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Preface

Frontal zones and fronts are natural boundaries in the ocean. Drastic changes in the properties of oceanic waters, - evidently of frontal origin -, like sharp interfaces between warm and cold water masses or changes of current direction, were known to seamen since at least the 15^{th} century. Phenomenological studies of surface effects of oceanic fronts relate to the middle of the 19^{th} century. A great contribution to the understanding of the physical nature of fronts was made by the pioneer studies of the Japanese oceanographer Michitaka Uda in 1938. However the intense investigation of fronts only began in the 1970's as a consequence of the accumulation of numerous observations in the ocean, their analysis, the development of theoretical hydrodynamic concepts and the wide use of new oceanographic equipment and methods (especially remote sensing) which made it possible to measure oceanic properties with high space and time resolution. There was a gradual reconsideration of the views of fronts as rather static and almost impenetrable boundaries separating water masses, widely accepted by the traditional descriptive oceanography before the 1970's. An approach viewing the fronts as a physical phenomenon with a complex inner dynamics possessing self-supporting characteristics received more and more recognition among scientists. The fronts were then regarded as one important unit in the chain of the energy transfer from scale to scale (the "energy cascade") from the elements of the global oceanic circulation down to small-scale phenomena. Besides permanent frontal zones of a climatic nature, including large oceanic currents of the Gulf Stream type, a variety of fronts exists in the ocean associated with coastal currents, gyres, eddies, upwellings, intrusions in the intermediate waters, river discharges into coastal zones, etc. Frontal instabilities, in their turn, give rise to the formation of eddies and jets with their own frontogenetic mechanisms and lifetime from a day to two or three years which produce cross-frontal water exchange and horizontal mixing in the neighbouring waters. So, oceanic fronts are multiscale in both space and time. Besides, various phenomena and processes are associated with fronts, such as high biological productivity and abundant fishing, anomalies in conditions of sound propagation, anomalies of wind waves, high velocity of jet currents, sharp changes of sea color, intense vertical movements, local weather conditions etc. Large-scale fronts have important effects on the weather and also on the climate.

An important contribution to the study of oceanic fronts was made by Professor Konstantin N. Fedorov (corresponding member of the USSR Academy of Sciences). His fundamental work "The Physical Nature and Structure of Oceanic Fronts" published in its Russian edition in 1983 and by Springer-Verlag in 1986 remains a basic reference for all oceanographers involved in the study of fronts, it contains a summary of all the data collected in the beginning of the 80's.

The possibilities of the traditional descriptive approach to the problem of the frontal zones are not exhausted yet. Many regions of the World Ocean have not been actually explored, even within the limits of this approach, or the information about them remains fragmentary and not systematized. The investigation of the Norwegian, Greenland, Barents, and Bering Seas has been going on since the end of 19^{th} century. A great amount of field observations has been collected (the Subarctic Seas are among the best explored regions of the World Ocean). Many descriptions of their background hydrology are available but, unfortunately, the information about the characteristics of the fronts remains very fragmentary. Still, the existing observations constitute a rich data base to construct a useful depiction of these fronts, - which, within the water area of the Norwegian, Greenland and Barents Seas are part of the climatic North Polar Frontal Zone (denoted NPFZ in the following) -, even within the limits of the traditional hydrological approach. This analysis can then be complemented by the results of specialized experiments carried on, during the last two decades, to explore frontal processes within some separate segments of the NPFZ, allowing to describe them from the point of view of the modern conception of fronts.

This book presents the systematization and description of accumulated knowledge on oceanic fronts of the Norwegian, Greenland, Barents, and Bering Seas, and it is partly based on the book by V.B. Rodionov and A.G. Kostianoy "Oceanic Fronts of the North-European Basin Seas" published in Russian in 1998. The work is based on the numerous observational data, collected by the authors during special sea experiments directed to the investigation of physical processes and phenomena inside certain parts of the NPFZ and in the northern part of the Bering Sea, on archive data of the USSR Hydrometeocenter and other research institutions, as well as on a wide scientific literature published in Russian and Western editions. The book contains general information on the oceanic fronts of the Subarctic Seas, brief history of their investigation, state of the knowledge, as well as detailed description of the thermohaline structure of all frontal zones in the Norwegian, Greenland, Barents, and Bering Seas and of neighbouring fronts of Arctic and coastal origins. Special attention is given to the study of the multifrontal character of the NPFZ and of peculiarities of its internal structure at different sections, to the description of diverse oceanic features observed in the NPFZ, as well as to some characteristics of the horizontal and vertical fine structure of hydrophysical fields in the NPFZ. Observations are completed by the results of the numerical modeling of the northern Bering Sea where an extensive survey was carried out for five years in the scope of the NSF ISHTAR Program. The main features of the northern Bering Sea's summer ecohydrodynamics are investigated with the help of three-dimensional direct and inverse models developed at the GeoHydrodynamics and Environment Research Laboratory (GHER) of the University of Liege, Belgium.

Chapter 1 is devoted to brief definitions, terminology and a review of the main characteristics and methods of investigation of oceanic fronts. Chapter 2 gives a brief history of exploration and oceanographic investigations, and a state of the art review of the research on oceanic fronts in the Subarctic Seas. Chapter 3 and 4 give a system oriented description of different fronts in the Norwegian, Greenland, and Barents Seas. Chapter 5 discusses the general circulation in the Northern Bering Sea using the results of the ISHTAR program and the application of the 3D GHER direct and inverse models. Chapter 6 is devoted to the research of the multifrontal character of the NPFZ and to the peculiarities of the internal structure of the various segments. Chapter 7 reviews mesoscale structures and processes which determine the internal structure of one or the other frontal zone.

The book is addressed to specialists working in various fields of ocean physical sciences and studying the cascade of problems: from ocean climate to small-scale processes and from remote sensing of the ocean to numerical and laboratory modeling. The material and hypotheses presented in the book will be helpful in formulating theoretical hypotheses and in improving the methods of mathematical modeling of oceanic processes. It may also be useful to specialists in ocean acoustics, marine biology, chemistry and ecology, to students and post-graduate students specializing in oceanology, and to those interested in oceanographic research.

A. Kostianoy and V. Rodionov benefited from the invaluable support of Konstantin N. Fedorov who was their scientific supervisor in the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences. The core of field data used for the analysis was acquired during the 25th expedition of R/V *Professor Molchanov* organized by S.S. Makarov, Head of the laboratory in the USSR Hydrometeocenter (1989). It was very gracious of him to provide some archival hydrological materials too. The crew under his leadership - S.N. Galkin, I.E. Ivanov, A.A. Kutalo, and T.I. Shekhovtsova helped in conducting the research work and in the processing of field and archived data. The authors are very grateful to the colleagues of the Murmansk Branch of the Arctic and Antarctic Research Institute I.A. Labedev and V.V. Denisov, and to a colleague from the Acoustic Institute of the USSR Academy of Sciences I.A. Aleksandrov for his productive cooperation in the research and for providing with a set of interesting materials. A. Kostianoy and V. Rodionov are very grateful to their colleagues in the P.P. Shirshov Institute of Oceanology Dr. I.M. Belkin, A.V. Berezutskiy, A.B. Grabovskiy, Dr. N.P. Kuzmina, S.E. Maksimov, Dr. A.G. Ostrovskiy, A.M. Pavlov, Dr. N.A. Sheremet, and Dr. V.E. Sklyarov for participating in joint research, assistance and support at different stages of the present research program. The authors would like to express a special gratitude to Prof. A.G. Zatsepin, Dr. A.I. Ginzburg, and Prof. V.N. Pelevin for helpful discussions of the work and valuable critical comments. The previous Russian Edition of the book by V.B. Rodionov and A.G. Kostianoy "Oceanic Fronts of the North-European Basin Seas" (1998) was supported by the Russian Ministry of Science Federal Research Marine Program.

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scientific research but also how to do it in the convivial spirit which characterizes a performing research team.

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Moscow and Liege, March 2002

Contents

Chapter 1. Terminology, Definitions, Basic Characteristics and Methods of Investigation

1.1. Definition of frontal zones and fronts

In published works on fronts the authors, as a rule, use various definitions of the terms "frontal zone", "frontal interface", "front", "frontal line". The differences in definitions are related to the concepts of frontal zones accepted by the different authors. Each definition is acceptable and generally applicable to resolve specific problems and describe certain aspects of the investigated phenomenon. Stepanov (1960) noted a connection of the frontal phenomena with convergences in the ocean. Studying the fronts of the Gulf Stream system Baranov (1966, 1972) defined frontal zones on the basis of the concepts of "water masses" as a broad transitional zone between various water masses, which is rather stationary in time and space. Describing the main climatic frontal zones of the World Ocean, Gruzinov (1986) defined them as "quasistationary zones of interaction between waters of various hydrological characteristics having individual ecosystems, which reveal themselves all over the thermocline by maximum horizontal gradients of hydrological characteristics and vertical currents". Gruzinov specifies that his work is concerned with "main" or climatic fronts. At the same time Baranov and Gruzinov added that from a climatic point of view, the frontal zone may be considered, as well, as a region of the ocean in which seasonal and interannual transitions of a given front occur. There are also a number of other definitions summarized by Fedorov (1983, 1986). These definitions, which are quite adequate to the problem of the physico-geographical description of the climatic frontal zones, however, do not single out features of their dynamics which produce a significant sharpening of contrasts of the main parameters, and cause the appearance of fronts of various scales (not only climatic) in this zone. These features are taken into account by the definition given by Fedorov (1983, 1986), according to which the frontal zone in the ocean is a zone "in which the spatial gradients of the main thermodynamic characteristics are very high in comparison with the average". This definition is not based on climatology concepts such as "water masses", "thermocline" etc., which require definitions by themselves, and implies the application of some appropriate numerical criterion selected by each investigator. As far as one of the purpose of the present book, in addition to the physico-geographical description of the North Polar Frontal Zone, is the description of its inner structure generated by frontal phenomena of smaller scales, the definition of the frontal zone given by Fedorov will be adopted here. Following Fedorov, the frontal interface will be defined as "a surface within the frontal zone, which coincides with the surface of the maximum gradient of one or several characteristics (temperature, salinity, density, velocity, etc.)". Then, strictly a "front" can be regarded as the result of the intersection of the frontal interface with any given surface, particularly with the free surface of the ocean or with an isopycnal surface (Fedorov, 1986).

It should be noted that the physical content of the term "frontal zone" does not require all main characteristics to undergo simultaneously a sharp modification in the zone. For example, one may observe only temperature fronts or only purely salinity fronts (Fedorov, 1983, 1986). Besides, in one frontal zone, can exist simultaneously several frontal interfaces, some only thermal or purely haline. The terms "thermal" or "temperature" front (if the salinity was not measured) and "salinity" front (if the temperature was not measured) are frequently used.

The North Polar Frontal Zone (NPFZ) in the Norwegian, Greenland and Barents Seas is a complicated oceanic feature, in which processes of all scales are represented. As a whole, NPFZ represents a climatic frontal zone generated by the interaction of two elements of the planetary circulation: relatively warm and salty waters of the Atlantic Ocean, which extend from the South to the North, and colder and fresher waters, which penetrate from Polar areas to the South, formed during general cooling, ice thawing and mixing thawing products with enclosing waters. A rather complicated bottom topography and the coastal line topography of the investigated region (see Figure 2.1) result in the division of main streams of waters into separate branches and, therefore, in the existence of the branchy system of permanent currents. The convergence of the currents and their interaction with elements of the topography and the coast line result in the NPFZ to be divided into several frontal zones of smaller scales (hundred km). Besides the interaction of sea water with continental drainage waters transported by secondary branches of the general circulation leads to the formation of frontal zones also. Thus the climatic NPFZ is a system of frontal zones with various characteristics. However it is necessary to remember that these frontal zones are "only separate parts of the NPFZ, and, therefore, they must be regarded as climatic".

According to the definition, the gradients of temperature and salinity across the frontal zones should considerably exceed the average climatological gradient. For the region being studied the average climatic values of the horizontal gradients of temperature and salinity are not higher than respectively 0.01°K/km and 0.001‰/km.

A characteristic feature of the majority of frontal zones of this water area is a multifrontal internal structure, i.e. the presence of several fronts (very often of different types). Permanent fronts related to persisting climatic causes, fronts of synoptic or seasonal nature, and also small-scale fronts of local origin are present, justifying the separation made by Fedorov between "frontal zone" and "front".

To determine the location of fronts, one can use a criterion similar to the above mentioned criterion for the delimitation of the frontal zones:

$$\partial T/\partial x >> \overline{(\partial T/\partial x)} \text{ and } \partial S/\partial x >> \overline{(\partial S/\partial x)},$$

where $\partial T/\partial x$ and $\partial S/\partial x$ are local characteristics of the fields of temperature and salinity determined by measurements with high space resolution (< 20 km), and

$\overline{(\partial T/\partial x)}$ and $\overline{(\partial S/\partial x)}$ are average values of horizontal gradients in the given frontal zone.

1.2. Basic characteristics of frontal zones and fronts

With the present definition of frontal zones and fronts, it is necessary to prescribe the variables and parameters which are needed to define and describe them. They should be chosen such as to take advantage of – and systemize – all the information accumulated over the years and combine them with the results of modern techniques of investigation. The selected critical variables and parameters must take into account the three-dimensional structure of frontal zones and fronts.

1. Expansion of the frontal zone and the direction of its extension

It is necessary to understand precisely what frontal zone one has to deal with, and to define its boundary. Fronts with different characteristics, belonging to different frontal zones may be in immediate proximity of each other, i.e. the frontal zones have coalesced. In the majority of such cases (certainly if the zones do not merge all over their stretch), it is reasonable to single out frontal zones and to consider fronts as belonging to different frontal zones.

To determine the expansion and the directions of the frontal zones, satellite images are among the most informative. In most cases, infra red (IR) - images allow to define immediately the most indicative parameters. A more complicated method is the use of polygon surveys of various types with the help of towed systems and, also, airborne thermal surveys. Besides it is possible to make polygon or zigzag surveys with the help of Expendable Bathythermograph (XBT), aerial XBT (AXBT) or CTD (conductivity, temperature, depth) probes that take even more time and do not meet the requirements of the synchronism that is indispensable for the investigation of the majority of the frontal zones. A more reliable method could be a simultaneous survey by several vessels but this is rarely realized because of financial difficulties. It is necessary to note that even with the use of satellite images or route measurements it is desirable to have a number of basic hydrological casts in order to be confident that one deals with a selected frontal zone, and to exclude high-gradient parts generated by other physical causes.

2. Width of the frontal zone on the ocean surface or at any other typical surface

The full width of the frontal zone should be defined as the distance between points beyond which the gradients of the studied hydrophysical characteristics, measured along the surface and perpendicularly to the frontal zone, fall beyond a stipulated value (Figure 1.1). The magnitude of the gradients and the set of the hydrophysical characteristics depend on the problem to be solved and in each concrete case can be determined differently.

The width of the frontal zone can be defined by various methods. The best one is to conduct polygon or route measurements. It can be done by a scanning satellite IR-radiometer (if gradients in the temperature field are implied) or remote measurements in other wave bands. However satellite observations allow a definition of the frontal zone's width only approximately, with a resolution of ~ 10 km. In this connection, it would be better to use the contact route measurements alongside with remote measurements (for example, a thermal drag-net at several depth levels or a towed thermograph at one of the horizons). Airborne surveys give quite satisfactory results as well. For a more reliable interpretation of the

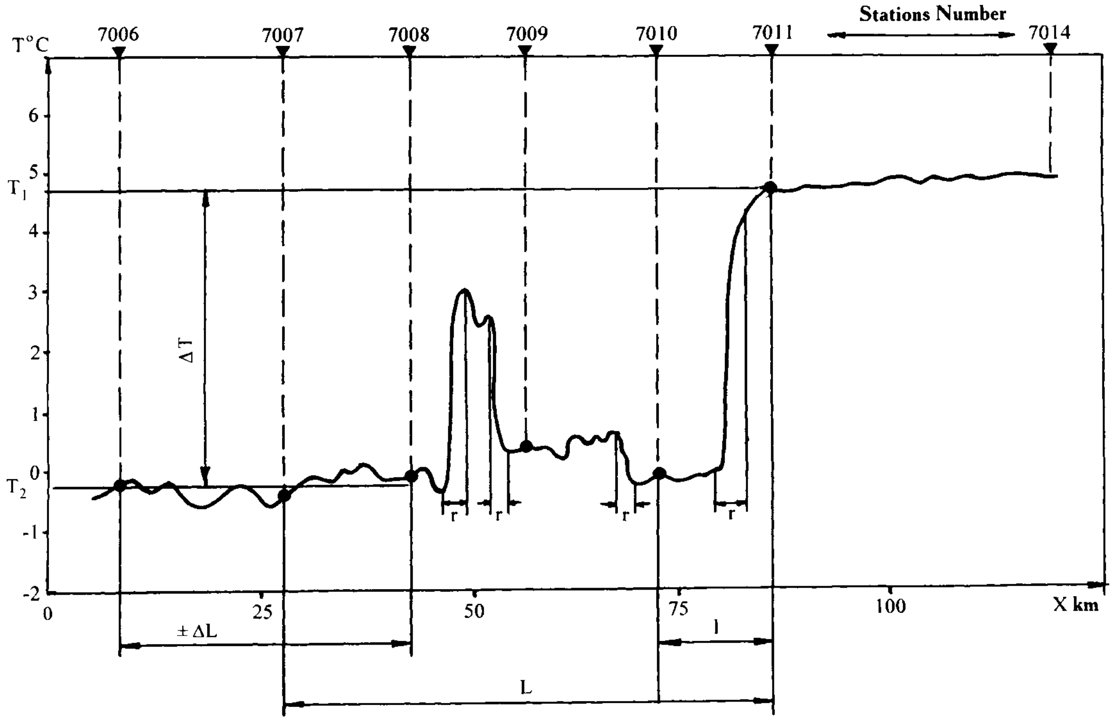

Figure 1.1. Sea surface temperature across the frontal zone revealed from continuous registration in the 25 cruise of R/V *"Professor Molchanov"*.
∇ - hydrological stations, L – width of the frontal zone, l – distance between hydrological stations, ± ΔL accuracy of determination of the frontal zone width, r – frontal interfaces (fronts with typical width of few km), ΔT – temperature drop across the frontal zone.

polygon and route surveys, it is useful to compare them with one or more hydrological sections. The use of sections alone, however, does not in most cases allow to define trustworthily the frontal zone's width. For this purpose, one would need rather extended sections with small time and space intervals, practically possible to realize only with expendable probes or towed systems, such as a thermal drag-net. It must be noted that the width of the frontal zone may be different at various horizons and depends on the set of defining parameters.

3. Depth of the frontal zone

Criteria for defining the depth of the frontal zone may be very different. Usually one sets a minimum magnitude of the horizontal gradients or one estimates the maximum depth at which the horizontal gradients decrease at a certain rate in relation to either the maximum or observed gradients on the given horizon. Quite frequently (but not always), the maximum depth of the frontal zone coincides with the depth of the layer of sharp change of the defining parameters. In many cases, however, the depth of the frontal zone differs according to the selection of defining variables and parameters and thus depends on the purpose of the study and of the equipment available.

To determine the maximum vertical extension of the frontal zone, it is necessary to conduct soundings along sections that are larger than the zone's width and up to depths that are deeper than the maximum depth of the frontal zone. Usually several sections made in different parts of the frontal zone are quite sufficient. The space separation of stations is not of major importance in this case.

4. General T, S-characteristics of the frontal zone

General T, S- characteristics are reflected by the average horizontal gradients of temperature, salinity and other oceanic parameters across the zone; a mutual disposition of isopycnals, isotherms and isohalines in the cross-section of the frontal zone; the character of the dominant variability of the frontal zone (alongside with zones, in which essential gradients of temperature and salinity are simultaneously marked, quite often purely temperature or salinity frontal zones may be met). The relative importance of the contributions of the temperature and the salinity in the density variability are usually used as numerical indices. For the estimation of the vertical stability of different layers, a vertical density ratio R_ρ, which describes the ratio of the contributions of vertical changes in temperature and salinity in vertical density changes, is thus calculated. In the case when the temperature contribution is stabilizing and the salinity contribution is destabilizing:

$$R_\rho = \beta\,(\partial S/\partial z)\,/\,\alpha\,(\partial T/\partial z);$$

in the opposite case:

$$R_\rho = \alpha\,(\partial T/\partial z)\,/\,\beta\,(\partial S/\partial z),$$

where $\partial T/\partial z$ and $\partial S/\partial z$ are respectively the vertical gradients of temperature and salinity in the layer considered, $\alpha = -1/\rho\cdot\partial\rho/\partial T$ is the thermal expansion coefficient, $\beta = 1/\rho\cdot\partial\rho/\partial S$ is the saline contraction coefficient in the linearized equation of the sea water state equation (when P = const) $\rho = \rho_0\cdot(1-\alpha\cdot\Delta T+\beta\cdot\Delta S)$ (Mamaev, 1987). When $R_\rho\leq 0$, there is an absolutely stable situation; in the case of $R_\rho>1$ there is an absolutely unstable situation; when $0<R_\rho\leq 1$ there is a relatively stable situation, for which the development of a differential-diffusion convection causing the formation of a vertical fine structure of hydrophysical fields is rather typical (Fedorov, 1976).

Besides, for the evaluation of the relative contribution of horizontal changes of temperature and salinity across the frontal zone, the horizontal equivalent of the density ratio is calculated:

$$R_\rho^{H} = \alpha\,(\partial T/\partial x)\,/\beta\,(\partial S/\partial x),$$

where $\partial T/\partial x$ and $\partial S/\partial x$ are respectively the horizontal gradients of temperature and salinity across the frontal zone in some layer or at some horizon. In the case of negative horizontal T, S-correlation ($R_\rho^H<0$) the salinity makes additional contribution to the density change across the frontal zone. In the case of $R_\rho^H>0$ contributions of temperature and salinity in density - partially and when $R_\rho^H = 1$ completely - compensate one another.

The classification of frontal phenomena according to their physical characteristics has been made following Fedorov (1983, 1986, 1988). In particular, he proposed the classification of frontal zones and fronts of the World Ocean according to their scales and the degrees of their geostrophic adjustment, their origin and mechanisms of formation. Also there are selection principles of the surface of the frontal interface by a maximum value of pressure, temperature and salinity gradients at isopycnal surfaces, and the contents of terms "baroclinity", "thermoclinity" and "haloclinity" are explained as the presence of correspondingly high values of the pressure, temperature and salinity gradients at isopycnal surfaces. A surface of maximum values of the pressure gradient (maximum of baroclinity) at isopycnal surfaces coincides with the stem of the along front current. The presence of a distinct degree of "thermoclinity" and "haloclinity" should result in a formation of temperature and salinity intrusions.

In (Fedorov, 1983, 1986) the phenomenon of multifrontality of the climatic frontal zones of the World Ocean is described and explained by a hierarchy of frontogenetic mechanisms. It helps to connect (qualitatively for now) the character and frequency of recurrence of the vertical fine structure of ocean waters with a degree of "thermoclinity" and "haloclinity" of the front, i.e. with the gradient of temperature and salinity on isopycnal surfaces near the frontal interface. A relationship was established between the fine structure of the frontal zones with the degree of "baroclinity", "thermoclinity" and "haloclinity". At the same time it was established that inside the same frontal interface at its different parts or inside one frontal zone the ratio of degrees of "thermoclinity", "baroclinity" and "haloclinity" can be different. It was shown that near purely baroclinic fronts the intrusive fine structure, with temperature inversions compensated by salinity inversions, is completely absent, whereas the step-like fine structure is, on the contrary, very typical (Fedorov, 1988; Fedorov and Meschanov, 1989).

In this connection the typification of the frontal zones and fronts, from the point of view of the degree of its "baroclinity", "thermoclinity" and "haloclinity", seems rather promising. The inclinations of isopycnals γ_ρ, isotherms γ_T and isohalines γ_S can be used to measure them.

The inclinations of the isolines may be considered as a local feature, which is defined in any point (for example, on the frontal interface). In this case they can be expressed as:

$$\gamma_T = (\partial T/\partial x)/(\partial T/\partial z)$$

$$\gamma_S = (\partial S/\partial x)/(\partial S/\partial z)$$

$$\gamma_\rho = (\partial \rho/\partial x)/(\partial \rho/\partial z)$$