water

Article

On the Role of Freshwater Budgets in the Formation of Salinity Extremes in the Ocean Interior

Valery Sosnin and Grigory Dolgikh *

V.I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch Russian Academy of Sciences, 690041 Vladivostok, Russia; sosnin@poi.dvo.ru

* Correspondence: dolgikh@poi.dvo.ru

Abstract: We propose interpreting the vertical structure of waters not only in space but also over time, taking into account the continuous variability of the ocean and the independence of temperature and salinity parameters. This approach allows us to consider, in real conditions, the entire spectrum of short- and long-term extrema of both characteristics, either separately or together at the same depth. Vertical distributions of temperature and salinity transform separately and independently of each other under the influence of heat and freshwater budgets, which change at different time scales. Each of the parameters has its own active layers with corresponding time scales. Changes in the signs of heat and freshwater budgets and subsequent changes in the characteristics of the surface layer cause the appearance and disappearance of separate extrema of temperature and salinity in the water column. Using a salinity field as an example, we have shown that each of the extrema, in their vertical distribution from the near-surface to the intermediate depths, is a temporary phenomenon with various lifetime scales and is located at the lower boundary of the corresponding active layers. In some areas of the ocean, temperature and salinity extrema exist together at the same depth. Volumes of water with such characteristics and explicit boundaries should be considered water masses.

Keywords: variable ocean; interaction with the atmosphere; active layer; independent temperature and salinity; salinity extrema; lifetime; water mass

Citation: Sosnin, V.; Dolgikh, G. On the Role of Freshwater Budgets in the Formation of Salinity Extremes in the Ocean Interior. *Water* **2024**, *16*, 2341. https://doi.org/10.3390/w16162341

Academic Editor: Guangyi Wang

Received: 15 July 2024
Revised: 6 August 2024
Accepted: 16 August 2024
Published: 20 August 2024

1. Introduction

It is generally accepted that the water column is similar to a sandwich cake in that it contains layers of various water masses, which spread around the ocean from their formation areas along isopycnals. Particular attention has been drawn to low-salinity water masses, which are observed at intermediate depths and distinguished by a minimum vertical distribution of salinity. They are associated with low-salinity surface waters at the high latitudes of the southern and northern hemispheres, spreading towards the equator. The mystery surrounding this type of water mass is that, in reality, it does not have the properties that it seems to be endowed with; the lack of tracers and its supposed spreading mean that it is not isopycnal. These circumstances force us to be critical of the T-S method of interpretation of the vertical water structure.

This method is based on the idea of a functional relationship between temperature and salinity. However, such a supposition is only possible if the ocean has a "hard lid" and so has no interaction with the atmosphere. In other words, it is a stationary ocean. Indeed, in the classical theory of water masses, the surface layer is excluded from the stationary T-S analysis due to the influence of the atmosphere. As a result, the active layer concept is disregarded.

In reality, each independent parameter of temperature and salinity should have active layers in accordance with the characteristics of heat and freshwater balances of different climatic zones. Taking into account the multi-scale variability of the ocean, it is possible to distinguish daily, synoptic, seasonal, and even long-lived active layers. The latter are associated with the variability of chains of the climatic system over large time scales. The current freshwater balance of the oceans represents only one of the possible phases of its long-term variability. Thus, precipitation predominates in subarctic (subantarctic) latitudes, providing a desalinated sea surface there. On the other hand, evaporation dominates at middle and low latitudes, leading to salinity increasing in the upper layer. These processes have been going on for a long time, forming active layers that have an extra-long lifetime.

Field observations demonstrate the different kinds of temperature and salinity extremes in the ocean, from near-surface to intermediate depths, which involve some contradictions—not all of them are recognized as water masses. In particular, the shallow salinity minimum is perceived as a seasonal phenomenon rather than a water mass. However, the salinity minimum at intermediate depths is considered as a water mass, but it is not isopycnal and, contrary to expectations, does not have any tracers. It is impossible to guarantee its origin from any sources on the ocean surface. Moreover, water masses very rarely have explicit boundaries. The reason for this contradiction is that the T-S method was intended for a stationary ocean without an atmosphere, while, in reality, it is used to study a variable ocean.

Some researchers have recognized the problems with the concept of water masses and believe in the extension of traditional ideas [1]. However, practice shows that this direction of research allows all questions to remain open.

In our opinion, the only way to overcome the contradictions is to take into account the independence of temperature and salinity, the interaction of the ocean with the atmosphere, and its variability at different time scales.

If one takes into account the influence of the atmosphere, it is possible to include in the interpretation of the vertical water structure active layers and the extremes of temperature and salinity in them—factors that previously were not considered at all [2]. Future ideas for the interpretation of the water structure tend to separate the vertical distribution of independent temperature and salinity characteristics functionally related to heat and freshwater budgets. An analysis of the reasons for the appearance and disappearance of their extrema in the active layer will allow us to definitively establish what kind of water volume should be considered an "alien water mass" with definite boundaries that are brought in from another area of the ocean.

Such approach in the investigation of the vertical thermohaline structure of the ocean, considering the processes of ocean–atmosphere interaction in different time scales up to the extremely large will be very useful for specialists in climatology, physical oceanography, and paleoceanography.

The purpose of this paper is to interpret the vertical salinity distribution in a variable ocean and identify the cause-and-effect relationships between the appearance and disappearance of salinity extremes in different time scales from the near-surface to the intermediate depths under the influence of a variable freshwater budget.

2. Types of Temperature and Salinity Extremes

Extremes in the vertical temperature and salinity distribution are observed from the near-surface to the intermediate depths. More often, they exist separately, but in some cases, they coexist at the same depths.

Extremes in the temperature field are found, as a rule, in areas with a negative heat budget, typical for high latitudes. Here, one can observe a temperature minimum at subsurface depths (subsurface dichothermal layer) and a temperature maximum at intermediate depths (warm intermediate layer). These extremes are often called layers, although they are also assumed to be water masses.

Temperature extremes are not permanent everywhere. In particular, in the western part of the subarctic Pacific zone, they manifest all the year round; however, in the central and eastern regions, both can disappear simultaneously and reappear over time.

In the middle latitudes of this climatic zone, at the beginning of autumn cooling, a local temperature maximum is often detected at the near-surface depths. This is rarely mentioned in the literature and is absent in the classification of extrema. It lasts for up to several hours.

Extremes in the vertical salinity distribution are generally found in areas with a negative freshwater budget. Here, at subsurface depths, both maxima and minima of salinity can be observed. The latter occurs in different oceans up to 800–1300 m. In arid zones of the ocean, salinity minimum at intermediate depths is observed constantly, but at the boundaries of the zone exists only in a dry season. In addition, in the upper layer of the ocean, salinity minima appear in the near-surface layers at daily [3] and synoptic time scales [4].

A minimum in vertical distribution of salinity can be observed even in areas with a positive annual freshwater budget in the subarctic (subantarctic) zone of the ocean. Here, it exists locally and only for a short time at the near-surface layer during the season of negative freshwater budget.

There are some uncertainties in the interpretation of temperature and salinity extrema. For example, salinity minima in the vertical distribution of salinity observe at different depths but only at intermediate depths, they associate with water masses. Shallow salinity minima are not included in this category and are simply considered "seasonal" [5–7].

The salinity minimum at intermediate depths is considered as a water mass but does not possess isopycnicity. The results of observations demonstrate that the suspected spreading of these water masses towards the equator in the northern and southern hemispheres is not isopycnal [6,8–13]. Furthermore, contrary to generally accepted opinion, it has no tracers that can confirm its formation on the sea surface. Thus, in the northern part of the Pacific Ocean, the extrema in the vertical distribution of tritium and freons occur at the same depth but 300–600 m above the salinity minimum [14–16]. The maximum dissolved oxygen concentration also occurs above the salinity minimum [17–19].

Moreover, there is no consensus about the geographical location of the formation area of low-salinity water masses in the northern Pacific. In addition to the subarctic front zone [12,20,21], it can be located in the Gulf of Alaska [22–24], the Sea of Okhotsk [24,25], and in the Kuril Current region [26].

There is no way to establish a correlation between the salinity minimum at intermediate depths and chemical elements in the southern hemisphere. High concentrations of nitrates, phosphates, and silicates are found much deeper and have no extremes [8,10,27–29]. The distribution of CFC-11, CFC-12, CO_2, and CH_4 on meridional sections in the South Pacific does not indicate their direct connection with the salinity minimum [30–34]. The maximum oxygen concentrations here, like in the northern hemisphere, occurs at shallower depths than the salinity minimum [10,28,29,35–38].

Thus, observation data demonstrate that the depth of the salinity minimum at intermediate depths does not coincide with the depth of high oxygen concentrations in any ocean. This indicates that there is no direct correlation between those two extremes. It means they do not have a common source of formation. This also applies to the region of the subantarctic front, where conditions for the development of deep convection exist. Here, the salinity minimum also lies deeper than the high oxygen concentrations.

Moreover, north of the subantarctic front, high oxygen concentrations in the water interior are associated with a completely other water mass, exactly with the Subantarctic Mode Water, which is located at a shallower depth and does not have an extreme on the T-S curve [39–41]. Here, the classical conception of water masses meets with several contradictions. Firstly, the salinity minimum, considered an s Antarctic water mass of low salinity with a classic extreme on the T-S curve, does not have any tracer. Secondly, high oxygen concentrations in reality are associated with another water mass, which does not have an extreme on the T-S curve. Such interpretation of water masses contradicts the classical water mass quantity definition [42] (p. 71). Thus, rather than together representing one water mass, the extremes of salinity and oxygen separately represent two completely different water masses with different formation areas.

It should be noted that, in the southern hemisphere, just north of the subantarctic front, the salinity minimum at intermediate depths has not been observed to be constant but periodical. It disappears and reappears over large areas of the ocean at the same time [43,44]. In this case, one should no longer talk about a specific geographical position of the formation area but about the season favorable for its detection in the water column, namely the season of evaporation dominance [44].

The same area exists in the north Pacific, where a salinity minimum in the water column is observed only in the dry season; This is a transition zone between areas with different signs of freshwater balance [45].

Thus, the salinity minimum at intermediate depths, which is associated with a water mass of low salinity, does not have the properties considered inherent to it. In addition, in a certain area of the ocean, this water mass can be observed only seasonally, what is unusual.

In general, temperature and salinity extremes can be observed in different climatic zones of the ocean and exist independently of each other, but in some areas, they can be found together at the same depths. For example, they present at intermediate depths in the Atlantic Ocean, west of the Strait of Gibraltar, and at intermediate depths in the Arabian Sea, where waters from the Gulf of Oman spread. In addition, one can find such a combination of temperature and salinity extremes on shelf slopes, in areas of deep convection, and in ocean troughs with a thermal water outlet.

Thus, there are different types of temperature and salinity extremes in the water column, the interpretation of which is ambiguous. The reason is that the T-S method used for the interpretation of the vertical water structure initially was intended for the ocean without considering the atmosphere but today is applied to the ocean, which interacts with the atmosphere. To overcome contradictions in water structure interpretations, one needs to take into account the interaction of the ocean with the atmosphere, the independence of temperature and salinity parameters, their functional relationship with heat and freshwater budgets, and ocean variability at different time scales.

The ocean varies at different time scales, up to millions of years [46–48]. These changes are difficult to detect if one examines the ocean alone. However, this is possible within the framework of the climate system: the variability of elements over large geological time scales is well documented.

Significant changes in the climate system started with geological processes independent of external forcing. The characteristics of the land surface had been changing for a long time, resulting in the formation of new features of atmospheric circulation, followed by changes in other elements of the climatic system [49]. The uplifting of the Tibetan and Himalayan plateaus took over 40 million years and occurred, most likely, in several stages [50–52]. The last stage took place 2.6 million years ago [52] and was accompanied by an intensification of the Asian winter [51] and summer [53] monsoons. The development of the Asian monsoon led to a connection between the lower and middle troposphere of two monsoon systems (Asian and African) into one integrated system [53], which involved the completion of the formation of centers of atmospheric action in a way close to the modern one.

The continuous restructuring of atmospheric circulation finished with two simultaneous events: the emergence of land cover glaciation about 2.54 million years ago [54] and the freshening of the subarctic Pacific, by which a stable halocline formed approximately 2.73 million years ago [55]. Features of freshwater balance, which observed still today, appeared in the ocean: the dominance of precipitation at high latitudes and the predominance of evaporation at middle and low latitudes. These phases of freshwater balance variability have persisted since that time, forcing the formation of a salinity field in the ocean: the freshening of the surface layer in the subarctic and the increasing salinity of the upper layer in arid zones. This large-scale ocean variability conditionally can be called as geological.

To evaluate the opportunities that produce such approach, let us compare, for example, the interpretation of extremes in the vertical salinity distribution within the framework of a traditional analysis for a stationary ocean and for a variable ocean, where temperature and salinity are independent of each other and the ocean interacts with the atmosphere.

3. Materials and Methods

To study the vertical distribution of salinity, we used 2009 oceanographic data from the World Ocean Database and data from Argo drifting buoys. The Ocean Data View program [56] was used for data processing.

The intra-annual variability of the vertical distribution of salinity at different latitudes was investigated in the southern hemisphere for three oceans and the northern part of the Pacific Ocean. In this work, we used only actual data, without averaging over time or space. From the available dataset for the southern hemisphere, we determined the southern position for the water structure with a salinity minimum at intermediate depths and the northern boundary of the water structure without a salinity minimum. For the northern part of the Pacific Ocean, we determined the northern position of the water structure with a salinity minimum at subsurface depths and the southern position of the water structure without a salinity minimum. In addition, we noted the presence of a salinity minimum at near-surface depths in subarctic and subantarctic zones of the ocean.

4. Stationary Ocean

At the beginning of the last century, due to the small amount of field observation data, the ocean was considered alone. There was no concept of its temporal variability and interaction with the atmosphere. Under such conditions, to interpret the vertical water structure, V. Helland-Hansen proposed the joint representation of temperature and salinity as one T-S curve [57]. The analysis of this curve suggests that the water column consists of several layers of different origin. Regardless of which characteristics have extrema in the vertical distribution, the shape of the T-S curve turns out to be surprisingly uniform for large areas of the ocean, which seems to confirm the existence of extended flat, parallel layers with constant properties. A. Defant and G. Wust explained the presence of minima and maxima in the vertical distribution of temperature and salinity by the horizontal spreading of waters with such properties from other regions of the ocean [58]. The supposed horizontal layers were called "water masses," and the extrema on the T-S curves became associated with their cores.

Later, a theoretical basis for the interpretation of T-S curves was proposed [2,42,59–61]. Boundary conditions for the heat and salt diffusion equations describing the vertical distribution of temperature and salinity were set inside the ocean at the boundaries of water masses but not on the surface [59]. The concept of a "water mass" became widespread and researchers started to use it in practice. The first definition of the concept was given by A.D. Dobrovolsky [62]. Later, researchers returned to this issue more than once [63,64].

Let us note that temperature and salinity can be functionally coupled only in an ocean that does not interact with the atmosphere. In this case, its surface must be shut with a "hard lid". The lack of interaction with the atmosphere, and, consequently, the lack of variability in both characteristics, makes the ocean stationary. The use of the T-S method for such ocean makes it possible to associate the origin of the characteristics' extrema only with horizontal isopycnal advection. The fact that water masses are inextricably linked with ocean currents is one of the main postulates of the water mass concept. In the absence of atmospheric influence, the role of currents in the formation of a vertical distribution of temperature and salinity properties appears to be dominant from the surface to the bottom layers. Within the framework of a stationary ocean model, such ideas seem logical.

However, practice shows that, in the real ocean, the condition of isopycnicity of the assumed spreading of water masses is not fulfilled. The interpretation of the vertical water structure with the T-S method involves contradictions that cannot be overcome within its framework.

Let us note that the classical theory of water masses excludes the surface layer of the ocean from the "stationary T-S analysis" precisely because of atmospheric influence [2,62,65].

For this reason, the upper layer is not considered stationary, and extremes of temperature and salinity are not considered [2] (p. 244).

In addition, the active layer that exists in the real ocean is never mentioned when the vertical water structure is interpreted by the T-S method. The reason for this is quite understandable: the active layer cannot exist without the ocean–atmosphere interaction.

The way to overcome contradictions is the rejection of the T-S method for interpreting the water structure in the variable ocean. In reality, the ocean constantly exchanges with the atmosphere via heat and freshwater to generate unceasing changes in the boundary conditions on the sea surface. The vertical distribution of independent temperature and salinity fields must be investigated separately, taking into account the functionally associated heat and freshwater budgets and the interaction with the atmosphere at different time scales.

5. Variable Ocean

Let us examine the variability of the vertical salinity distribution in a tropical zone with a negative freshwater budget (Figure 1).

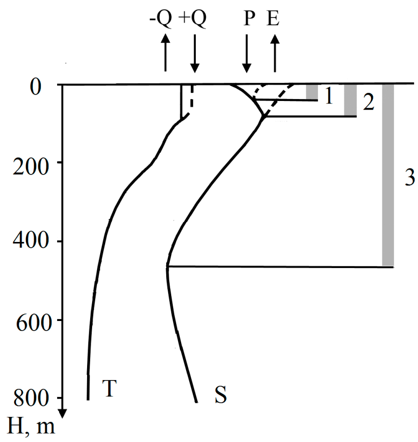

Figure 1. Characteristic vertical distribution of temperature and salinity in the arid zone of the ocean. Explanation: 1—active layer of synoptic time scale; 2—active layer of seasonal time scale; 3—active layer of great (geological) time scale.

The temperature and salinity profiles for different phases of heat and freshwater budget variability are presented here. The dotted line demonstrates the salinity distribution during the phase of evaporation dominance. During this season, the maximum salinity values are located at the ocean's surface, and there is only one extreme in its vertical distribution: the salinity minimum at intermediate depths (Figure 1).

It should be noted that even Yu. A. Ivanov [66] proposed that, when studying the distribution of oceanological characteristics, one needs to investigate each of them, keeping in mind the surface boundary conditions affecting their variability.

Observations show that diurnal, synoptic, seasonal, and long-term active layers can be distinguished in the ocean interior due to changes in the signs of the freshwater budgets at corresponding time scales.

During the season precipitation predominates, the salinity values on the surface decrease. The salinity value at subsurface depths turns out to be higher in absolute value and becomes the maximum for this certain vertical distribution. As freshening increases, the salinity values in deeper layers turn out to be maximal. The extreme occurrence depth of the salinity maximum is achieved when extreme seasonal freshening occurs on the surface. Moreover, the salinity values that were initially located at those depths become extreme for this profile. The characteristics of the salinity maximum at subsurface depths—salinity value and occurrence depth—change throughout the season due to freshwater budget changes [67]. Therefore, this extreme is a temporary phenomenon of a seasonal scale; it does not connect with horizontal advection but appears and disappears in the water column during the corresponding phase of freshwater balance variability. The extreme occurrence depth represents the lower boundary of the active layer of the seasonal time scale.

The phase of precipitation dominance ends with the freshening of the surface layer—a necessary initial condition for the subsequent appearance of another extreme at near-surface (subsurface) depths, the salinity minimum, in the water column. The change in the sign of the freshwater balance under the dominance of evaporation leads to a rise in salinity values in the upper layer. Moreover, on the surface, the salinity increases faster than at subsurface horizons and eventually becomes larger in absolute value [3,4,68,69]. This means that the salinity minimum in the vertical salinity distribution appears at near-surface depths as a background to the higher salinity values in the surface layer (Figure 1).

The characteristics of the salinity minimum—occurrence depth and salinity value in its core—change continuously as the freshwater balance changes and depend on the duration of the dry period. Figure 1 demonstrates one of the salinity minima at a smaller time scale in the near-surface layers. Its occurrence depth represents the lower boundary of the active layer of the synoptic (daily) time scale.

The process of a salinity minimum's appearance in the water column follows the same scenario for different time scales: daily [3], synoptic [4], or seasonal [45,68,69]. Essentially, it represents a process of salinity increasing in the upper ocean layer during the phase of evaporation dominance. The duration of this process continues as long as the salt flow from the surface continues. The change in the sign of freshwater balance with the dominance of precipitation leads to the disappearance of the salinity minimum as an extreme. Thus, the salinity minimum, despite the differences in occurrence depths, is a temporary phenomenon at different lifetime scales.

Let us examine the vertical distribution of salinity in the North Pacific at different times and in different areas where there are different signs of freshwater budget (Figure 2).

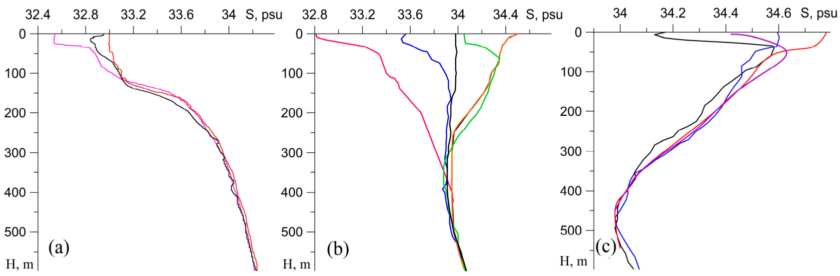

Figure 2. Typical vertical distribution of salinity in areas with different signs of freshwater balance: (**a**) positive; (**b**) transition zone; (**c**) negative. Salinity profiles are located between 160° E and 160° W: (**a**) 48° N; (**b**) 43° N; (**c**) 38° N.

The subarctic zone of the Pacific Ocean has a positive freshwater budget; therefore, the surface layer has the maximum freshening (Figure 2a). The intra-annual variability of the salinity field leads to the fact that, at near-surface depths, one can find a salinity minimum, which has a short lifetime. Salinity profiles do not have any extremes in the deep-water column.

The transition zone between areas with different signs of freshwater budget (Figure 2b) has a much greater amplitude of intra-annual salinity variability. Different time scales' variability in the value and sign of the freshwater budget is the reason for the appearance and disappearance of salinity extremes of different signs and lifetime scales. During a year, one can observe here the near-surface salinity minimum of the synoptic time scale, the subsurface salinity maximum of the seasonal time scale, and a salinity minimum at intermediate depths, which also has a seasonal lifetime scale.

The position of the salinity minimum at intermediate depths throughout the North Pacific, according to the freshwater budget, is shown in Figure 3.

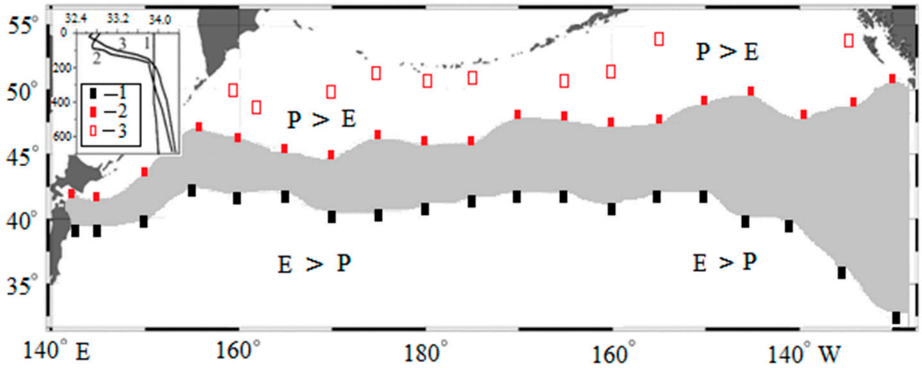

Figure 3. Area of the seasonal existence of a salinity minimum at intermediate depths in the North Pacific Ocean (shaded). Explanation: 1—seasonal southern boundary of the water structure without a salinity minimum; 2—seasonal northern position of the water structure with a salinity minimum; 3—salinity minimum at near-surface depths in the subarctic zone. The insert shows corresponding salinity profiles.

Here, we mark the area within which the salinity minimum detected only seasonally during the dry season. The transition zone between areas with different signs of freshwater budget can be traced throughout the entire North Pacific, with 300–400 miles across (Figure 3). The northern periphery of it represents the seasonal northern boundary of salinity minimum occurrence at subsurface depths. The southern boundary of the transition zone represents the seasonal southern position of the water structure without a salinity minimum.

The quintessence of the transition zone is that, in a given area of the ocean, seasonal changes in the sing of freshwater budget inevitably lead to the appearance and disappearance of a salinity minimum in the vertical distribution of salinity at a seasonal time scale, regardless of the presence or absence of horizontal advection.

During the wet season, the ocean surface becomes fresher, and up to approximately 42° N, the vertical distribution of salinity looks like that in the subarctic, without extremes at subsurface depths. Here, at a depth of about 300–350 m, one can observe a salinity minimum, which is completely isolated from the ocean surface at this time. This is the largest occurrence depth of a salinity minimum, which appears and disappears in a region throughout the year, representing a temporary seasonal phenomenon [45].

During the evaporation-dominated season, the area of the salinity minimum at subsurface depths shifts northward, up to approximately 46° N. At this time, due to the increase in salinity values in the surface layer, those salinity values that initially were on subsurface horizons turn out to be the minimum for the given salinity profile. The seasonal growth of salinity values in the surface layer is the reason for the appearance of a salinity minimum at subsurface depths—not at one point but over broad areas.

South of the transition zone, there is an area with a negative freshwater budget (Figure 2c). In this area, the salinity minimum at intermediate depths in vertical salinity distribution does not disappear each year. The characteristic feature of the given area is the presence of maximum salinity values on the surface. This is the essence of the arid zone: for a long time, the salt flow here is directed deep into the ocean. The presence of a seasonal salinity maximum at subsurface depths is a consequence of the positive phase of freshwater budget variability of a seasonal time scale. This seasonal temporal attribute of the salinity profile manifests in the background of its long-term variability due to its generally negative trend (Figure 1).

Thus, the salinity minimum at intermediate depths in the North Pacific consists of two sections: seasonal for transition zone and long-lived for arid zone.

Field observations demonstrate the existence of a similar transition zone in the southern hemisphere located at the boundary of areas with different signs of freshwater budget—within which the salinity minimum, as noted earlier [44], can be observed only seasonally (Figure 4).

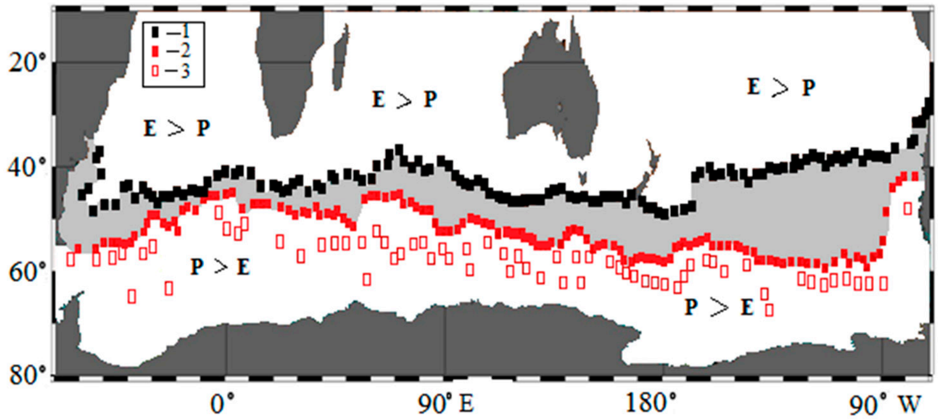

Figure 4. Area of the seasonal existence of a salinity minimum at intermediate depths in the southern hemisphere (shaded). Explanation: 1—seasonal northern boundary of the water structure without a salinity minimum; 2—seasonal southern position of the water structure with a salinity minimum; 3—salinity minimum at near-surface depths in the subantarctic zone.

A transition zone exists throughout the southern hemisphere, but its size varies significantly in different oceans. The appearance and disappearance of the salinity minimum at a seasonal time scale is not synchronous but variable due to seasonal changes in the sign of the freshwater budget along the entire subantarctic front, regardless of the peculiarities of water dynamics. The salinity minimum is not surface ocean water and, therefore, it does not contain high oxygen concentrations. Consequently, oxygen cannot be a tracer for the salinity minimum. In turn, a seasonal salinity minimum, as a temporary phenomenon, cannot be the source of a salinity minimum at intermediate depths in the arid zone.

North of the transition zone in the southern hemisphere, in the area where evaporation dominates over precipitation, the salinity minimum in the water column exists all the year-round. This means that the salinity minimum at intermediate depths in the southern hemisphere, like in the northern, consists of two sections with different lifetime scales.

Thus, the salinity minimum at intermediate depths in both hemispheres is not a complete structure. It consists of two parts: a deep-water minimum, which does not disappear every year; and a seasonal shallow-water minimum on its northern (southern) periphery. In the framework of the representation of ocean variability over a large time scale, it would be more accurate to call the salinity minimum at intermediate depths, which does not disappear every year, a long-term phenomenon rather than a permanent feature. The nature of the seasonal origin of the salinity minimum is quite clear: it appears in the water column every year during the season when evaporation prevails.

The negative freshwater budget of the tropical zones of North Pacific reflects the fact that evaporation has dominated here for a long time. This explains salinity increases in the upper layer and salt flux into the deep ocean. These processes have been occurring here over a period of more than 2.73 million years [55] and continue at present not only in the seasonal active layer but also in the underlying layers. A negative freshwater budget is a necessary condition for the existence of the salinity minimum in the water column, not only for short time scales but also for long ones.

Thus, a water column deeper than the seasonal active layer can be considered a long-term active layer with an extra-long lifetime scale whose formation is still ongoing. The lifetime of this active layer corresponds to the duration of the negative phase of the freshwater budget existing in this climatic zone. A salinity minimum at intermediate depths representing its lower boundary is a long-lived but still temporary phenomenon. It has no connection with the ocean surface and with the horizontal spreading of waters from other regions, what explains the absence of any tracers in its core.

The greatest depth of salinity minimum occurred in areas with the highest salinity values in the surface layers. This corresponds to the functional relationship between the salinity and the freshwater budget. Salt fluxes from the surface create a water of a higher density in deep layers, which becomes the salinity minimum. If salt fluxes from the surface have different rates in adjacent areas, one can find a deeper occurrence depth of salinity minimum for the region with the greater magnitude or longer duration of the salt fluxes. Thus, the different values of freshwater balance on the surface in various regions of the arid zone explain the difference in the occurrence depths of the salinity minimum and, correspondingly, the lack of isopycnicity of its staying (not spreading!) at intermediate depths.

Thus, all separate salinity minima in the vertical salinity distribution from near-surface horizons to intermediate depths represent temporary phenomena of different lifetime scales. In essence, all of them are local and are not associated with horizontal advection. The characteristics of the freshwater budget determine their lifetime, occurrence depth, and distribution in the ocean. All of them observed during the negative phase of freshwater budget variability. The occurrence depths of salinity minima represent the lower boundary of the active layer of the corresponding lifetime scale. They appear and disappear in the water column on the background of salinity values' variability in the surface layer. All of these processes occur under the stable water stratification conditions.

The presence of active layers of different lifetime scales in the water interior contradicts the idea for existing of stationary layers in the water column. It seems that a continuously variable ocean cannot contain any unchangeable elements that not influenced by atmospheric forcing. Nonetheless, there are some specific water volumes that fully correspond to the classical concept of "water masses".

6. On the Idea of Water Masses

The concept of water masses originated from the interpretations of the oceanographic data from the central part of the Atlantic Ocean, where the waters from the Mediterranean Sea are present at intermediate depths. Here, the method of T-S of analysis identifies extrema with a salinity minimum and maximum, which were initially considered as the cores of two different water masses [58,60]. Researchers believed that the salinity minimum represents low-salinity waters from the subarctic. However, many years later, it was recognized that this salinity minimum should be considered "secondary" or false [2] (p. 331).

The vertical distribution of temperature and salinity in this region of the ocean presents only one alien water mass originated from the Mediterranean Sea. In fact, it was recognized that the salinity minimum in this case is not a water mass at all. In general, this means that the idea proposed by A. Defant and G. Wüst [58] based on the method of T-S analysis of the indispensable vertical intermittency of water layers of different origins was erroneous. In reality, this area of the Atlantic Ocean contains only one water mass in the water column that corresponds to their classical definition. One can clearly differentiate this water mass on the vertical salinity and temperature profiles by the increased values of both characteristics. It has clearly defined boundaries in space, so it can definitively be identified as an intrusion of waters from the Mediterranean Sea. This sea is an actual source of water that one can observe at certain intermediate depths in the Atlantic Ocean—not only near the Strait of Gibraltar [70] but also far from it [71]. These waters differ from the surrounding ones in that they have both extremes existing simultaneously at the same depth.

Similar water column properties can also be observed in the deep waters of the north Atlantic. Analogous properties in the water interior can also be observed in other areas of the World Ocean: for example, in the western part of the Arabian Sea, where waters from the Gulf of Oman spread. The extremes in the vertical distribution of temperature and salinity for all these waters actually have a common origin, associated with deep convection and (/or) horizontal advection. These waters spread as a uniform water volume from a definite source, thus fully corresponds the classical definition of a water mass [62].

These also include shelf waters involved in slope convection and sliding along the continental slope to intermediate depths in the areas of Greenland, the Sea of Japan, the Sea of Okhotsk, the Irminger Sea [72], and other high-latitude regions. Some of them may not fit the classical definition of water masses because of the small volumes, but for intermediate depths, they are alien waters that have their own distinctive properties.

Perhaps the word "alien" is a key word for understanding the idea of water masses. There should be attributes in the water column that make it possible to definitively discriminate a limited water volume from surrounding waters that originate from another area. Such attributes may be joint extremes of temperature and salinity at the same depths. This water volume must also have a characteristic chemical tracer. If one can discriminate such water volume in the variable ocean, then we are undoubtedly dealing with an actual water mass.

Intrusions of relatively small volumes of water of various origins in wide interfrontal zones, for example, in the area of the mixing and mutual penetration of Kuroshio and Oyashio waters, are also related to this category of waters. They represent lenses of subarctic waters surrounded by tropical ones and lenses of tropical waters among subarctic ones. All of them have definite boundaries in space and specific sizes; they differ from surrounding waters in bearing extremes of both characteristics at once.

Perhaps some kind of classification of water masses according to their volume or lifetime is needed, but this is outside the scope of the discussion here.

Field practice demonstrates that the variable ocean contains limited water volumes to which the term "water mass" fully applies. The classical definition of water masses requires clarification. The definition of a "water mass" as stated by A.D. Dobrovol'skij [62] might be supplemented and concretized as follows: a water mass is a relatively large volume of water with explicitly definite boundaries, formed in a certain area of the World Ocean—in the source of the origin (formation area) of this water mass—possessing over a long period an almost constant and continuous distribution of physical, chemical, and biological characteristics. It forms an integrated complex that spreads as one, differing from surrounding waters by exhibiting both extremes of temperature and salinity at the same depth at the same time.

7. Conclusions

The main attribute of the variable ocean interacting with the atmosphere is the presence of active layers of different lifetime scales. The time scale of the interaction processes determines their temporal and spatial scales. Changes in the boundary conditions on the ocean surface account for the appearance and disappearance of salinity extremes in the vertical salinity distribution from the near surface to the intermediate depths. One has to draw distinctions between the water structure conditions with the separate or joint existence of temperature and salinity extremes.

All of the separate extremes in the vertical salinity distribution represent the temporary phenomena of different lifetime scales; their occurrence depth is the lower boundary of the corresponding active layer of the definite time scale. No one separate salinity extreme has a tracer; its origins are not related to horizontal advection.

The coexistence of both independent temperature and salinity extremes at the same depth in the water interior indicates their common origin. This is an objective reason for identifying an isolated water volume (a water mass), whose existence and spread in the water column are associated with horizontal advection and/or deep convection at high latitudes. All water masses have specific tracers.

Author Contributions: G.D.—problem statement, discussion, and writing of the article. V.S.—data processing, visualization, and writing of the article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a grant from the Russian Science Foundation, grant number 123072000039-5 "Development of a climate monitoring system for the Far Eastern seas of Russia and the Northwestern Pacific Ocean based on multiplatform observations and operational hydrodynamic modeling".

Data Availability Statement: Third-party data. Restrictions apply to the availability of these data.

Acknowledgments: The authors are grateful to N.I. Rudyh for the assistance in working with the database.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tomczak, M. Water masses: We can see them, but can we define them? *Ocean. Model.* **1991**, *93*, 8–10.
2. Mamaev, O.I. *Temperature-Salinity Analysis of World Ocean Waters*; Gidrometeoizdat: Leningrad, Russia, 1970; 364p.
3. Fedorov, K.N.; Ginzburg, A.I. *Subsurface Layer of the Ocean*; Gidrometeoizdat: Leningrad, Russia, 1988; 303p.
4. Sosnin, V.A.; Torgaeva, O.I. A study of interannual variability of salinity in the Sea of Japan. *Russ. Meteorol. Hydrol.* **2000**, *6*, 49–54.
5. Reid, J.L. The shallow salinity minima of the Pacific Ocean. *Deep-Sea Res.* **1973**, *20*, 51–68. [CrossRef]
6. Yuan, X.; Talley, L.D. Shallow salinity minima in the North Pacific. *J. Phys. Oceanogr.* **1972**, *22*, 1302–1316. [CrossRef]
7. Masujima, M.; Yasuda, I. Distribution and modification of North Pacific Intermediate Water around the subarctic frontal zone east of 150° E. *J. Phys. Oceanogr.* **2009**, *39*, 1462–1474. [CrossRef]
8. Tsuchiya, M. Circulation of the Antarctic Intermediate Water in the North Atlantic. Ocean. *J. Mar. Res.* **1989**, *47*, 747–755. [CrossRef]
9. Talley, L.D. Distribution and formation of North Pacific Intermediate Water. *J. Phys. Oceanogr.* **1992**, *23*, 517–537. [CrossRef]
10. Tsuchiya, M.; Talley, L.D.; McCartney, M.S. Water-mass distribution in the western South Atlantic; A section from South Georgia Island (54 S) northward across the equator. *J. Mar. Res.* **1994**, *52*, 55–81. [CrossRef]
11. You, Y. Quantitative estimate of Antarctic Intermediate Water contribution from Drake Passage and the southwest Indian Ocean to the South Atlantic. *J. Geophys. Res.* **2002**, *107*, 3031. [CrossRef]
12. You, Y. Unveiling the mystery of North Pacific Intermediate Water formation. *EOS* **2005**, *86*, 65–71. [CrossRef]
13. Rusciano, E.; Speich, S.; Ollitrault, M. Interocean exchanges and the spreading of Antarctic Intermediate Water south of Africa. *J. Geophys. Res.* **2012**, *117*, C10010. [CrossRef]
14. Van Scoy, K.A.; Fine, R.A.X.; Ostlund, H.G. Two decades of mixing tritium into the North Pacific Ocean. *Deep-Sea Res.* **1991**, *38* (Suppl. S1), 191–219. [CrossRef]
15. Van Scoy, K.A.; Druffel, E.R.M. Ventilation and transport of thermocline and intermediate waters in the northeast Pacific during recent El Ninos. *J. Geophys. Res.* **1993**, *98*, 18083–18088. [CrossRef]
16. Watanabe, Y.W.; Harada, K.; Ishikawa, K. Chlorofluorocarbons in the central North Pacific and southward spreading time of North Pacific Intermediate Water. *J. Geophys. Res.* **1994**, *99*, 25125–25213. [CrossRef]
17. Reid, J.L. *Intermediate Waters of the North Pacific Ocean*; Johns Hopkins Press: Baltimore, MA, USA, 1965; Volume 2, pp. 1–85.
18. Kenyon, K.E. Shallow salinity minimum of the eastern North West Pacific. *J. Phys. Oceanogr.* **1978**, *8*, 1061–1069. [CrossRef]
19. Kawabe, M.; Fujio, S.; Yanagimoto, D.; Tanaka, K. Water masses and currents of deep circulation southwest of the Shatsky Rise in the western North Pacific. *Deep-Sea Res. I.* **2009**, *56*, 1675–1687. [CrossRef]
20. Kil'matov, T.R.; Kuz'min, V.A. *Subarctic Front of the Pacific Ocean: Structure, Dynamic, Modelling*; Dal'nauka: Vladivostok, Russia, 1990; 114p.
21. Talley, L.D.; Nagata, Y.; Fujimura, M.; Iwao, T.; Kono, T.; Inagake, D.; Hirai, M.; Okuda, K. North Pacific Intermediate Water in the Kuroshio/Oyashio Mixed Water Region. *J. Phys. Oceanogr.* **1995**, *25*, 475–501. [CrossRef]
22. Kuksa, V.I. *Intermediate Waters of the World Ocean*; Gidrometeoizdat: Leningrad, Russia, 1983; 272p.
23. Van Scoy, K.A.; Olson, D.B.; Fine, R.A. Ventilation of North Pacific intermediate Water: The role of Alaskan Gyre. *J. Geophys. Res.* **1991**, *96*, 16801–16810. [CrossRef]
24. You, Y.; Suginohara, N.; Fukasawa, M.; Yasuda, I.; Kaneko, I.; Yoritaka, H.; Kawamiya, M. Roles of the Okhotsk Sea and Gulf of Alaska in forming the North Pacific Intermediate Water. *J. Geophys. Res.* **2000**, *105*, 3253–3280. [CrossRef]
25. Talley, L.D. At Okhotsk Sea anomaly: Implication for ventilation in the North Pacific. *Deep-Sea Res.* **1991**, *38* (Suppl. S1), 171–190. [CrossRef]
26. Yasuda, I. The origin of the North Pacific Intermediate Water. *J. Geophys. Res.* **1997**, *102*, 893–909. [CrossRef]
27. Thompson, R.O.R.Y.; Edwards, R.J. Mixing and water mass formation in the Australian Subantarctic. *J. Phys. Oceanogr.* **1981**, *11*, 1399–1406. [CrossRef]
28. Suga, T.; Talley, L.D. Antarctic Intermediate Water circulation in the tropical and subtropical South Atlantic. *J. Geophys. Res.* **1995**, *100*, 13441–13453. [CrossRef]
29. Bostock, H.C.; Sutton, P.J.; Williams, M.J.M.; Opdyke, B.N. Reviewing the circulation and mixing of Antarctic Intermediate Water in the South Pacific using evidence from geochemical tracers and Argo float trajectories. *Deep-Sea Res. Part I* **2013**, *73*, 84–98. [CrossRef]

30. Gordon, A.L.; Weiss, R.F.; Smethei, W.M., Jr.; Warner, M.J. Thermocline and intermediate water communication between the South Atlantic and Indian oceans. *J. Geophys. Res.* **1992**, *97*, 7223–7240. [CrossRef]
31. Maamaatuaiahutapu, K.; Garcon, V.C.; Provost, C.; Boulahdid, M.; Osiroff, A.P. Brazil-Malvinas confluence: Water mass composition. *J. Geophys. Res.* **1992**, *97*, 9493–9505. [CrossRef]
32. Fine, R.A.; Maillet, K.A.; Sullivan, K.F.; Willy, D. Circulation and ventilation flux of the Pacific Ocean. *J. Geophys. Res.* **2001**, *106*, 22159–22178. [CrossRef]
33. Yoshida, O.; Inoue, H.Y.; Watanabe, S.; Suzuki, K.; Noriki, S. Dissolved methane distribution in the South Pacific Ocean in austral summer. *J. Geophys. Res.* **2011**, *116*, C07008. [CrossRef]
34. Schmidtko, S.; Johnson, G. Multidecadal warming and shoaling of Antarctic Intermediate Water. *J. Climate* **2012**, *25*, 208–221. [CrossRef]
35. Wyrtki, K. The subsurface water masses in the western South Pacific Ocean. *Aust. J. Mar. Freshw. Res.* **1962**, *13*, 18–47. [CrossRef]
36. Tsuchiya, M.; Talley, L.D. Water-property distribution along an eastern Pacific hydrographic section at 135 W. *J. Mar. Res.* **1996**, *54*, 541–564. [CrossRef]
37. Koshlyakov, M.N.; Tarakanov, R.Y. Intermediate waters of the South Pacific. *Okeanology* **2005**, *45*, 485–503.
38. Woo, M.; Pattiaratchi, C. Hydrography and water masses off the western Australian coast. *Deep-Sea Res. Part I* **2008**, *55*, 1090–1104. [CrossRef]
39. McCartney, M.S. A Voyage of Discovery, George Deacon Anniversary Volume. In *Subantarctic Mode Water*; Angel, M.V., Ed.; Pergamon: New York, NY, USA, 1977; Volume 24, pp. 103–119.
40. Rintoul, S.R.; England, M.H. Ekman transport dominates local air-sea fluxes in driving variability of Subantarctic Mode Water. *J. Phys. Oceanogr.* **2002**, *32*, 1308–1321. [CrossRef]
41. De Brauwere, A.; Jacquet, S.H.M.; Ridder, F.; De Dehairs, F.; Pintelon, R.; Schoukens, J.; Bacyens, W. Water mass distribution in the Southern Ocean derived from a parametric analysis of mixing water masses. *J. Geophys. Res.* **2007**, *112*, C02201. [CrossRef]
42. Shtokman, V.B. *On the Water Masses of the Central Part of the Arctic Ocean*; Arkticheskii Nauchno-Issledovatel'Skii Institut: Saint Petersburg, Russia, 1943. (In Russian)
43. Wong, A.P.S. Subantarctic Mode Water and Antarctic Intermediate Water in the South Indian Ocean based on profiling float data 2000–2004. *J. Mar. Res.* **2005**, *63*, 789–812. [CrossRef]
44. Holte, J.W.; Talley, L.D.; Chereshkin, T.K.; Sloyan, B.M. The role of air-sea fluxes in Subantarctic Mode Water formation. *J. Geophys. Res.* **2012**, *117*, C03040. [CrossRef]
45. Sosnin, V.A.; Rudyh, N.I. Salinity minimum in the North Pacific. *Russ. Meteorol. Hydrol.* **2013**, *8*, 51–60. [CrossRef]
46. Monin, A.S. *Weather Forecast as a Physics Problem*; Nauka: Moscow, Russia, 1969; 184p. (In Russian)
47. Monin, A.S.; Kamenkovich, V.M.; Kort, V.G. *Variability of the World Ocean*; Gidrometeoizdat: Leningrad, Russia, 1974; 262p. (In Russian)
48. Monin, A.S.; Shishkov, Y.A. *History of the Climate*; Gidrometeoizdat: Leningrad, Russia, 1979; 407p. (In Russian)
49. Sosnin, V.A. On the possible connection of the elements of the climatic system. *Vestnik FEB RAS* **2011**, *6*, 72–79. (In Russian)
50. Harrison, T.M.; Copeland, P.; Kidd, W.S.F.; Yin, A. Raising Tibet. *Science* **1992**, *255*, 1663–1670. [CrossRef]
51. Xiao, J.; Zhisheng, A. Three large shifts in East Asian monsoon circulation indicated by loess-paleosol sequences in China and late Cenozoic deposits in Japan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1999**, *154*, 179–189. [CrossRef]
52. Zhisheng, A.; Kutzbach, J.E.; Prell, W.L.; Porter, S.C. Evolution of Asian Monsoon and phased uplift of the Himalayan Tibetan plateau since Late Miocene times. *Nature* **2001**, *411*, 62–66. [CrossRef] [PubMed]
53. Fluteau, F.; Ramstein, G.; Besse, J. Simulating the evolution of the Asian and African monsoons during the past 30 Myr using an atmospheric general circulation model. *J. Geophys. Res.* **1999**, *104*, 11995–12018. [CrossRef]
54. Clark, P.V.; Alley, R.B.; Pollard, D. Northern hemisphere ice-sheet influence on global climate changes. *Science* **1999**, *286*, 1104–1111. [CrossRef]
55. Haug, G.H.; Sigman, D.M.; Tiedemann, R.; Pedersen, T.F.; Sarnthein, M. Onset of permanent stratification in the subarctic Pacific ocean. *Nature* **1999**, *401*, 779–782. [CrossRef]
56. Schlitzer, R. Ocean Data View. 2008. Available online: http://odv.awi.de (accessed on 12 March 2024).
57. Helland-Hansen, B. Nogen hydrografiske metoder. *Forh. Skand. Naturf. Mote* **1916**, *16*, 357–359.
58. Defant, A.; Wust, G. Die Mischung von Wasserkorpern im System S = f (T). "Rapports et Proces Verbanx reunions du cons". *Perm. Intern. Pour l'Explorationde Mer* **1930**, *LXVIII*, 40–47.
59. Ivanov, A.V. The development of the θ, S–Curve theory. *Probl. Arktiki* **1943**, *2*, 68–74. (In Russian)
60. Shtokman, V.B. The fundamental of θ, S–Curve theory as an investigation method of mixing and transformation of water masses. *Probl. Arktiki* **1943**, *1*, 32–71. (In Russian)
61. Ivanov, A.V. To the theory of θ, S–Curves. *Izv. AN SSSR Seriya Geogr. Geofiz.* **1946**, *10*, 529–547. (In Russian)
62. Dobrovol'skij, A.D. On the designation of the water masses. *Okeanologiya* **1961**, *1*, 12–24. (In Russian)
63. Tomczak, M. Some historical, theoretical and applied aspects of quantitative water mass analysis. *J. Mar. Res.* **1999**, *57*, 275–303. [CrossRef]
64. Emery, W.J. Water types and water masses. In *Encyclopedia of Ocean Sciences*; Steele, J., Ed.; Academic Press: Cambridge, MA, USA, 2001; pp. 3179–3187. ISBN 9780122274305. [CrossRef]

65. Sverdrup, H.U.; Johnson, M.W.; Fleming, R.H. *The Oceans, Their Physics, Chemistry and General Biology*; Prentice-Hall: New York, NY, USA, 1942; 1087p.
66. Ivanov, Y.A. Water masses and distribution of the oceanological parameters. *Okeanologiya* **1963**, *3*, 803–807. (In Russian)
67. Sosnin, V.A.; Belonozhko, V.P. On the seasonal variability of subsurface salinity maximum in the North Pacific. *Okeanology* **1991**, *31*, 42–46.
68. Sosnin, V.A. On the role of the freshwater budget at the origin of the salinity minimum at intermediate depths in the Northern Pacific. *Russ. Meteorol. Hydrol.* **2007**, *32*, 453–460. [CrossRef]
69. Sosnin, V.A.; Rudyh, N.I. Salinity minimum in the upper layer of the Sea of Japan. *Russ. Meteorol. Hydrol.* **2015**, *40*, 814–819. [CrossRef]
70. Wesson, J.C.; Gregg, M.C. Mixing at Camarinal Sill in the Strait of Gibraltar. *J. Geophys. Res.* **1994**, *99*, 9847–9878. [CrossRef]
71. Berezutskii, V.; Maximov, S.E.; Rodionov, V.B.; Sklyarov, V.E. Mediterranean water structure in the central Atlantic: Results of remote acoustic and conductivity-temperature-depth measurements. *J. Geophys. Res.* **1994**, *99*, 20375–20379. [CrossRef]
72. Falina, A.; Sarafanof, A.; Mercier, M.; Lherminer, P.; Sokov, A.; Daniault, N. On the cascading of dense shelf waters in the Irminger Sea. *J. Phys. Oceanogr.* **2012**, *42*, 2254–2267. [CrossRef]