Influence of the North Atlantic dipole on climate changes over Eurasia

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Abstract. In this paper, some hydrophysical and meteorological characteristics of negative (1948-1976 and 1999-2015) and positive (1977-1998) phases of the Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO) in the North Atlantic and Eurasia are constructed and investigated. Specifically, the near-surface temperature, sea-level atmospheric pressure, wind speed, heat content of the upper 700 m ocean layer, water temperature and salinity at various depths, the latent and sensible heat fluxes from the ocean to the atmosphere are analyzed. The fields obtained are in good agreement and complement each other. This gives important information about the hydrometeorological conditions in the region under study. Analysis of these data has shown that in the upper 1000 m North Atlantic layer there is a thermal dipole which can be interpreted as an oceanic analog of the atmospheric North Atlantic Oscillation (NAO). An index of the North Atlantic Dipole (NAD) as the difference between the mean heat contents in the upper 700 m oceanic layer between the regions (50º-70º N; 60º-10º W) and (20º-40º N; 80º-30º W) is proposed. A possible physical mechanism of the internal oscillations with a quasi-60-year period in the North Atlantics-Eurasia system of ocean-atmosphere interactions is discussed.

1. Introduction

There is some evidence that the current climate changes are mostly caused by anthropogenic factors [1, 2]. Natural factors, such as heat fluxes from the ocean to the atmosphere [3], also participate in this process. The existence of this effect is indirectly suggested by the fact that the heat content of the upper layer of North Atlantic waters changed considerably in the mid-1970s. This probably caused a change in the climatic scenario of this region [4]. An event of this type is the increase in the heat content of water in the Gulf Stream region in 1980-1995 [5]. These are hydrometeorological events of high energy. Therefore, the oscillations of the North Atlantic hydrophysical regime directly affect the climate of the North-American and Euro-Asian continents [6, 7].

The large-scale changes in the intensity and direction of heat fluxes of the ocean-atmosphere interaction affect the thermobaric characteristics of atmospheric centers of action, such as the Iceland cyclone and the Azores anticyclone, through the feedforward and feedback interrelations in the dynamics of the global climatic system [8]. The 1976/77 and 1998/99 PDO and IPO phase transitions caused global climatic shifts [9, 10, 11, 12, 13, 14]. These effects apparently caused a phase change in the NAO in the mid-1970s that affected the number of cyclones and the near-surface temperature in North Atlantic, as well as the transfer of heat from this region to the Euro-Asian continent [15]. In this paper, an attempt is made to determine the physical mechanism of these events, with most attention given to the thermohaline circulation of the North Atlantic Ocean.

2. Observations and method of data processing

The analysis is based on the most reliable independent sources among the most complete global average monthly databases [16]. Mean monthly fields of sea-level atmospheric pressure (HadSLP2) and near-surface temperature (CRUTEM4) processed by the Met Office Hadley Centre (United Kingdom) with a spatial resolution of 5ºx5º for 1850-2015 are analyzed [17, 18]. To obtain climatic wind patterns at various levels, mean monthly fields with a resolution of 2.5ºx2.5º are used from the NCEP/NCAR 1948-2015 reanalysis datasets [19]. The results obtained for the atmospheric pressure, wind, and near-surface temperature are verified with the data of the 1851-2011 NOAA CIRES 20th Century Reanalysis v2c (USA) [20], the 1900-2010 European ERA-20C Reanalysis [21], and the 1958-2013 Japanese JRA-55 Reanalysis [22]. Sea surface temperature (SST) was taken from the COBE SST2 of Japan Meteorological Agency with a resolution of 1ºx1º for 1850-2014 [23].

A combined analysis is performed with 3-months means of heat content anomalies (with a resolution of 1ºx1º) of the upper 700 m oceanic layer and mean water temperature anomalies at 16 depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, and 700 meters) for 1955-2015 produced by the National Oceanographic Data Center (NODC) [24]. To obtain a more accurate quantitative estimate, the oceanic temperature and salinity values at 24 different depths up to 1500 m are taken from the mean monthly Ishii Ocean Analyses Project data with a resolution of 1ºx1º in 1945-2012 [25]. The depth of an upper active layer (for the regions of deep convection) is determined by "sigma-t" criterion [26] for 1900-2000 using the results of an experiment called Historical of the CMIP5 project with a combined ocean-atmosphere general circulation model called MPI-ESM-MR [27]. The upper active layer of the ocean is the near-surface ocean water layer subject to a direct action of atmospheric processes and affecting the atmosphere through turbulent energy and mass transfer. To analyze the latent and sensible heat fluxes from the ocean to the atmosphere in 1958-2015, OAFlux (NOAA) data with a resolution of 1ºx1º are used [28].

The mean fields of the above characteristics for negative (1948-1976 and 1999-2015) and positive (1977-1998) PDO phases are calculated separately. The mean field for the previous period is subtracted from the mean field for the period chosen. The difference shows the changes that took place for the periods. A six-year smoothing moving average is used to construct the curves shown below. The seasonal variations are removed by subtracting the climatic values of the characteristics under investigation over the entire time interval.

3. Discussion of the analysis results

The field of difference for November-March mean sea level pressure (SLP) between the 1977-1998 and 1948-1976 periods (figure 1a) in the North Atlantic shows a negative anomaly northward and a positive anomaly southward of the 50th parallel. This corresponds to a positive phase of NOA. The field of difference for the November-March mean wind speed at 850 hPa between the 1977-1998 and 1948-1976 periods (figure 1c) has cyclonic circulation anomalies corresponding to the barometric structure (figure 1a), with center to the east of Greenland and in the Greenland Sea, as well as anticyclonic circulation anomalies, with center to the west of the Azores Islands. The pattern of wind field anomalies (figure 1c) indicates that in 1977-1998 there is (in comparison to the previous period) an increase in the north-eastern trade wind, southern wind in the Sargasso Sea zone, and western transport from the North Atlantic to the Euro-Asian continent along the 50° parallel north.

The field of difference of the mean SLP for November-March between the 1999-2015 and 1977-1998 periods (figure 1b) in the North Atlantic has anomalies mostly of the opposite sign (in comparison the field of figure 1a) corresponding to a negative phase of NAO: positive SLP anomalies in the Iceland cyclone and negative ones in the Azores anticyclone. The field of difference of the mean November-March wind speed at 850 hPa between the 1999-2015 and 1977-1998 periods (figure 1d) corresponds to the SLP field in figure 1b, and has anomalies that are typical for weakening of the western transport from the North Atlantic to the Euro-Asian continent along the 50° parallel north.

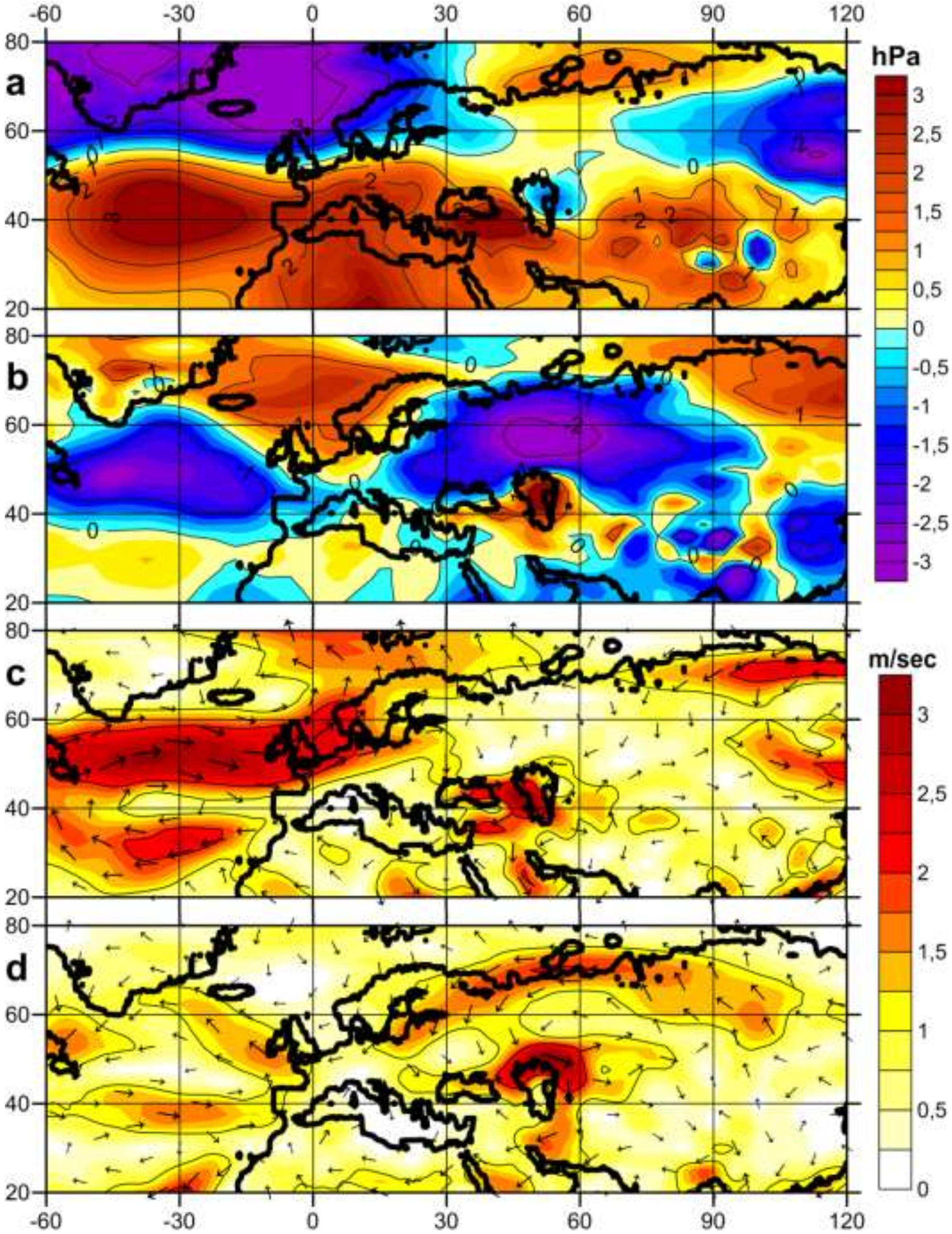

Figure 1. Fields of difference of mean sea-level atmospheric pressure for November-March between 1977-1998 and 1948-1976 (a), and between 1999-2015 and 1977-1998 (b); fields of difference of mean wind velocity at 850 hPa for November-March between 1977-1998 and 1948-1976 (c), and between 1999-2015 and 1977-1998 (d).

The field of mean November-March depths of the ocean mixed layer thickness defined by Sigma T (MLOTST) (figure 2a) shows that in the cold period of the year the major deep convection zones (depths more than 1 km) are located in the Labrador and Greenland Seas zone. Also, large MLOTST depths (200-300 m) are observed in the North-Atlantic current zone. The Labrador Sea and North-Atlantic current zones are separated by a small-depth (about 50 m) MLOTST band. This indicates that there is a considerable difference in the thermohaline conditions of these two zones. The field of mean MLOTST depths for the warm (May-September) time of the year (figure 2b) has much smaller MLOTST values in comparison to those of the cold period (figure 2a). This corresponds to weakening of the influence of the ocean on the atmosphere in the warm period of the year in comparison to that in the cold one.

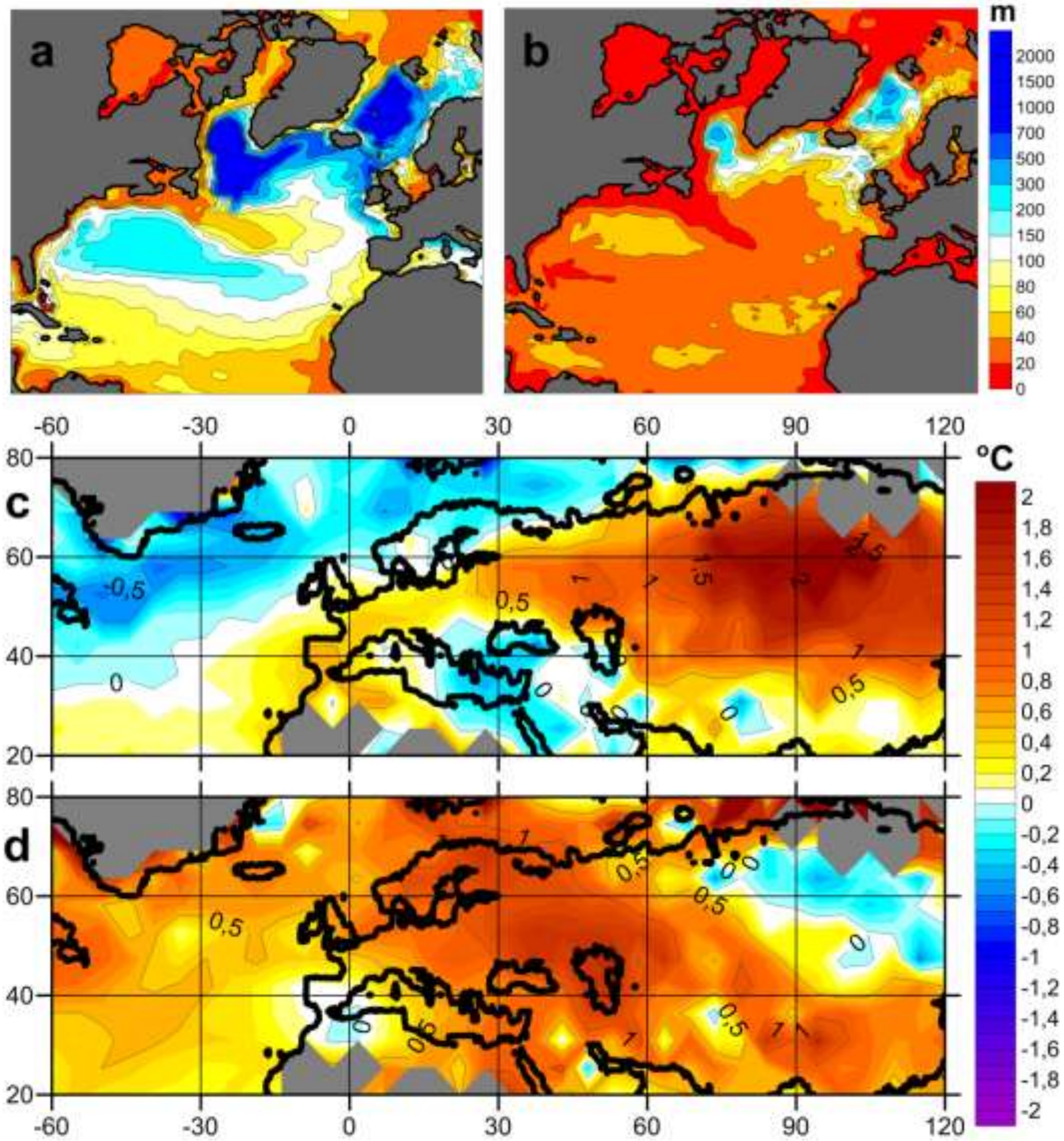

Figure 2. Fields of mean depths of the ocean mixed layer thickness for November-March (a) and May-September (b). Fields of difference of mean near surface temperatures for November-March between 1977-1998 and 1948-1976 (c), and between 1999-2015 and 1977-1998 (d).

The field of difference of the mean November-March near surface temperatures (NST) between 1977-1998 and 1948-1976 (figure 2c) is in good agreement with the corresponding fields of SLP and wind speed (figures 1a and 1c). Figure 2c clearly shows a zone of negative NST anomalies in the Labrador Sea, to the south of Greenland and to the north-east of the Newfoundland Island. This anomaly is in a region of western wind enhancement along the 50th parallel, from where this heat is transported to the Euro-Asian continent experiencing an abrupt NST growth since the mid-1970s. The field of difference of the November-March NST means between 1999-2015 and 1977-1998 (figure 2d) shows positive anomalies in North Atlantic and negative ones over a part of Siberia. In the author's opinion, this is due to a weakening of the western transport along the 50th parallel and decrease in the heat transfer from the northern part of the Atlantic Ocean to the Euro-Asian continent, which is typical for 1999-2015 (in comparison to 1977-1998) (figure 1d).

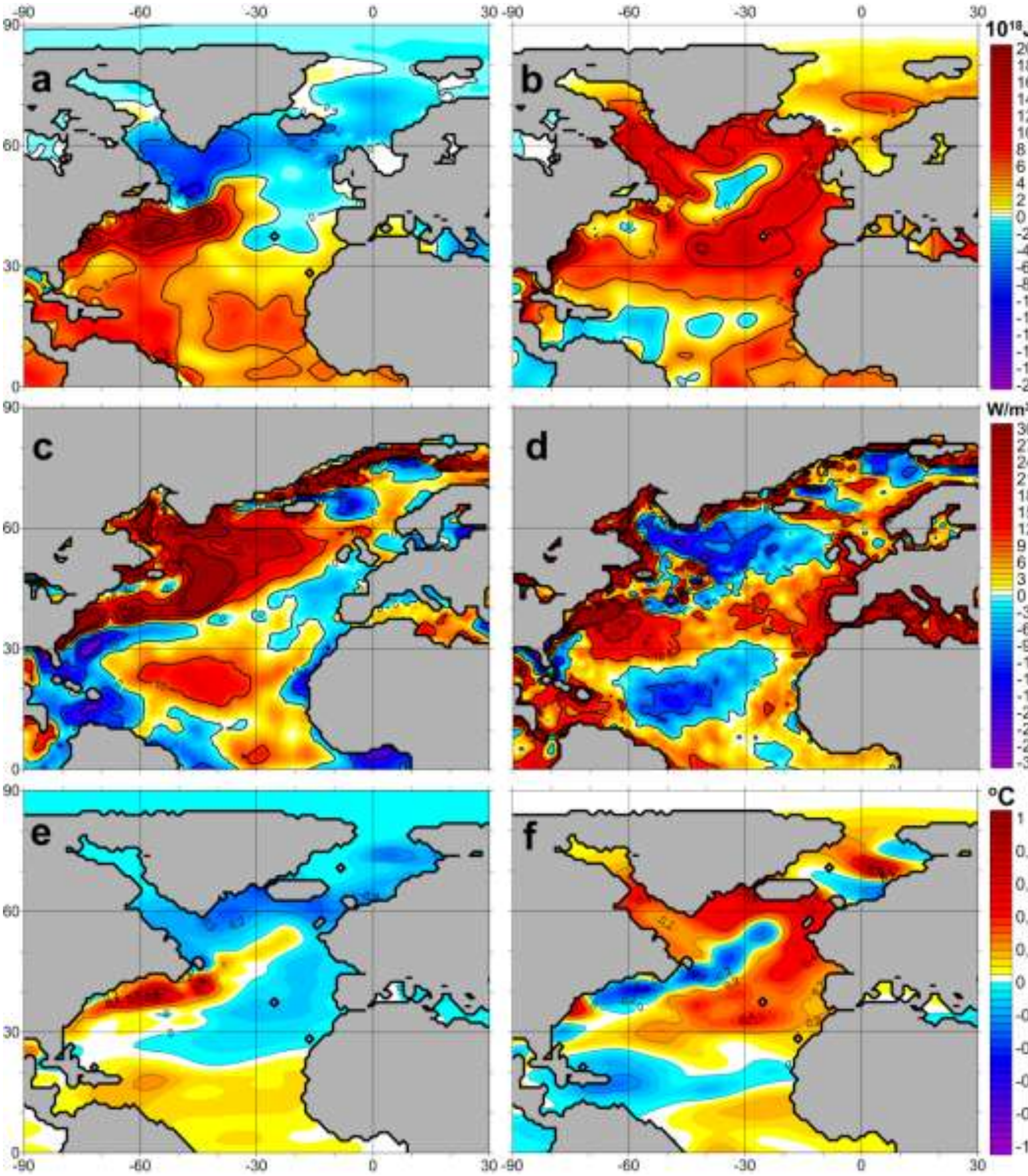

Figure 3. Fields of difference of the mean heat contents in the upper 700 m ocean layer between 1977-1998 and 1955-1976 (a) and between 1999-2015 and 1977-1998 (b). Fields of difference of the mean November-March latent and sensible heat ocean-atmosphere fluxes between 1977-1998 and 1958-1976 (c), and between 1999-2015 and 1977-1998 (d). Fields of difference of the mean ocean temperatures at a depth of 500 m between 1977-1998 and 1948-1976 (e) and between 1999-2012 and 1977-1998 (f).

Consider the upper 700 m ocean layer. The field of difference of the mean heat contents between 1977-1998 and 1955-1976 (figure 3a) shows the North Atlantic Ocean heat losses mostly to the north of the 50th parallel and gains to the south. The situation is different for the Labrador Sea zone between

1999-2015 and 1977-1998 (figure 3b): its heat content increased in 1999-2015 in comparison to that in 1977-1998 [29]. Thus, when one NAO phase changes for the opposite one, the heat is redistributed between the northern and southern parts of the North Atlantic. Hence, inter-decadal changes in the ocean heat content in the North Atlantic current and Labrador Sea zones after the removal of a linear trend probably caused by global climate warming are opposite in sign.

The field of difference of the mean November-March latent and sensible heat fluxes from the ocean to the atmosphere between 1977-1998 and 1958-1976 (figure 3c) demonstrates positive anomalies of heat transfer from the ocean to the atmosphere in the Labrador Sea zone. This corresponds to a decrease in the ocean heat content in this region (figure 3a). The field of difference of the mean November-March latent and sensible heat fluxes from the ocean to the atmosphere between 1999-2015 and 1977-1998 (figure 3d) shows negative anomalies of heat transfer from the ocean to the atmosphere in the Labrador Sea zone. This corresponds to an increase in the ocean heat content in this region (figure 3b).

The field of difference of the mean ocean temperatures at a depth of 500 m between 1977-1998 and 1948-1976 (figure 3e) shows negative anomalies in the Labrador Sea zone. This phenomenon may be explained by the enhancement of the cold Labrador current caused by the cyclonic wind anomaly (figure 1a), as well as by the regional cooling of the upper ocean layer due to the deep winter convection and the corresponding increase in the ocean heat transfer to the atmosphere (figure 3c). In figure 3e special attention must be given to the positive ocean temperature anomalies in the North Atlantic current zone. According to our calculations, these phenomena may be caused by the enhancement of the trade wind, as well as by the positive anomaly of the southern wind in the Sargasso Sea zone (figure 1c). Both factors have a “one-way” effect creating an additional flow of warm tropical waters to the Mexican Gulf. This affects the thermodynamic characteristics of the Gulf Stream current, which, in turn, affects the North Atlantic current. The anomalies of the field of difference of the mean ocean temperatures at a depth of 500 m between 1999-2012 and 1977-1998 (figure 3f) are almost opposite to those in figure 3e. In Figs. 3e and 3f between the regions of subtropical anti-cyclonic and subpolar cyclonic gyres, there is a dipole structure, which was detected by using sea level data [30, 31]. This structure could be called as the North Atlantic Dipole (NAD).

The fields of difference between the time periods of the mean temperature and salinity of the North Atlantic Ocean at various depths up to 1500 m show that NAD is most pronounced at the depths from 500 m to 700 m. In the present paper, a NAD index as the difference of the mean heat contents of the upper 700 m ocean layer between the regions (50º-70º N; 60º-10º W) and (20º-40º N; 80º-30º W) is proposed. It differs from the index of the Atlantic Multidecadal Oscillation (AMO), which is calculated as the mean surface temperature anomaly of the North Atlantic Ocean (20º-70º N; 80º-0º W) with lineal trend removing. It does not take into account the deep ocean temperature and the NAD dipole structure. Also, in calculating the AMO index there are problems associated with the removal of linear trend and the correction for the measurement device arrays affecting the resulting series. The NAD index proposed above is calculated as the difference between two regions and, hence, these problems have less effect on the series than when the index is calculated for only one of the regions [32, 33].

Figure 4a presents the NAD index, AMO index and the NAO index calculated as the difference of the mean SLP anomalies between the Azores maximum (20º-40º N; 40º-20º W) and the Iceland minimum (50º-70º N; 45º-25º W) regions. The NAD and NAO indices complement each other, since they are calculated, respectively, as the difference of the upper ocean layer heat content and the atmospheric pressure between almost the same regions. They characterize the largest part of the North Atlantic ocean-atmosphere system, and not just its atmospheric or oceanic component. The more than 50-years variation of the NAD and NAO indices (figure 4a) demonstrates the following interesting peculiarities: after the removal of inter-annual variations (influence of the El Niño – Southern Oscillation) the NAO index is ahead of the NAD index, although they have high negative correlation with each other. Thus, it can be concluded that on multidecadal timescales the atmosphere has a dominant role in the atmosphere-ocean system, which contradicts some earlier results that North

Atlantic Ocean control on atmosphere-ocean interaction on multidecadal timescales [8]. However, there is no large time shift between the NAD and NAO indices, whereas the phases of the AMO index variations are shifted considerably (by about 6 years) with respect to those of the NAO index (figure 4a) [34].

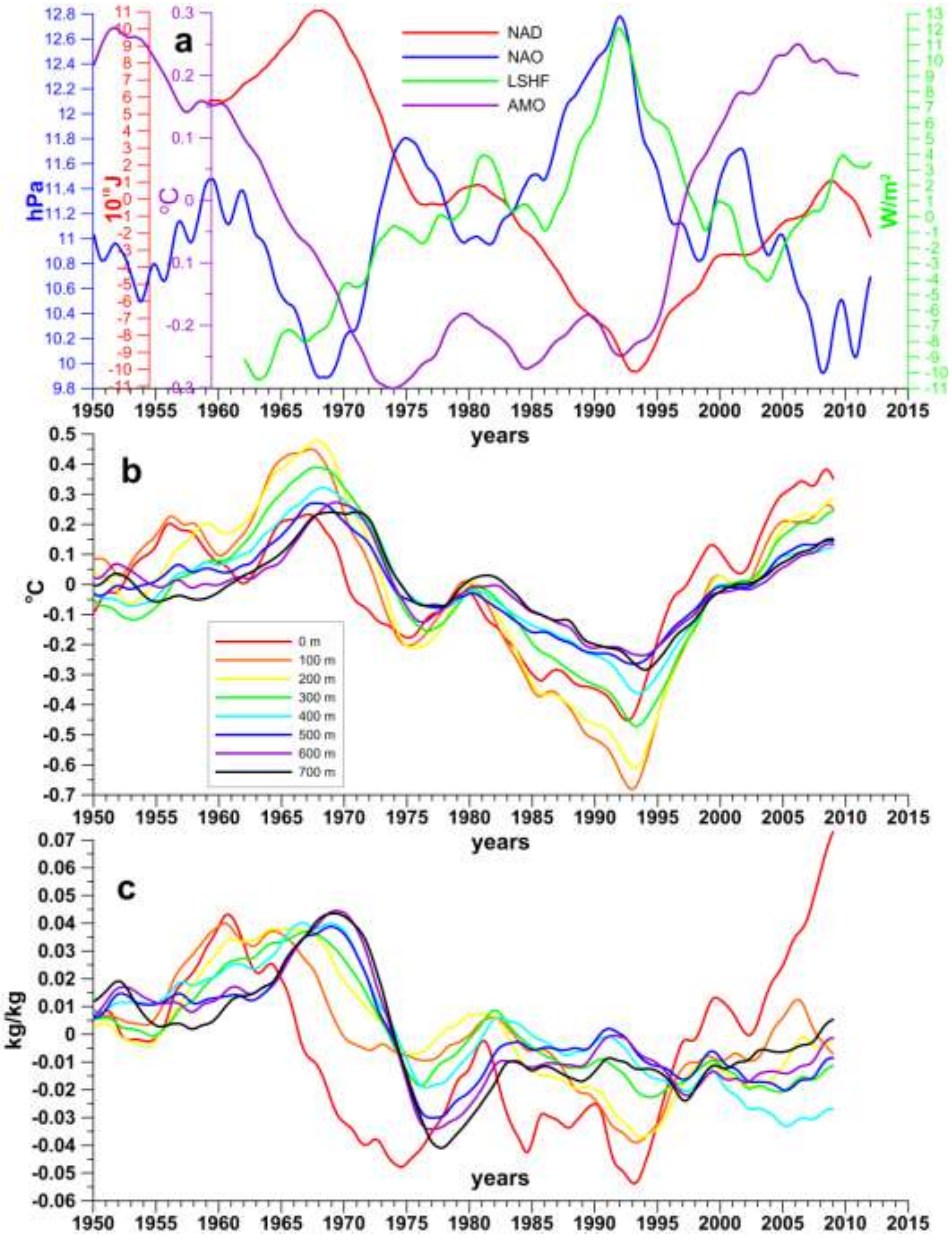

Figure 4. NAD (red), NAO (blue) and AMO (deep purple) indices (a). Time series of differences of mean values between (50º-70º N; 60º-10º W) and (20º-40º N; 80º-30º W), anomalies of latent and sensible heat fluxes from the ocean to the atmosphere (green) (a), anomalies of the ocean temperature (b) and salinity (c) at various depths.

The time series of the differences of the mean anomalies of latent and sensible heat fluxes from the ocean to the atmosphere between the regions (50º-70º N; 60º-10º W) and (20º-40º N; 80º-30º W) are presented in figure 4a. They demonstrate a high positive correlation with the NAO index and a negative one with the NAD index. Such, indeed, is the case, since with increasing latent and sensible heat fluxes from the ocean to the atmosphere the heat content of the ocean decreases, and with decreasing heat fluxes it increases.

Figures 4b and 4c show the time series of the differences of the mean ocean temperature and salinity anomalies at various depths between the regions (50º-70º N; 60º-10º W) and (20º-40º N; 80º-30º W). Notice that the temperature and salinity variations in the upper ocean layers are ahead of those in the lower layers. This again shows that the atmosphere on multidecadal timescales has a dominant role in the atmosphere-ocean system.

It follows from figure 4 that in the early 1990s there was a climatic shift in the North Atlantic: there is a strong bend in the series in 1992/93. This may be associated with the 1991 Pinatubo volcano eruption. After this event, starting from 1992/93, decreased latent and sensible heat fluxes from the ocean to the atmosphere and increased heat content in the North Atlantic have been observed [35]. These could lead to the “hiatus” in the Siberian climate warming in the cold time of the year observed over the 1999-2015 period [36].

4. Conclusions

A dipole structure of inter-decadal variations in the heat content of the ocean and heat fluxes from the ocean to the atmosphere has been detected in the North Atlantic. The following fact deserves special attention: the cyclonic and anti-cyclonic atmospheric circulation anomalies, as well as the decrease and increase in the ocean heat content, take place concurrently and quasi-synchronously in the Iceland minimum and Azores maximum regions. Owing to this, the western heat transport anomalies along the 50th parallel increase or decrease the transport of heat from the Atlantic Ocean to the Euro-Asian continent, and the climate in Europe and Siberia becomes more marine or more continental [37]. The very fast climate warming of the Euro-Asian continent that began in the 1970s may be associated with the enhanced heat transport from the North Atlantic in this period. This is evident from the fields and time series obtained in the present paper. The hiatus of this warming after 1999 may be due to the decreased heat transfer from the North Atlantic Ocean to the Eurasian territory.

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