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The Role of Nonlocal Processes in Upper Layer Heat Budget in the North Atlantic

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Abstract. The physical processes that determine spatio-temporal variability of the upper mixed layer (UML) temperature in the North Atlantic have been investigated. The study of physical processes is based on the closed UML heat budget. The components for the mixed layer temperature balance are computed using the monthly data from ORA-S3 ocean reanalysis over the period 1959 — 2011. This paper deals with the relative contribution of heat budget terms into generating the both intra-annual and interannual-to-decadal variations of the UML temperature. The result of the study shows that the local heat flux on the ocean surface plays a major role in the intra-annual cycle of the UML temperature, while the nonlocal processes, such as advection and diffusion of heat, affect the interannual-decadal variability of the UML temperature. The obtained results are vital for studying the physics of ocean-atmosphere interactions.

1. Introduction

In the North Atlantic, the upper mixed layer (UML) temperature is characterized by significant interannual-to-interdecadal anomalies that directly affect the climate system [1]. According to the hypothesis of Bjerknes [2], the atmospheric forcing mainly causes the sea surface temperature anomalies (SSTA) at mid-latitudes on seasonal-to-interannual scales, but decadal or longer SSTAs are caused by changes in the ocean circulation. There are different points of view on the contribution of local atmospheric forcing and internal ocean dynamics to generating the upper ocean temperature anomalies at these time scales. In addition, a number of studies devoted to the heat budget evaluation in the North Atlantic basin are carried out using the unclosed heat budget or with omission of some heat balance equation terms without their precise evaluation. This approach leads to the erroneous description of physical processes that affect the ocean temperature change.

Analysis of the intra-annual changes in the heat balance, both for the entire Northern Hemisphere [3] and the North Atlantic [4], showed that for the large-scale processes (with typical spatial scales 500×500 km and more) in the upper ocean heat budget the local temperature changes dominate, in their turn these changes depends on the surface heat fluxes. In this case, both the heat advection caused by ocean currents and the horizontal mixing yield negligible contribution. Many recent studies, which use data with better spatial resolution, show an importance of other mechanisms that regulate the seasonal cycle of the UML temperature [5]. Thus, relative importance of the mixed layer temperature balance components at an intra-annual scale in different regions of the North Atlantic is still a subject of wide discussion.



The analysis of the large-scale SSTA spatial-temporal variability shows that the characteristics of their interannual variability essentially depend on the season [6]. As to the low-frequency changes in the upper ocean temperature, some authors make point that the radiative forcing of aerosols is the main reason for the interdecadal climate change in the North Atlantic [7]. One should note that the model studies show a possibility of long-live anomalies emergence in the atmosphere (including a decadal scale) without taking into account its interaction with the ocean [8]. Meanwhile, the ocean plays an active role in the SSTA formation on decadal and longer time scales which is confirmed by a number of studies [9]. The aim of the research is to reveal relative importance of the upper ocean heat budget components in the North Atlantic on various space-time scales. The research is based on analysis of the closed heat balance for the upper ocean layer using homogeneous and long-term data sets.

2. Data and methods

The monthly data from ORA-S3 oceanic re-analysis for the period 1959–2011 [10] for the North Atlantic (0–70° N, 8–80° W) were used. In addition to that, the data on net heat fluxes on the ocean surface over the North Atlantic, which were taken from the ERA-40 atmospheric re-analysis dataset [11] for the period of January 1959–June 2002 and operative analysis by the ERA-40 model for the period from July 2002 to December 2011, were also used. The heat fluxes from the atmospheric re-analysis and the ERA-40 operative analysis were used as boundary conditions for the ocean model in the ORA-S3 re-analysis.

On the assumption that the UML temperature is vertically homogeneous, the UML heat budget equation is as follows:

$$T_t = -UT_x - VT_y - \frac{W'_{-H}T_{-H}}{H} + \frac{Q_0 - Q_{-H}}{\rho_0 C_P H} + HED \quad (1)$$

Here, ρ_0 is the density of sea water in the UML, C_P is the heat capacity of sea water at constant pressure (their product is taken as a constant), and H and T are the thickness and temperature of the UML. In the mixed layer, the average components of the current velocity vector are designated as U and V in the zonal and meridional directions, respectively. W'_{-H} is the vertical velocity of currents normal to the base of the UML, taking into account the horizontal inhomogeneity of the ocean ($W'_{-H} = W_{-H} + U_{-H}H_x + V_{-H}H_y$). T_x (H_x) and T_y (H_y) are zonal and meridional gradients of the UML temperature (mixed layer depth). The x axis is eastward oriented, the y axis is oriented to the north, and the z axis is oriented vertically upward. The coordinate system origin is located on the undisturbed ocean surface.

In this equation, T_t is a partial derivative of the UML temperature; UT_x , VT_y and $W'_{-H}T_{-H}/H$ are zonal, meridional and vertical heat advection in the UML, respectively; and Q_0 and Q_{-H} are heat fluxes at the ocean surface and the base of the UML. The heat flux at the base of the UML Q_{-H} depends on the rate of turbulent entrainment ($DH/Dt = \partial H/\partial t + U_{-H}H_x + V_{-H}H_y$), temperature differences in the transition layer ($T_0 - T_{-H}$) and the vertical velocity at the base of the UML W_{-H} . It is estimated from the Kraus–Turner ratio, which is generalized for the case of a horizontally heterogeneous ocean [12]:

$$Q_{-H} = \begin{cases} \rho_0 C_P (T_0 - T_{-H}) \cdot \left(\frac{DH}{Dt} + W_{-H} \right) & \text{at } \left(\frac{DH}{Dt} + W_{-H} \right) < 0 \\ 0 & \text{at } \left(\frac{DH}{Dt} + W_{-H} \right) \geq 0 \end{cases} \quad (2)$$

The calculation procedure for this heat balance component is described in details in [13].

The value of HED – horizontal eddy diffusivity was computed as in [14]:

$$HED = (1.5 \cdot 10^3 + F) \cdot (T_{xx} + T_{yy}) + F_x T_x + F_y T_y \quad (3)$$

Here, F is a function proportional to the square of the local strain rate $((V_x + U_y)^2)$ and $(T_{xx} + T_{yy})$ is the Laplacian of the UML temperature.

In addition to these components, the total UML heat balance also contains different-type errors, only some of them can be directly estimated from the data available. A posteriori error analysis showed that their integral effect is of the order of 10% of the magnitude of the main components of the UML heat budget.

Taking into account that when analyzing the average annual UML heat budget, the right-hand side of equation (1) contains the covariance of the seasonal fluctuations of the current vector components and the UML temperature gradients. In addition to above mentioned the average annual UML heat budget includes the estimations uncertainty of average annual heat fluxes at the ocean surface and the base of the UML ($\delta Q_0 + \delta Q_{-H}$). The value of δQ_0 was assumed 20% of Q_0 [15]. This erroneous magnitude can be regarded as lower-boundary estimation [16]. The error in Q_{-H} estimation is not crucial due to the insignificant contribution of Q_{-H} to the average annual UML heat budget on the extended North Atlantic basin.

3. Results and their analysis

In general, all UML heat budget components are important on an intra-annual scale. The significant changes in the values of UML heat balance components from winter to summer are observed. Meanwhile, there are pronounced regional peculiarities in the formation of seasonal UML temperature variation. The balance of partial derivative of the UML temperature, the surface heat fluxes and horizontal eddy diffusion stipulates the intra-annual UML heat budget in the middle and high latitudes. We confirmed that horizontal heat advection mainly contributes to the UML temperature intra-annual variability in the vicinity of intense ocean currents. Seasonal variability of vertical heat advection is most intense in the tropical latitudes. The heat fluxes at the base of the UML Q_{-H} insignificantly affect the UML temperature change over the whole water area. The small area in the North Atlantic Deep Water formation region is an exception. Here, the turbulent entrainment can cause more than a third of the UML temperature changes. However, the zonal-mean values of the heat budget components on the intra-annual scale in the North Atlantic are characterized by the dominance of the local UML temperature change, which is compensated by surface heat fluxes (figure 1). The heat advection and horizontal eddy diffusivity generally make a small contribution to the heat budget at such spatial scale. The Equatorial Atlantic is an exception. Thus, significant intra-annual fluctuations of all UML heat budget components and the UML heat balance dependence on the spatial averaging scale are recorded.

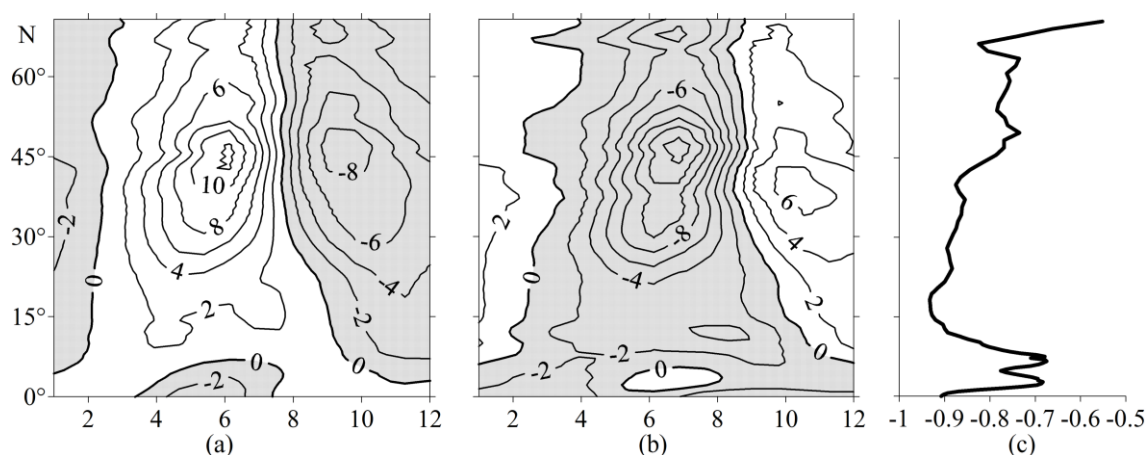


Figure 1. Intra-annual variability of zonal-mean values of the partial derivative of the UML temperature (a), surface heat fluxes (b) in the North Atlantic ($\times 10^{-7}$ °C/s) and correlation coefficients between them (c).

The UML heat balance is quasistationary on the interannual-to-decadal scale. The heat budget is mainly caused by the changes in advective heat transports and horizontal eddy diffusivity (figure 2).

Moreover, the largest contribution of horizontal eddy diffusivity to the interannual variability of the average annual UML temperature occurs in the northwestern part of the North Atlantic and in the subpolar gyre. The partial derivative of the UML temperature is small at considered scale. Contribution of heat fluxes at the base of the UML to the change in the average annual UML temperature is insignificant. The contribution of surface heat fluxes at the basin's majority is less than 30%. However, in some areas it exceeds 40%, for example, in the Gulf Stream recirculation zone and the eastern part of subtropical gyre.

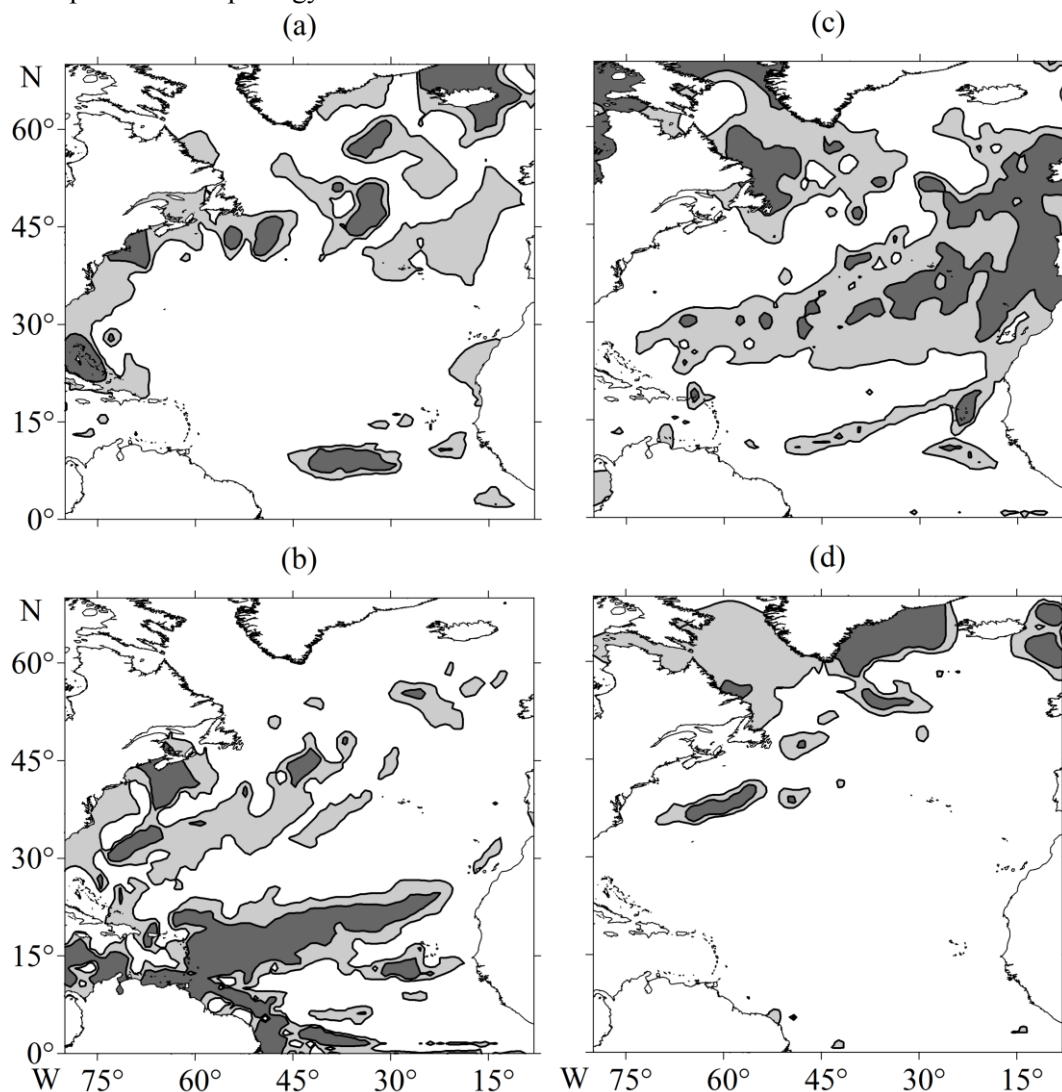


Figure 2. The relative contribution (in %) of the UML heat balance constituents in the North Atlantic, calculated for the right-hand side of equation (1): total horizontal (a) and vertical (b) heat advection, heat fluxes at the ocean surface and the base of the UML (c) and horizontal eddy diffusivity (d). The intensity of the hatch shading characterizes the value of the contribution: light gray – more than 30%, dark gray – more than 45%.

The evaluation of heat balance equation terms for the average annual data can substantially vary from the monthly field calculations. This discrepancy is explained by the close relationship between the fluctuations of the current vector components and the UML temperature gradients on a seasonal scale in certain regions of the North Atlantic, especially at the low latitudes. The uncertainties

associated with inaccurate evaluation of average annual surface heat fluxes are also important in the central and eastern parts of the North Atlantic.

At an extended part of the North Atlantic (excluding the subpolar gyre), the partial derivative of the UML temperature is small if compared to the main components of heat budget equation throughout the year (figure 3). The nonlocal processes – advection of heat (horizontal and vertical) and horizontal eddy diffusivity are the main terms in the equation (1) on the analyzed scale. The surface heat fluxes variability is important outside the zone of action of intense ocean currents in the subtropical and subpolar gyres. In summer, when ocean circulation weakens in the upper layer, surface heat fluxes variability is also important in the vicinity of the intense currents. In the tropical latitudes, these variations do not impact the UML heat budget throughout the year. The heat fluxes at the base of the UML are important on interannual-to-decadal scale only during the period of intensive autumn-winter convection in the part of subpolar gyre and in the vicinity of the North Equatorial Countercurrent in spring.

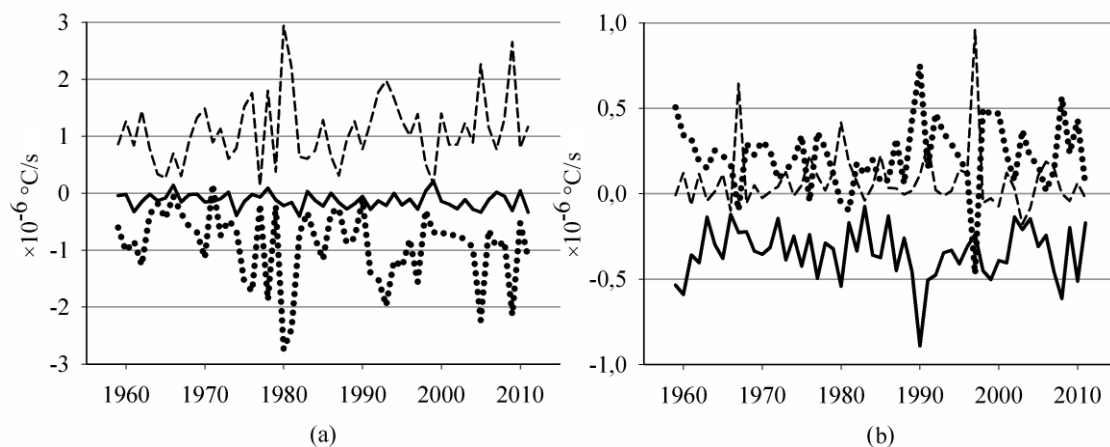


Figure 3. Time series of the partial derivative of the UML temperature (solid line), vertical heat advection (dashed line) and horizontal eddy diffusivity (dotted line) in the mesh nodes with the coordinates of 10° N 40° W for January (a) and 50° N 15° W for April (b).

The variance, which characterizes the variability of the UML heat budget components, and the contribution of each term to the interannual-to-decadal UML temperature variability in the North Atlantic substantially depend on the season. At the same time, nonlocal processes, such as heat advection and horizontal eddy diffusivity, mainly determine the interannual-to-decadal UML temperature variability on the extended part of the North Atlantic basin. The subpolar gyre region is an exception. Here, nonstationarity (especially in the spring) and heat fluxes at the ocean surface and the base of the UML (mainly in winter and autumn, respectively) are important.

4. Conclusion

The contribution of individual components of the UML heat budget on the intra-annual and interannual-to-decadal scales do not match one another. The surface heat flux plays a crucial role in the intra-annual cycle of the UML temperature. The nonlocal processes, such as heat advection and diffusion, are important in the interannual-to-decadal variability of UML temperature. In addition, the influence of various processes on the UML heat balance is determined by the scales of space-time averaging and regional features.

The results of the study specify modern understanding of the role of physical processes in generating the large-scale upper ocean temperature anomalies on the interannual-to-decadal scale in the North Atlantic. It should be taken into account that underestimation of the relative contribution of the heat budget components to the total heat balance is stipulated by the low space-time data resolution that leads to the error emergence in separate term computations. However, using datasets with higher

space-time resolution in future studies, especially for the western boundary currents, will deliver detailed analysis of the peculiarities of impact of atmospheric forcing and internal ocean dynamics on the evolution of the thermal anomalies on interannual-to-decadal scale.

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