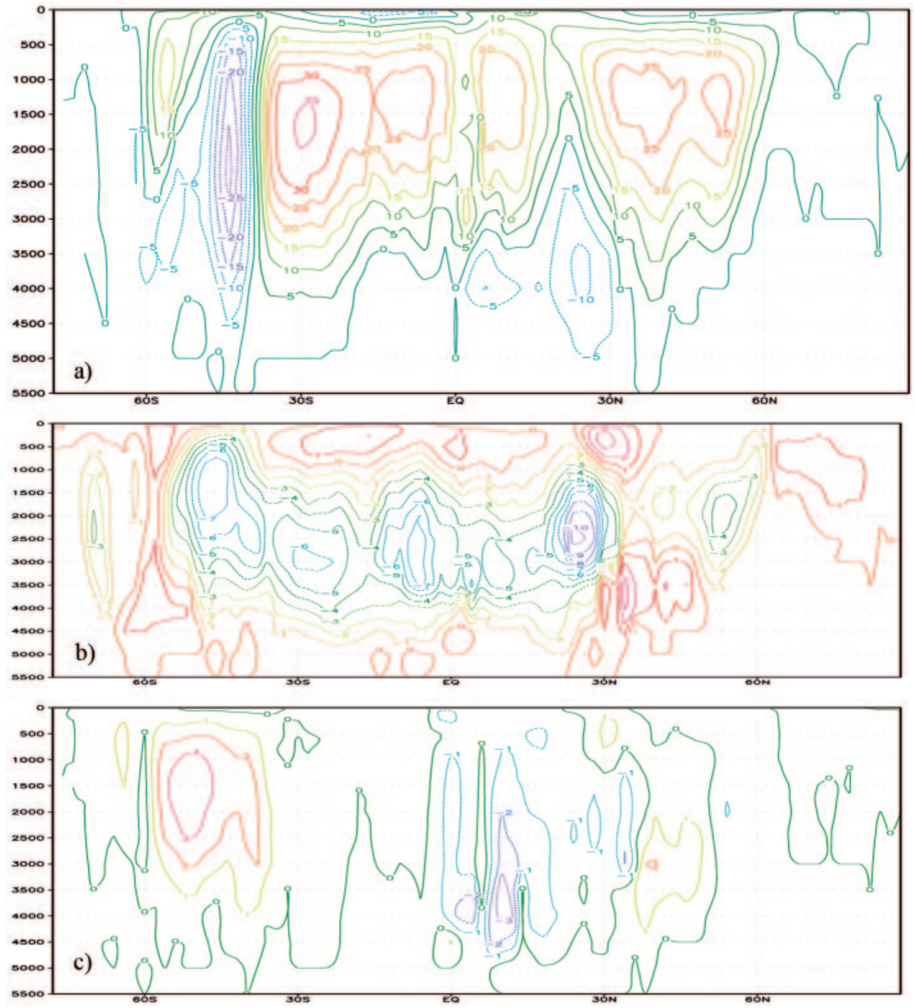

Fig. 8. – (a) Model AMOC (Sv) in RUN0 (1860-1899). b) The difference of AMOC for RUN1 (2801-2100) and RUN0 (1860-1899). c) The difference of AMOC for RUN1 and RUN2 (2081-2100).

by 16–31% in 2100. It is necessary to underscore that this reduction can be associated with the temperature decrease of the water masses at mid depth (sect. **2**). Moreover, fig. 8c shows that only a small part of the AMOC reduction induced by global warming can be explained by increasing of fresh water flux from Arctic rivers and Greenland. The rest of the decrease must be induced by other forcings, probably by the change of surface heat balance. Other studies, for example, Weaver *et al.* [11] also show that heat flux rather than fresh water flux change is mainly responsible for reducing of AMOC in global warming conditions.

4. – Natural variability of AMOC

To study the natural variability of the AMOC and associated variability of surface temperature, a 300-year control run with prescribed pre-industrial forcing was studied.

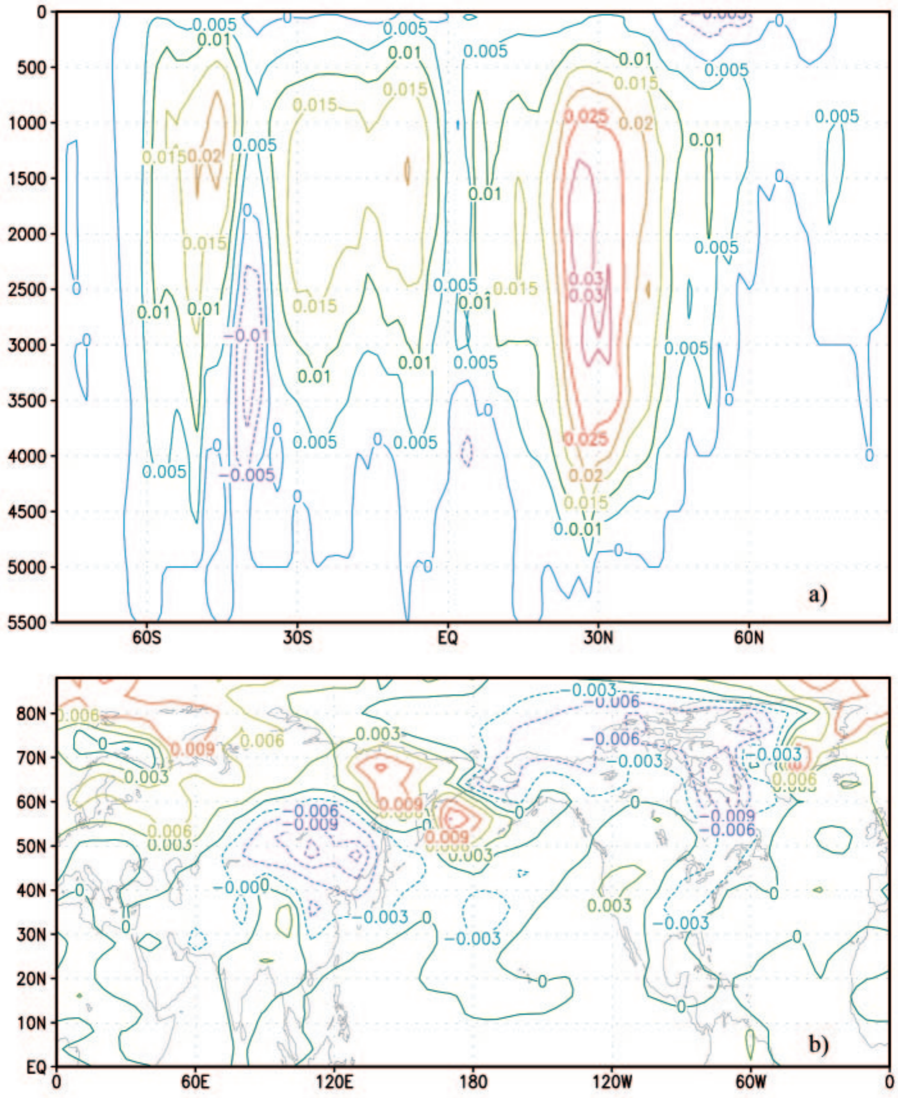

Fig. 9. – The first SVD of 10-year mean AMOC (a) and surface temperature (b).

SVD of annual mean, 5-year mean and 10-year mean AMOC and near-surface air temperature (TS) were calculated. The study shows that in 5-year and 10-year data the first SVDs intensify the AMOC and warm the Arctic and Europe (fig. 9). The first SVDs for annual mean data look different and can be explained as the Arctic oscillation signature in surface temperature—positive anomaly in the northern Eurasia, and negative anomaly in the eastern Canada (not shown).

Figure 10 shows a 10-year mean TS anomaly in the Atlantic-European high-latitude sector (50W-60E, 60-90N) for 10-year periods with positive anomaly of AMOC (positive expansion coefficient of the first SVD) with different time shifts. Time shift of M months means that we calculated temperature anomaly, averaged over 10-year periods,

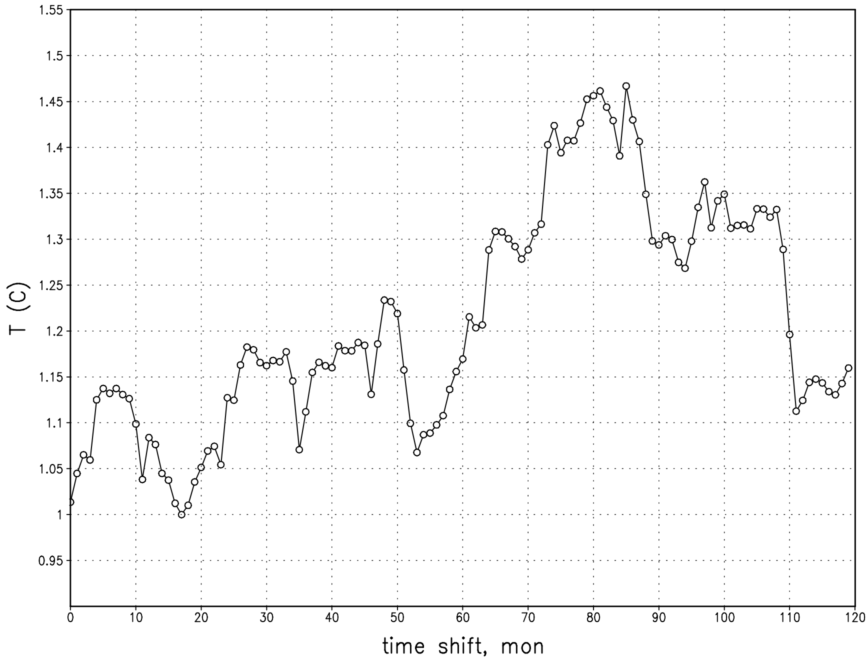

Fig. 10. – TS 10-year anomaly (°C) in region 50W-60E, 60N-90N for periods with positive 10-year mean AMOC index (expansion coefficient for AMOC of SVD-1). Number at x-axis means time shift (months) between surface temperature and AMOC. Positive means AMOC leads.

M months after a positive anomaly of the AMOC. Temperature anomaly was calculated as temperature averaged over appropriate 10-year intervals, minus temperature averaged over the entire model integration. For high AMOC and time shift 0, we have temperature anomaly of 1 °C in the chosen sector. The temperature anomaly increases with time shift and has maximum of 1.45 °C with a shift of 80 months. This means that probably the ocean circulation influences the TS rather than vice versa.

Conclusions

The study of coupled variability of SLP and Atlantic Ocean temperature at 1000 m shows that for observations and model data in the case of high NAO index we have negative temperature anomaly to the north of 55N, while local maxima and minima of temperature anomalies are located in different places in the model and the observations.

Observations and model results show a positive temperature trend in 1979-2000.

Our model study of the influence of fresh water flux change on global warming shows that only a small part of modelled reduction of the AMOC in global warming conditions can be attributed to the change of Arctic river and Greenland runoff. The main cause of the reduction of the AMOC is probably the change of ocean heat balance.

The analysis of model natural variability of the 10 year mean AMOC and the surface temperature shows that increasing the AMOC is correlated with warming in the Atlantic sector of Arctic and Northern Europe. On average, positive anomaly of the AMOC is associated with an anomaly of 1 K in this region.

The maximum of the surface temperature anomaly (1.45 K) appears 80 months after a strong increase in the AMOC.

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