Studies of sea areas with airborne lidar. Part 2. Long routes

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Return signals of the airborne lidar, used in sensing of seawaters near North Scotland, have been processed. During five flights seawaters have been studied along 100 to 1000-km long routes. The horizontal distribution of the water extinction factor ε for sounding radiation was found to be irregular having both the turbidity and transparency spots with the size ranging from 0.5–1 to several tens of kilometers. On the average, the standard deviation of ε is 10 to 15%, but in some individual cells, it can reach 30 and even 80%. Energy spectrum of fluctuations of ε values in the cells with the size less than 60 km follows, on the whole, the 5/3 exponential law. The autocorrelation function halfwidth for ε is up to several kilometers.

In 1997 aircraft-laboratory of the Institute of Atmospheric Optics carried out research flights over water areas surrounding Northern Scotland. Its territory and the routes of five flights are shown in Fig. 1.

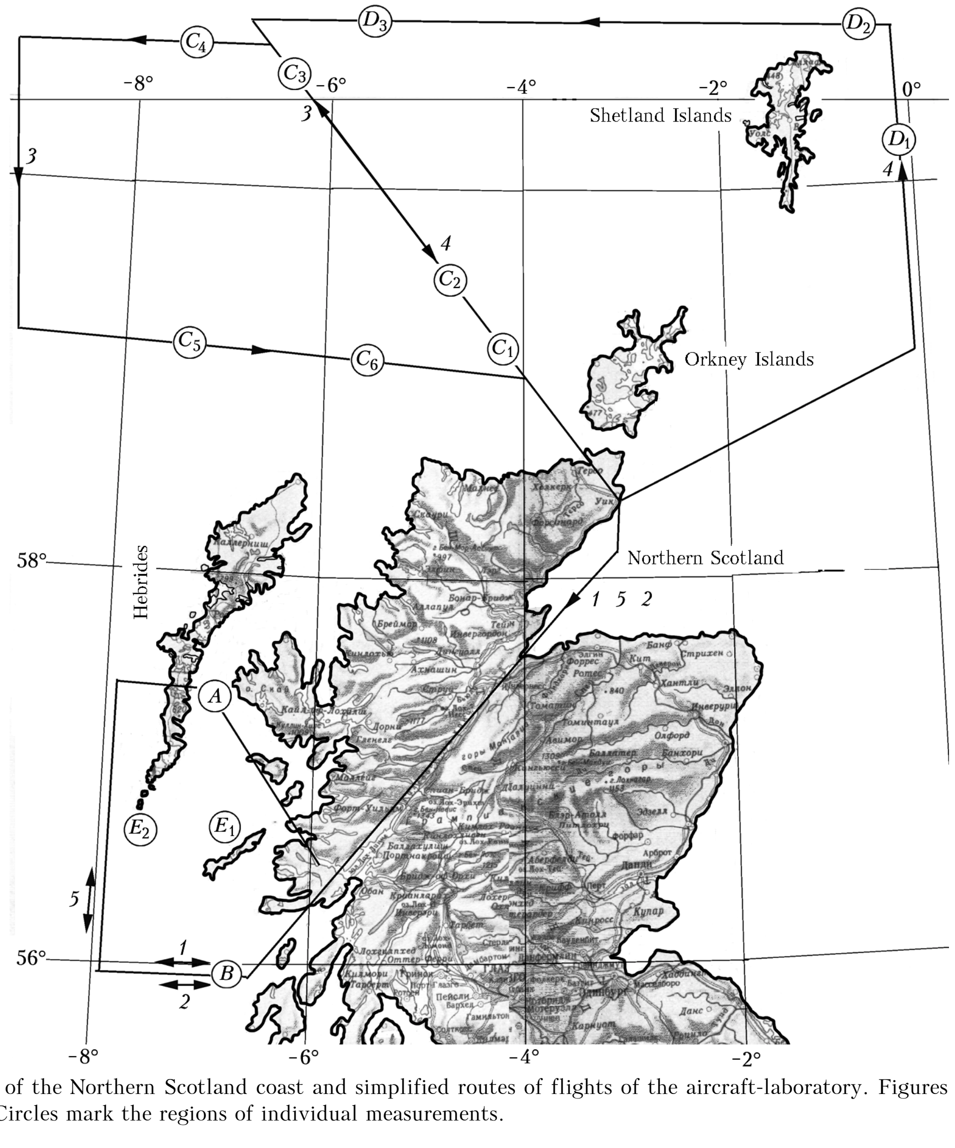

Fig. 1. The map of the Northern Scotland coast and simplified routes of flights of the aircraft-laboratory. Figures at lines mark the flight numbers. Circles mark the regions of individual measurements.

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Our goal was to determine how variable is the upper (10–20 m) layer of the sea in relation to the index of radiation extinction, and to estimate the horizontal size of water inhomogeneities and the statistical regularities of fluctuations. The scales from tens of meters to hundreds of kilometers were considered. Distribution of the optical properties over such distances was not investigated earlier by means of airborne lidars. Another interesting moment is in the fact that the northern branch of the Gulf Stream, which affects the optical properties of water, washes British Islands from the west.

The instrumentation employed (Makrel–2 lidar), the algorithm for processing the return signals (statistically stabilized method of logarithmic derivative), and reliability of the results obtained have been discussed in Ref. 1.

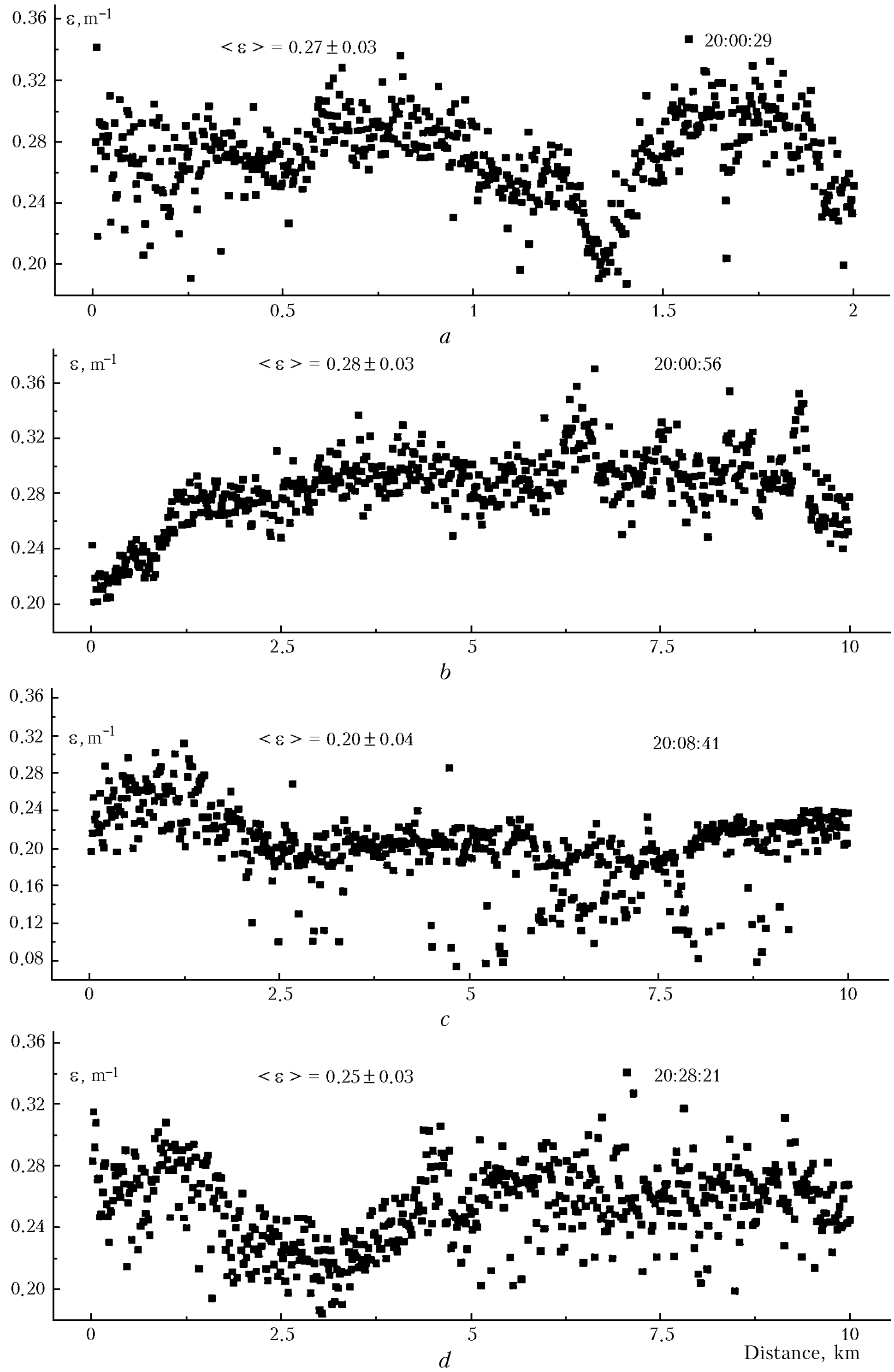


Fig. 2. Horizontal sections of the extinction index in the flight No. 1 (region *A*, Fig. 1).

Let us consider the results obtained using as the examples separate parts of the routes, as well as the entire bulk of data compiled.

The data shown in Fig. 2 correspond to the part *A* of Fig. 1 (Hebridean sea, flight No. 1, May 30, 1997), Greenwich time. The frame a of Fig. 2 was obtained at 25-Hz repetition rate of sounding shots, i.e., 600 shots correspond to 24 sec of flight time, or 2.1 km of the distance covered. It is seen that variations of the extinction index ε essentially exceed the measurement errors (approximately 12%, Ref. 1). The distance between the most turbid points (local maxima of turbidity) is equal to 0.5–1.0 km. The repetition rate of the laser shots for next frames was decreased to 5 Hz (18 m of flight between the shots). The field-of-view angle of the lidar was 8 mrad, the altitude of the lidar above the sea was about 350 m.

The frame shown in Fig. 2*b* was obtained just after previous one. A domelike inhomogeneity is well seen in it. Its length, if refer to the extreme points on the left and on the right, is 120 seconds of flight, i.e., 10.5 km. Smaller spots of enhanced ε value are masked by its fluctuations.

The frames shown in Figs. 2*c* and *d* are presented with time gap of about 10 minutes from previous part of the figure, and about 50 km far from each other. But, as in Fig. 2*a*, there are other inhomogeneities, i.e., the areas with more transparent water in comparison with the surrounding waters.

Figure 3 illustrates data obtained during the flight No. 2 (June 1, 1997), it corresponds to the region *B* in Fig. 1. The ε values in Fig. 3 are a continuous sequence at the distance of 42.2 km (pulse repetition rate 5 Hz, field-of-view angle 10.6 mrad, flight height 320 m). One can consider the mean value of the extinction index for all four files as constant, taking into account overlapping standard deviations of ε. The size of big spots of enhanced turbidity ("convex") is 2 to 4 km. The biggest, in Fig. 3, spot of enhanced transparency ("concave", time 12:38:27) has the length about 8–9 km.

Figure 4 corresponds to flight over free part of the sea, without any effect of islands. Position of its fragments is shown in Fig. 1 by the points C_i, $i = 1, \ldots, 6$. The length of each fragment is equal to 10.5 km. Lower boundary of cloudiness changed, forcing the aircraft to change sometimes the flight altitude from usual 330 to 120–130 m. One can see here the characteristic difference from the previous cases of sounding the inner sea, namely the absence of well-pronounced inhomogeneities of ε. The trends of variations of ε are sufficiently smooth. Possibly, it can be explained by the circumstance that the northern branch of the Gulf Stream passing near Great Britain did not interact with the chain of Hebrides and its bottom effects during the experiment.

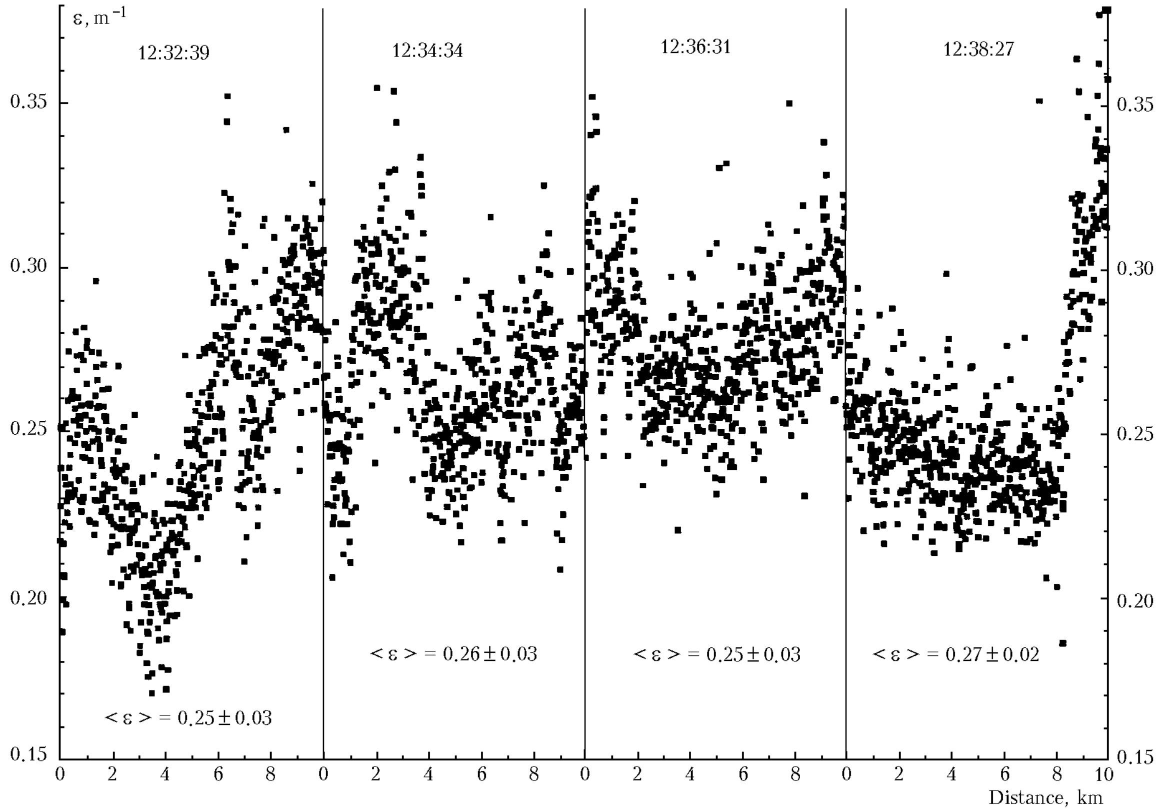


Fig. 3. Horizontal section of ε in the flight No. 2 (region *B*, Fig. 1).

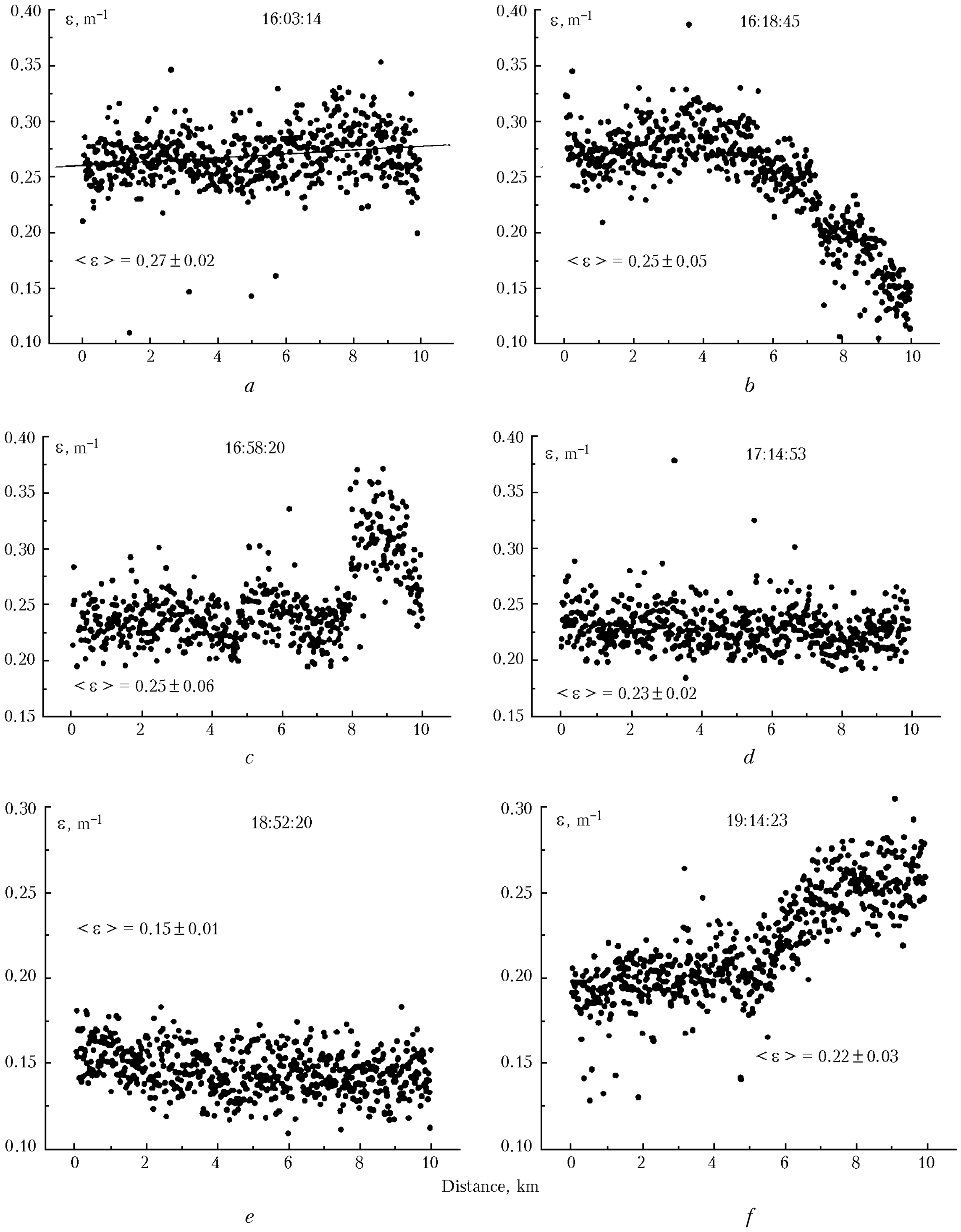


Fig. 4. Fragments of the horizontal section of ε in the flight No. 3 (regions C_i, Fig. 1).

Three fragments of flight No. 4 are shown in Fig. 5. They are marked by positions D_1–D_3 in Fig. 1. All of them contain local extremes on the background of trends. The curve of the increase of the mean ε value in Fig. 5*a* is observed on the distance about 40 km with the modulation of spots of enhanced turbidity of the size 3 to 7 km. Absolute values of ε change more than twice, multiply exceeding fluctuations and measurement errors. The aircraft moved directly toward the north.

Similar situation is shown in Fig. 5*c* observed in a significant time after turn to the west. In the center to the left there is a 20-km spot of ε with three local maxima. It is interesting that this region of measurements D_3 lies not farther than 120 km along the straight line from the region C_3. However there was (see Fig. 4) much more homogeneous water 2 days before. Analysis of the causes of this phenomenon is out of the frameworks of this paper. Now we will return to comparison of the data of flights No. 3 and 4.

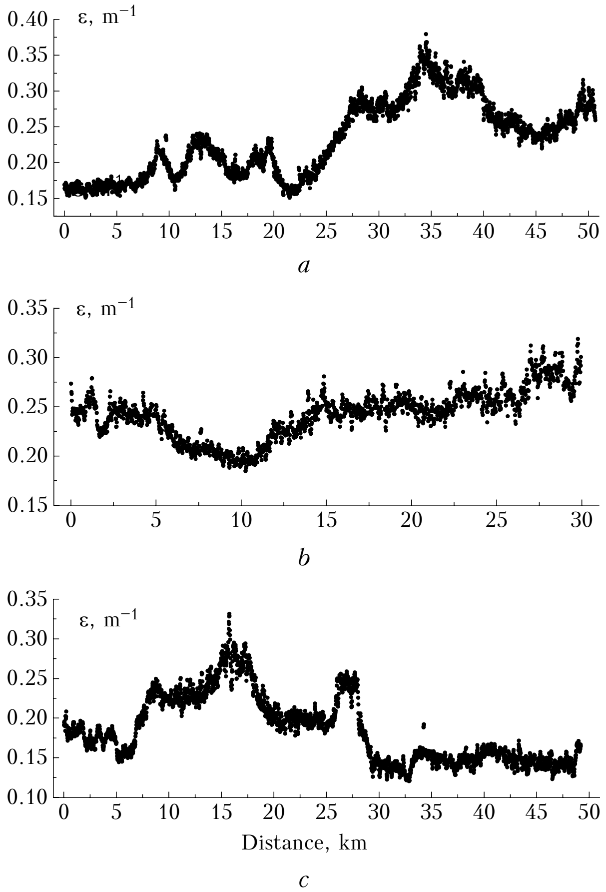


Fig. 5. Fragments of the horizontal section of ε in the flight No. 4 (regions D_i, Fig. 1).

Let us briefly characterize the flight No. 5, which passed over the same, in general, route as flights No. 1 and 2. Measurements in this case were performed along straight lines in the regions E_1 and E_2 (see Fig. 1). Qualitatively the profiles of $\varepsilon(L)$ are similar to that shown in Figs. 2 and 3, so we do not consider them separately.

Let us consider longer fragments of the flights.

The profile $\varepsilon(L)$ for the coinciding parts of the routes in the flights No. 3 and 4 is shown in Fig. 6*a*. Its length is about 615 km. It is seen in Fig. 6 that spatial variations of the extinction index ε are the same along both routes. Let us remind that the time difference between them is 2 days. Linear distance between them was 30 to 40 km, according to the pilot line, and the routes did not cross.

Let us estimate the size of the largest inhomogeneities. The spot of enhanced turbidity of the width of about 160 km with the inner structure of the local extremes of ε lies in the center of Fig. 6 between 3.3 and 4.6°. The absolute value of ε increases on the average from 0.16 m^{-1} at the border of the spot to 0.22 m^{-1} in its center, i.e., approximately by 40%. To the left and to the right from it there are the "spots of transparency" of the width of about 40 km.

To the left, on the coordinates 1.5 and 2.5°W there are the centers of two other spots of turbidity of the width of 70 and 90 km. Mean values of ε increase there from 0.25 to 0.31 m^{-1} (by 25%) and from 0.21 to 0.31 m^{-1} (by 55%), respectively.

Then, as in Ref. 1, correlation functions were calculated (Fig. 6*b*). The correlation radius at the level of 0.3 of maximum at 90% confidence interval was equal to 2.6–3.5 km.[1] Let us remind that water in the inner sea of Hebrides was sounded,[1] and the length of the flight routes was 40 to 50 km. The path length in this paper, in Fig. 6*b*, is increased by one order of magnitude, and the width of correlation functions (at the same level of 0.3) is 1.5 and 2.6 km, i.e., it is of the same order of magnitude. No effect of free sea on the autocorrelation is observed in this case. Secondary maxima of correlation are less than the significant values.

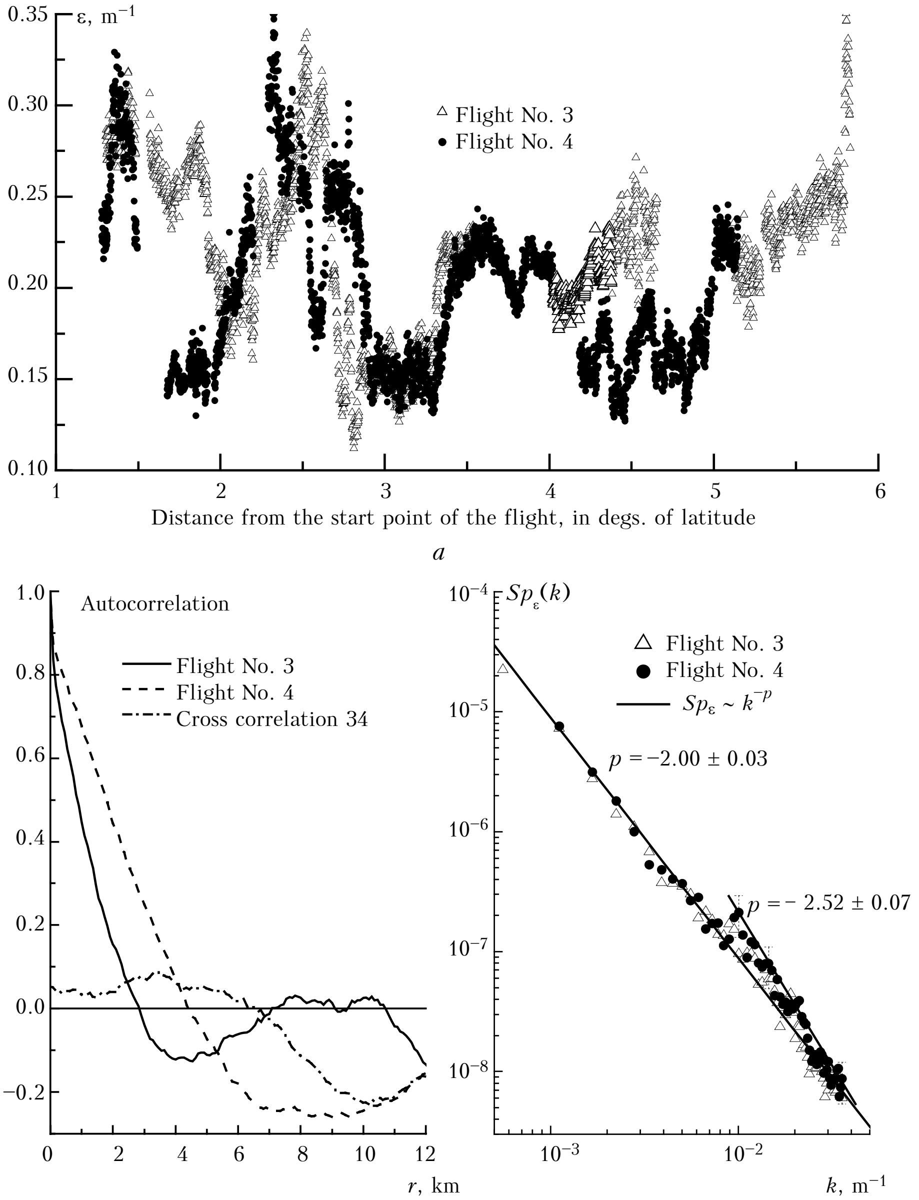
The cross-correlation function between the profiles of ε for these two flights, as is seen in Fig. 6, has insignificant values (it was calculated up to the spatial displacement of the order of 100 km). Thus, in spite of formal similarity of these profiles, they are not related to each other.

As is seen in the data presented, correlation analysis can yield data on the structure of the variations of ε values only on the scale up units of kilometers. So spectral analysis using fast Fourier transform was applied for subsequent quantitative representation of the long series of observations.

The energy spectrum of fluctuations of the values of the extinction index at its expansion in terms of spatial wavelengths λ (or wavenumbers k) is shown in Fig. 6*c*. In general, the canonical power law $Sp(k) \sim k^{-p}$ is fulfilled in the size range of inhomogeneities of ε from 0.1 to 7 km. As is known, $p = 5/3$, or 1.67 in the inertial range of turbulence. A peak of spectrum is observed at $\lambda \approx 0.6$ km, then $p = 2.52$, i.e., 7.5/3 on the average for both routes. Analysis of possible causes of this fact is out of the frameworks of this paper.

Figure 7 illustrates the data obtained during flight No. 3, which passed only over the sea without crossing islands, shallow water, and without additional evolutions of the aircraft, i.e., it includes the part considered in Fig. 6. The abscissa is the local time, numbers in circles correspond to the points of the turn from one tack to another (the path contained 4 long tacks with sounding).

As is seen in Fig. 7, horizontal profile of the extinction index has fluctuations of different spatial periods with strong variations of ε values, that is characteristic of the areas with significant gradients of transparency caused by the turbulent disturbances at the borders of streams.



a

b *c*

Fig. 6. Joint part of the flights No. 3 and 4: extinction index ε (*a*); auto and cross-correlation functions of ε (*b*); spectra of the ε value fluctuations at the common part of both routes (*c*).

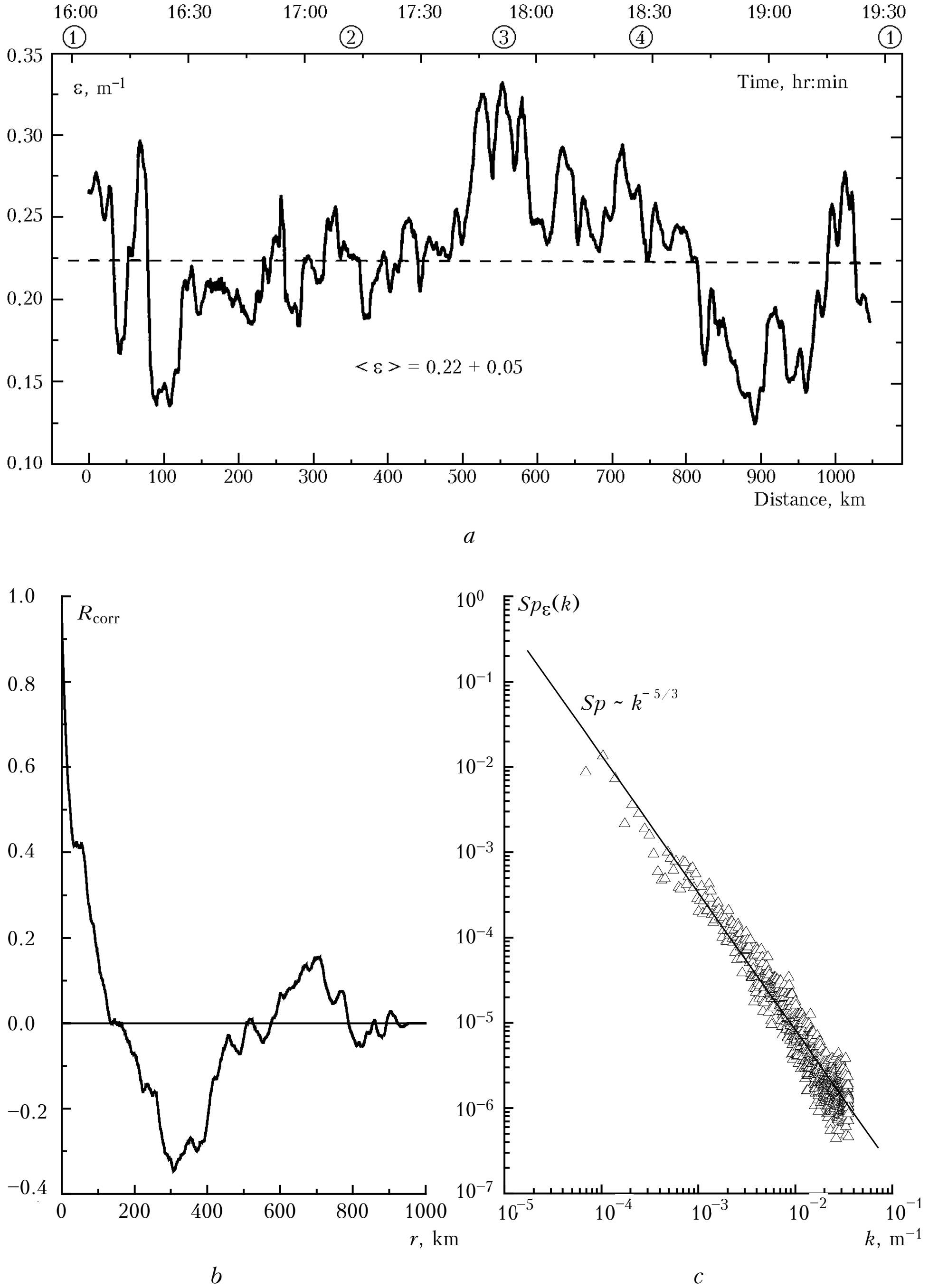
The mean over the entire route ε value is equal to 0.224 m^{-1} with the standard deviation 0.212 m^{-1}, i.e., the seawater in this area is optically inhomogeneous. For example, in the time interval between 17:45 and 18:00 one can either isolate one more turbid spot with the length about 80 km (15 minutes of flight) or assume that it is modulated by three smaller 25-km long spots. ε = 0.25 km^{-1} at the borders of this spot, and 0.32–0.33 km^{-1} in the center, i.e., it increases by 32%. The increase of turbidity is greater in the spot with the center at 16:18, approximately by 80–90%. The changes of ε in the spots of "turbidity" or "transparency" are weaker.

Of course, the estimate of the size of more "turbid" or more "transparent" spots is quite arbitrary; it strongly depends on the discrimination threshold chosen. If the threshold ε value is accepted to equal to its mean value 0.224 m^{-1} in Fig. 7*a*, then such a modulated spot of the enhanced turbidity in the interval of flight time between 17:30 and 18:41 has the approximate length of 379 km. At the same time, the part with the ε value below the mean value (the spot of "transparency" in the time interval between 16:20 and 16:50) is approximately 160 km long.

The autocorrelation function R_{corr} of ε(*r*) for the entire flight is shown in Fig. 7*b* for uniformity. According to our estimate, the step at $R_{\text{corr}} = 0.42$ is the result of "sewing" the normalized files[1] and it does not change the general behavior of the autocorrelation. The correlation radius for the threshold we accepted earlier at $R_{\text{corr}} = 0.3$ is 70 km. It is close to 20 km for the generally accepted $R_{\text{corr}} = 0.5$, i.e., in any case, it has the order of tens of kilometers. Let us remind that we have flown along that long path only once.

The stationary process occurring in the given interval of spatial scales confirms the shape of the spectrum (Fig. 7*c*) calculated for the whole bulk of all realizations. Let us remind that the lowest-frequency processes, i.e., the trends, are removed at the stage of data preparation. The spectrum is approximated by the (−5/3)-power law within the entire range of wave numbers that characterizes the stationary process of the transfer of energy contained in the optically detectable inhomogeneities in a randomly inhomogeneous medium within the inertial interval of wavelengths.

On the whole, one can state that no surprises are observed for that long sample of $\varepsilon(r)$ values for optical inhomogeneities ranging in size from 0.2 to 60 km.



a

b *c*

Fig. 7. Continuous 1000-km long part of the flight No. 3: extinction index ε (*a*); autocorrelation function of ε (*b*); spectrum of fluctuations of all the ε values collected (*c*).

Thus, analyzing the airborne data obtained during the flights along long paths, on can draw the following conclusions.

The parts of the size from 0.5 to 160 km with the enhanced or reduced values relative to the mean value ε (spots of "turbidity" or "transparency") are observed along the 100 to 1000-km long flights. The rms fluctuations of ε observed along relatively long paths are approximately 12%. All flights were carried out under conditions of the absence of well-developed cyclonic phenomena. At the same time, the ε values at the borders and in the centers of some spots can differ by 30%, on average. Once, the turbidity of up to 80% has been observed.

The width of the autocorrelation function of fluctuations of ε values is most often close to several kilometers.

The spectrum of fluctuations of ε values (after filtering out the processes with the size above 60 km) follows, on the whole, the "−5/3" power law although more quick decrease is observed sometimes for inhomogeneities with the size less than 500 m.

References

1. G.P. Kokhanenko, I.E. Penner, and V.S. Shamanaev, Atmos. Oceanic Opt. **14**, No. 12, 1038–1042 (2001).