ON THE ROLE OF HEAT ADVECTION BY OCEAN CURRENTS IN THE LARGE-SCALE INTERACTION OF THE OCEAN AND THE ATMOSPHERE

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ON THE ROLE OF HEAT ADVECTION BY OCEAN CURRENTS IN THE LARGE-SCALE INTERACTION OF THE OCEAN AND THE ATMOSPHERE

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It has long been evident that the ocean exerts an enormous thermal influence on the atmosphere (maritime and continental climate). An important factor in the thermal interaction of the ocean and the atmosphere is the redistribution of heat in the oceans by ocean currents.

Since the beginning of this century many oceanographers have turned to the study of heat advection in oceans and seas (Helland-Hansen, Nansen, McEwen, Defant, Wiese, Shuleikin, Zubov, Shtokman, Belianskii, Duvanin, and others). The initial data for estimating variability in the transport of heat by ocean currents were deep-water hydrological observations on so-called standard sections intersecting the principal flows of ocean currents. Classical examples of such standard sections are the systematic hydrological observations along the Kola meridian in the Barents Sea (1925-1941 and 1948-1968); in the Faroe-Shetland Channel (from 1927 to 1958); and across the Kuroshio Current in the region of the Japanese Islands (from 1951 to 1964). However, even when analyzing data from the indicated standard sections, researchers encountered great difficulties in determining heat transport by ocean currents because of methodological errors in the organization of such observations; frequent and considerable interruptions in the observations; substantial asynchrony of the observations on these sections and, as a consequence, the introduction into the calculations of heat transports of significant errors due to high-frequency variability of the hydrological characteristics.

The substantial influence of high-frequency variability of hydrological characteristics on determining the magnitude of the heat transport of a current is associated with a methodological feature of the calculation, carried out by the formula:

$$Q_T = c\rho L \int_0^H v(h)\, T(h)\, dh, \tag{1}$$

where c is the heat capacity of water; ρ is the specific weight; L is the length of the hydrological section; $T(h)$ is the mean water temperature in layer h; $v(h)$ is the mean velocity of the geostrophic current in layer h, calculated from the distribution of temperature and salinity of the water from the ocean surface to a conventionally chosen reference horizon at depth H (the depth of the presumed absence of current).

A shortcoming of the indicated method is the extremely approximate estimate of the instantaneous (not time-averaged) current velocity, as well as the fact that the method makes it possible to calculate only the value of the geostrophic component of the total (actually observed) current. This circumstance was the main reason why systematic hydrological observations on standard sections, begun in many countries in the 1920s–1930s of this century for the purpose of studying

of the regime of oceanic circulation and the redistribution of heat and salts in the ocean.

Still less accurate estimates of the magnitude of heat advection by ocean currents are given by the heat-balance calculation method often used by oceanographers. In this method, the magnitude of heat advection is determined as the residual term of the balance equation, which includes all errors in determining the individual components of the ocean heat balance.

Theoretical studies of heat advection by ocean currents have been based mainly on solutions of the well-known heat-conduction equation, which for a unidirectional flow has the form

$$\partial\theta/\partial t = A\,\partial^2\theta/\partial x^2 -$$

$$-v\,\partial\theta/\partial x. \tag{2}$$

However, the impossibility, at present, of giving a correct estimate of the principal parameters of this equation—the turbulent exchange in the ocean A and the velocity regime of ocean currents v—creates great difficulties also for the development of theoretical studies of this important problem.

The aim of the present study is to prove that, if a sufficiently representative indicator of the variability of heat advection by ocean currents is chosen—one that does not require knowledge of the characteristics of turbulent exchange in the ocean and of the current velocity—then the study of this phenomenon can proceed with considerably fewer difficulties.

Fig. 1. Graph of seasonal and annual fluctuations in the heat-content value of waters in the Pacific Ocean (in the region of the Kuroshio Current)

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Such an indicator, in our opinion, may be the value of the heat content of the ocean-current flow, calculated from the working section for each given moment of time, i.e.

Fig. 1. Graph of seasonal and annual fluctuations in the heat-content value of waters in the Pacific Ocean (in the region of the Kuroshio Current)

$$\theta = c\rho \iint_S T(h,l)\,dh\,dl, \tag{3}$$

where T is the water temperature; h and l are the depth (vertical thickness) and the width of the current, determining the area of the working section S.

By the indicated method, deep-water observations of water temperature along the Shiono–Misaki section, which crosses the Kuroshio Current along 135°40′ E from the coasts of Japan to its far southern boundary, were processed. Systematic seasonal observations on this section were processed for the period from 1954 to 1964. The results of the processing are shown in the graphs of Fig. 1.

Graph *a* in Fig. 1 shows the seasonal (thin line) and mean annual (thick line) changes in heat content in the upper 10-meter layer; *b*—in the 0–200 m layer, and *c*—in the 0–1000 m layer. The depth of 1000 m in the given section approximately corresponds to the lower boundary of the Kuroshio Current or to the depth of the baroclinic layer of the ocean in this region. For clarity in comparing the variability of heat content by layers of the water column, the ordinate axis shows not the calculated absolute sums, but conditional sums of heat content ($n\theta_{10}$; $n\theta_{200}$; $n\theta_{1000}$). This method of representation does not disturb the relation between the amplitudes of seasonal and interannual fluctuations of heat content within each layer considered.

Analysis of the results obtained shows that fluctuations in the magnitude of heat content in the upper (0–10 m) and active (0–200 m) layers of the ocean have a sharply expressed seasonal course with an annual period, determined by the regime of incoming solar radiation; the mean annual values of heat content in these layers reveal interannual changes, but their amplitude is considerably smaller than that of the seasonal (intra-annual) fluctuations. Changes in heat content in the baroclinic layer of the ocean (down to the depth of the lower boundary of the Kuroshio Current) have, as their principal component, interannual fluctuations with amplitudes greater than those of seasonal fluctuations. The period of the interannual fluctuations of heat content of the baroclinic layer,

Fig. 2

Figure 2: Fig. 2

approximately (because of the shortness of the observational series), may be estimated at 7-8 years, which agrees satisfactorily with the period of circulation of water masses in the North Pacific system of currents. It is characteristic that such large-scale fluctuations in heat advection by the Kuroshio Current lead to changes in the mean temperature of the baroclinic layer of the ocean in the region of this current by 3-4° C.

Fig. 2. Graphs of the multi-year course of changes in mean annual values of heat content of the water column, air temperature, and total solar radiation. 1—annual values of total solar radiation (mean for 5 stations); 2—mean annual air temperature at the Nadze and Khotidzima stations; 3—mean annual water temperature at the 10 m horizon (mean over the section); 4—mean annual heat content in the 0-200 m layer (θ_{200}); 5—mean annual heat content in the 0-1000 m layer (θ_{1000})

Comparison of the curves of changes in mean annual heat-content values in the 10-, 200-, and 1000-meter layers with the curves of the course of mean annual values of total solar radiation and air temperature over the region considered (see Fig. 2) shows a good synchronous relation between the regime of incoming solar radiation and fluctuations of heat content in the active layer of the ocean; changes in heat content in the baroclinic layer correlate better (with a time shift) with air temperature.

The result obtained leads to the conclusion that in the thermal regime

of the active layer of the ocean the leading role belongs to atmospheric processes and, chiefly, to solar radiation. Interannual changes in air temperature over the ocean, however, apparently depend to a greater extent on fluctuations in the advection of heat by currents, i.e., on changes in the heat content of the baroclinic layer of the ocean. Although these changes are small (3-4° for the entire layer), the large difference in the heat capacities of water and air, as well as the considerable area of the current' s surface, lead to a substantial effect in the long-term course of the thermal regime of the atmosphere, as is observed in nature. One example of this may be the ice-free port of Murmansk, where the mean annual air temperature is almost 20° higher than the mean-latitude temperature. Such an anomalously warm climate in the southern part of the Barents Sea is a consequence of heat advection by the North Atlantic Current.

Thus, in the long-term course of the thermal interaction of the ocean with the atmosphere in regions of powerful ocean currents—and perhaps over the entire ocean area (this will be shown by further research)—the leading role belongs to the ocean.

The conclusion obtained satisfactorily explains the synchronism in changes of the temperature of surface water, and even in the active layer, over large ocean areas, which has recently been discovered by a number of researchers (Ivanov, Shishkov, Bjerknes, Handzawa, Namias, and others). Indeed, if the thermal regime of the active layer of the ocean is determined mainly by the external heat exchange governed by the balance of solar radiation, then changes in water temperature at the ocean surface should have planetary features. Other atmospheric processes acting on the ocean surface (cloudiness, precipitation, atmospheric circulation) also have a planetary character. Hence the facts of the existence in the oceans of extensive areas occupied by comparatively rapidly developing positive or negative anomalies of water temperature in the surface layers are quite understandable. However, in the deep layers of the ocean the dominant role in the redistribution of heat belongs to ocean currents. Since the speed of the oceanic circulation is small on average, the influence of heat advection by currents on heat exchange between the ocean and the atmosphere manifests itself slowly and substantially only for large-scale processes of this interaction.

The analysis carried out of changes in heat content in the baroclinic layer of the ocean indicates that, in this interaction, the atmosphere (including radiative processes) gives its energy to the ocean in the high-frequency band (seconds-months), and receives energy from the ocean in the low-frequency band (years-decades). Despite the purely qualitative nature of this conclusion, it appears that the importance of taking into account the advection of heat by ocean currents in estimating the thermal interaction of the ocean with the atmosphere is nevertheless quite obvious.

In connection with this, there arises the need for the earliest possible organization of systematic deep-water hydrological observations on a system of standard thermal sections, rationally distributed over the area of the World Ocean. The basic requirements for such a network of oceanographic sections should be: simultaneity of observations over the entire network of sections, crossing of the full width of each ocean current being studied (taking into account the scale of current meandering), and maximum speed of passage along the section with measurements of water temperature down to the lower boundary of the baroclinic layer.

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Note: Figure translations are in progress. See original paper for figures.

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