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Method for Correction of Surface Mooring Current Velocity Data Distorted by Wind Waves

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Abstract—A method is proposed for correcting the synoptic component of velocity series obtained from autonomous mooring stations and distorted by wind waves. The method is based on the fact that the synoptic spatiotemporal scales in the atmosphere and ocean are different and on the assumptions inferred from the results of the Megapolygon-87 experiment. The overestimation of the measured current vector is obtained as a function of the velocity of the local geostrophic wind, which is used as an indirect parameter of the wave intensity. The actual current velocities are estimated by their extrapolation to the hypothetical calm condition, which corresponds to a zero atmospheric pressure gradient. The use of the method for the Megapolygon-87 data reduces the error in the synoptic velocity component from its systematic overestimation of 50–120% to its stochastic value of 15–20%.

INTRODUCTION

The direct velocity measurements represent one of the most important and expensive sources of information on the oceanic currents. A set of the Russian polygon experiments (from Polygon-70 to Atlantex-90, see, e.g., [2]) with the use of moorings, which were deployed over vast areas with a high spatial resolution, allowed the estimation of the basic characteristics of synoptic eddies in the open ocean and of the mechanism of their interaction with large-scale currents.

Unfortunately, the wave-induced movements of a surface buoy usually result in a marked distortion (overestimation, as a rule) of the velocity values recorded by the current meter secured to the mooring [5]. For example, an assumption was proposed and verified [3] that the peaks of kinetic energy observed in the field of synoptic eddies in the Megapolygon-87 area (MP87) in the Pacific subarctic frontal zone during typhoon events (Fig. 1) are associated rather with the wind wave effect on the mooring surface buoy, which is transmitted to the depth through the taut cable, than with the energy transfer from the atmosphere to the ocean. The hypothesis was then supported by experiments [1].

The appreciation of the importance of this effect contributed to the improvement of the equipment for future experiments. Meanwhile, there have been almost no attempts to correct the data already obtained. This can probably be explained due to the complexity of the problem. To solve the problem in its complete formulation, we need high-quality synchronous observation data on the wind waves, hydrodynamical models for the actual moorings in the presence of such waves, and reliable current meters for the moorings.

In the present study, we attempt to indirectly assess the effect of wind waves for given periods with subsequent extrapolation to calm conditions. The use of this method for the MP87 data reduces the error in the current velocity values for periods of more than several days almost by an order of magnitude. The corrected data satisfactorily agree with the quasi-geostrophic dynamics of the synoptic currents [9].

DATA

Although the overestimation of the measured velocity values caused by the surface waves is probably characteristic of all the mooring areas, the MP87 is a polygon where this effect is more pronounced due to the typhoons and hurricanes. The MP87 area is about 500 × 500 km and is centered in the region of 40° N and 155° E. From July to October 1987, the area was provided with 177 moorings deployed according to a triangle scheme with a step of 40 km. The current measurements were carried out with POTOK meters at levels of 120, 400, 1200, and 4500 m. The instruments recorded two components of the current velocity vector averaged over 30 min. In spite of the instrumental and informational losses, about 400 thousand high-quality velocity records were obtained, which is equivalent to a 22.8-year-long series.

Additional data used in this study were obtained from more than 1600 hydrological stations in the MP87 area, subsurface moorings in the WESPAC experiment [7] (which operated in the MP87 area in 1980–1982), and the *Geosat* satellite altimetry (http://ibis.grdl.noaa.gov/SAT/gdrs).

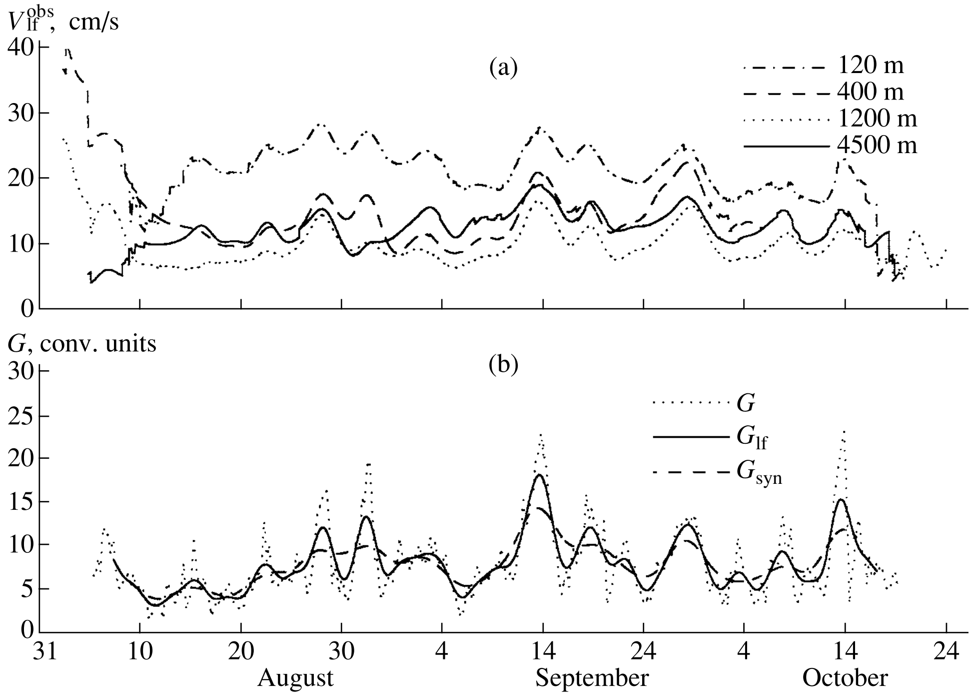

Fig. 1. Time series of (a) the absolute value of the low-frequency velocity component $V_{\mathrm{lf}}^{\mathrm{obs}}$ averaged over the MP87 area measured at four levels and (b) the total G, low-frequency G_{lf}, and synoptic G_{syn} components of the root-mean-square horizontal gradient of the atmospheric pressure at the sea level averaged over the MP87 area.

METHOD

During the MP87 experiment, there were no days when the sea surface was calm. In other words, there are no velocity data for which the wave effect can be assumed to be negligible and which can be used as a reference point. The idea of the proposed method is to choose a sufficiently convenient parameter that characterizes the intensity of the wind waves (at least, indirectly) in order to find the correlation between the velocity overestimation and this parameter and, if the correlation exists, to extrapolate the observation data to the hypothetically calm sea surface condition.

The root-mean-square value of the horizontal gradient of the atmospheric pressure at the sea surface averaged over the MP87 area was used as a parameter that characterizes the wind waves. This parameter, designated as G, was obtained by digitizing the 6-h facsimile weather maps received from Tokyo. It is evident that this value, variations of which can be seen in Fig. 1b, is proportional to the velocity of the geostrophic wind. Although the dynamics of the atmospheric boundary layer and the wind waves are rather complex, it can be reasonably expected that greater G values correspond to more developed waves and that absolutely calm conditions are possible only for $G = 0$. This is the first assumption of the method proposed.

The second important assumption is that the actual oceanic synoptic currents induced by storms are relatively weak. Indeed, although the direct observations [8] of hurricane Gilbert in the Gulf of Mexico indicate pronounced currents caused by the wind field, it was shown that the general structure of the velocity anomalies agrees well with the model of a linear quasi-inertial wave, which is steady-state in the hurricane coordinate system. In the Eulerian mooring coordinate system, such currents look like a peak and decay of inertial oscillations. In order to exclude this high-frequency component from the velocity observed, for which the relationship between the actual physics and wave effect is unknown, the MP87 series were smoothed with the use of the Hanning filter with a half-width corresponding to the local inertial period (about 18 h).

For the sake of convenience, let us assume

$$G = G_{\mathrm{hf}} + G_{\mathrm{lf}}, \quad G_{\mathrm{lf}} = G_{\mathrm{st}} + G_{\mathrm{syn}}, \qquad V_{\mathrm{lf}}^{\mathrm{obs}} = V_{\mathrm{st}}^{\mathrm{obs}} + V_{\mathrm{syn}}^{\mathrm{obs}}, \tag{1}$$

where the indices "hf" and "lf" denote the high-frequency and low-frequency components, respectively, which are separated using the filter mentioned above. The lf component was divided into the st component, which represents a part of the lf signal during storm events, and the syn component, which corresponds to the frequency band of synoptic and large-scale currents. This separation was performed using the same filter with a half-width of 8 days. According to the second assumption, in contrast to the observed velocity $V_{\mathrm{lf}}^{\mathrm{obs}}$, its true value is $V_{\mathrm{lf}}^{\mathrm{tr}} \approx V_{\mathrm{syn}}^{\mathrm{tr}}$ Hereinafter, $V = (u, v)$ is the horizontal velocity vector.

The third assumption is based on the results of the previous analysis [1, 3]. We assume that the overestimation of the velocity weakly affects its direction. This assumption is indirectly supported by Fig. 2, which shows that the relative value of the longitudinal variations of the synoptic velocity in the MP87 data strongly exceeds that of the WESPAC [7]. The assumption also does not contradict Fig. 3, which shows well the agreement between the two statistical characteristics of $V_{\mathrm{lf}}^{\mathrm{obs}}$. They should be the same if the statistics of the actual accelerations are isotropic and there is no wave effect on the direction of the measured velocity.

The fourth assumption is that the value of the overestimation of the synoptic component of the velocity is proportional to its true value. At first sight, this assumption looks strange, but it is supported by the MP87 data and can be easily explained. For example, Fig. 4 shows the correlation between the minimum (before the storm) and the maximum (its peak) values of $V_{\mathrm{lf}}^{\mathrm{obs}}$ recorded on September 24–30, 1987, at a level of 1200 m. This suggests that the effect of the storm was stronger for the moorings located in initially stronger currents. An explanation for this is the permanent presence of pronounced high-frequency motions (predominantly inertial ones [4]) in the MP87 area. It is easily seen that, if $V_{\mathrm{lf}}^{\mathrm{tr}} = 0$ and the directions of instantaneous velocity are distributed isotropically, then $V_{\mathrm{lf}}^{\mathrm{obs}} = 0$ does not depend on the value of the overestimation of the total measured velocity. For the simple case of isotropic high-frequency perturbations of velocity ($|V_{\mathrm{hf}}^{\mathrm{obs}}| = \mathrm{const}$) of a steady-state current $V_{\mathrm{lf}}^{\mathrm{tr}} = \mathrm{const}$, it can be shown that, if $|V^{\mathrm{obs}}| = F(|V^{\mathrm{tr}}|)$, where V^{tr} and V^{obs} are the instantaneous values of the actual and observed velocities, then the asymptotic $V_{\mathrm{lf}}^{\mathrm{obs}}$ for $|V_{\mathrm{lf}}^{\mathrm{tr}}| \ll |V_{\mathrm{hf}}^{\mathrm{tr}}|$ can be written as

$$V_{\mathrm{lf}}^{\mathrm{obs}} = V_{\mathrm{lf}}^{\mathrm{tr}}/(2|V_{\mathrm{hf}}^{\mathrm{tr}}|)\partial(F(|V_{\mathrm{hf}}^{\mathrm{tr}}|)|V_{\mathrm{hf}}^{\mathrm{tr}}|)/\partial(|V_{\mathrm{hf}}^{\mathrm{tr}}|). \quad (2)$$

Finally, the fifth fundamental assumption is that $V_{\mathrm{lf}}^{\mathrm{obs}}$ varies synchronously for all the moorings. For the MP87 area, this is valid for 80% of the moorings. This is illustrated by Fig. 5, which shows the hodographs of 49 series of $V_{\mathrm{lf}}^{\mathrm{obs}}$ at a level of 1200 m from September 21 to October 2, 1987. Indeed, the sizes of the atmospheric eddies significantly exceed the area of the MP87 experiment, and the velocities of their movement are high. This results only in a several-hour time lag in the development of the storm at different moorings. Such a time lag is not distinguishable for the periods included in $V_{\mathrm{lf}}^{\mathrm{obs}}$. The "explosion" of the phase trajectories presented in Fig. 5 (their repulsion from the coordinate origin) during the storm is the best illustration of the effect studied in the present paper. On the completion of the storm, the trajectories do not return to their initial positions due to the natural evolution of synoptic currents, which is of particular scientific interest. Meanwhile, the study of the evolution is hardly possible before removing the storm effect. As can be seen from Fig. 1, $V_{\mathrm{lf}}^{\mathrm{obs}}$ varies almost synchronously with G_{lf} and the correlation coefficients for various levels are 0.7–0.8.

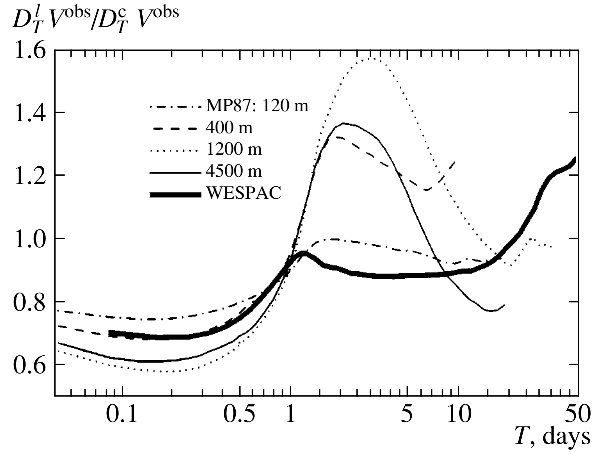

Fig. 2. Comparison of the ratios of the intensity of the longitudinal and azimuthal acceleration components in the MP87 experiment (at four levels) and in the WESPAC experiment (averaged over all the instruments) depending on the width T of the low-pass Hanning filter applied in advance. D_T^l and D_T^c denote the absolute values of the longitudinal $(d_t \ldots)_l$ (along the direction of the current velocity vector) and azimuthal $(d_t \ldots)_c$ (normal to the velocity) components of the time derivatives of the smoothed vector V^{obs} averaged over corresponding datasets.

All these assumptions allow us to reduce the problem of the correction of the velocity vectors at an individual mooring to the correction of the scalar absolute value of the current velocity $V_{\mathrm{lf}}^{\mathrm{obs}}$ averaged over the MP87 area. Figure 6 shows the sense of the method for estimating the true value of $V_{\mathrm{syn}}^{\mathrm{tr}}$ used in the present study. The covariation $V_{\mathrm{lf}}^{\mathrm{obs}}$ and G_{lf} is approximated by a linear dependence, and $V_{\mathrm{syn}}^{\mathrm{tr}}$ is defined as an intersection of these lines with the ordinate axis (where $G_{\mathrm{lf}} = 0$). The use of the method in practice is difficult due to a series of factors. First, we have managed to perform a satisfactory approximation only in the periods of pronounced variations of G_{lf}, thus, obtaining only a few independent discrete estimates of $V_{\mathrm{syn}}^{\mathrm{tr}}$ throughout the MP87 period. In addition, in the periods of weak waves, the dependence can be interpreted as a nonlinear one with a wide scattering of the parameters. This probably

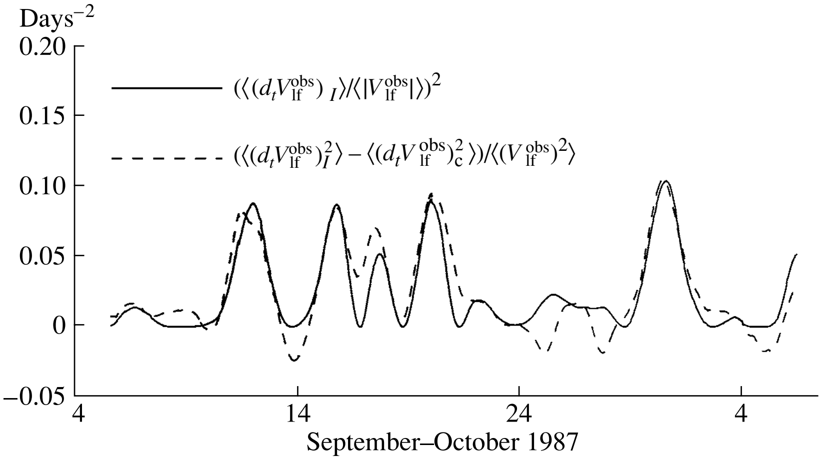

Fig. 3. Fragment of the MP87 data at 1200 m showing the agreement between $(\langle(d_t V_{\rm lf}^{\rm obs})_l\rangle/\langle|V_{\rm lf}^{\rm obs}|\rangle)^2$ and $(\langle(d_t V_{\rm lf}^{\rm obs})_l^2\rangle - \langle(d_t V_{\rm lf}^{\rm obs})_c^2\rangle)/\langle(V_{\rm lf}^{\rm obs})^2\rangle$ and supporting the assumption that waves weakly affect the direction of the measured velocity. <...> denotes the synchronous averaging throughout all the moorings.

results from the restrictions of our assumptions, which are valid for abruptly changing weather conditions. In addition, the instrument failures and the deployment of additional moorings also changed $V_{\rm lf}^{\rm obs}$ due to the horizontal nonuniformity of the currents.

Among the set of methods tested that yield similar results for the central moments of storms, the most simple and reliable one is the following. The amplitudes of A_G and A_V of the "stormy" $G_{\rm st}$ and $V_{\rm st}^{\rm obs}$ were calculated as

$$A_G = 2\{(G_{\rm st})^2\}^{1/2}, \quad A_V = 2\{(V_{\rm st}^{\rm obs})^2\}^{1/2}, \qquad (3)$$

where $\{\ldots\}$ denotes smoothing with the use of a Hanning filter with an 8-day width. The true values of $V_{\rm syn}^{\rm obs}$ were then assessed for each of four observation levels as

$$V_{\rm syn}^{\rm tr} = V_{\rm syn}^{\rm obs} - G_{\rm syn}A_V/A_G. \qquad (4)$$

Finally, the corrected vectors of the synoptic current velocities in the series obtained using individual current meters were calculated by scaling the syn vectors with a coefficient $\alpha(t;\, z) = V_{\rm syn}^{\rm tr}/V_{\rm syn}^{\rm obs}$, which varies with time and depth. Figure 7a shows the time trend of the corrected module of the synoptic velocity component averaged synchronously throughout all the moorings. The steps in Fig. 7a, similar to those in Fig. 1a, are associated with the nonsynchronous startup and shutdown of the instruments at the individual moorings.

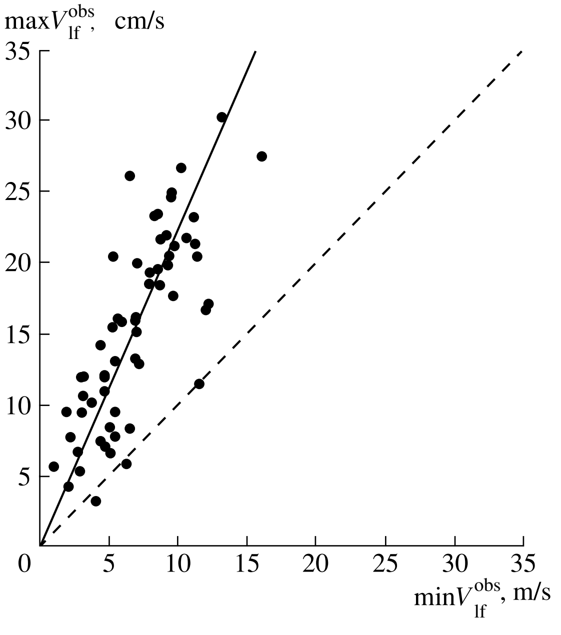

Fig. 4. Relationship between $V_{\rm lf}^{\rm obs}$ before the storm on September 24–30, 1987, (min) and at the moment of its maximum development (max) measured at a level of 1200 m.

DISCUSSION

The present study is devoted to correcting the effect of wind waves on the results of the current velocity measurements from the surface moorings. Though the effect is probably strong at all frequencies [5], the method proposed corrects only the overestimated synoptic component of the velocity. Figure 7b shows the value of such an overestimation that reaches a twofold value during particularly severe storms. It is interesting that the effect reaches its maximum at intermediate depth levels. It seems that the high-frequency (the surface wave frequencies) oscillations of the cable decay somewhat at great depths due to the decrease in its cur-

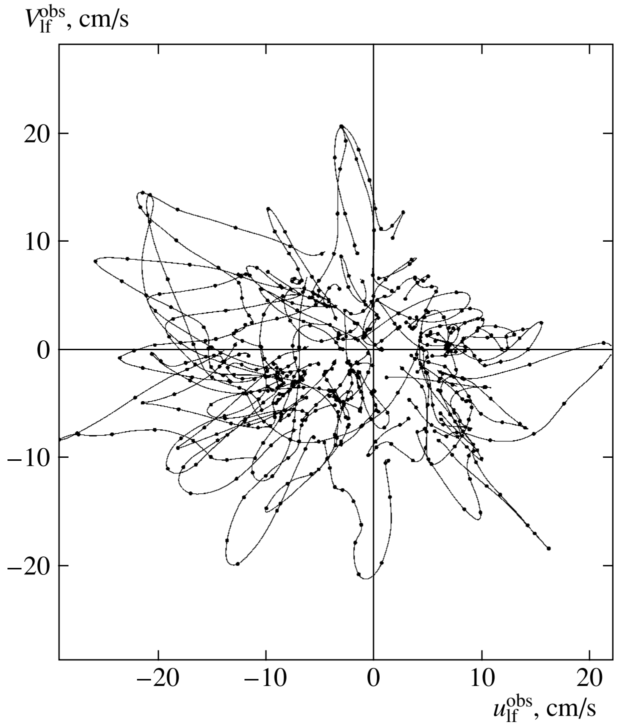

Fig. 5. Hodographs of the velocities $V_{\mathrm{lf}}^{\mathrm{obs}}$ measured with the use of 49 current meters at a level of 1200 m from September 21 to October 2, 1987. The time interval between the points is 24 h.

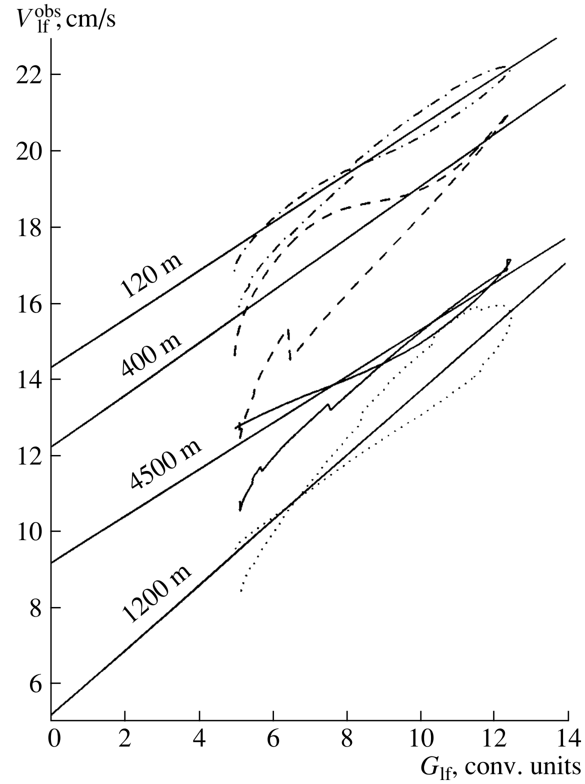

Fig. 6. Linear extrapolation used for the estimation of $V_{\mathrm{syn}}^{\mathrm{tr}}$ (the storm during September 24–30, 1987).

vature. In contrast, the top level (120 m) probably lies in the range of the longest waves, which attenuates the vertical oscillations of the instrument with respect to the ambient water responsible for the overestimation of the velocity measured.

The substance of the method used in the present study is as follows. Let a system (velocity measurements in our case) be perturbed by a parasitic factor (surface waves in our case). Even though this factor acts permanently but varies essentially over the chosen coordinate (or time), it is possible to eliminate its total effect by investigating the sensitivity of the system to the variations of the factor. The problem is simplified if we can introduce a parameter (G in our case) with respect to which these perturbations are close to linear ones. Choosing such a parameter is subject to art and luck of researcher, and the linearity is difficult to prove without additional (independent) data.

The assumptions adopted in the present method are of different importance. For example, extrapolation (4) is more important than the fourth assumption on the linearity of the dependence of the velocity overestimation on its true value. This can be illustrated using a simple example. Let us consider a two-dimensional vector field V whose components are distributed according to the Gaussian law with a zero mean value. Let us distort V by increasing the length of each vector by a constant value δ

$$V^{\mathrm{obs}} = V(|V| + \delta)/|V| \qquad (5)$$

and try to correct such an error by scaling $V^{\mathrm{tr}} = V^{\mathrm{obs}}A$ (A = const).

One can show that, if A is optimal, then the mean square deviation of V^{tr} from V is $\sigma = \langle|V|\rangle\delta/(\langle|V|\rangle + \delta)/(4/\pi - 1)^{1/2}$, which for $\langle|V|\rangle \approx \delta$ yields $\sigma \approx \delta/4$. In other words, the error is reduced by a factor of four. This means that, even though the dependence of V^{obs} on V is approximated incorrectly, $\langle|V|\rangle$ is determined correctly.

Several methods to verify the validity of the results of the correction are possible.

1. *Comparison with the WESPAC data.* The mean speed recorded with the current meters mounted on the subsurface moorings along 152° E in 1980–1982 [7] at levels close to 1200 m was 7.0 cm/s. For the MP87 experiment, this value was twice as great (14.0 cm/s). The relationship does not change after the low-pass filtering, and the mean values of $V_{\mathrm{lf}}^{\mathrm{obs}}$ were 5.1 and 10.2 cm/s, respectively. As a result of correction, the mean value of $V_{\mathrm{syn}}^{\mathrm{tr}}$ diminishes down to 6.3 cm/s. The relative contributions of the interannual variability and spatial nonuniformity of the statistics of the synoptic

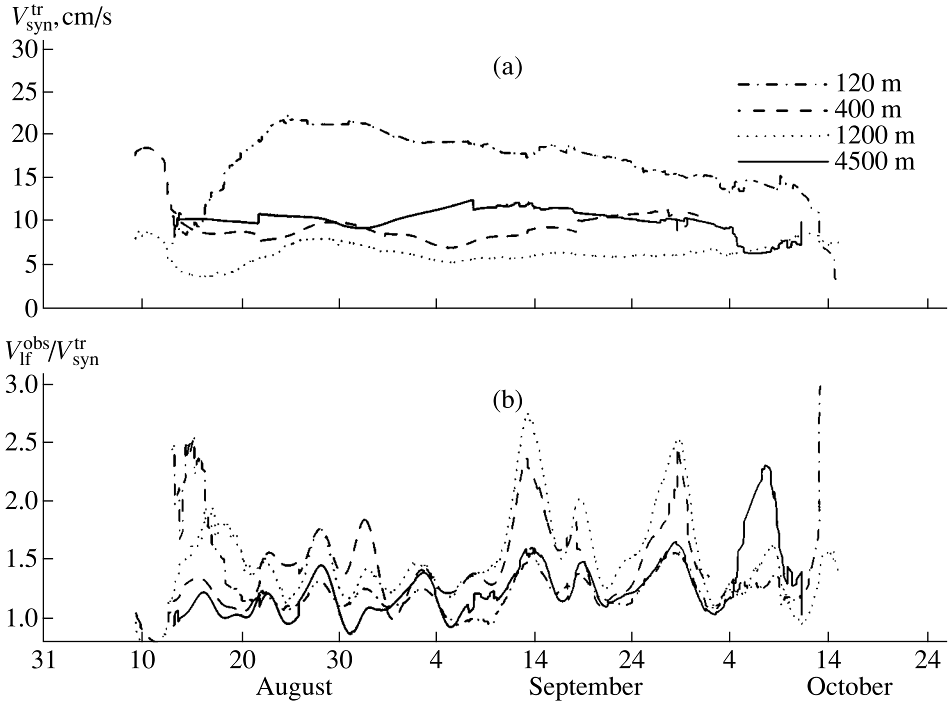

Fig. 7. Time series of (a) the absolute value of the corrected synoptic velocity component V_{syn}^{tr} averaged over the MP87 area (for four levels) and (b) the coefficient of velocity overestimation before the correction $V_{lf}^{obs}/V_{syn}^{tr}$.

currents in the region to the residual difference are unclear.

2. *Comparison with the hydrology.* More than 1600 hydrological stations were occupied during the MP87 experiment, and only in a few cases did their location, time, and quality allow us to compare the vertical shear of the geostrophic velocity ΔV^{geo} calculated from the density profiles with the velocity difference between the pairs of instruments at 120 and 1200 m of the same mooring. The correlation between ΔV^{geo} and ΔV_{syn}^{tr} is somewhat better than that between ΔV^{geo} and ΔV_{lf}^{obs}. At the same time, the accuracy of ΔV^{geo} itself is rather low.

3. *Comparison with the Geosat satellite altimetry.* The repeated observations of the sea level along the satellite tracks allow one to assess the time variations of the geostrophic component of the current velocity at the sea surface normal to the track. As in item 2, the variations of V_{syn}^{tr} at 120 m in the MP87 area were in better agreement with the altimetry than those of V_{lf}^{obs}. Nevertheless, it is difficult to reach any conclusions due to the scarcity of synchronous data and the large distance of the top level from the surface in the MP87 experiment.

4. *Horizontal tracer advection.* Although special analysis of the evolution of tracers was not performed, the velocities of the movements of submesoscale anomalies, such as an interthermocline lens [6] near the 1200-m level, were found to be in better agreement with the local values of V_{syn}^{tr} and to be smaller than V_{lf}^{obs}.

5. *Correspondence to the quasi-geostrophic dynamics.* The methods of the assessment of the data quality listed in items 2–4 were used in [9] together with the dynamical hypotheses in the framework of the problem of simultaneous assimilation of the data on the velocity, density, and altimetry in the quasi-geostrophic numerical model. The best indicator of the quality of the data correction proposed is the fact that the corrected data were easily assimilated by the model even in the absence of horizontal viscosity. In contrast, the initial series of the MP87 velocity data provide no stable solution for any values of this parameter.

The estimate of the residual error in V_{syn}^{tr} as 15–20% based on items 1–5 looks rather reasonable. Part of the error is probably associated with the presence of a swell that was independent of the local wind in the MP87 area. Our experience with the MP87 data correction allows us to assume that data from other major polygons were also affected by waves. This is confirmed by the difference between the velocity data from the mooring and the trajectories of SOFAR neutrally buoyant floats in the POLYMODE area as well as by the unrealistically high values of the vertical velocity component estimated from the data of the first survey of the Mesopolygon-85 experiment with the use of the equation for temperature advection (Maximenko, unpublished). The use of multiannual dynamically interpolated wind data (NCEP and ECMWF) would allow us to correct the entire historical archive of polygon databases and, no doubt, would change many conclusions made previously on the basis of them.

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