The role of winter net heat fluxes on the modulation of the upper mixed layer temperature and depth in the North Atlantic by the reanalysis data

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Abstract. The role of winter net heat fluxes (NHF) on the upper mixed layer (UML) temperature and depth variability over the North Atlantic is studied using ocean reanalysis data products. The monthly data from the ORA-S3 (1959–2011), GODAS (1980–2020), GECCO3 (1948–2018) datasets were used. The correlation coefficients were calculated between the anomalies of the NHF on the ocean surface and the UML temperature and depth with a shift of 1 month when the former were leading. In most of the North Atlantic, negative correlations between the UML temperature and the NHF preceding 1 month were found. Here, the UML temperature anomalies are probably caused by changes in heat exchange with the atmosphere. Areas of significant positive correlations across all data sets are concentrated in the area of the transition of the Gulf Stream to the North Atlantic Current. Almost the entire water area of the North Atlantic is occupied by positive correlations between the mixed layer depth in winter and the NHF on the ocean surface, with the latter leading for 1 month.

1. Introduction

The upper mixed layer (UML) of the ocean is a layer that forms as a result of turbulent mixing when interacting with the atmosphere. As a result of this interaction, the main hydrophysical parameters (temperature, salinity, density) are distributed uniformly along the vertical within the UML. The mixed layer depth (MLD) depends on the exchange of heat, mass and momentum between the upper layer of the ocean and the atmosphere.

The study of the processes occurring in the UML is of great importance for understanding climate variability. The UML thickness modulates its heat capacity and the ability to accumulate heat from the atmosphere. In addition, the change in the position of the UML lower boundary determines the participation of the deeper layers of the ocean in the exchange of heat with the atmosphere. The study of the UML heat balance plays an important role in understanding the processes that cause changes in the UML temperature [1–5].

In many works, studies of the UML regional variability and its sensitivity to changes in atmospheric forcing have been carried out [6, 7]. The results of model studies [8, 9] showed that the net heat fluxes (NHF) forcing dominates in the UML characteristics variability in the winter season. In this case, wind stress anomalies are ineffective in the formation of sea surface temperature (SST)
variability. Analysis of the cross correlations of the MLD with both the NHF and the wind stress showed that their contribution is mostly at the same level, with a more pronounced correlation for the NHF [7]. However, modern data sets make it possible to consider large water areas over long time periods. This is especially important because the atmospheric forcing is characterized by spatio-temporal heterogeneity caused by the peculiarities of atmospheric circulation and its variability.

The aim of the study is to identify regions in the North Atlantic with a different nature of prevailing atmospheric forcing, expressed by the NHF, on the UML temperature and depth in the winter season by analyzing the ocean reanalysis data.

2. Data and methods

The monthly data on the upper ocean temperature and MLD presented here are taken from the Ocean Reanalysis System 3 (ORA-S3) for the period 1959–2011 [10], the Global Ocean Data Assimilation System (GODAS) for the period 1980–2020 [11] and the German contribution to the Estimating the Circulation and Climate of the Ocean system (GECCO3) for the period 1948–2018 [12]. The monthly data on the NHF on the ocean surface are taken from the atmospheric reanalyses: ERA-40 [13], NCEP-DOE AMIP-II Reanalysis [14] and NCEP/NCAR Reanalysis [15], respectively. These datasets were used to force the ocean model in the reanalyses listed above. The North Atlantic water area is limited by coordinates (0–70 °N 8–80 °W). The vertical z-axis is directed upward. Positive values of the NHF on the ocean surface mean the outflow of heat from the ocean to the atmosphere.

Ocean reanalysis is a calculation of one or another numerical model of ocean circulation with the assimilation of available observational data that are non-uniformly distributed in space. Discrepancies may arise between different reanalyses, both due to different models with their own characteristics, and due to the use of different data assimilation procedures in them [16].

Note that we are using ready-made MLD data. The MLD in the ORA-S3 reanalysis is taken to be equal to the depth at which the Richardson number \((R_i)\) reaches the critical value [10]. In the GECCO3 reanalysis the depth-independent critical gradient \(R_i\) was chosen to control the MLD [12]. Both of these techniques use the \(R_i\) to determine the position of the UML lower boundary. In the GODAS reanalysis, the MLD is the depth where the buoyancy difference with respect to the surface level is equal to 0.03 (cm/s²) [https://www.psl.noaa.gov/data/gridded/data.godas.html].

Based on the ocean temperature data, for each of the reanalyses used, the average temperature was calculated within the space and time variable MLD for each month for the entire available period. The UML temperature is assumed to be constant over the MLD and corresponds to the SST. Further, the UML temperature and depth values in January, February and March and the NHF values with a shift of one month in December, January and February were identified. Then, using the least squares method, the linear trend for the available period was removed from all variables. After that, the values of the correlation coefficients were calculated between the obtained anomalies of the NHF on the ocean surface and the UML temperature and depth with a shift of 1 month when the former were leading. The relationship between the NHF and the UML characteristics is more pronounced when the UML processes are delayed by 1 month. This shift is due to the thermal inertia of the UML [7, 17, 18].

3. Results

The values of the correlation coefficients between the UML temperature in January, February and March and the NHF on the ocean surface with the latter leading for 1 month are shown in figure 1. Most of the North Atlantic water area is occupied by negative correlations. Here, the UML temperature anomalies are probably caused by changes in heat exchange with the atmosphere. Areas of significant negative correlations are located in the Gulf Stream recirculation area and in the Tropical Atlantic, as well as in the Gulf Stream itself before its separation from the continental slope, with the exception of the GODAS data in February and March. This means that the UML cooling (the negative UML temperature anomaly) in the winter season is preceded (with a shift of 1 month) by an increase in heat outflow from the ocean surface (the positive NHF anomaly).
Figure 1. Cross correlation of net heat fluxes (NHF) (positive upward) and UML temperature (TEMP) anomalies from ORA-S3 (a, b, c), GODAS (d, e, f) and GECCO3 (g, h, i) data. All figures represent the corresponding one-month lag correlations, where UML temperature lags the forcing by one month. The left column shows correlation between net heat flux anomalies in December and the UML temperature in January (a, d, g). The middle column shows correlation between net heat flux anomalies in January and the UML temperature in February (b, e, h). The right column shows correlation between net heat flux anomalies in February and the UML temperature in March (c, f, i). Colour code is in such a way that blue shading represents negative correlations and red shading – positive correlations. Black thick line shows the values of the correlation coefficient ±0.5.

The areas of significant positive correlations for all datasets are concentrated in the area of the transition of the Gulf Stream to the North Atlantic Current. Here, an increase in heat outflow from the ocean surface (the positive NHF anomaly) in the winter season is accompanied by an increase in the UML heat content for the next month. In these regions, the formation of temperature anomalies is significantly influenced by inner ocean processes in the UML (see, for example, [1 and 5]). In addition, positive correlations in these areas indicate that here the variability in the UML drive the
formation of the variability of the atmosphere, due to the change in the intensity of the transfer of heat to it brought by warm currents. On the whole, it can be stated that, in areas of negative correlations, the NHF between the atmosphere and the ocean affect the formation of the SST anomalies. And, conversely, in areas of positive correlations, the SST anomalies are formed under the influence of inner ocean processes.

**Figure 2.** Cross correlation of net heat fluxes (NHF) (positive upward) and mixed layer depth (MLD) anomalies from ORA-S3 (a, b, c), GODAS (d, e, f) and GECCO3 (g, h, i) data. All figures represent the corresponding one-month lag correlations, where mixed layer depth lags the forcing by one month. The left column shows correlation between net heat flux anomalies in December and the mixed layer depth in January (a, d, g). The middle column shows correlation between net heat flux anomalies in January and the mixed layer depth in February (b, e, h). The right column shows correlation between net heat flux anomalies in February and the mixed layer depth in March (c, f, i). Colour code is in such a way that blue shading represents negative correlations and red shading – positive correlations. Black thick line shows the values of the correlation coefficient ±0.5.
However, there are some peculiarities in the fields of the correlation coefficients obtained from the reanalyzes data. The UML temperature anomalies according to ORA-S3 data in a narrow vicinity of the equator (0–5 °N) do not show significant correlation with the NHF preceding 1 month. The UML temperature anomalies according to GODAS data in January and February show a weak positive correlation with the NHF anomalies preceding 1 month, and the UML temperature according to GECCO3 data shows a significant positive correlation. In the vicinity of 10 °N 40 °W the UML temperature anomalies according to GODAS data in January and February show a weak positive correlation with the NHF anomalies preceding 1 month. According to the data of two other reanalyzes, a weak negative correlation is noted here. In the Guiana Current, the UML temperature anomalies, according to GODAS data, show a positive and significant correlation with the NHF anomalies preceding 1 month, but this is not observed according to the data of two other reanalyzes. The UML temperature anomalies, according to the ORA-S3 and GODAS data, in the Labrador Current show a significant positive correlation with the NHF anomalies preceding 1 month. At the same time, the UML temperature anomalies, according to the GECCO3 data, here show a negative correlation in January, and a positive correlation in March. The UML temperature anomalies according to the ORA-S3 data in the East Greenland Current and according to the GODAS data at the southern tip of Greenland show a negative correlation with the NHF anomalies preceding 1 month, and the UML temperature anomalies according to the GECCO3 data show a weak positive correlation.

The values of the correlation coefficients between the MLD in January, February and March and the NHF on the ocean surface with the latter leading for 1 month are shown in figure 2. Almost the entire water area of the North Atlantic is occupied by positive correlations. An increase in heat outflow from the ocean surface (the NHF positive anomaly) in the winter season is accompanied by the UML deepening for the next month (the MLD positive anomaly).

However, there are some peculiarities in the fields of the correlation coefficients between the MLD anomalies and the NHF on the ocean surface. The MLD anomalies according to ORA-S3 and GECCO3 data in the vicinity of 0–10 °N show a weak positive relationship with the NHF preceding 1 month, and according to the GODAS data, there are areas of insignificant negative values of the correlation coefficients. The MLD anomalies according to the ORA-S3 data in the Gulf Stream (42 °N 55 °W) show a significant negative correlation with the NHF preceding 1 month, and according to the data of two other reanalyzes, a significant positive correlation is noted here. The MLD anomalies according to the GODAS data in the Labrador Current show a significant positive correlation with the NHF preceding 1 month, and according to the data of two other reanalyzes, a significant positive correlation is noted here. The MLD anomalies according to GODAS and GECCO3 data in the area of deep convection in the Labrador Sea show a significant positive correlation with the NHF preceding 1 month, and according to ORA-S3 data, there is no significant correlation in this region. The MLD anomalies in February and March in the inner part of the subtropical gyre show a positive correlation with the NHF preceding 1 month according to ORA-S3 and GODAS data, and an insignificant negative correlation according to GECCO3 data.

In this work, different definitions of the MLD are used for the discussed ocean re-analyzes. Since the technique for determining the MLD using the *Ri* is rather crude, there is no fundamental difference between the results obtained from the ORA-S3 and GECCO3 data. The *Ri* takes into account stratification and measures the combined effect of buoyancy forcing and vertical current shear. The MLD according to GODAS data is defined by the difference criterion. This method allows defining the MLD as the depth where the oceanic property (buoyancy) has changed by a critical value from a reference depth near to the surface. Our results show that it is more correct to use the MLD values obtained using the *Ri* criterion. Determining the exact position of the UML lower boundary will make it possible to clarify the impact of winter NHF on the UML temperature and depth variability. Our results are independent of the length of the time series. Since the correlations were obtained both for short time series (GODAS data – 41 years) and for long time series (ORA-S3 data – 53 years and GECCO3 data – 71 years).
4. Conclusion

In most of the North Atlantic water area, negative correlations were found between the UML temperature and the NHF preceding 1 month. Here, the UML temperature anomalies are probably caused by changes in heat exchange with the atmosphere. The UML cooling in the winter season is preceded (with a shift of 1 month) by an increase in heat outflow from the ocean surface. Areas of significant positive correlations across all data sets are concentrated in the area of the transition of the Gulf Stream to the North Atlantic Current. Here, an increase in the heat outflow from the ocean surface in the winter season is accompanied by an increase in the UML heat content for the next month and is probably caused by the inner ocean processes.

Almost the entire water area of the North Atlantic is occupied by positive correlations between the MLD in winter and the NHF on the ocean surface, with the latter leading for 1 month. An increase in heat outflow from the ocean surface in the winter season is accompanied by the formation of unstable stratification in the UML and, as a consequence, the UML deepening for the next month.

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References

[1] Kelly K A and Qiu B 1995 J. Phys. Oceanogr. 25 2361–73
[2] Alexander M A, Scott J D and Deser C 2000 J. Geophys. Res. 105 16823–42
[3] Dommenget D and Latif M 2002 Clim. Dyn. 19 277–88
[4] Dong S and Kelly K A 2004 J. Phys. Oceanogr. 34 1214–31
[5] Polonsky A B and Sukhonos P A 2017 Izv. Atmos. Ocean. Phys. 53 459–66
[6] Adamec D and Elsberry R L 1984 J. Phys. Oceanogr. 14 1670–76
[7] Pookkandy B, Dommenget D, Klingaman N, Wales S, Chung C, Frauen C and Wolff H 2016 Clim. Dyn. 47 2991–3010
[8] Alexander M A and Penland C 1996 J. Climate 9 2424–42
[9] Zhao B and Haine T W N 2005 Ocean Modelling 9 211–29
[10] Balmaseda M A, Vidard A and Anderson D L T 2008 Mon. Wea. Rev. 136 3018–34
[11] Behringer D W and Xue Y 2004 Proc. Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (Washington: AMS)
[12] Köhl A 2020 Q. J. R. Meteorol. Soc. 146 2250–73
[13] Uppala S M, Källberg P W, Simmons A J et al 2005 Q. J. R. Meteorol. Soc. 131B 2961–3012
[14] Kanamitsu M, Ebisuzaki W, Woollen J, Yang S, Hnilo J J, Fiorino M and Potter G L 2002 Bull. Amer. Meteorol. Soc. 83 1631–43
[15] Kalnay E, Kanamitsu M, Kistler R et al 1996 Bull. Amer. Meteorol. Soc. 77 437–71
[16] Krüger J, Müller W and Storch J-S 2012 Clim. Dyn. 39 795–810
[17] Frankignoul C and Hasselmann K 1977 Tellus 29 284–305
[18] Diasnkii N A 1998 Izv. Atmos. Ocean. Phys. 34 197–213