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OSCILLATIONS IN THE JET STRUCTURE OF THE ANTARCTIC CIRCUMPOLAR CURRENT SOUTH OF AFRICA ACCORDING TO SATELLITE ALTIMETRY DATA: TIME SERIES CALCULATION AND AVERAGE CHARACTERISTICS

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As part of the task of studying oscillations in the meridional shift of the jet structure and changes in the intensity of currents in the Antarctic Circumpolar Current zone south of Africa (9.875° W–25.125° E) according to absolute dynamic topography (ADT) data published on the website: http://marine.copernicus.eu, the procedure for calculating time series of these parameters of currents with a ten-day discreteness is described. In this case, the jet structure is understood as the alternation in the meridional direction of zones of increased and decreased values of the absolute dynamic topography (ADT) gradient modulus, $|\nabla\zeta|$. For the period of satellite altimetry observations 1993–2018, a comparison was made of series calculated for the entire sector without division into narrow meridional bands and with division and subsequent averaging over a set of these bands. It is shown that these series constructed in two different ways can either differ significantly or be almost identical to each other. In addition, a calculation was made of the zonal distributions of some characteristics of the series that are essential for spectral analysis: root mean square deviation, the share of a long-term linear trend and the share of long-term oscillations in the total variance of the series.

Keywords: Dynamic topography, satellite altimetry, jets, Antarctic Circumpolar Current, long-term fluctuations

1. Introduction

The Antarctic Circumpolar Current (ACC), which encircles the Antarctic continent from west to east, is divided into jets (Burkov, 1994; Orsi et al., 1995), i. e. zones characterized by increased current velocities on the ocean surface. These zones correspond to an increased slope of the absolute dynamic topography (ADT, ζ) on the ocean surface, and in the depths of the ocean they are matched by increased slopes of isopycnic surfaces. ADT isolines (isohypses) are the flow lines of the geostrophic current on the ocean surface. In the Southern Hemisphere, greater ADT values remain to the left of the current direction, while in the Northern Hemisphere, they stay to the right. Accordingly, the crowdings of isohypses (zones of increased ADT gradients, $\nabla\zeta$) on ADT maps correspond to jets. The alternation of zones of increased and decreased values of the ADT gradient modulus in the direction transverse to the current is understood as the jet structure of currents.

According to the concepts (Orsi et al., 1995), which are considered classical today, three jets are distinguished in the ACC zone throughout the entire circumpolar circle, traditionally called the Subantarctic, Polar and Southern ACC fronts. A finer splitting of the ACC into jets, up to 9 throughout the entire circumpolar circle, was asserted in (Sokolov, Rintoul, 2009a). In regional studies, to the south of Africa (Tarakanov, Gritsenko, 2014a; Tarakanov, Gritsenko, 2014б) and in the Drake Passage (Tarakanov, Gritsenko, 2018), up to 12 jets were distinguished.

Jet currents, including the ACC jets, concentrate the kinetic energy of the ocean space, which they receive as a result of the interaction of the ocean with the atmosphere, along with eddies formed as a result of baroclinic instability of these currents caused by the slope of isopycnal surfaces. The main transport of the ACC is concentrated in the jets (e. g., Thompson, Sallée, 2012). The jets are a dynamic barrier that significantly impedes horizontal water exchange across them (Naveira Garabato et al., 2011; Thompson, Sallée, 2012; Chapman, Sallée, 2017). In those sectors of the ACC where a stable jet structure is observed, for example, when crossing submarine ridges, water exchange across the current is virtually absent. At the same time, in those areas of the Southern Ocean where the ACC expands significantly, space appears for meandering of jets with subsequent separation of meanders in the form of eddies, which provide water exchange across the current. In particular, eddy water exchange, along with abyssal currents below the crests of ridges crossing the ACC, provides compensation for the northward flow of the purely drift current in the surface layer (Koshlyakov, Tarakanov, 2011). During this water exchange, there is also an upwelling of deep waters to the surface at high latitudes, compensating for the increase in the flow of the purely drift current in the ACC band in the northward direction. At the same time, there is an upwelling of biogenic elements from the depths to the surface (Palter et al., 2013; Freeman et al., 2018), which is also thus associated with the dynamics of jet streams. It should be noted that despite the high concentrations of nutrients in surface waters, the productivity of Antarctic waters remains low due to the limited iron content (Venables, Moore, 2010; Bristow et al., 2017). The exception is those areas where jets pass near islands and submarine ridges. In this case, the interaction of jets with the shelf and slope leads to the erosion of bottom sediments and the gradual rise of iron-rich suspended matter along the current (Sokolov, Rintoul, 2007; Klocker, 2018).

The role of current jets in the Southern Ocean described above determines the need to study their long-term dynamics. In particular, estimates of long-term oscillations (including linear trends) of the meridional shift of the ACC jet structure may be significant for predicting changes in the productive regions of the Southern Ocean. At present, there is no consensus on the presence of a systematic meridional shift of the ACC jets. Most modern studies do not detect it (see the review in (Chapman et al., 2020), as well as in (Tarakanov, 2021)). At the same time, the author of the present work in papers (Tarakanov, 2021; Tarakanov, 2023b; Tarakanov, 2024) showed the presence of a significant shift in the meridional structure in the ACC zone in the region south of Africa. Even earlier, the average long-term southward shift of the entire jet structure of the ACC throughout the entire Antarctic ring was stated in the work (Sokolov, Rintoul, 2009b). Another important characteristic of the jets for assessment is their intensity (velocity), which is related to the kinetic energy content in the upper ocean layer. Long-term changes in this parameter are a response to changes in the wind effect on the ocean surface. To date, the author of the article is not aware of any systematic studies of changes in the intensity of the ACC jets. In (Tarakanov, 2023), estimates were obtained for seasonal changes in the meridional shift and changes in the intensity of the current for the sector south of Africa.

The work (Tarakanov, 2021) was the first in which the author of the present paper investigated the long-term meridional shift of the ACC jet structure south of Africa, where this current has a quasi-zonal direction. In particular, a method for calculating such a shift was developed in it, based on linear regression analysis and including an error estimate. The method evaluates the evolution of the shape of the curves of the dependence of the ADT gradient modulus, $|\nabla\zeta|$, on latitude or ADT. This also implies the calculation of the long-term change $|\nabla\zeta|$, which is understood as a change in the current intensity. This identification is due to the fact that $|\nabla\zeta|$ differs from the geostrophic velocity, u, on the ocean surface only by the factor $|g/f|$ (g is the acceleration due to gravity, f is the Coriolis parameter). Thus, the time variability of $|\nabla\zeta|$ and $|u|$ are identical or almost identical with a correction for the specified factor. Thus, in (Tarakanov, 2023b) a qualitative and good quantitative agreement was shown between the results of calculations of the long-term linear change in the jet structure of the ACC based on each of the parameters $|\nabla\zeta|$ and $|u|$. In (Tarakanov, 2023b) the methodology was improved, and in (Tarakanov, 2024) zonal distributions of the shift in the jet structure and changes in the intensity of currents for the ACC sector south of Africa were calculated based on this methodology. In particular, a significant heterogeneity of these distributions was noted, which leads to noticeable quantitative differences in the results of calculations of the sector-averaged values of the specified parameters with and without division into narrow meridional bands. In (Tarakanov, 2023a) the methodology was modified and supplemented to assess seasonal oscillations of these parameters in the same ACC sector using harmonic regression analysis.

Present paper opens a series of works in which, for the same ACC sector south of Africa as in (Tarakanov, 2024), an assessment is given of the variability on different time scales of zonal and sector-averaged distributions of the jet structure meridional shift and changes in the current intensity. The position of the sector (from 9.875° W to 25.125° E) and the ACC bands are shown in Figure 1. Present work describes the preparation of data for such a study, which consists of constructing time series of the specified parameters, investigating the properties of these series associated with the methods of their construction, and providing estimates of some of their average and spectral characteristics. The methodological basis for such a construction is linear regression analysis. By analogy with works (Tarakanov, 2021; Tarakanov, 2023a; Tarakanov, 2024), the calculation of the series is carried out through the ACC gradient module. Section 2 describes the data on the basis of which the series were calculated, Section 3 describes the method for calculating the series, Sections 4, 5, 6 discuss some of the results of the analysis of the calculated series, and Section 7 contains the main conclusions of the work.

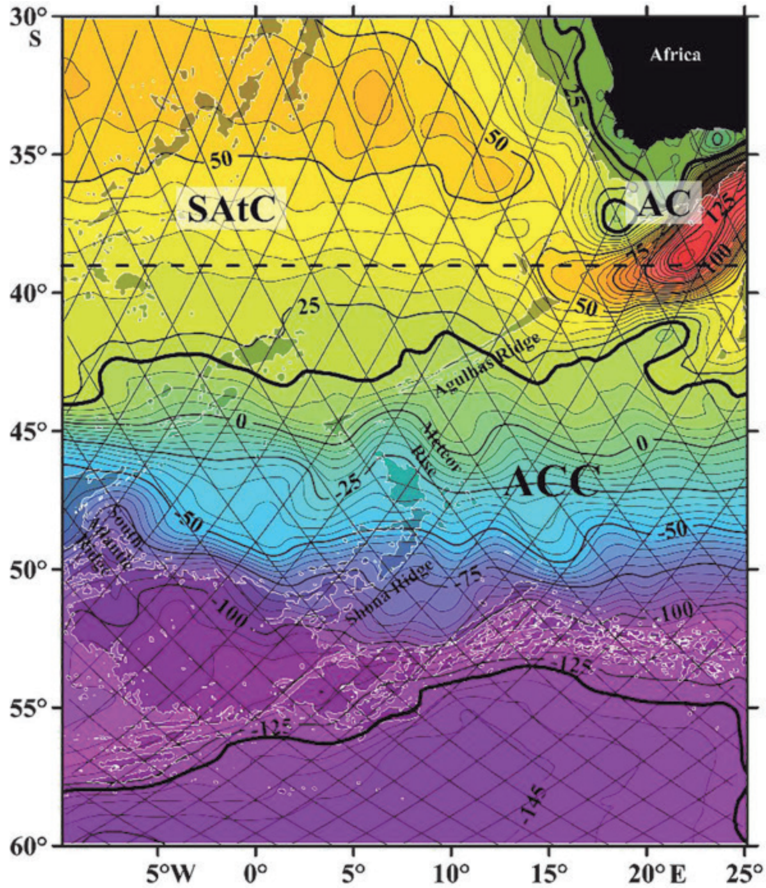

Fig. 1 – Mean dynamic topography (isolines and color shading) in the region south of Africa (9.875° W–25.125° E). Bold isolines of –130 and 20 cm show the conventional boundaries of the ACC, approximately corresponding to the results of (Tarakanov, Gritsenko, 2014a). The abbreviation AC designates the Agulhas Current, in which the ADT values also fall within the range typical for the ACC; SAtC stands for the South Atlantic Current. The shaded areas outlined by white lines correspond to ocean areas with depths less than 3000 m. The oblique lines show the main tracks of the T/P, Jason-1, -2, -3 satellites. The dashed line at 39° S shows the northern limit for calculating the curves of the dependence of h on ζ

2. Data

As in (Tarakanov, 2021; Tarakanov, 2023a; Tarakanov, 2023b; Tarakanov, 2024), in present work we used daily gridded ADT data from the SEALEVEL_GLO_PHY_L4_MY_ 008_047 product for the period 1993–2018, which is produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu). The ADT data are given for non-integer degrees of longitude and latitude – 0.125, 0.375, 0.625, 0.875. Synoptic (instantaneous, i.e. at a certain point in time) ADT is the sum of the mean (over time) ADT and the instantaneous sea level anomaly (SLA), determined on the basis of satellite altimeter measurements. The above product uses the MDT CNES-CLS22 (Jousset et al., 2022) version of the mean ADT, which is calculated based on various measurements of hydrophysical parameters in the ocean depth, satellite altimetry data, geoid and mean sea level models, and wind reanalysis data. The mean ADT map for the sector under study is shown in Figure 1. The ADT data are interpolated from the satellite tracks recorded on the Earth's surface onto a regular grid for each day. Figure 1 shows the layout of the so-called main tracks of the TOPEX/Poseidon (T/P) and Jason-1, -2, -3 satellites with altimeters in the region south of Africa, which are repeated with a periodicity of $\tau \approx 10$ days throughout the entire period of satellite altimetry observations.

3. Calculation of time series

The calculation of time series of the meridional shift of the jet structure and changes in the intensity of currents is performed both for the entire ACC sector south of Africa, i.e. without division into meridional bands, and with division for the purpose of analyzing the zonal distributions of these parameters. In the last case, the calculation for each band is performed using the same method as for the entire sector as a whole. According to the conclusions of (Tarakanov, 2024), the optimal width of the meridional bands is 2.5 degrees of longitude. First, daily maps of the ADT gradient modulus, $|\nabla\zeta|$, are calculated based on daily ADT data, which are then averaged over a certain period of time and along the direction on the ocean surface. Averaging is performed for each meridional band and for the entire sector as a whole. In our case, averaging is performed for ten days and along the latitude or isohypses. It should be noted that in (Tarakanov, 2021; Tarakanov, 2023b; Tarakanov, 2024) the averaging was 1 year to estimate the linear long-term changes in the parameters, while in (Tarakanov, 2023a) the months (January, February, etc.) were averaged separately for the entire observation period to estimate the seasonal variation. The series of ten-day curves of the modulus of the ADT gradient obtained in present work for each meridional band and for the entire sector as a whole were analyzed for the temporal variability of the shape of these curves. Linear regression analysis allows us to divide this change into a linear shift across the latitude, i. e. along the meridian, or across the isohypses, i. e. along the ADT scale, and a change in the current intensity, i. e. the ADT gradient modulus. In this way, the time series of the shift and the change in the current intensity were calculated relative to their average values for the entire observation period. In the case of calculations with division into meridional bands, the time series were also averaged over the entire set of 14 2.5-degree bands. In the future, the constructed series will be analyzed in order to identify oscillations in the specified parameters on different time scales.

Let us present the algorithm of preliminary data processing in more detail. For $|\nabla\zeta|$, the averages are calculated for the meridional band and for each ten-day interval, the curves of its dependence on the parameter a (latitude, φ or ADT, ζ). We will designate the curves obtained in this way as $h(a)$. For the region south of Africa, the calculation of $h(a)$, as in (Tarakanov, 2021; Tarakanov, 2023b; Tarakanov, 2024), is limited from the north by 39° S in order to cut off the northern periphery of the Agulhas Current (AC) and its cyclonic eddies, the ζ values in which fall into the range characteristic of the ACC (Figure 1). When constructing the series of h dependences on ζ, the shift of the ACC jet structure south of Africa by a total of 8.6 cm over the period of satellite altimetry observations from 1993 to 2018, obtained in (Tarakanov, 2021; Tarakanov, 2023b) from calculations via $\langle|\nabla\zeta|\rangle$, is taken into account. These series are reduced to the ζ' scale corresponding to the middle of the time interval 1993–2012, which in turn corresponds to the averaging interval of the mean dynamic topography of the MDT CNES-CLS18. The methods for calculating the $h(a)$ curves are described in detail in (Tarakanov, 2021). Thus, a set of 949 such curves was obtained for each meridional band over a 26-year period.

Based on the set of ten-day curves calculated above, the derivative with respect to a of the distribution $\bar{h}$ is calculated. For each i-th argument (latitude or ADT value), the $\bar{h}$ values are the average for the entire observation period ($\bar{h}_i = \frac{1}{L}\sum_{l=1}^{L} h_{i,l}$, L is the number of time counts):

$$x_i = \frac{\bar{h}_{i+1} - \bar{h}_{i-1}}{2\Delta a}. \tag{1}$$

In formula (1) for $i = 1$ it is necessary to replace i-1 with 1, and for $i = N$ it is necessary to replace $i + 1$ with N, where N is the total number of values of the argument a, $2\Delta a$ is replaced by Δa. The values of the anomaly of the modulus of the ADT gradient are also calculated for each l-th ten-day period and each i-th value of the argument:

$$y_{i,l} = h_{i,l} - \bar{h}_i. \tag{2}$$

A pair of distributions $x_{i,l}$ and $y_{i,l}$ (i = 1, N; l = 1, L) can be represented on one plane with a parametric dependence on a. On this plane, for some range of a, for example, corresponding to the ACC band, a linear regression between x and y is estimated. In this case, the coefficient k of the linear regression with the opposite sign represents the linear shift of the ACC jet structure for the entire observation period:

$$k(x,y) = \frac{\sum_{i=1}^{N}(y_i - \tilde{y})(x_i - \tilde{x})w_i}{\sum_{i=1}^{N}(x_i - \tilde{x})^2 w_i}, \tag{3a}$$

and the free term of the regression is the change in h for this range for the same period:

$$b(x,y) = \tilde{y} - k(x,y)\tilde{x}. \tag{3b}$$

The tilde sign above means averaging over index i; w_i are weighting coefficients, where $\sum_{i=1}^{N} w_i = 1$. In this paper, we take $w_i = 1/N$ for a corresponding to the latitude, and $w_i = s_i / \sum_{j=1}^{N} s_j$ for a corresponding to ζ; here s_i is the estimate of the area of the map sections bounded by the isohypses $\zeta_i \pm \Delta\zeta/2$. The difference between the edge values of the range a will be further understood as the calculation scale $\check{a}$, and the central value a_0 as the median latitude or the median value of the ADT, depending on the choice of the parameter a.

Thus, for each meridional band and for the entire studied sector of the ACC, for each pair $\breve{a}$ and a_0, a pair of sets of L values of the shift of the jet structure and the change in the intensity of currents relative to their average values for the entire observation period is obtained.

4. Comparison of time series with and without division into meridional bands

Examples of time series of jet structure shifts and changes in the current intensity, shown in Figure 2, show that these series, constructed in different ways from the same data, i.e. without division into meridional bands and with division and subsequent averaging over a set of bands, can differ significantly from each other. These differences can be quantitatively assessed by two parameters, which are the Pearson correlation coefficient R_P and the ratio of root-mean-square deviations (RMSD) R_{RMS}:

$$R_P = \frac{cov(c,\bar{\bar{c}})}{RMS(c)RMS(\bar{\bar{c}})}, \tag{4}$$

$$R_{RMS} = \frac{RMS(\bar{\bar{c}})}{RMS(c)}. \tag{5}$$

Here c is the shift, i. e. $-k$, or the change in the current intensity, b; the double overbar is averaging over a set of meridional bands; $cov(c,\bar{\bar{c}})$ is the covariance of the c and $\bar{\bar{c}}$ series. The distributions of the R_P and R_{RMS} parameters depending on the calculation scale and the median values of latitude and ADT are shown in Figures 3 and 4, respectively. These figures also highlight the conventional boundaries of the ACC by latitude (57° and 42° S) and by the ADT scale (–130 and 20 cm) in accordance with (Tarakanov, 2021). The estimates of R_P and R_{RMS} for the examples of series in Figure 2 are given in the figures themselves.

First of all, we note the generally positive correlation of the series constructed with and without division into bands. Only on small scales of calculation are inclusions of weak negative correlation observed (Figures 3a, 3b, 4a, 4b). The series of the shift of the jet structure relative to the latitude are characterized mainly by a weak correlation, with the exception of the northern periphery of the ACC zone, and low values of R_{RMS}, i. e. significantly smaller values of the RMSD in the calculation with division into bands (Figures 2a, 3a, 3c). The series of changes in the current intensity relative to the latitude scale, constructed in different ways (Figures 2b, 3b, 3d), are very well correlated, with the exception of several spots on small scales of calculation, and the ratio of their RMSD is close to unity. In calculations relative to the ADT scale, the correlation of the shift series without and with division into bands is generally significantly higher than in calculations relative to latitude, especially on medium and large scales of calculation (Figures 3a, 4a), and the ratio of the RMSD is close to unity (Figures 2c, 4c). The series of changes in the intensity of currents are generally well correlated on medium and large scales, although to a somewhat lesser extent than in the case of calculation relative to the latitude scale. At the same time, the RMSD is higher for the series calculated with division into bands, and on medium scales it is significantly so (Figures 2d, 4d).

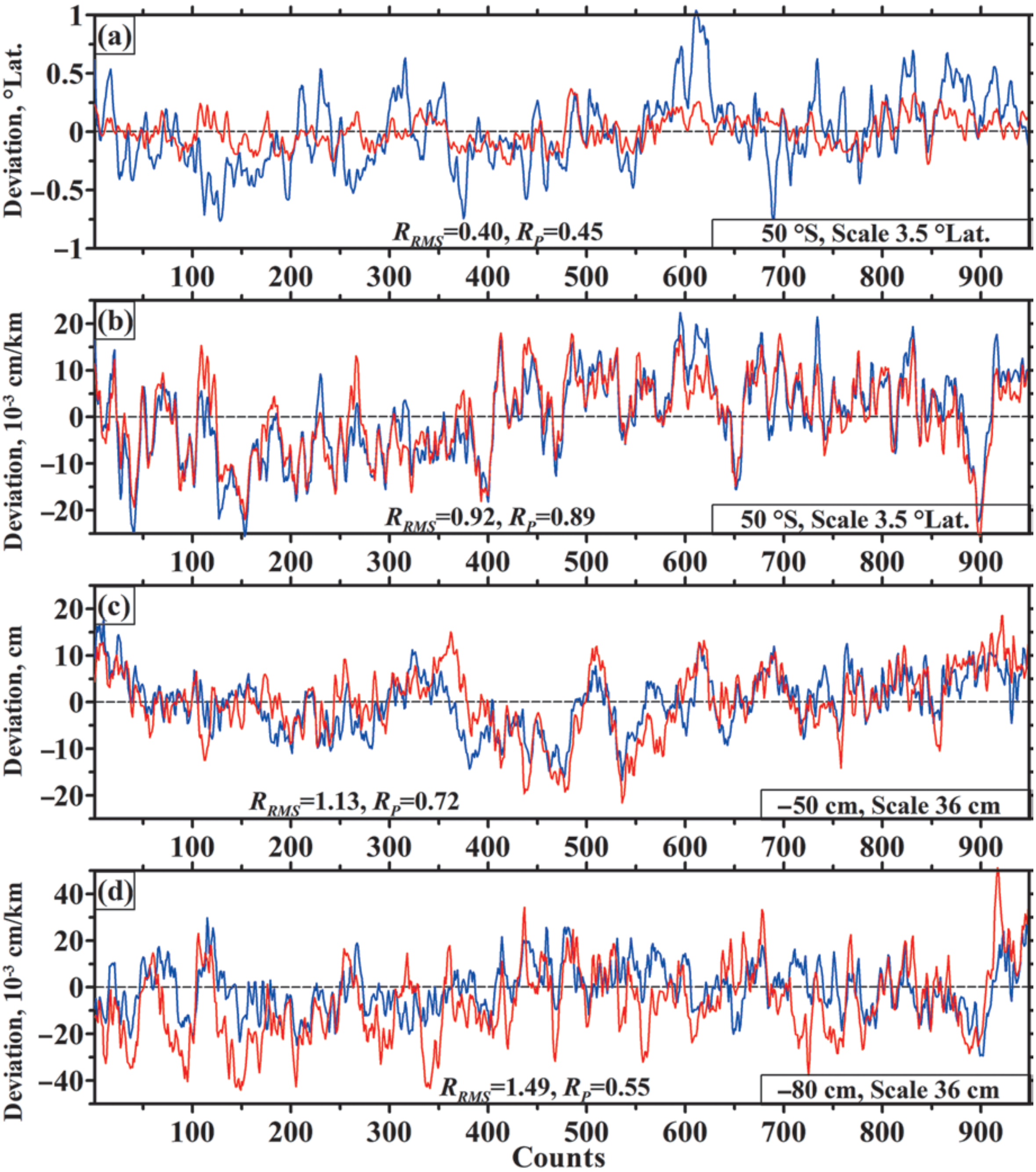

Fig. 2 – Time series of the meridional shift of the jet structure and the change in the current intensity, constructed for the entire ACC sector south of Africa with division into meridional bands (red curves) and without division (blue curves): (**a**) – shift (°lat.) relative to latitude; (**b**) – change in the current intensity (10^{-3} cm/km) calculated relative to latitude; (**c**) – shift (cm) relative to the ADT scale; (**d**) – change in the current intensity (10^{-3} cm/km) calculated relative to the ADT scale. One count corresponds to 10 days. The figures also show the values of the calculation scales, median latitudes (or ADT values), as well as estimates of the Pearson correlation coefficients (see formula (4)) and the RMSD ratios (see formula (5)), of the corresponding series

The above-described pattern of the R_P and R_{RMS} distributions leads to important conclusions regarding the further analysis of the series spectra constructed for the ACC sector south of Africa. The spectra of the series of current intensity changes, constructed in different ways, will be close in the case of calculation relative to latitude on all scales and similar in calculation relative to the ADT scale on medium and large scales. To a lesser extent, the similarity of the spectra will be characteristic of the series of the jet structure shift relative to the ADT scale. In the case of the series of shift relative to latitude, significant discrepancies can be expected in the spectra, both in the frequency values of the spectral peaks and in the intensities of the peaks.

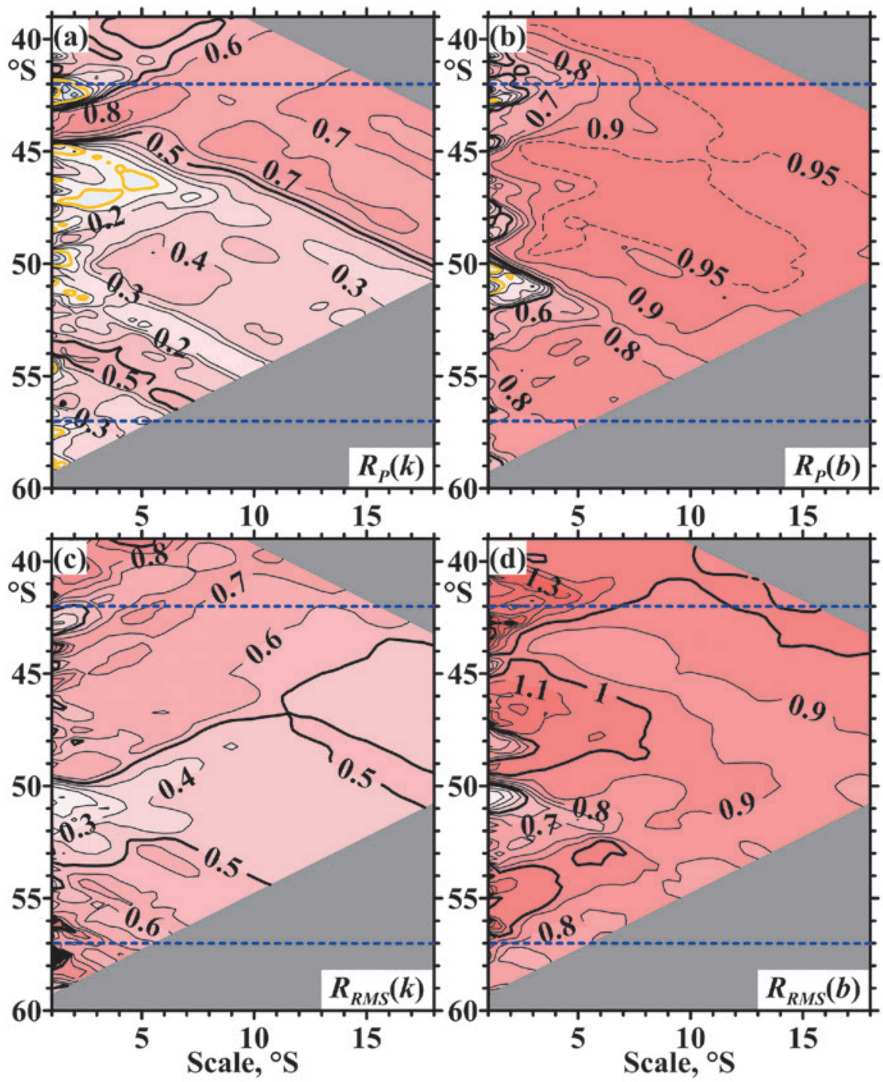

Fig. 3 – Distributions of the Pearson correlation coefficients (see formula (4)) and the RMSD ratios (see formula (5)) of the series calculated with and without division into meridional bands, depending on the calculation scale and the median latitude: (**a**), (**b**) – Pearson correlation coefficients, (**c**), (**d**) – RMSD ratios; (**a**), (**c**) – series of the meridional shift of the jet structure, (**b**), (**d**) – series of changes in the intensity of currents. Yellow isolines in Figure (**a**) and (**b**) are zero values of the correlation coefficient. Horizontal dashed lines are the conventional boundaries of the ACC by latitude, in accordance with (Tarakanov, 2021)

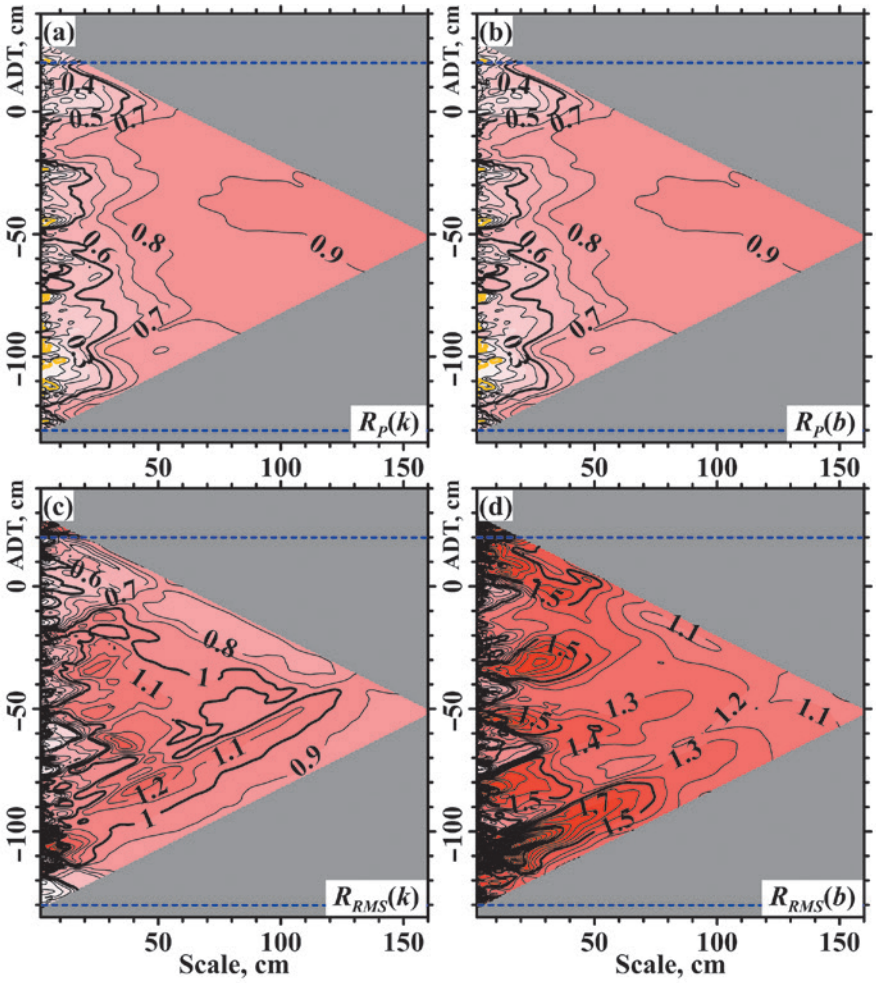

Fig. 4 – Distributions of Pearson correlation coefficients (see formula (4)) and RMSD ratios (see formula (5)) of series calculated with and without division into meridional bands, depending on the calculation scale and median values of the ADT: (**a**), (**b**) – Pearson coefficients, (**c**), (**d**) – RMSD ratios; (**a**), (**c**) – series of the jet structure shift, (**b**), (**d**) – series of changes in the current intensity. Yellow isolines in Figure (**a**) and (**b**) are zero values of the correlation coefficient. Horizontal dashed lines are the conventional boundaries of the ACC on the ADT scale, in accordance with (Tarakanov, 2021)

5. Zonal distributions of some characteristics of time series

A common feature of the zonal distributions of the RMSD of the series of meridional shift of the jet structure and the series of change in the intensity of currents depending on the median latitude is a decrease in the RMSD values with an increase in the calculation scale (Figure 5). The same feature is observed for the RMSD of the series calculated for the entire sector as a whole with and without division into bands; the corresponding curves are also shown in Figure 5. The RMSD of the shift in the studied sector generally increases in the direction from south to north and from west to east (Figures 5a, d, i). The maximum RMSD values in the northeastern part of the ACC band

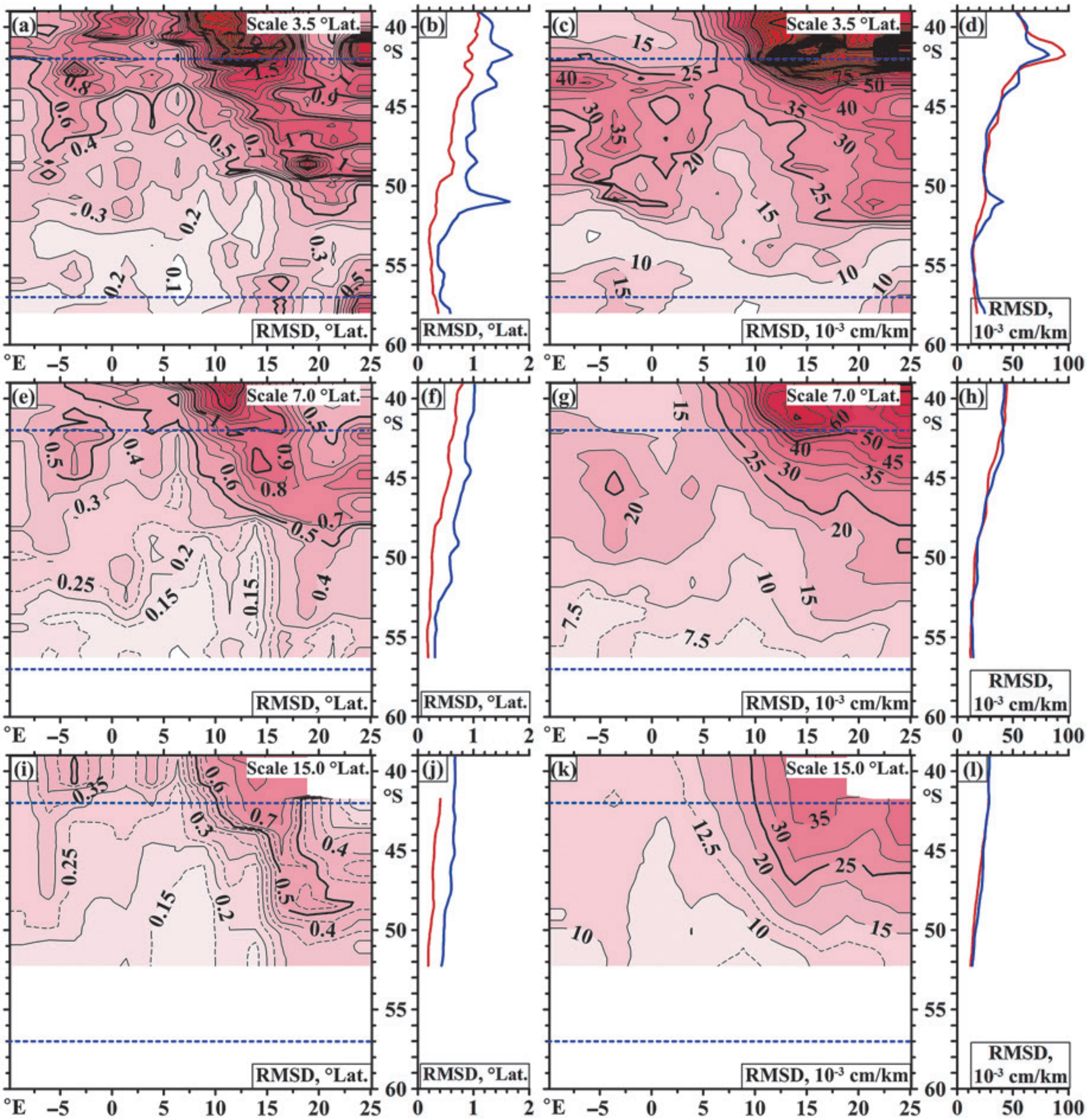

Fig. 5 – Distributions of the RMSD of the meridional shift of the jet structure (°latitude) and the change in the current intensity (10^{-3} cm/km) for the ACC sector south of Africa for different calculation scales depending on the median latitude: (**a**), (**d**), (**i**) – zonal distributions of the shift; (**b**), (**e**), (**j**) – curves of the shift calculated for the entire sector as a whole with division into meridional bands (red curves) and without division (blue curves); (**c**), (**g**), (**k**) – zonal distributions of the change in the current intensity; (**d**), (**h**), (**m**) – curves of the change in the current intensity calculated for the entire sector as a whole with and without division into meridional bands. The rest is as in Figure 3

exceed 1° latitude on small calculation scales. In the eastern half of the sector, the Agulhas Current-Agulhas Countercurrent zone adjoins the ACC zone from the north. To the east of approximately 17° E in this zone, the meridional shift is significantly hindered by the continental slope of Africa. As a result, the RMSD in the northward direction decreases here, which on large scales of calculation leads to the formation of a meridional maximum of the RMSD inside the ACC band (Figures 5d, i). To the west of the indicated longitude, there is no such limitation and the RMSD in the northward direction increases. The tendencies in the spatial distribution of the RMSD of the change in the current intensity are the same as for the shift. However, in the AC zone in the northward direction, the RMSD increases in the entire junction band of the AC and ACC, and to the west of it, in the South Atlantic Current (SAtC) zone, on the contrary, the RMSD decreases. As a result, in the eastern part of the studied sector, on large scales, the maximum of the RMSD of this parameter is formed inside the ACC band.

In the context of further calculation of the spectra of the series of meridional shift of the jet structure and changes in the current intensity, it is of interest to estimate the share of the total variance of oscillations accounted for by the long-term linear trend in these series. Figure 6 shows the zonal distributions of such shares depending on the median latitude, as well as the share curves for the series calculated for the entire sector. The maximum values of the shares in the zonal distributions reach 20 % in the case of a shift and 28 % for a change in intensity. Moreover, there is no obvious tendency to decrease or increase their values when changing the calculation scale. The zones (spots) of increased share values are exactly the same as the spots of increased values of long-term linear meridional shift and changes in the current intensity (Figure 5 from (Tarakanov, 2024)). For the shift, this is the area between the South Atlantic Ridge and the chain of elevations Agulhas Ridge – Meteor Rise – Shona Ridge. For the change in the intensity of the current this is the same region, as well as the southern periphery of the ACC. We also note the discrepancy between the spots of increased values of the shares of variance, falling on the linear trend, and the zones of increased RMSD (cf. Figures 5 and 6). The curves of shares, calculated for the entire sector by different methods, are similar, but can differ significantly quantitatively (Figures 6b, d, e, h, k, m). The maximum estimates of the share can reach 30 % in the case of calculation without division into bands.

Zonal distributions of the RMSD of the series of the meridional shift of the jet structure and the change in the intensity of currents depending on the median values of the ADT, as in the case of calculations relative to the latitude, are characterized by a decrease in the values of the RMSD with an increase in the scale of calculation (Figure 7). On small scales in the distributions of the RMSD of both parameters (Figures 7a, c), the increased values of the RMSD form several spots in the western and eastern parts of the studied sector in the central and northern bands of the ACC zone. Towards the southern periphery, the values of the RMSD decrease. The same tendency is observed towards the northern periphery of the ACC in the distributions of the RMSD of the shift over the entire sector and the RMSD of the change in the intensity of the current in the eastern half of the sector. On medium scales of calculation (Figures 7e, g), out of several spots of increased values of the RMSD, two remain in each of the distributions. In the distribution of the shift RMSD they are displaced to the average range of the ADT inside the ACC band, and in the distribution of the intensity change RMSD they are displaced to the ACC peripheries, to the north in the west and to the south in the east. As a result, on small and medium scales in the shift series RMSD calculated for the entire sector as a whole without and with division into bands, a zone of increased shift RMSD values is observed inside the ACC band (Figures 7b, e), and the RMSD of the series of the current intensity changes increases to the northern periphery of the ACC (Figures 7d, h). On large scales of calculations, the zone of maxima in the zonal distributions of the RMSD of both parameters disappears.

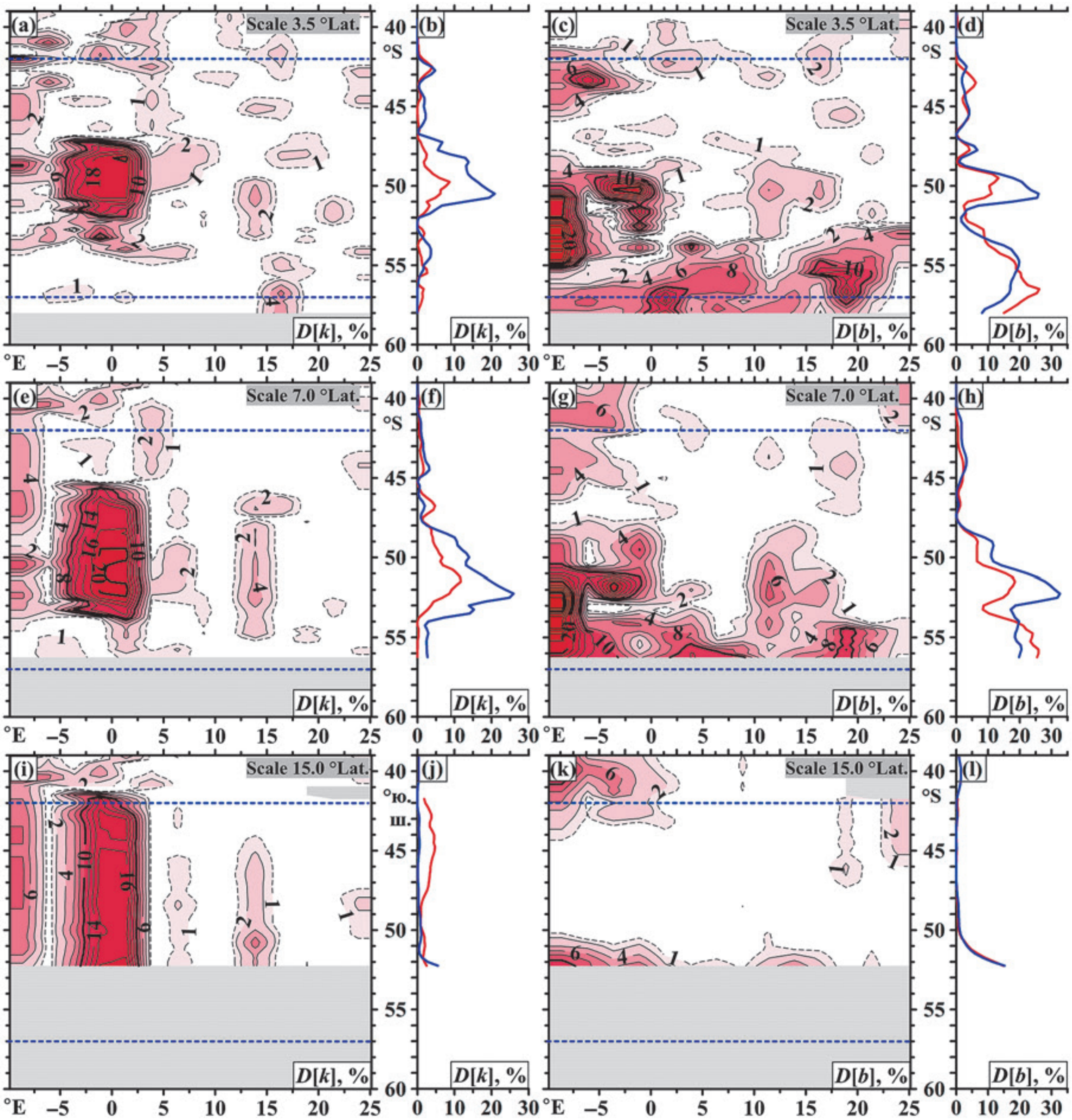

Fig. 6 – Distributions of the share of oscillation variance (%) caused by the long-term linear trend in the series of the meridional shift of the jet structure and the change in the current intensity for the ACC sector south of Africa for different calculation scales depending on the median latitude: (**a**), (**d**), (**i**) – zonal distributions for the shift; (**b**), (**e**), (**j**) – curves of the share calculated for the entire sector as a whole with division into meridional bands (red curves) and without division (blue curves); (**c**), (**g**), (**k**) – zonal distributions for the change in the current intensity; (**d**), (**h**), (**l**) – curves of the share calculated for the entire sector as a whole with and without division into meridional bands. The rest is as in Figure 4

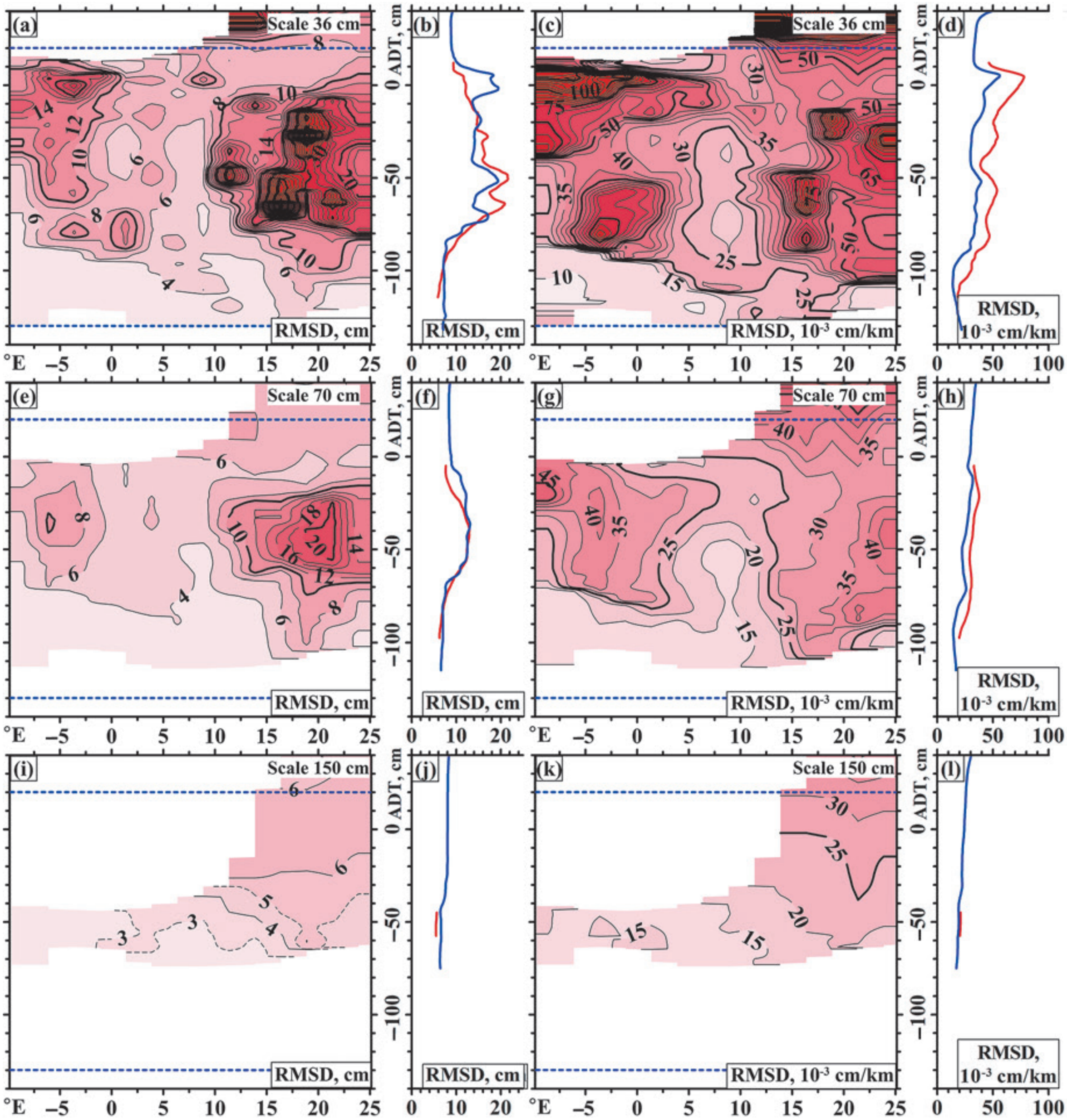

Fig. 7 – Distributions of the RMSD of the meridional shift of the jet structure (cm) and the change in the current intensity (10^{-3} cm/km) for the ACC sector south of Africa for different calculation scales depending on the median values of the ADT: (**a**), (**d**), (**i**) – zonal distributions of shift; (**b**), (**e**), (**j**) – curves of the shift calculated for the entire sector as a whole with division into meridional bands (red curves) and without division (blue curves); (**c**), (**g**), (**k**) – zonal distributions of the change in the current intensity; (**g**), (**h**), (**l**) – curves of the change in the current intensity calculated for the entire sector as a whole with and without division into meridional bands. The rest is as in Figure 3

In calculations relative to the ADT scale, as in the case of calculations relative to latitude, the zonal distributions of the share of the total variance of oscillations accounted for by the long-term linear trend in the series of the shift of the jet structure and changes in the intensity of currents (Figure 8) correspond very well to the spots of increased values of this trend (Figure 8 in (Tarakanov, 2024)). Likewise, there is no tendency for the share values to decrease or increase when the calculation scale changes, and there is a discrepancy between the spots of increased shares and the zones of increased values of the RMSD (cf. Figures 7 and 8). The share values are less than in the calculation relative to latitude and do not exceed 15 % anywhere. In contrast to the calculation relative to latitude, the share curves calculated for the entire sector in different ways can be both similar and significantly different from each other in shape (Figures 8b, d, f, h, k, m).

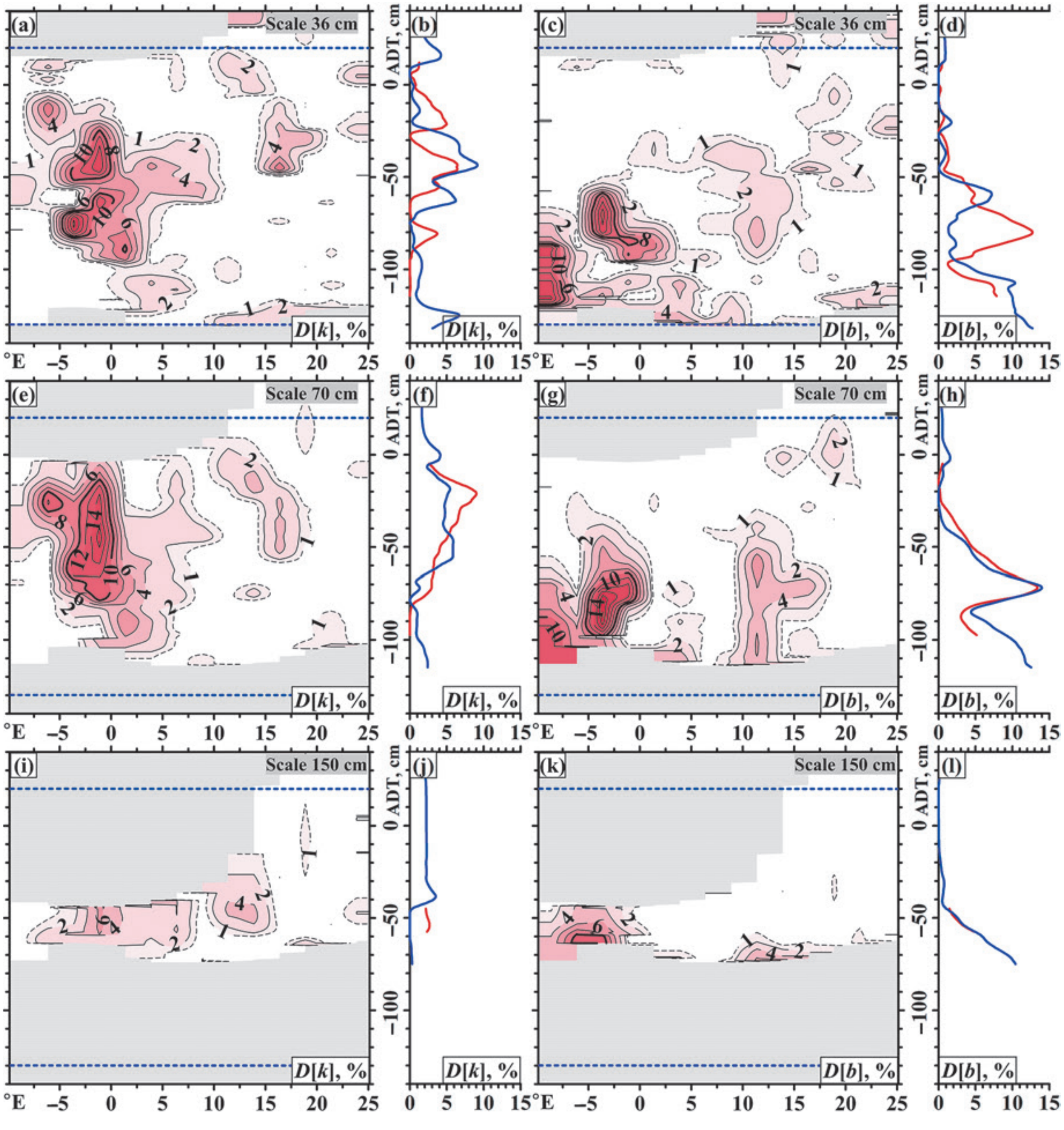

Fig. 8 – Distributions of the share of oscillation variance (%) caused by the long-term linear trend in the series of the meridional shift of the jet structure and the change in the current intensity for the ACC sector south of Africa for different calculation scales depending on the median values of the ADT: (**a**), (**d**), (**i**) – zonal distributions for the shift; (**b**), (**e**), (**j**) – curves of the share calculated for the entire sector as a whole with division into meridional bands (red curves) and without division (blue curves); (**c**), (**g**), (**k**) – zonal distributions for the change in the current intensity; (**d**), (**h**), (**l**) – curves of the share calculated for the entire sector as a whole with and without division into meridional bands. The rest is as in Figure 4

The main conclusion that follows from examining Figures 5 Figures 8 is that in the zonal distributions of the values of the share of variance attributable to the long-term linear trend and the RMSD of the series of the parameters under consideration, there is a discrepancy between the spots of their increased values, i.e. the increased values of the linear trend are in no way caused by the overall high amplitude of oscillations of the corresponding series, and vice versa.

6. Estimation of the share of long-term oscillations

Figure 9 shows the increasing (from low to high frequencies) shares of variance of oscillations in the shift series and the change in the current intensity in the variants with respect to latitude (scale 3.5° latitude) and the ADT scale (scale 36 cm). The high-frequency "tail"

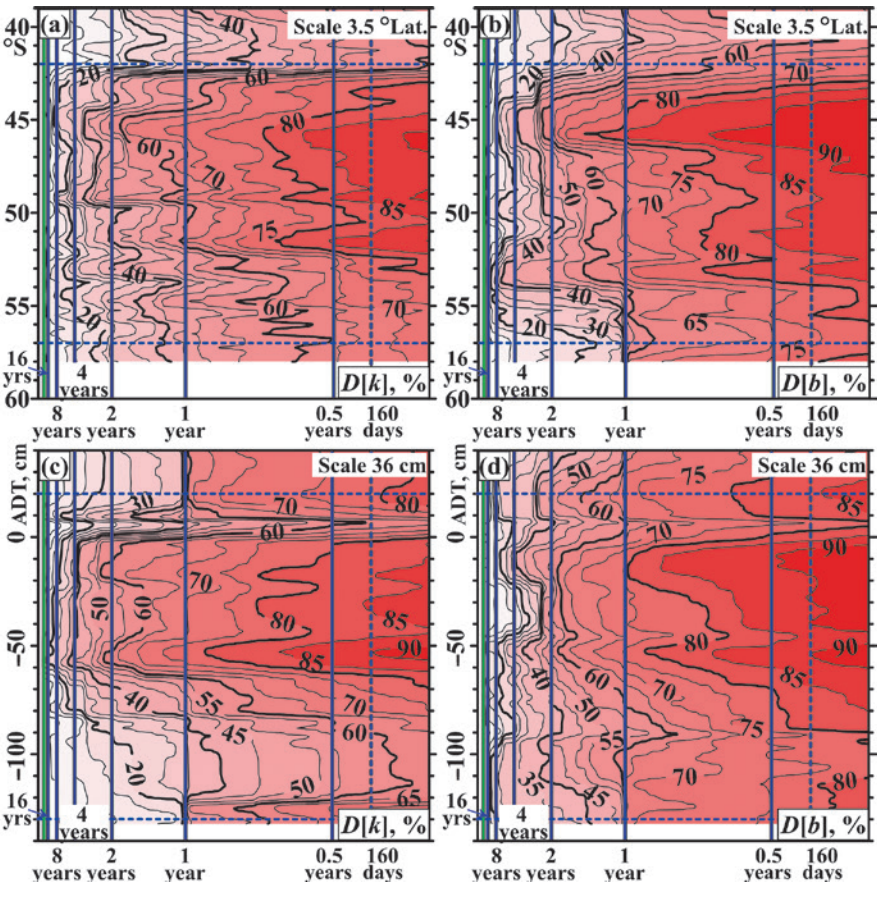

Fig. 9 – Cumulative share (%) of oscillation variance depending on wave numbers and median latitude or median ADT values, constructed as a cumulative total (from low to high frequencies) for series calculated for the entire sector without dividing into bands: (**a**) – shift of the jet structure of currents relative to latitude on the calculation scale of 3.5° latitude; (**b**) – same as (**a**), but for change of the current intensity; (**c**) – shift of the jet structure of currents relative to the ADT scale on the calculation scale of 36 cm; (**d**) – same as (**c**), but for change of the current intensity. Green vertical line corresponds to the full length of the series of 9490 days; purple solid lines – periods of 0.5, 1, 2, 4, 8, 16 years; purple dotted line – period of 160 days, for which the distributions in Figure 10 were calculated

of the distribution of the cumulative share of variance is not shown in Figure 9. The series are calculated as a whole for the entire sector without dividing into meridional bands. The linear trend was preliminarily subtracted from each series, i.e. these series were additionally processed in comparison with the procedure described in Section 3 of this paper. Thus, the share of variance per zero wave number is zero in all series. Figure 10 shows the zonal distribution of the cumulative share of variance in the shift series and the change in the current intensity, accumulated from low frequencies to a period of 160 days, depending on the median latitude and ADT values for the above-mentioned scale values. The specified period is taken as a conventional boundary between long- and short-term oscillations. The long-term linear trend was also preliminarily subtracted from these series. Note that the qualitative pattern of oscillation distributions by frequency ranges on other scales is similar and we do not provide figures for them.

Figure 9 shows that the share of long-term oscillations in the series of both parameters is higher in the northern and central parts of the ACC zone. Towards the southern periphery of the ACC, the share of such oscillations decreases, while on the northern periphery, they decrease sharply. The zonal distributions of the cumulative share of variance over a 160-day

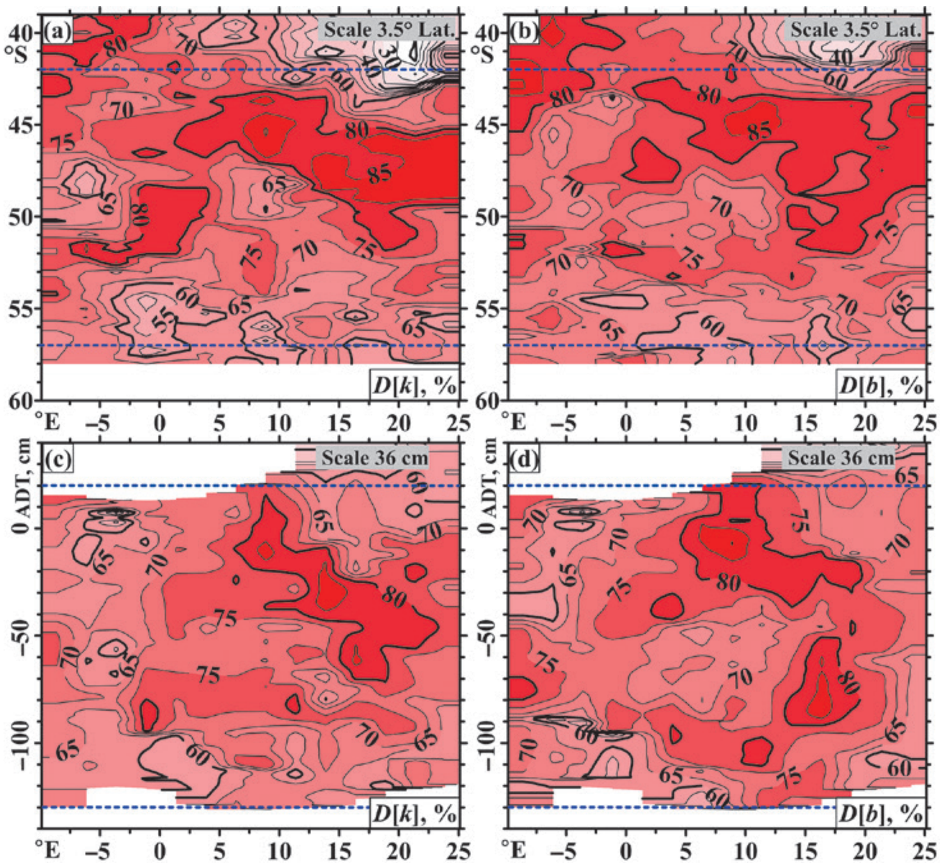

Fig. 10 – Zonal distributions of the cumulative share of the variance of the jet structure shift series and the change in the current intensity, accumulated from low frequencies to a period of 160 days: (**a**) and (**b**) – shift and change in the current intensity, respectively, depending on the median latitude for a calculation scale of 3.5° latitude; (**c**) and (**d**) – the same, but depending on the median values of the ADT for a calculation scale of 36 cm

period (Figure 10) generally demonstrate the same features. The only exception is the zone of junction of the northern periphery of the ACC with the AC and SAtC zones, where there is obvious zonal heterogeneity of distributions in the calculations with respect to latitude (Figures 10a, b). In this case, in the SAtC zone (the western part of the sector), long-term oscillations remain predominant (75–80 % share). In the AC zone (the eastern part of the sector), short-period oscillations obviously prevail both in the shift of the jet structure and in the change in the intensity of the current. The cumulative share of variance accumulated from the low-frequency side locally decreases here to 20 %. Everywhere, except for the junction zone of the AC and ACC, there is a positive correlation between the distributions of the cumulative share of variance in the calculations relative to latitude (Figures 10a, b) and the corresponding RMSDs (Figures 5a, c). The central and northern parts of the ACC zone are areas of mainly increased values of these parameters, while the southern periphery of the ACC is of decreased values. To a lesser extent, the same correlation is expressed in the calculations relative to the ADT scale, especially for the series of changes in the current intensity (compare Figure 7a, c and Figure 10c, d). Note that the characteristic values of the share of long-term oscillations in the ACC band are 60–90 % both in the calculations relative to latitude and relative to the ADT scale.

7. Conclusions

In present paper, within the framework of the task of studying the oscillations of the meridional shift of the jet structure and changes in the intensity of currents in the ACC zone south of Africa using the ADT data published on the website http://marine.copernicus.eu, a procedure is described for calculating time series of the specified parameters with a ten-day discreteness, which approximately corresponds to the full period of flight of all the main tracks by satellites with an altimeter. The procedure is based on linear regression analysis. The series are calculated both for the entire sector as a whole and for individual meridional bands for different calculation scales and median latitudes and ADT values. Then, the average series for the set of meridional bands are also calculated. Based on the data processed in this way, it is shown that:

1. The series constructed for the entire sector as a whole in the variants without division into meridional bands and with division and subsequent averaging over a set of bands can either differ significantly or be almost identical to each other. In particular, the series of the current intensity change are very close to each other, both in calculations relative to latitude and relative to the ADT scale, which should be reflected in the similarity of their spectra. This result allows us to reduce the spectral analysis of series of changes in current intensity, constructed with and without division into bands, to the analysis of only one of the series. At the same time, the shift series calculated in two different versions may differ significantly from each other, especially in the case of calculation relative to latitude. This conclusion means that spectral analysis of shift series constructed in two different ways should be carried out separately from each other.

2. In the zonal distributions of the values of the share of variance attributable to the long-term linear trend and the RMSD of the series of the parameters under consideration, there is a discrepancy between the spots of their increased values, i.e. the increased values of the linear trend are in no way due to the overall high amplitude of oscillations of the corresponding series, and vice versa.

3. In the zonal distributions of the RMSD and the share of long-term oscillations in calculations relative to latitude, there is a positive correlation. The central and northern parts of the ACC zone are areas of mainly increased values of these parameters, while the southern periphery of the ACC is spots of decreased values. To a lesser extent, the same correlation is expressed in calculations relative to the ADT scale.

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КОЛЕБАНИЯ СТРУЙНОЙ СТРУКТУРЫ АНТАРКТИЧЕСКОГО ЦИРКУМПОЛЯРНОГО ТЕЧЕНИЯ К ЮГУ ОТ АФРИКИ ПО ДАННЫМ СПУТНИКОВОЙ АЛЬТИМЕТРИИ: РАСЧЕТ ВРЕМЕННЫХ РЯДОВ И СРЕДНИЕ ХАРАКТЕРИСТИКИ

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В рамках задачи изучения колебаний меридионального сдвига струйной структуры и изменения интенсивности течений в зоне Антарктического циркумполярного течения к югу от Африки (9.875° з. д. – 25.125° в. д.) по данным абсолютной динамической топографии (АДТ), публикуемым на сайте: http://marine.copernicus.eu, описана процедура расчета временных рядов указанных параметров течений с десятидневной дискретностью. При этом под струйной структурой понимается чередование в меридиональном направлении зон повышенных и пониженных значений модуля градиента АДТ, $|\nabla\zeta|$. Для периода спутниковых альтиметрических наблюдений 1993–2018 гг. выполнено сравнение рядов, рассчитанных для всего сектора к югу от Африки целиком без разделения на узкие меридиональные полосы и с разделением и последующим осреднением по набору этих полос. Показано, что эти ряды, построенные двумя разными способами, могут как существенно отличаться, так и быть практически идентичными друг другу. Кроме того, выполнен расчет зональных распределений некоторых характеристик рядов, существенных для проведения спектрального анализа: среднеквадратичных отклонений, доли долговременного линейного тренда и доли долговременных колебаний в полной дисперсии рядов.

Ключевые слова: динамическая топография, спутниковая альтиметрия, струи, Антарктическое циркумполярное течение, долговременные колебания

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