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V. B. SHTOKMAN, M. N. KOSHLYAKOV, R. V. OZMIDOV, L. M. FOMIN, A. D. YAMPOLSKII

LONG-TERM MEASUREMENTS OF THE VARIABILITY OF PHYSICAL FIELDS AT OCEANIC POLYGONS AS A NEW STAGE IN OCEAN RESEARCH*

(Presented by Academician A. N. Kolmogorov, 2 XII 1968)

Until comparatively recently, the circulation of ocean waters was considered from a completely different point of view than motions in the atmosphere. The variability of wind speed and its gustiness, easily accessible to observation, had long given rise to the view that atmospheric motions are extremely labile; as early as the 1910s these were examined by meteorologists from the standpoint of the theory of turbulent fluid motions. The situation in oceanology was different. The stability of the ocean and the constancy of its characteristics at intermediate and great depths, established by expeditions separated by intervals of many tens of years, reinforced the view that the physical fields in the ocean, throughout its entire thickness, were only slightly variable, with the exception of the thin surface layer directly subject to the influence of the wind. Views of this kind, once established, served as the basis for organizing oceanographic expeditions, during which observations were made separated by distances of hundreds of kilometers and, in time, by several days or even weeks.

It is true that, in addition to such observations, long-term observations of currents, temperature, and salinity had long been carried out at fixed points in the seas from anchored vessels. In this case the observed variability of currents was associated exclusively with particular wind directions. However, a statistical analysis of discrete measurements of currents by means of coarse instruments at a fixed point near the western coast of the Caspian Sea, first carried out by Shtokman over the course of a month in 1935 (^1), showed that the current vector in the horizontal plane at different depths pulsates strongly in an entirely random manner, while the wind speed may remain unchanged in direction and be small (^2, ^3). Applying to the analysis of measurements of this kind the usual statistical techniques used in the study of turbulence, Shtokman discovered a sharp anisotropy in the pulsations of the horizontal current vector, similar to that observed in experiments near a wall bounding a turbulent flow (^4). The statistical scales of turbulence calculated in the usual way showed that, on the coastal slope of the sea, there are irregular pulsations of current velocity with periods of several hours and days, caused by turbulent eddies whose horizontal dimensions are estimated at several kilometers.

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* V. B. Shtokman originated the idea of organizing and interpreting long-term measurements of physical fields at marine and oceanic polygons, and also formulated the tasks and directed the preparation of the experiment plan. R. V. Ozmidov and M. N. Koshlyakov played the leading role in developing the experiment plan, with M. N. Koshlyakov directing the hydrological measurements at the polygon. All work at the polygon was headed by L. M. Fomin and A. D. Yampolskii. The latter also played the leading role in preparing the expedition plan and its technical organization.

The corresponding Reynolds stresses of this kind of horizontal macroturbulence proved to be a million times greater than the turbulent stresses caused by the vertical turbulent exchange of momentum ([3]). Thus, as early as 1935 a path was indicated for the direct study of marine horizontal macroturbulence, quite accessible to the rough means of hydrological measurement techniques. This path opened broad prospects in the study of the dynamics of the real ocean. In particular, it was of great interest to test, under marine and oceanic conditions, the results of contemporary statistical theories of turbulence, and first of all the relations of Kolmogorov' s theory of locally isotropic turbulence, which had already proved valid for atmospheric turbulence.

It proved possible to repeat the 1935 observations on a more extensive scale only in 1956, off the shores of the Black Sea, where, on a peculiar "polygon," at the initiative of V. B. Shtokman, staff members of the Laboratory of Sea Dynamics of the Institute of Oceanology carried out measurements of currents, temperature, and salinity of the water on two vessels over the course of 18 days. From these measurements R. V. Ozmidov ([5]) calculated a set of statistical characteristics of marine macroturbulence; moreover, it was established for the first time that the correlation and structural functions of the field of the horizontal components of velocity satisfy the laws of locally isotropic turbulence down to time scales on the order of several days.

The measurements on polygons in the Caspian and Black seas mentioned here were a preparatory stage for carrying out analogous work in the ocean. The first trial experiment, conducted on a polygon in the Atlantic in 1958, further broadened our ideas about the variability of oceanological characteristics interpreted from the standpoint of statistical hydromechanics. The processing of the results of current measurements at three multi-day stations of one-month duration (located at the vertices of a right triangle with legs of 70 and 90 miles), which continued for several years, made it possible to arrive at diverse conclusions set forth in papers ([6–8]). One of the most important and interesting conclusions drawn by R. V. Ozmidov is the conclusion concerning the discreteness of

Fig. 1. Location of the polygon (n) in the Arabian Sea and diagram of the installation of anchored buoys (inset)

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the ocean' s energy supply, concentrated in definite portions of the frequency spectrum of current pulsations ([9]).

The threefold experience of work on marine and oceanic polygons prompted the authors of the present communication to continue similar investigations on ever-increasing scales. It became evident that work on oceanic polygons represented a new stage in the study of the ocean, the main task of which consists in investigating the variability of physical fields interpreted from the standpoint of statistical hydromechanics.

At the same time, it is important that the duration of observations and their spatial extent be coordinated with the scales of the motions under study. Apparently, in the ocean there exists an enormous range of such scales, from 1 cm to a thousand kilometers. For investigation of the small-scale region, low-inertia instruments with observation durations of a minute or tens of minutes are necessary. For the study of medium and large scales, it is possible to use cruder instruments with discrete recording, but on condition of a longer duration of observations. It is known that the latter must be 10 times greater than the period of fluctuations of the quantities under study. An approximate estimate of the duration of observations T and the linear scales L of a polygon is obtained from the equality $L = 0.1UT$, where U is the advective current velocity.

The more extensive work planned by the authors on an oceanic polygon of two months' duration pursued mainly the solution of the following tasks: 1) Determination of a set of statistical characteristics of fluctuations of current velocity; in particular, their temporal and spatial spectra (the latter had not been determined at all for the ocean). 2) In-

study of the order of magnitude of the terms in the equations of hydrodynamics as a function of the averaging scales. 3) An assessment of the validity of the so-called frozen-turbulence hypothesis as a function of the averaging scales (i.e., the possibility of replacing local derivatives of velocity with respect to horizontal coordinates by local derivatives with respect to time). 4) Refinement of the regions of energy supply in the frequency spectra of fluctuations and investigation of the direction of the turbulent-energy flux in the large-scale part of the spectrum. 5) Estimation of the rates of adjustment of the field of masses to a time-varying current field and the validity of geostrophic equilibrium as a function of the averaging scales. 6) Investigation of the features of the vertical and horizontal structure of the quasi-stationary current field and other hydrological characteristics.

Fig. 1. Location of the polygon (n) in the Arabian Sea and diagram of the

installation of anchored buoys (inset)

Similar work was successfully carried out in January–March 1967 by an expedition of the Institute of Oceanology of the USSR Academy of Sciences in the northwestern part of the Indian Ocean, where 7 autonomous anchored buoys (Fig. 1), patrolled by the research vessel *Vityaz*, were deployed on a 60 × 60-mile polygon. The site of the polygon was deliberately chosen in an area of comparatively flat ocean floor, in order to exclude in advance additional disturbances of the velocity field caused by sharp changes in bottom relief, and to investigate even without them the complex fluctuations of velocity as a function of a smaller number of, and moreover unavoidable, factors.

The arrangement of the buoys (inset in Fig. 1) was chosen so as to estimate the statistical characteristics of eddies with scales from 10 to 80 miles (from 20 to 150 km). On each buoy, over an interval of 2 months, the speed and direction of the current were measured every 30 min by autonomous BVP recorders at depths of: 25; 50; 100; 150; 200; 300; 400; 600; 800; 1000 and 1200 m. In addition, on specially deployed buoys deep currents were measured at horizons of 1500; 2000; 3000 and 4000 m (with an ocean depth in the polygon area of 4100 m). To investigate the high-frequency part of the spectrum of current fluctuations, two additional buoys were installed with BVP-2 instruments, recording the current at the above-mentioned 11 depths at 5-min intervals. Such measurements make it possible to investigate the temporal spectrum of pulsations of current velocity from 10–20 min to 5–6 days.

Table 1

Vertical distribution of the root-mean-square deviations σ_u, σ_v, constituting the velocity of relatively smoothed means with a period of 25 h

Depth, m	σ_u	σ_v	Depth, m	σ_u	σ_v
25	6,21	5,30	400	4,07	4,70
50	5,83	4,70	600	3,55	4,49
100	7,18	8,53	1000	4,03	4,94
200	7,13	6,08	1200	4,59	4,62
300	3,51	3,58			

In addition to measurements of current velocity, at 3 buoys the water temperature was measured at 6 depths in the layer 25–200 m by photothermographs. In addition, for a general characterization of the fields of temperature, salinity, and density, two hydrological surveys were carried out in a rectangular area (including the buoy installations) of 210 × 300 miles. The hydrological stations

during surveys formed a square grid with a spacing of 30 miles. To assess the spatial and temporal variability of the vertical structure of the hydrological elements in the region of the work, about 100 stations with closely spaced measurement horizons were carried out, as well as 5- and 2-day hydrological stations; records were made of the vertical distribution of temperature by a frequency bathythermosonde and of short-period temperature fluctuations by thermostrings in drift and while the vessel was under way.

As a result of the work carried out at the polygon, more than 280 thousand separate measurements of the horizontal vector of the current velocity and more than 60 thousand temperature values were obtained. Processing of this unique, enormous body of material is now being conducted on electronic computers according to specially developed programs.

As an example, Fig. 2 presents graphs of the spectral density of the kinetic energy of currents. It is evident from the graphs that the energy of oscillations with periods from 6 hours to several minutes is small in comparison with the energy of longer-period motions.

Fig. 2. Distributions of the spectral density of energy S at the horizon of 25 m (1) and 300 m (2), calculated from data with previously filtered-out long-period (more than 24 hours) oscillations

Table 1 gives an example of the values of the root-mean-square deviations of the components σ_u and σ_v at different depths according to short-period measurements over an interval of 6 days. As can be seen, these deviations change little in a layer of considerable thickness.

In the near future the authors propose to organize measurements at a new polygon, with a duration of work of not less than 6 months. The experience of the work carried out has shown that such an experiment, which will make it possible to investigate the variability of large-scale velocity fields (of the order of 1000 km), is entirely feasible.

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Shirshov Institute of Oceanology
Academy of Sciences of the USSR

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