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Stratification background conditions for development of double-diffusion processes in the North Pacific

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Abstract—Based on mean multiyear temperature and salinity data structural zones and layers are isolated. Within their limits there are favourable conditions for the development of processes such as layer convection and salt fingers. It is shown that distribution of their parameters is conditioned by location of intermediate water mass boundaries and front interfaces. Stability of the density ratio value R_ϱ for various areas is revealed. The obtained results are in good agreement with STD = sounding data. Compared are profiles of R_ϱ and local estimates of heat and salt fluxes for various structural zones.

The effectiveness of the convective mechanism of double-diffusion—the source of small-scale separation of watery masses and intensification of heat-and salt-carrying processes in the ocean—is confirmed by data obtained theoretically, by observation and by laboratory experiments [1, 2]. Double-diffusion processes—salt fingers and layer convection—are developed in layers with unstable stratification of temperature or salinity provided there is a given relation of signs and values of the vertical gradients. These processes can encompass large areas and can play a noticeable role in the balance between advection, climatic factors which destabilize stratification and vertical stirring of the watery mass.

Assumptions about the possibility of development of convective processes in the ocean in the form of salt fingers were confirmed in the works of Steru [5], Turner [1] and other authors, who performed the first experiments to study the dynamics of double-diffusion processes under test conditions. At the end of the 'sixties valid data emerged about the presence of well-expressed steps in the vertical temperature and salinity profiles in different regions of the ocean. The connection between such formations with the occurrence of salt fingers has been established by observation. Salt fingers have been found not only in the regions of distribution of stepwise structure, but in vast areas of subtropical rotations with relatively low intensity of small-scale disturbances of temperature and salinity profiles. Much research of the last few years has been directed towards finding the connection between those processes with macrostructural activity, intrusion dynamics and stirring of water in frontal zones, determination of identification criteria, quantitative evaluation and examination of their universality. Analysis of the results obtained leads to unexpected deductions and new understanding of the mechanisms connecting small-scale processes and their large-scale consequences [6]. It became clear that double-diffusion processes can be activated over a large area and encompass large depth ranges, and can lead to relatively faster localized changes in stratification, which are commensurable with predominating periods of internal waves, and play an important role in large-scale thermocline circulation and stirring of watery masses [3, 4, 7].

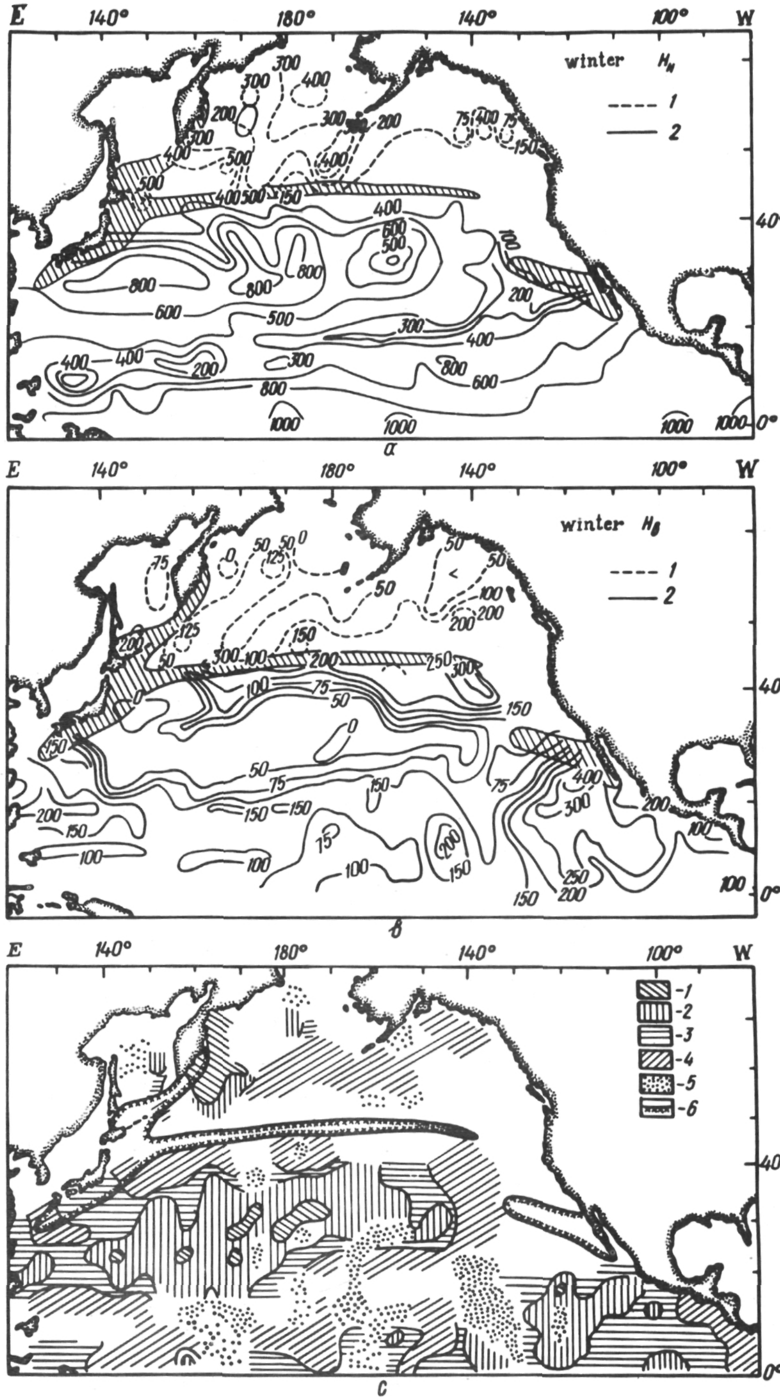

Figure 1. Topography of (a) lower and (b) upper boundaries of selected layers: 1, layer-convection regime; 2, salt fingers and distribution of parameters R_ϱ^ϱ. (c) 1, $1 < R_\varrho \leqslant 2$; 2, $2 < R_\varrho \leqslant 3$; 3, $3 < R_\varrho \leqslant 5$; 4, $R_\varrho > 5$; 5, data unavailable; 6, mixed processes.

Previous analysis of typical *T*, *S* curves of different regions of the Pacific Ocean allows the deduction of the presence of a defined connection between the position of the zones which are good for the development of processes of this category with the borders of under-surface and intergraphical features of large-scale distribution of temperature, salinity and average values of heat and salt currents on the ocean surface. We can assume that in sub-arctic waters the processes of layer convection which provide transfer of heat and salts towards the surface will be important, and in subtropical and equatorial tropical areas the salt fingers will be important.

To separate structural zones and boundaries of layers in which favourable background conditions for development of different processes exist, analysis of many data for past years regarding temperature and salinity of the northern Pacific Ocean has been performed in this work, which has been systematized upon a 5° spherical trapezoid for summer (August) and winter (February) seasons [8, 9] and for materials of STD-probing. Upper and lower borders of these layers were found on the basis of *T*, *S* curves and extremes of $T(t)$ and $S(t)$ profiles. They corresponded to the following conditions of stratification. *XP/TS* is the condition of layer convection, *TC/XP* is the salt-finger regime. Index *T* means a layer of warm water, *X* means colder water, *S* and *P* mean higher and lower salinity, respectively. The density relation R_ϱ [1, 2] was used to show the possible intensity of double-diffusion processes, all of which characterize the temperature and salinity in the total hydrostatic stability of the layer. $R_\varrho = \alpha\Delta t/\beta\Delta S$ was calculated for a salt-finger regime and for layer convection, $R_\varrho' = \beta\Delta S/\alpha\Delta T$. Results of the temperature difference ΔT and salinity difference ΔS were calculated for the middle of the given layer. Coefficients α and β were calculated by the method used in reference [10].

In Fig. 1 maps of upper and lower boundaries of extracted layers for a depth range of 0–1000 m in the winter period are shown. Traced precisely in them are two structural zones, differing in character of processes, which correspond to sub-arctic waters and an area located to the south of the sub-arctic front. In the front area, between 40° and 50° N, the type of the processes is being changed. In Fig. 1a and b those areas in the limits of which there exist conditions for layer convection and salt fingers are shaded. According to the results of bathythermograph and STD observations, in these areas a large member of intrusion formations are constantly present.

Figure 1a shows that the field of distribution and topography of the lower boundary of the layer, corresponding to the regime of salt fingers, approximately coincides with the position of the nucleus of the North Pacific and Antarctic watery masses (south of latitude 10–20° N) with lowered salinity [11]. The maximum depth of the lower boundary is up to 800–1000 m. The boundaries are traced in the western part of sub-tropical currents and in the equatorial zone. The minimum depth of the lower boundary layer (100–300 m) is found in North Pass at the current region and in the region of distribution of the Californian watery mass of lowered salinity. The topography of the upper boundary selected layer (Fig. 1b) agrees, in principle, with the position of the nucleus of the under-surface watery mass of increased salinity [11]. Their maximum depth (above 200 m) was observed in the eastern part while the minimum depth (0–50 m) was in the centre of the subtropical currents.

It is worth nothing that in different regions around the surface layer a few extremes were observed at the same time on *T*, *S* curves. In this case the horizon was taken as the boundary of the upper layer corresponding to the maximum salinity value.

For a salt-finger regime, the maximum values of total layer thickness are observed in the equator region, where they reach 600–800 m, and minimum values (200–400 m) are seen in the range of 10–20° at latitude 35–40° N and east of 160°.

The boundaries of layer distribution corresponding to the layer-convection regime are determined by the characteristic properties of the atmospheric distribution of parameters of the cold under-surface (in the summer period) and warm intermediate layers [11]. In sub-arctic structured waters the depth of the lower boundary of the selected layer increases going from east to west from 75–150 to 400–500 m, and the upper boundary from north to south by 0 to 200 m (Figs. 1a and b).

During the summer period the general diagram of distribution of boundaries and thicknesses of layers is essentially constant. In sub-arctic regions the maximum inclinations of upper and lower layer boundaries in comparison with winter periods are noted; these are caused by seasonal changes in the temperature and salinity. At this time of year the maximum values of total thickness (800–900 m) are observed in the Kurilo-Kamchatka region and in the central part of the Okhotsk Sea. An interesting feature of the maps considered above is the presence of a certain region in which the conditions necessary for development of double-diffusion processes are absent in summer and winter. This is situated in the eastern Pacific Ocean between 30 and 40°N.

Figure 1c shows a distribution map of parameter R_ϱ, calculated for the middle of the selected layer (horizons 400–500 m for the salt-finger regime, 100–125 m for the layer-convection regime). The processes considered are most effective in the range of $1 < R_\varrho < 2$, but can be developed for still larger values of R_ϱ [5, 12] . It can be seen that minimum values of R_ϱ, equal to 1–3 units, are traced in a relatively small area in the western sub-arctic region and in the limit of subtropical structured waters. Fields where R_ϱ are observed to be nearer to critical values $3 < R_\varrho < 5$ occupy ~50% of the water area south of 40°N in the northern region. In different regions the values of R_ϱ were not evaluated because of the absence of data [8, 9] or because of non-coincidence of the depths of selected horizons and the position of boundaries of selected layers.

Results of layer parameters obtained on the basis of the average of many years' data only characterize the main distinctions of stratification background, caused by the difference between climatic and dynamic conditions of different latitudinal zones. In general, they agree with existing representations about distribution of characteristics of intermediate watery mass, heat and salt flow values on ocean surface as well as background values of parameter R_ϱ [7, 11, 6]. Compare the maps obtained from probing data, which yield more exact local evaluations of temperature and salinity gradients and R_ϱ; then perform selective treatment of material from the probe observations, which are included in components of data base according to the Pacific Oceanological Institute.

While analysing probing data it is easier to operate with the value of Turner angle (Tu), coupled with the value of density ratio through the expression $R_\varrho = -\tan(Tu + 45°)$ [13]. This characteristic gives visual graphical representation of R_ϱ over a wide range of changes of values and signs of temperature and salinity gradients. The values $-90° < Tu < -45°$ correspond to the layer-convection regime while $45° < Tu < 90°$ corresponds to the salt-finger regime. $|Tu| < 90°$ corresponds to hydrostatically stable stratification, and $|Tu| > 90°$ to unstable stratification. In the range of Tu changing from $-90°$ to $-72°$ and from 72° to 90° double-diffusion processes should be active.

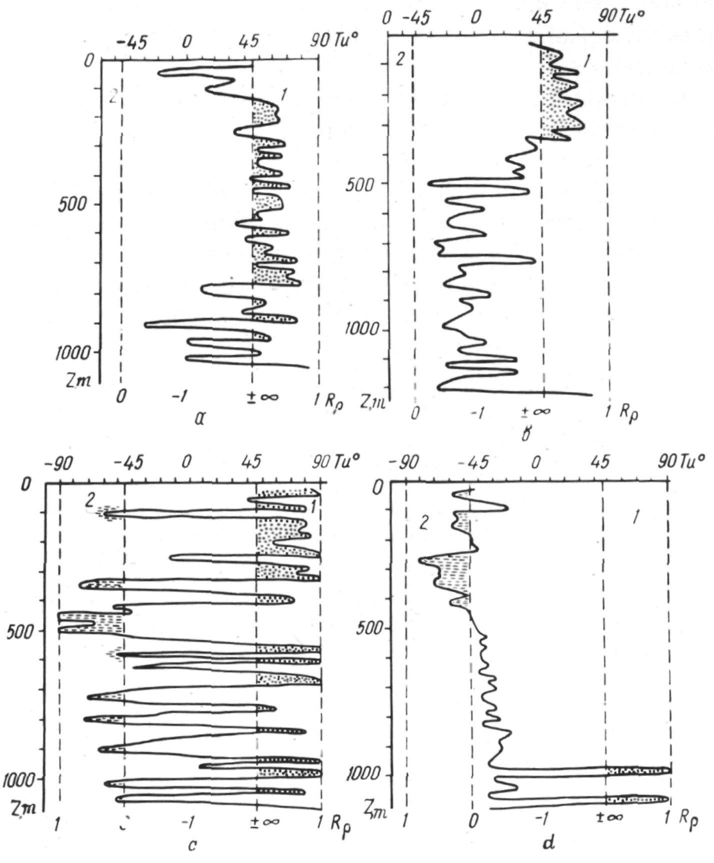

Figure 2. Distribution of Turner angle value according to probing data in the equatorial zone (a), in the subtropics (b), the field of a sub-arctic front (c) and in sub-arctic structured waters (d): 1, salt-finger regime; 2, stepwise (layer)-convection regime.

Typical $Tu\,(z)$-curves for different structural zones, calculated according to data observed with the help of hydrological complex 'Istok-4' for layers with thickness $\Delta z = 10$ m are shown in Fig. 2. It can be seen that the position of upper and lower boundary layers with different types of processes agrees with the results of calculations averaged over many years' data (Fig. 1). The value of the Turner angle changes on the vertical axis from $-90°$ to $+90°$, i.e. disturbances to the $T(z)$ and $S(z)$ profiles are compensated by density. In the equatorial zone (Fig. 2a), a layer with a favourable relationship of vertical temperature and salinity gradients for a salt-finger regime is traced between horizons up to 150–1050 m. In its lower part the maximum values of Tu are observed corresponding to values in the range $1 < R_\varrho < 2$. In the subtropics (Fig. 2b) this layer is positioned between horizons 60–360 m. Also, in 10% of the layer's volume critical values of R_ϱ ($Tu > 72°$) were noticed.

The vertical structure of water zone of a sub-arctic front in the range of the upper 1000-m layer is characterized by multiple inversion formations. Here the maximum amplitudes of Tu fluctuation (Fig. 2c) are registered. Analysis of $Tu(z)$ curves leads to the deduction that more favourable conditions existed for development of salt-fingers (lower level of inversion layers) than for layer convection (upper level of inversion layers).

In the western sector of the region of sub-arctic structured waters between horizons 50 and 420 m, the layer corresponding to stepwise convection regime is prominently displayed (Fig. 2d).

In this way the maps constructed (see Fig. 1) reflect the basic behaviour of the atmospheric distribution of layers in whose limit double-diffusion processes can play an important role in vertical stirring of the water mass. Together with other mechanisms of heat and mass transfer, the processes mentioned make a noticeable contribution to the dynamics of thin-structured formation, to the form of the small-scale profile disturbances, to the vertical flows of the melt, and to the *T*, *S* curves. In this context the positions on which theoretical models of Stern [4] and Schmidt [6] are based are represented as sufficiently feasible.

Approximate estimates of vertical fluxes of heat F_T and salinity F_S, based upon processes of layer convection and salt fingers, can be achieved according to STD-sounding data using expression from ref. [14]. These data are based upon results of laboratory experiments. Such evaluations satisfactorily agree with quantities of flows, defined by way of direct measurements.

It has been established that values of logarithms of heat and salt fluxes conditioned by salt-fingers changed on the vertical axis from $-7 \cdot 5$ to $-4 \cdot 4$°C m s^{-1} and from $-8 \cdot 1$ to $4 \cdot 7$°/$_{oo}$ m s^{-1} respectively. The layer-convection regime was characterized by lower values of F_T and F_S. The highest mean values of log (F_T) and log (F_S) for these stations were observed in the subtropics ($-5 \cdot 8$°C m s^{-1} and $-6 \cdot 3$°/$_{oo}$ m s^{-1}) and the least in waters of sub-arctic structures ($-7 \cdot 4$° C m s^{-1} and $-9 \cdot 6$°/$_{oo}$ m s^{-1}). In the zone of sub-arctic front maximum mean values of log (F_T) and log (F_S) for both varieties of processes were noticed. They were $-5 \cdot 3$°C m s^{-1} and $6 \cdot 0$°/$_{oo}$ m s^{-1} (salt-fingers) and $-6 \cdot 5$°C m s^{-1} (layer-convection). These estimates agree with results of similar calculations done by Horne [14] and other authors. Equivalent values for the coefficients of vertical 'turbulent' diffusion outperform corresponding values of coefficients of molecular exchange by 10^3–10^4 times (for heat) and 10^5–10^6 times (for salt).

It should be noticed that more correct evaluation of the F_T and F_S fluxes can be obtained only upon due consideration of the role of dynamic factors: shifting currents, internal waves, small-scale turbulence. It has been established that salt-fingers can change their form in the presence of internal waves and shifting currents and that the process develops sporadically. Normally salt-fingers are actived on high-gradient sub-layers of temperature and salinity, conditioned by kinetic effects of internal waves or cases of local stirring in thermoclines. At the same time substantial upheaval in the amount of salt in the atomsphere is observed.

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