Transport and turbulence characteristics for the northeastern Sakhalin shelf conditions

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Introduction

To understand the dynamics of pollutants, one should know their transport characteristics (conditioned by velocities of currents and particles) and calculated turbulent parameters (vertical and horizontal turbulence caused by shift instability, surface disturbance, near-bottom friction, and other factors).

Transport characteristics, responsible for the trajectory of pollution migration, can be accurately calculated for the set of hydrometeorological situations by means of wind and current characteristics and other factors.

Determination of turbulent parameters is a more complicated task, as, due to the absence of unified descriptive methods, much depends on a modeler's expertise and approach to the problem. For applied purposes, turbulent parameters can be calculated by two approaches, analogous to Euler and Lagrange media equations. For numerical modeling, the method of "Monte-Carlo" (Lagrange equation), using turbulent parameters set up as the rate of turbulent fluctuations, provides many more possibilities. Turbulence parameters of a definite zone are conditioned by hydrometeorological and hydrological factors, with sea water temperature, salinity, density, surface waves, currents and wind being the most important.

Model description

Pollutant transport and the sedimentation zone have been calculated by means of a three-dimensional advective–diffusive model based on the "Monte-Carlo" method using the generator of random numbers for non-determined processes imitation in accordance with Ozmidov (1986).

The basic equations describing the trajectories of migrating markers are as follows:

$$\frac{dx}{dt} = u(x_i, y_i, z_i, t) + u'(x_i, y_i, z_i, t);$$

$$\frac{dy}{dt} = v(x_i, y_i, z_i, t) + v'(x_i, y_i, z_i, t); \qquad (1)$$

$$\frac{dz}{dt} = w(x_i, y_i, z_i, t) + w'(x_i, y_i, z_i, t) + w_0(x_i, y_i),$$

where,

x_i , y_i , z_i - coordinates of the *i*-marker;
u, v, w - velocity components of water motion (currents);
u', v', w' - rate components of turbulent fluctuations;
w_o - sedimentation rate of TSS (total suspended solids).

Concentration of pollutants in volume V is determined in accordance with weight and distribution of markers.

$$C = \frac{\Delta n \cdot P}{\Delta V \cdot m}, \qquad (2)$$

where,

Dn - number of markers in volume ΔV;
P - source capacity (kg/s);
m - number of markers released in a time unit.

The conditions set at the boundaries are partial sedimentation, evaporation, or reflection, depending on the specific characteristics of these boundaries and pollutants. Reflection or sedimentation numbers are conditioned by the adhesion coefficients. For the bottom boundary these coefficients are determined in accordance with Beloshapkov (1994a,b).

The sedimentation rate of the TSS phase w_o for light and medium fractions in (1) is found over the balance equation of three forces for ball-shaped particles of the given equivalent radius (Kurganov, 1973):

$$W_0 = \frac{g(r_i - r(z)) l_i^2 \sqrt{1 + 0.862 \lg k}}{m r(z)(18 + 0.61\sqrt{g(r_i - r(z)) l_i^3 / (m^2 r(z))})} \qquad (3$$

where,
l_j - characteristic diameter of a particle;
r_i - specific weight of a particle;
$r(z)$ - water density;
k - geometric shape coefficient;
µ - viscosity coefficient determined from the empirical equation; for fresh water it is as follows:

$$m = \frac{0.01775}{1 + 0.0337t + 0.000221t^2}\ , \qquad (4)$$

where, t - temperature (C°).

Based on the concept of normal spectrum distribution of ocean turbulence, one can write the equation of fluctuating rate components in (1) for each statistic test:

$$\begin{aligned} u' &= s_u\sqrt{-2 \cdot \ln P} \cdot sgn(l); \\ v' &= s_v\sqrt{-2 \cdot \ln P} \cdot sgn(l); \qquad (5) \\ w' &= s_w\sqrt{-2 \cdot \ln P} \cdot sgn(l), \end{aligned}$$

where,
P - random value uniformly dispersed in interval {0;1};
l - randomly takes the values 1 and –1.

The equations of root-mean-square deviations are derived from the assumption that the basic dispersion value is directly conditioned by the current (Pukhtyar, 1981) together with wind and near-bottom corrections produced by in-a-row expansion of parametrization of the wind waves effect (t) on turbulence $a \approx k_1 z t\ exp(-k_2 z)$ and parameterization of the near-bottom friction effect (near-bottom friction is proportional to ($z - h$)^2.

Thus, the equation of the turbulent fluctuation rate is as follows:

$$\text{ó}_u = \sqrt{2 + 0.196v_x^2 + 0.076_y^2}$$
$$* (K_1 + K_2 exp(-\text{Æ}z) + \frac{K_3}{\text{â}\,(h - z)^2 + 1});$$

$$\text{ó}_v = \sqrt{2 + 0.196v_y^2 + 0.076v_x^2}$$
$$* (K_1 + K_2 exp(-\text{Æ}z) + \frac{K_3}{\text{â}\,(h - z)^2 + 1}); \qquad (6)$$

$$\text{ó}_w = {}^{a}\sqrt{\text{ó}_u^2 + \text{ó}_v^2} * f(Ri),$$

where,

v_x, v_y	- liquid current velocities (cm/s);
K_1, K_2, K_3	- parameters of relative contribution of various processes into agitation;
α	- scale of the surface disturbance effect (wind waves);
β	- near-bottom conditions effect (sea floor features);
γ	- transition parameter characterizing the mean relation between horizontal and vertical diffusion (0.083 number is used)
f(Ri)	- function determined by the Richardson criterion, that decreases turbulent mixing under stable stratification and intensifies it under unstable stratification conditions.

General pollution transport tendencies in the area of the northeastern Sakhalin shelf

Accidental spills are dangerous by over-the-sea-surface migration of pollutants with positive floatability (oil spills). The sedimentation rate of the pollutants with negative floatability is high and they easily precipitate and mix in the sea water column, thus impacting a smaller area. However, the role of turbidity tails produced by drilling mud and cutting in oil drilling operation must be estimated by the impact assessment provided.

Generalization of hydrometeorological data collected in the area of northeastern Sakhalin shelf helped to distinguish the following typical seasons:

- Summer, July–September (September – the highest mean sea water temperature, although wind regime tends to change);
- Autumn, October–December (characterized by intensive northwestern winds and the absence of unbroken ice cover);
- Winter (ice), January–April (fast ice and unbroken ice cover);
- Spring, May–June (ice cover destruction and the beginning phase of summer thermohaline structure formation).

The wind regime has been characterized, statistics have been analyzed, and duration characteristics of situations and correlation of one-into-another-situation transits have been studied for summer and autumn. Figures 1 and 2 illustrate the reoccurrence distribution and characterization of situations for summer and autumn. For the distinguished wind situations, the total current fields have been constructed. Modal long-time data rows have been constructed with the help of reoccurrence characteristics and the total component of currents. Comparative reoccurrence characteristics of the model current and observation row data for autumn are shown in Figure 3.

The northeastern Sakhalin shelf is characterized by intensive currents with predominant along-shoreline transport and high tidal current velocities. In summer winds get weaker, the predominant vectors are south and southeastern. The possibility exists for pollutants to migrate slightly northward. Weak and moderate winds can cause the pollutants transported by surface currents to migrate westward (to a shoreline) rather than eastward. This was also proved by the correlation analysis of synchronous observations of wind and currents. Due to greater reoccurrence of strong winds directed eastward, the probability for pollutants to migrate to a shoreline can increase. During a 10-day period an oil spill can transfer at a distance of 200 km.

In autumn, winds intensify and change their direction, northern and western components become predominant. Accordingly, an oil spill transported by surface currents will migrate south and southeastward. The probability for pollutants to migrate to a shoreline is 1.5–2 times greater than in summer. Under the influence of typical autumn northwestern winds, an oil spill can cover 400 km in 10 days.

In winter, when the sea in the area under discussion is clean and semi-clean, the tidal currents tend to slow down with transport direction and turn southward. With mean velocity 20 cm/s, the total transport can cover 150 km to the south in 10 days.

Sedimentation rate of TSS

The sedimentation rate of TSS depends mostly on grain size and less on sea water density. The characteristic diameter of bottom soil, drilling mud and cutting grains ranges between 1.5 and 0.005 mm with the main bulk of solids being over 0.1 mm in diameter. For this size variety of grains, the characteristic sedimentation rate ranges between 5 and 0.0005 cm/s. Intensive summer stratification may have a different sedimentation rate of TSS in the surface and near-bottom layers which depends on hydrology. In the surface layer it may be 20% higher than in the near-bottom layer. It should be stressed that when very large volumes are discharged, the sedimentation rate increases due to the “lump” effect, where the main bulk of discharged solids precipitates as a relative body large in size. Thus, sedimentation characteristics and the dimensions of the zones impacted due turbulence depend mainly on fractional composition and process intensity. Calculations showed that most (80%) of the drilling mud and cutting discharged in course of drilling operations precipitate within several hundred meters around the source, which agrees with the results of other model applications (O’Reilly, 1989).

Parameters of turbulent fluctuation rate

The dispersion of meridional, zonal, and vertical components of turbulent fluctuations was calculated from equations (6) for the surface and near-bottom horizons. Parameter α has been selected as the value to be inversely proportional to the characteristic scale of wind waves effect, 0.25 L, where L is the characteristic wind wave length. For deep water, the wavelength is calculated from

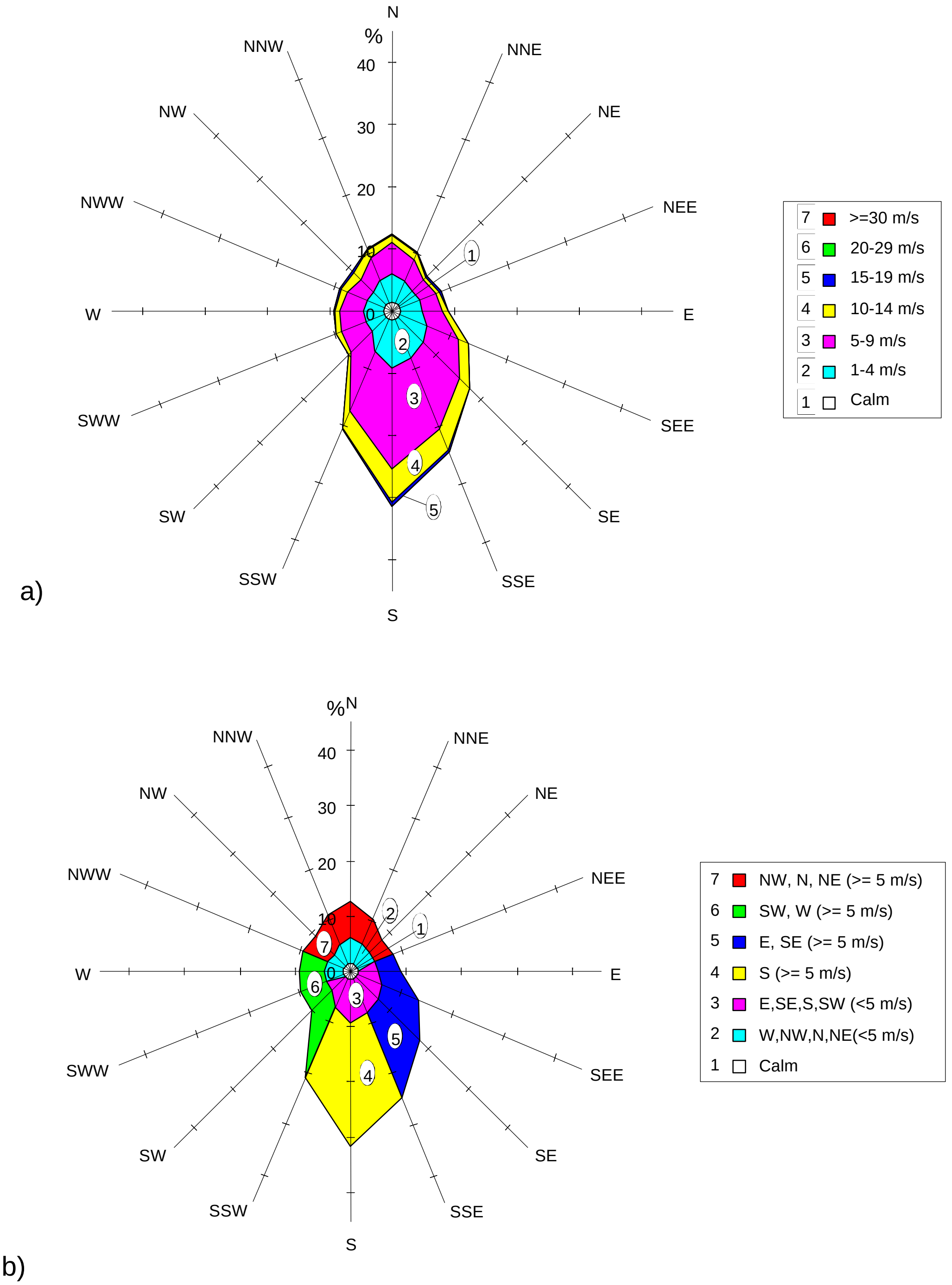

Fig. 1 (a) Summer reoccurrence of wind vectors and velocity (based on on-route ship observations) and (b) typical wind situations over the direction and velocity parameters for a summer season

relation $L = T^2 * g / 2p$, where T is the period of wind waves. Parameter b characterizes the thickness of the bottom boundary layer. For mean velocities of near-bottom currents this parameter is assumed equal 0.16. Coefficient K_1 was determined experimentally, and was found to be in the range 0.5–1.0. Coefficient K_2 was estimated in the range 0.1–0.5 over wind characteristics (we used 0.03 as wind velocity magnitude). Coefficient K_3 was assumed equal to 0.1–0.2.

An exponential equation for stable stratification characteristics usually proved to be the best. So,

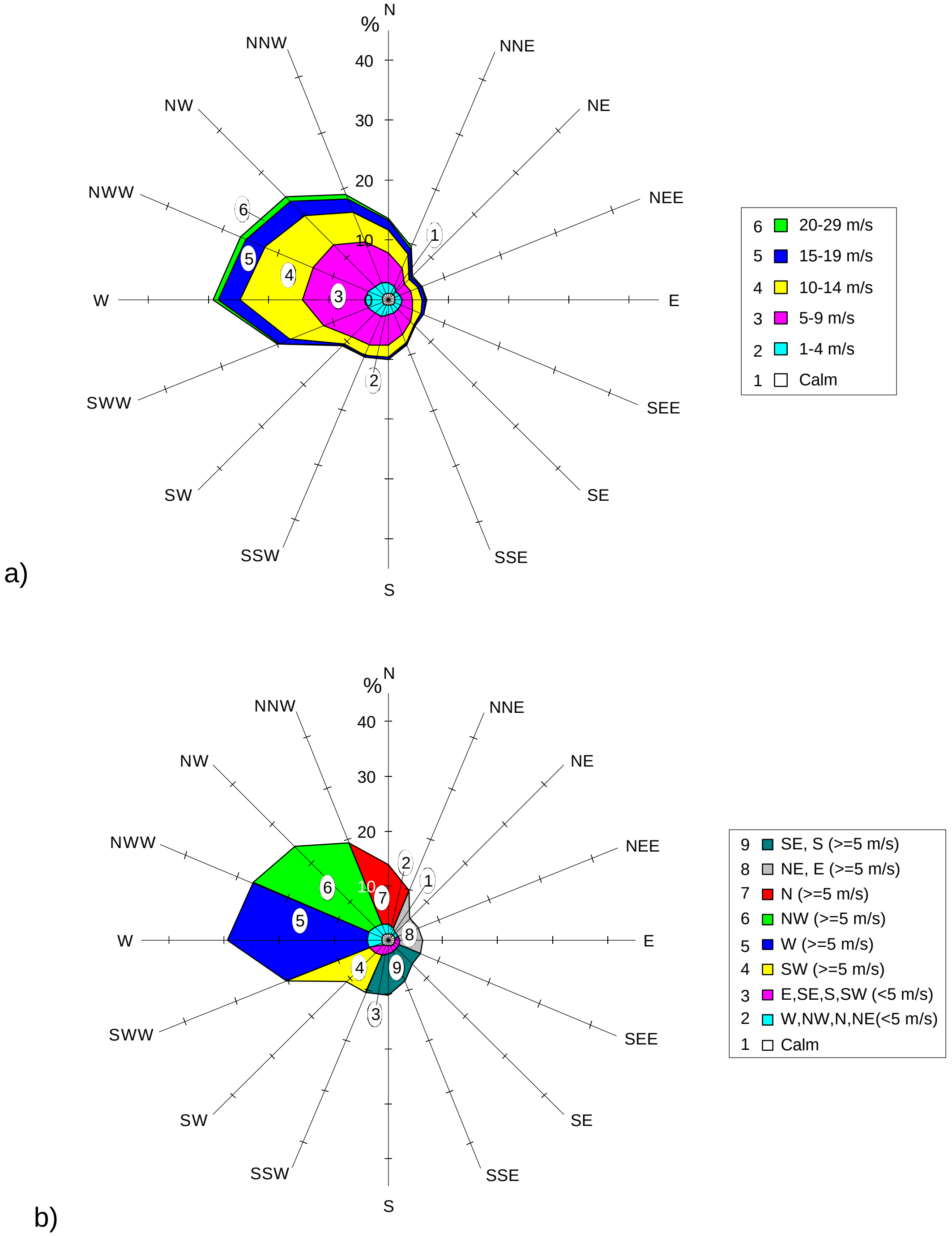

Fig. 2 (a) Autumn reoccurrence of wind vector and velocity (based on on-route ship observations) and (b) typical wind situations over the direction and velocity parameters for an autumn season

we assumed $f(Ri) = exp\ (\ \ 1.1 * Ri)$.

Variability intervals of current velocity magnitude for the northeastern Sakhalin shelf are:

- summer season - 20–70 cm/s;
- autumn season - 25–100 cm/s;
- winter season - 10–30 cm/s.

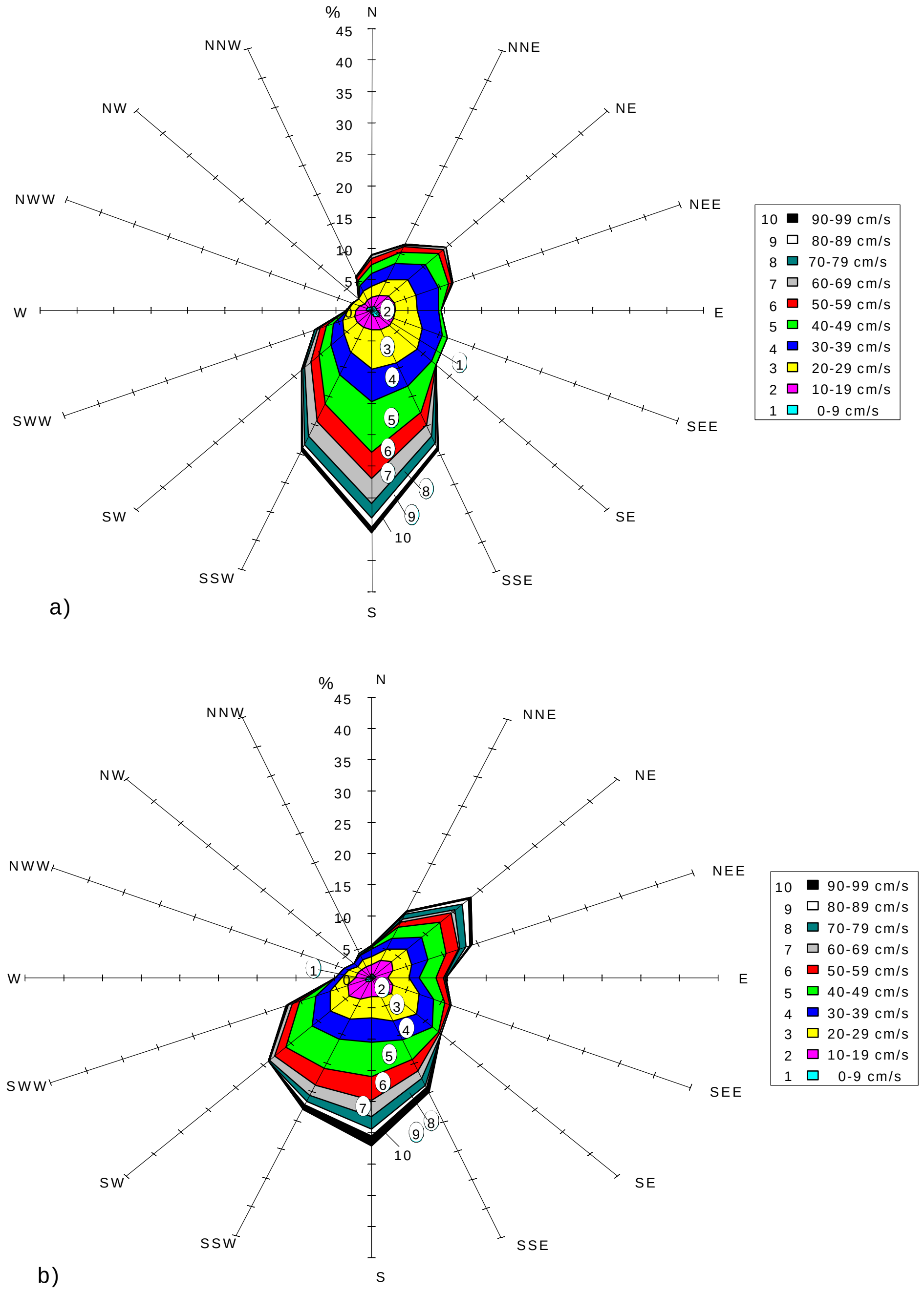

Fig. 3 Autumn reoccurrence of total currents in the area of the Arkutun-Dagi oil field calculated for a typical wind situation (a) and the comparative reoccurrence table of current direction and velocity developed on the basis of real data collected in September–October 1996 (b).

Figure 4 demonstrates the calculated graphs of mean seasonal dispersions of turbulent fluctuations, used in equations (1).

The analysis of instrumental data series added some understanding to the observed dispersion although the analyzed information was not sufficient to assess the turbulent properties of the characteristic surface waves. The method of instrumental data series processing included:

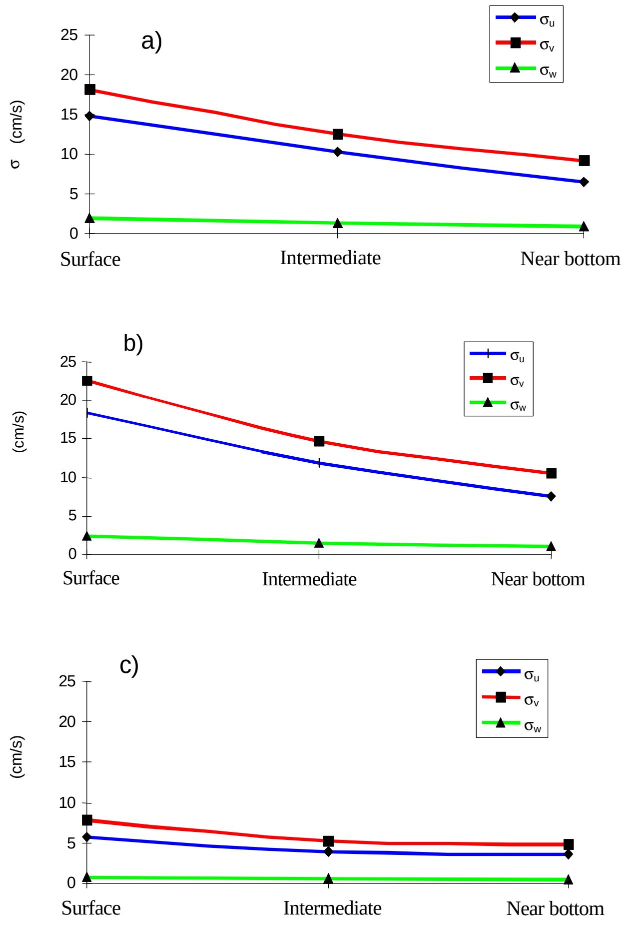

Fig. 4 Mean turbulence dispersion: (a) in summer, (b) in autumn and (c) in winter.

- distinguishing of tidal component;
- analysis of the time needed to reconstruct the fields of tidal currents under the influence of meteorological factors (determination of the time lag row coefficient);
- smoothing of a non-tidal data row by filtration methods with a characteristic time lag;
- distinguishing of the smoothed trend from a non-tidal data row;
- dispersion analysis (components inclusive).

Characteristic values of turbulence fluctuation components (velocity dispersion), obtained by means of the above-described technology with the help of instrumental observations are as follows:

- in summer - 3–6 cm/s;
- in autumn - 5–11 cm/s.

Different approaches to the turbulence problem may produce different dispersion values. However, the reported dispersion assessments generally describe seasonal and weather conditions. These assessments were tested with experimental results and compared with calculations from different models.

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