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Abstract

Full Text

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GEOPHYSICS

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The study of physical processes occurring at the boundary between the atmosphere and the ocean is inseparably connected with the investigation of the structure of the temperature field in the surface layer of water. Let us point, in particular, to the possibility of convective mixing arising in the upper layer of the sea in the presence of horizontal inhomogeneities of the temperature field (for example, the "overturning" of cold water lenses), which may prove to be one of the essential mechanisms of generation of ocean turbulence.

Continuous recording of the temperature of the water surface, necessary for determining its statistical characteristics, is carried out with towed electrothermographs. The results of continuous temperature measurements have so far been used mainly for refining and detailing maps of isotherms (see, for example, ([1])) and the characteristics of temperature variability in individual regions of the ocean ([2,3]), but in this case variability was considered as an auxiliary hydrological characteristic of a region, and not as a physical phenomenon (the exception is, perhaps, the study ([4]), carried out on the research vessel *Mikhail Lomonosov*). In origin, temperature inhomogeneities in the water column and at the water surface are sharply different. Therefore, the variability of temperature at the sea surface should be the object of special physical investigation.

Fig. 1. Examples of realizations of the temperature field in the surface layer of the ocean

The results set forth below were obtained during the first cruise of the research vessel *Akademik Kurchatov* in the Atlantic Ocean and the Mediterranean Sea in December 1966–January 1967. Measurements were made by means of an electrothermograph towed on a cable, with the sensor displaced 5 m from the

Fig. 2

Figure 2: Fig. 2

side of the vessel. The length of the cable was selected so that the sensor traveled at a depth of 10-30 cm. Sensors with a time constant of about 15 and 5 sec were used, which, at a towing speed of 18 knots, corresponds to spatial averaging of the order of 135-45 m. The temperature was recorded on a potentiometer tape. When the frequency of pulsations increased to several oscillations per minute, the signal was also recorded in digital form on punched tape by means of equipment for automatic perforation described in ([5]). Perforation was carried out at a frequency of one reading in 1 sec or in 5 sec. The punched data were fed for processing into the *Minsk-2* electronic computer on board the vessel.

The measurements began in the region of the English Channel and were carried out while the vessel was moving south through the Bay of Biscay and then along 18° W. longitude to the Romanche Trench. They were then continued in the Gulf of Guinea and, on the return—

northward along the coasts of Africa as far as Gibraltar and in the Mediterranean Sea. The character of the temperature variability proved to be different in different regions. One may distinguish: (a) jump-like changes in temperature; (b) inhomogeneities with scales on the order of tens of kilometers (large-scale); (c) inhomogeneities with scales on the order of kilometers (mesoscale). Examples of these types of temperature variability are shown in Fig. 1.

The jump-like changes in temperature observed in the Bay of Biscay and off the western coasts of Portugal were possibly associated with the influence of rivers.

Fig. 2. Structural functions of the temperature field $D(\tau)$, obtained with sensors having time constants of 15 sec and 5 sec. (a) and (b). Time and duration of the recording of the series: No. 1 –28 I, 16^{26}–17^{19}; No. 2 –28 I, 17^{19}–17^{48}; No. 3 –28 I, 18^{30}–19^{20}; No. 4 –29 I, 20^{00}–22^{00}; No. 5 –6 II, 17^{44}–20^{50}; No. 6 –18–19 II, 17^{20}–9^{50}.

The distances between the zones of jumps amounted to several tens of kilometers; the horizontal temperature gradient at such scales was on average equal to 0.02 deg/km. In the regions of jumps the temperature gradient was equal to 0.5–1 deg/km; the magnitude of the temperature difference was 0.2–0.8°.

Large-scale inhomogeneities were observed everywhere in the coastal regions. Their amplitude averaged 0.5°. Variability of a similar character is also encountered in the open ocean (as indicated by the data cited in ([2,3])), where it may be associated

with inhomogeneities of currents, optical properties of the water (determined by suspended matter and admixtures of biological and inorganic character) and surface films, which affect, for example, the rate of evaporation.

Mesoscale inhomogeneities are of great interest. They apparently arise when wave mixing is weakened and there is an intense radiative heat influx (records with short-period pulsations were obtained only in the daytime and in clear calm weather). These pulsations, as a rule, were observed against a background of long-period ones; however, in some cases it was possible to isolate portions of the records characterized by statistical stationarity and sufficiently long for statistical processing. For these portions the structure functions were calculated,

$$D(\tau) = \left\langle [T(t) - T(t+\tau)]^2 \right\rangle ,$$

where $T(t)$ and $T(t+\tau)$ are the temperature values at the times t and $t+\tau$. The length $r \approx u\tau$ of the path segments on which a statistically homogeneous structure was observed (u is the ship' s speed) reached hundreds of kilometers, which made it possible to determine the structure functions up to distances of the order of tens of kilometers. Examples of structure functions are given in Fig. 2a for a sensor with time constant $\tau_* = 15$ sec and in Fig. 2b for a sensor with $\tau_* = 5$ sec. Along the abscissa axis here the argument $\tau^{2/3}$ is plotted, and circles mark the points corresponding to the sensor time constant $\tau_*^{2/3}$.

To interpret these graphs, it is necessary to take into account the influence of averaging on the form of the structure function obtained from experimental data, which was considered in works ([6],[7]). The structure function of the smoothed process $\widetilde{D}(\tau)$ is related to the true structure function $D(\tau)$ for $\tau \gg \tau_0$ by the asymptotic relation (see, for example, work ([8])):

$$\widetilde{D}(\tau) \sim \int_0^\infty h(t)[D(\tau) - D(t)]\,dt = D(\tau) - \int_0^\infty h(t)D(t)\,dt, \tag{1}$$

where $h(t)$ is a smoothing function satisfying the condition $\int_0^\infty h(t)\,dt = 1$, and τ_0 is the time interval over which this function differs appreciably from zero. In the so-called inertial-convective interval of the turbulence spectrum, the structure function of the temperature field has the form ([9],[10])

$$D(\tau) = A\tau^{2/3}; \qquad A = cN\varepsilon^{-1/3}u^{2/3}, \tag{2}$$

where c is a numerical constant (for three-dimensional temperature fields $c \approx 3$), N is the rate of equalization of turbulent temperature inhomogeneities, and ε is the rate of dissipation of turbulent energy. Let $h(t) = \frac{1}{\tau_0} H\left(\frac{t}{\tau_0}\right)$; then, in the inertial interval for $\tau \gg \tau_0$, the smoothed structure function will have the form

$$\widetilde{D}(\tau) \sim A(\tau^{2/3} - B\tau_0^{2/3}), \tag{3}$$

where the constant B depends on the form of the function $H(\theta)$. Calculations of $\widetilde{D}(\tau)$ by the exact formula for different $H(\theta)$ showed that the asymptotic expression (3) is already a sufficiently good approximation for $\tau \geq 2\tau_0$. The segment $\Delta = \tau^{2/3}$ cut off by curve (3) on the abscissa axis is related to τ_0 by the relation $\tau_0 = B^{-3/2}\Delta^{3/2}$, where B depends on the form of the function $H(\theta)$. If $H(\theta) = 1$ for $\theta \leq 1$ and $H(\theta) = 0$ for $\theta > 1$, then $\tau_0 \approx 2.15\Delta^{3/2}$, while for $H(\theta) = e^{-\theta}$ one obtains $\tau_0 \approx 1.17\Delta^{3/2}$.

Graphs 2a and 2b show that the experimental structure functions are quite satisfactorily described by formula (3) in the range of time scales from ten minutes to an hour, which indicates the presence of an inertial interval extending from several kilometers to 30 km. The presence of mesoscale temperature pulsations,

obeying the "two-thirds law" (2), can be explained by the action of turbulent mixing produced by velocity pulsations. The validity of the "two-thirds law" for a certain interval of scales of horizontal motions in the surface layer of the ocean has been confirmed in a number of works indirectly—through the dependence of the coefficient of turbulent mixing K on the distance r: over a wide range of scales the law $K \sim r^{4/3}$ is satisfied, which is a consequence of the "two-thirds law" for the velocity field. Fulfillment of the "two-thirds law" for kilometer scales was established not only in deep-water regions of the ocean, but also in regions with depths of 50-100 m; from this one may conclude that the turbulent velocity field is significantly anisotropic and that the temperature inhomogeneities obeying the "two-thirds law" are associated precisely with two-dimensional horizontal turbulence.

For the structural functions in Fig. 2a, the quantity τ_0, determined by formula (3), coincides with the time constant of the sensor τ_*, whereas for the curves in Fig. 2b the time constant of the sensor is $\tau_* = 5$ sec, and the scales τ_0 are, for series Nos. 5 and 6, respectively, 25 and 80 sec (the spatial-averaging scales are 240 and 600 m). The form of the structural functions for series Nos. 5 and 6 corresponds to the fact that a smoothing process with a spatial averaging scale $u\tau_0$ acts on the structural function of the form (2); this process may be connected with intensive small-scale mixing, which evens out mesoscale temperature inhomogeneities generated at the expense of the energy of wind waves (see work (11)).

To characterize small-scale mixing, let us write the structural function (2), after introducing the length scale $L = (\chi^3/\varepsilon)^{1/4}$ (where χ is the coefficient of small-scale turbulent thermal conductivity), in the form $D(\tau) = c\Gamma^2 L^2 (u\tau/L)^{2/3}$, where $\Gamma^2 = N/\chi$ is the mean square of the mesoscale temperature gradient. Then the asymptotic formula for $\tilde{D}(\tau)$, taking smoothing into account, will have the form

$$\tilde{D}(\tau) = c\Gamma^2 L^2 \left[(u\tau/L)^{2/3} - (u\tau_0/L)^{2/3}\right]. \tag{4}$$

The smoothing scale L, produced by small-scale mixing, can evidently be identified with $u\tau_0$. Then the value of L for series Nos. 5 and 6 turns out to be, respectively, 200 and 640 m. Introducing $\operatorname{tg}\alpha = [\tilde{D}(\tau_2) - \tilde{D}(\tau_1)]/(\tau_2^{2/3} - \tau_1^{2/3})$, we obtain $\Gamma^2 = \mathrm{tg}\,\alpha/(cL^{4/3}u^{2/3})$. Using the above estimates for L, we find that the value of Γ for series No. 5 is 0.11 deg/km, and for series No. 6 it is four times smaller—0.03 deg/km.

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