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REVIEW

Historical findings of the Russian physical oceanographers in the Indian Ocean

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Abstract

This is a review paper related to three findings of Russian physical oceanographers in the Indian Ocean. Observations in the Indian Ocean were used to investigate mesoscale eddies, subsurface equatorial undercurrent, and internal tidal waves near the Mascarene Ridge. Two surveys with measurements of temperature and salinity profiles in the Arabian Sea in 1967 made possible mapping of mesoscale eddies. Repeated moored measurements of currents in the equatorial zone between 55°E and 85°E revealed the existence of seasonal subsurface easterly Tareev undercurrent. A moored array of current and temperature recorders near the Mascarene Ridge was deployed as an antenna for internal tides. The displacements of isotherms caused by internal tides were as large as 150 m. The wave propagated to the southeast from the ridge. The review is intended to summarize the phenomena of the ocean dynamics of the Indian Ocean now when the scientific community of oceanography celebrates the 50th anniversary of the Indian Ocean expedition and plans the second Indian Ocean expedition.

Background

The Indian Ocean differs from the Atlantic and Pacific Oceans not only in the fact that it does not have primary gyres north and south of the equator, but also the monsoons play a more prominent role in the atmospheric forcing. Consequently, the ocean circulation in the northern part of the Indian Ocean fluctuates on an annual basis. From the geomorphological viewpoint, the Indian Ocean is limited from the north by the Asia continent, which causes a monsoon type of the atmospheric circulation in the equatorial and tropical regions of the ocean. The latitudinal asymmetry of physical fields and their quasi-cyclic seasonal reconstruction are observed only in the northern part of the Indian Ocean. No similar phenomena exist in the other oceans.

In the 1960–1980s, Russian oceanographers carried out field research in the Indian Ocean. Most of the results presented here have been published in the Russian literature but are unknown to many international readers. The paper briefly describes instrumental observations and mapping of mesoscale eddies of the open ocean in the Arabian Sea in 1967; moored measurements of the subsurface equatorial undercurrent, and internal tides near the Mascarene Ridge. Russian oceanographers investigated these processes in the cruises in the second half of the 20-th century. They are part of our knowledge of the ocean dynamics of the Indian Ocean. We believe that our summary would be interesting to the readers now when the scientific oceanographic community celebrates the 50th Anniversary of the International Indian Ocean expedition (IIOE) in 1960–1965, in which 46 research vessels from 14 countries were involved, and plans a new international expedition.

The Polygon-67 experiment: the first mapping of mesoscale eddies of the open ocean

By the 1950s, the eddies of the oceanic synoptic scales (mesoscale rings with a horizontal scale of ~200 km) generated after the separation of meanders from the Gulf Stream and Kuroshio were well known (Iselin and Fuglister 1948). These eddies spread almost to the bottom (Kamenkovich et al. 1986). However, the existence of similar oceanic eddies in the Indian Ocean, and the question whether such eddies are typical for the ocean as a whole remained open. In 1959 and 1960, John Swallow the British oceanographer measured the currents in the Sargasso Sea at the depths of 2000 and 4000 m using

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neutral buoyancy floats that he constructed. He found strong nonstationary currents with characteristic scales of 20 days and 100 km. However, at that time, the paucity and spare nature of measurements made them insufficient to reveal the real physical nature of these currents (Swallow 1971).

Shtockman initiated an expedition to search for the mesoscale (synoptic) eddies in the open ocean in the southern part of the Arabian Sea (Polygon-67) (Shtockman et al. 1969). During this expedition, the R/V "Faddey Bellingshausen" carried out two hydrographic surveys of the region limited by longitudes 63°00′E and 66°30′E and latitudes 10°N and 15°N (Figs. 1, 2). The first survey was carried out from January 21 to February 7, 1967, during the period of the winter monsoon and the second from March 20 to April 6, 1967, in the transition period to the summer monsoon. The distance between stations in both surveys was 30 nautical miles (Fig. 2). The measurements using reversing thermometers and Nansen bottles were performed at 19 levels down to 1500 m. In addition to the deep reversing thermometers, unprotected reversing thermometers were applied at five levels to determine the depth of sampling. Water salinity was converted from chlorinity using titration.

The measurements of water density at standard oceanographic levels of the two surveys were subjected to isotropic smoothing over a horizontal plane that filtered out the perturbations of the density field with the wavelengths less than 110 km to remove the traces of internal waves, small eddies, other motions of this scale, and random errors of measurements. The smoothed density fields were used to calculate geostrophic currents based on the dynamic method relative to the 1500 m surface of zero currents. This approach was widely used at that time. However, the assumption that currents at 1500 m are zero leads to uncertainty that can be as high as a few cm/s depending on the real magnitude of currents at 1500 m. Figure 2 shows the resulting currents at a depth of 150 m based on the data of the first and second surveys. The contour lines of dynamic heights, and hence, the patterns of currents at the other depths for each of the surveys were similar to the structure at 150 m, however, the magnitude of the velocities monotonously decreased with depth. The time interval between the two surveys of the Polygon-67 experiment was equal to 2 months. According to the estimates of the velocity of eddy displacement (Kamenkovich et al. 1986), this time period is too long to determine whether the eddies in Fig. 2a are the same as in Fig. 2b. However, high degree of non-stationarity of the velocity fields is clearly seen.

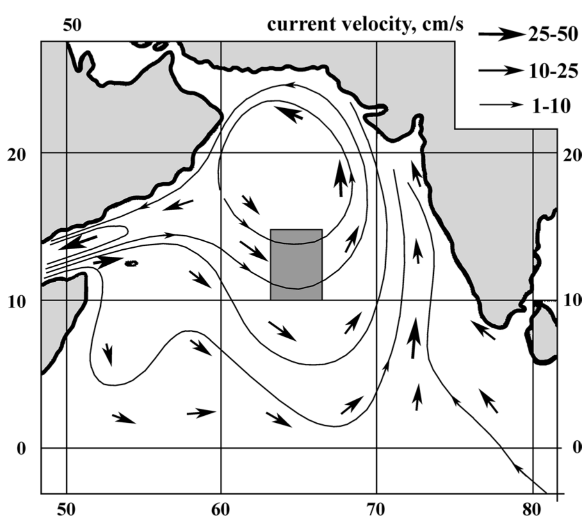

Fig. 1 Mean geostrophic currents at 10 m in the Arabian Sea during the period of the winter monsoon (Neiman 1970). The region of hydrographic surveys and moorings of the Polygon-67 expeditions is shown in *gray color*

According to modern concepts, baroclinic instability of large-scale currents is the primary cause of the formation of mesoscale eddies in the ocean (Kamenkovich et al. 1986). The eddies gain energy from the available potential energy of the large-scale currents related to the inclination of the isopycnal surfaces in the direction normal to the current. The theoretical characteristic horizontal scale of the eddies (the dominating wavelength of the field of eddy perturbations divided by 2π) is of the order of the Rossby scale.

$$L_R = \sqrt{\frac{gh\Delta\rho}{\rho_0}}/f$$

where g is the acceleration due to gravity; f is the Coriolis parameter; ρ_0 is the mean density of oceanic water; $\Delta\rho$ is the density difference across the main thermocline; and h is the depth of the middle part of the thermocline. In the region of the Polygon-67, $f = 3.14\ 10^{-5}\ s^{-1}$, $h = 200$ m, $\Delta\rho = 3.7\ kg/m^3$, which gives $L_R = 87$ km.

Unlike the solitary Gulf Stream or Kuroshio rings, mesoscale eddy perturbations in the open ocean are characterized by the fact that two neighboring eddies of different sign have a common region of maximum velocities (Fig. 2). In such a situation, we naturally assume that double diameter of the eddy or fourfold distance from the eddy center to the radius of maximum velocity is the dominating wavelength of the eddy field. According to Fig. 2, this distance is approximately equal to 130 km in the region of the Polygon-67 experiment, which results in the eddy scale $Le = (130\ km\ 4/2\pi) = 83$ km. We see a good coincidence between the theoretically predicted and observed scales of the eddy field.

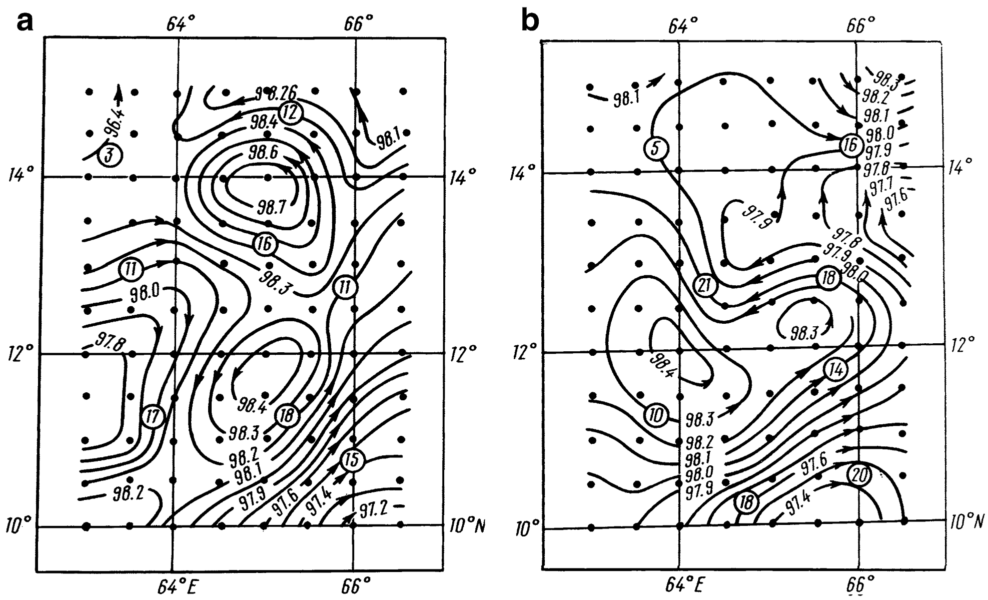

Fig. 2 Dynamic heights and geostrophic currents at a depth of 150 m based on the data of the first (January 21–February 7, 1967) (**a**) and second (March 20–April 6, 1967) **b** hydrographic surveys of the Polygon-67 expedition (Koshyakov et al. 1970). The numerals at the isobars are proportional to the weights of the water columns between 150 and 1500 m. The *dots* indicate the locations of the hydrographic stations with the measurements using the reversing thermometers and Nansen bottles. The *arrows* show the direction of the currents while the numerals in the *circles* denote the velocities in cm/s. We estimated uncertainties of the geostrophic velocities from the calculations as ±2 cm/s

The Tareev equatorial subsurface countercurrent in the Indian Ocean

In the winter of 1960, on cruise 31 of the R/V "Vityaz" organized by the Shirshov Institute of Oceanology within the International Indian Ocean Expedition, the Equatorial Subsurface Countercurrent was found at the equator. A similar current was previously found in the Pacific Ocean during the oceanographic works on the US R/V "Crawford" in 1952. It was named the Cromwell Current after the Chief Scientist of this oceanographic expedition T. Cromwell (Montgomery 1962). The Academy of Sciences of the USSR decided in 1974 to give the equatorial undercurrent in the Indian Ocean the name of the Russian oceanographer Boris Tareev (1931–1972).

The analysis of the equatorial subsurface countercurrents and their role in the circulation in the ocean is given in the books (Khanaichenko 1974; Kort 1977; Bubnov 1990; Kuznetsov and Neiman 2005; Neiman et al. 1997) and in many papers (Neiman 2013). Such distinguishing properties of the equatorial countercurrents as multiannual stability of mean parameters, large spatial scale (extension over a few thousand kilometers), and equatorial location allow us to relate these currents to the key elements of the general circulation.

The main characteristic property of the equatorial countercurrents in the three oceans is the following. The core of this eastward current is located within the equatorial band of latitudes approximately between 2°N and 2°S (Neiman et al. 1997). The current has quasi-cyclic fluctuations of the location of its core with a wavelength of approximately 1000 km and a period close to 7 days. This was theoretically (Monin 1972) and experimentally (Burkov and Monin 1974) confirmed.

A scheme of the distribution of the zonal velocity component based on the historical instrumental measurements of this current on cruise 31 of the R/V "Vityaz" (Ovchinnikov 1961) is shown in Fig. 3. The Tareev current with its core located exactly at the equator is clearly seen. The maximum velocity of 40 cm/s occurred at a depth of 140 m.

In the winter of 1960 and 1961 during cruise 31 of the R/V "Vityaz", the current measurements were carried out in the equatorial region of the Indian Ocean using moorings that were deployed for one day at five locations between 52°E and 91°E (Fomichev 1964). The monsoon change occurred in this year earlier than the usual climatic time; therefore, characteristic features of the spring circulation with eastward transport at the equator appeared in the zonal structure of wind velocity (Wyrtki 1973). The westward current was present in the surface layer. An eastward current beneath it, was found only at one station located at 92°E. On the basis of these facts, it was concluded in (Ivanov 1964) that the equatorial subsurface undercurrent exists only when the eastern wind appears at the equator.

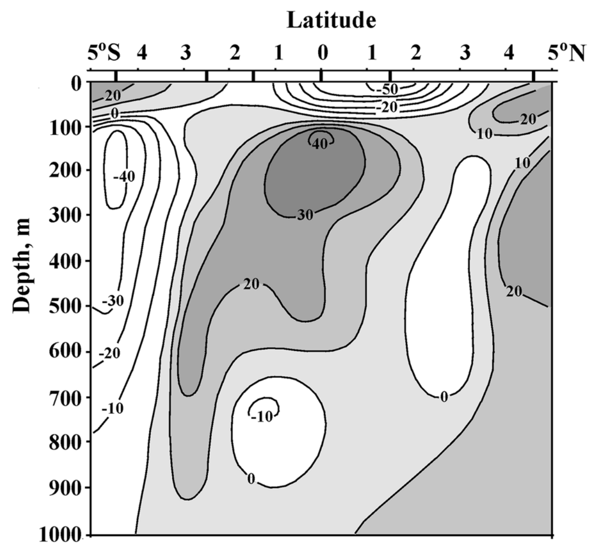

Fig. 3 Zonal component of velocity of the equatorial currents (cm/s) based on the data of cruise 31 of the R/V "Vityaz" in the winter of 1960 over the section along 68°E. The eastward currents are shown in *gray tone*

The American expedition LUSIAD was specially organized to study the equatorial subsurface countercurrent in 1962 and 1963 on the R/V "Argo" and "Horizon". The observations were carried out from the drifting ships over four meridional lines crossing the equator from 5°N to 5°S between 53°E and 93°E (Knauss and Taft 1964; Taft and Knauss 1967). These observations were supplemented by the data of the British expedition on the R/V "Discovery" operating in March–June 1964 in the western part of the Indian Ocean. The results of both expeditions showed that the Tareev current recently found by "Vityaz" exists at the equator at least in the boreal spring. However, time scales of velocity fluctuations were not determined because the measurements were very short.

In 1972, two USSR oceanographic ships "Dmitry Mendeleev" and "Akademik Vernadsky" carried out instrumental measurements in the equatorial region of the Indian Ocean (Krivosheya et al. 1977). The observations were made at four equatorial sites. The centers of these mooring clusters were located at 56°E, 61°E, 76°E, and 85°E meridians. Four to six moorings were deployed a few miles apart in each of the sites with 10–12 current meters in the depth range from the surface to 1000 m. The duration of continuous moored measurements of current velocities was only 3 days, which is extremely short. Such short time series are influenced by various short time phenomena. However, this experiment gave a spatial snapshot of the equatorial currents in the Indian Ocean.

Diagrams of the data of moored current measurements in 1972 at the equator along the 85°E averaged over 3 days are shown in Fig. 4. The general conclusions of the equatorial circulation in the winter season are as follows. A quasi-zonal westward winter Monsoon Current with the mean velocity in its core reaching 50 cm/s exists in a thin surface layer near the equator during the period of the northeastern monsoon winds from November to February. We note that during one of the days of the expedition at 61°E, a velocity of 134 cm/s was recorded in the surface current after the eastern wind intensified.

A subsurface eastward countercurrent is clearly seen in Fig. 4 under the forcing of the westward Winter Monsoon Current at all moorings. In the eastern part of the ocean several miles off the equator, the core of the Tareev current with a zonal velocity component of 25–35 cm/s was located at a depth of 300 m.

The most detailed data of all expeditions were obtained in cruise 55 of the R/V "Vityaz" in 1974 during the winter monsoon (Kort et al. 1975). In this expedition, the measurements were carried out over four meridional sections

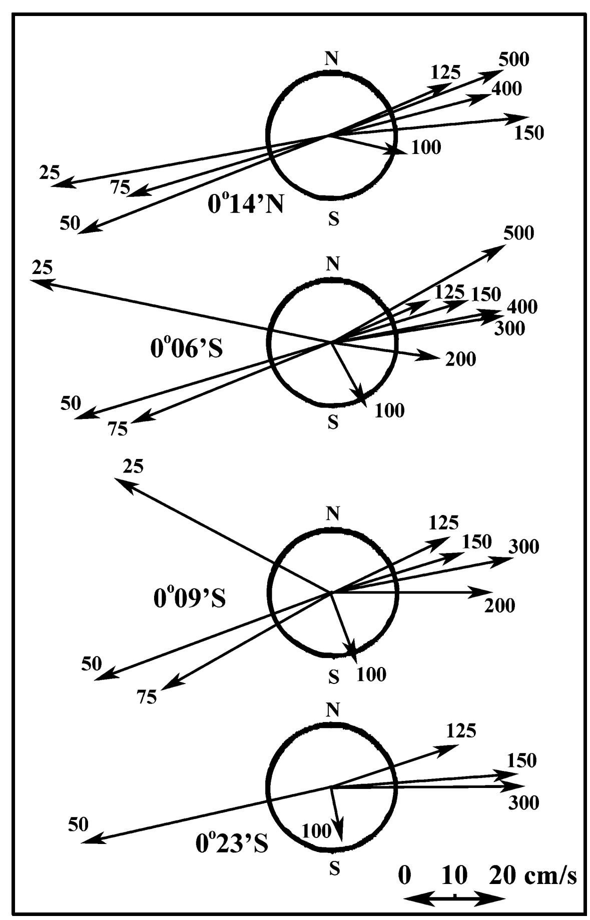

Fig. 4 *Vector diagrams* of the mean velocity near the equator at 85°E in the winter of 1972 based on the data of cruise 5 of the R/V "Akademik Vernadsky". The numerals near the vectors indicate the depths of measurements in meters

across the equator at 55°E, 65°E, 75°E, and 85°E between 3°N and 3°S. Ten moorings with current meters at ten depths from the surface down to the bottom were operating over each of the sections during 10 days.

A section of the zonal velocity component in the central part of the ocean is shown in Fig. 5. It is seen from the figure that the Tareev current is a separate jet, the maximum velocity of which is approximately 60 cm/s. It is distinguished over the background of the general eastern flow with a velocity within 10–20 cm/s.

Numerous field measurements demonstrated that the Tareev undercurrent in the Indian Ocean has several specific features unlike the countercurrents in the other oceans (Neiman et al. 1997). The main difference from the other equatorial countercurrents is that it has clearly pronounced seasonal monsoon variability. In the summer monsoon period, the surface Monsoon Current at the equator is directed to the east under the dominating southwestern monsoon wind forcing. In this period, the Tareev current loses its distinguishing feature (a subsurface flow opposing the surface current) and remains in the structure of the general eastward flow in the form of a subsurface core of increased velocities (Krivosheya et al. 1977). The field observations indicated that this occurs both during the seasonal variations in the surface wind and during comparatively short-period perturbations of the zonal component of wind velocity (Ivanov 1964). In the other words, as soon as the western wind that generates the eastward drift flow in the upper ocean begins to dominate at the equator, the classical two-layered vertical structure of the equatorial circulation with a subsurface countercurrent transforms to a simpler scheme of general eastward flow. There is no similar phenomenon in the Atlantic and Pacific because the westward Southern Equatorial Currents exist in these oceans at the equator throughout the entire year. In the boreal summer season, the Tareev current merges together with the eastward flow in upper layer and loses its attribute as a countercurrent.

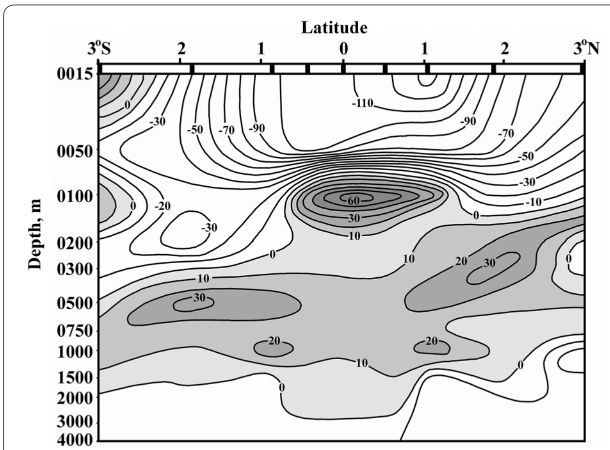

Fig. 5 Zonal component of velocity (cm/s) over the section along 64°30′E based on the data of cruise 55 of the R/V "Vityaz" in the winter of 1974. The eastward currents are shown in *gray tone*

The second specific feature of the equatorial countercurrent in the Indian Ocean is the deepening of its core from 100 m in the western part of the ocean to 300 m in the east. This is caused by the unique latitudinal inhomogeneity of the density field in the equatorial region of the Indian Ocean, which manifests itself in the zonal slope of isopycnals (Bubnov 1990). An opposite structure is observed in the other oceans: the cores of the Lomonosov and Cromwell currents ascend or even outcrop to the surface following the corresponding slope of the isopycnal surfaces.

Large internal tides at the Mascarene ridge

The Mascarene ridge is one of the regions of the largest isotherm displacement by internal tides in the open ocean (Morozov 2006). The array of moorings for the investigation of internal tides in March 1987 was planned on the R/V "Vityaz" assuming that internal tide is generated as a result of the interaction between the barotropic tidal currents with the Mascarene Ridge. After the generation, the internal wave propagates into the ocean at both sides of the ridge occupying the entire water column (Garrett and Kunze 2007). While planning the mooring array, we considered that the barotropic tide flow is generally concentrated in the underwater passage between the Saya de Malha and Nazareth banks (Morozov and Fomin 1989). The maximum velocities of the tide and most intense internal waves should be generated in this passage because the slopes of the ridge coincide with the slope of internal wave characteristics. A mooring array of six moorings was extended in the direction to the southeast from the strait between the two banks. A scheme of the experiment is shown in Fig. 6. The POTOK current and velocity meters manufactured at the Shirshov Institute were used on the moorings at depths of 100, 200, 500, 1000, 1200, 1800, and 2500 m. Strong generation was confirmed in the experiment. No strong currents were observed over the bank with a depth of 40–50 m.

The theoretical wavelength of the first mode of internal tidal wave was determined by numerical integration of the equation for the vertical velocities of internal waves with the realistic stratification and zero boundary conditions for vertical velocities at the surface and bottom. It appeared equal to 125 km, while the phase velocity was 2.8 m/s.

Vertical displacements caused by internal tides were calculated from the temperature time series (Fig. 7). The semidiurnal internal tidal fluctuations on two moorings are

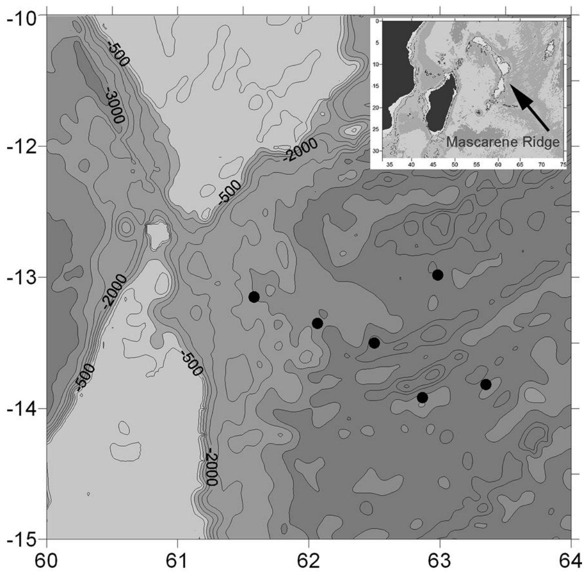

Fig. 6 *Bottom* topography (meters) and schematic location of moorings near the Mascarene Ridge (*black dots*), March 1987. A general *chart* is shown in the *inset*

clearly distinguishable. Their mean amplitude at a depth of 1200 m is 0.2 °C. Vertical displacements of isotherms were calculated from the measured vertical temperature gradient. They were equal to 120 m and correspondingly the amplitudes of the displacement from the mean position were 60 m. The maximum displacements exceed 150 m, while the minimum ones were approximately 65 m.

The amplitude variations are related to the moon phases. Internal tidal amplitudes are linked to the spring-neap cycle with a delay for propagation from the generation site to the mooring locations. This delay is approximately 3 days longer for the easternmost mooring than the western mooring, located ~200 km closer to the generation site near the ridge. Nonlinear interactions also contribute to the amplitude variations in time and space.

The spectral densities are characterized by a highly reliable peak at the semidiurnal frequency. A decrease in the energy of semidiurnal oscillations was found over the horizontal scales of the study region. Internal waves generated near the Mascarene ridge propagate over 2000 km, where their amplitude is reduced to the background level (Lozovatsky et al. 2003).

The eigenfunction for the oscillations of the first mode shown in Fig. 8 was calculated by numerical integration of the equation for the vertical velocity of internal waves with realistic stratification. The amplitudes of internal waves based on the spectral analysis of time series measured at different depths on the eastern mooring are also shown, which corresponds to the theoretical calculation assuming that the first mode dominates.

It is worth noting that the mode structure was formed at a close distance to the ridge (approximately at a distance of one wavelength). We have to consider that the ridge is a nonideal linear source because the ridge crest is not a straight line. Many beams of internal waves with random phases and amplitudes are generated near the ridge. Therefore, random phase shifts in the beams arriving from different points of the ridge crest facilitate faster compensation of vertical wave numbers and formation of the mode structure. High vertical coherence between the time series confirms the fact that the fluctuations were well developed over the vertical direction and that the mode structure was formed.

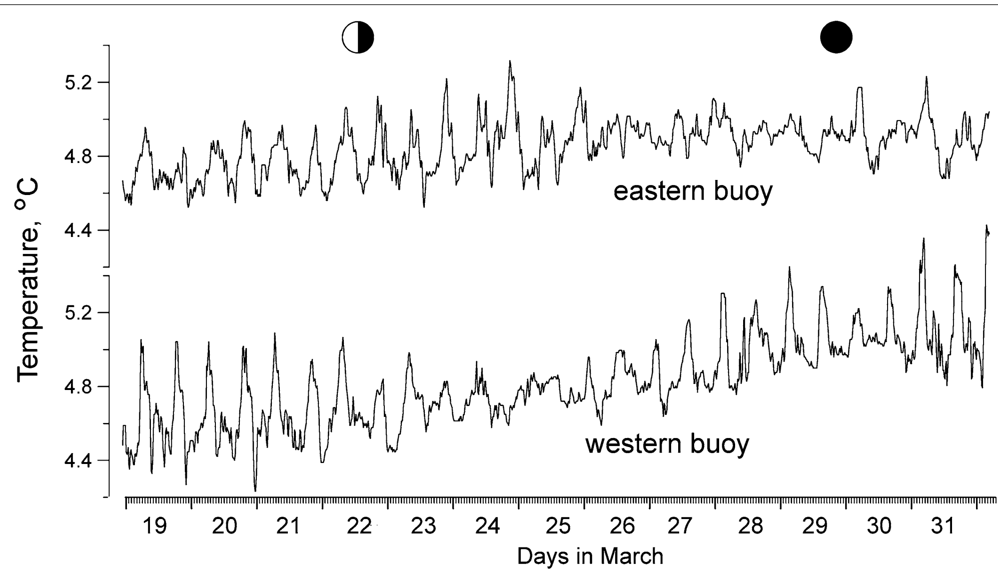

Fig. 7 Time series on the eastern and western moorings at a depth of 1200 m. Moon phases are shown in the figure

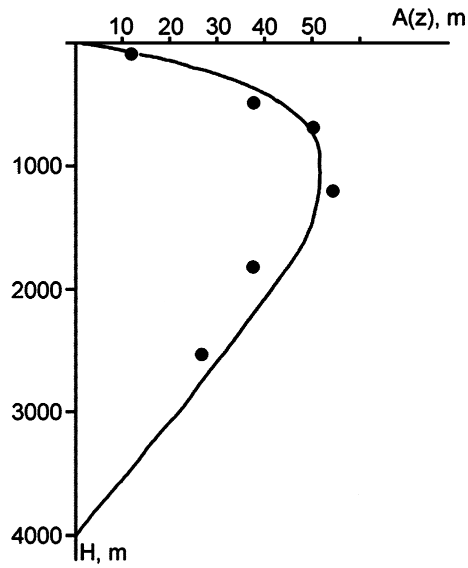

Fig. 8 Amplitudes of semidiurnal internal waves near the Mascarene Ridge. The curve corresponds to the calculation of the eigenfunction for the amplitude of internal waves; the *circles* show measurements at the easternmost mooring

High values of the horizontal coherence exceeding the 95 % confidence level were observed between different pairs of time series. Two-dimensional spatiotemporal spectra at the semidiurnal tidal frequency were calculated at different depths following (Barber 1963). An example of 2D spatiotemporal spectrum calculated from the data at 1200 m is shown in Fig. 9. The spectra at other levels are similar. The wavelength of internal tide is 140–150 km, and its direction is 110° from the strait between the banks.

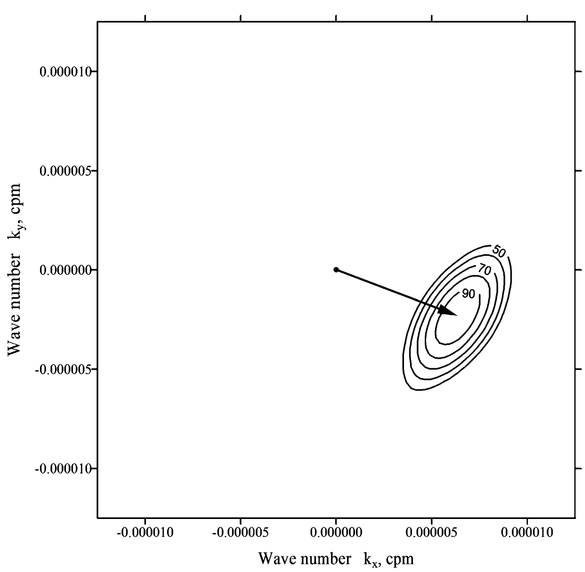

Fig. 9 Example of spatiotemporal spectrum calculated from the data at 1200 m. The spectrum isolines are shown as percentage of the maximum. The *arrow* shows the wavenumber vector

Conclusions

In this paper, we reviewed historical studies of mesoscale eddies, equatorial subsurface countercurrent, and internal tides in the Indian Ocean carried out by the Russian oceanographers in 1960–1980s. Following the previous oceanographic studies in the Indian Ocean, the investigation of the Tareev equatorial subsurface countercurrent should be continued since it is part of the Indian Ocean circulation. The study of equatorial countercurrent should become a component of the general program of the future International Indian Ocean Expedition along with the studies of intense internal waves, spreading of the Red Sea lenses, and other phenomena in the Indian Ocean.

Authors' contributions

MNK wrote the part about the Polygon-67 experiment. VGN wrote the part about the equatorial undercurrent. EGM wrote the part about internal waves. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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