FRONTS AND MIXING PROCESSES

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Contents

Summary

This chapter deals with various questions related to the diversity of fronts as natural boundaries between waters with different properties and their role in mixing in the ocean in both horizontal and vertical directions. Manifestation of fronts at the ocean surface (sharp changes in thermodynamic and optical parameters) and methods of their research, both in-situ and remote sensing, are considered. Definitions of a front and frontal zone and necessary terminology associated with manifestation of fronts in temperature and salinity fields and with slopes of isothermal/isohaline and isopycnal surfaces to isobaric ones (thermoclinic and baroclinic fronts, respectively) are given. Classification of fronts and frontal zones depending on their space-time scales and compliance with geostrophic balance is presented. Some examples of frontal zones and fronts with different frontogenetic mechanisms are provided: (i) the frontal zone of the Gulf Stream, with the sharp front at the current inner boundary; (ii) the frontal zone between shelf and slope waters in the North Western Atlantic; (iii) frontal zone of coastal upwelling; (iv) the marginal ice frontal zones adjoining the ice cover. Typical characteristics (horizontal temperature and salinity gradients, a type of temperature-salinity correlation, and thermoclinicity or baroclinicity) for the fronts within the frontal zones considered are presented, as well as their typical structural elements (eddies, filaments, intrathermocline lenses). The latter ordered structures, which are the result of frontal instability and have their own fronts, condition multifrontal structure of frontal zones and horizontal across-frontal transport for a distance up to several hundreds of kilometers (e.g., by upwelling filaments) and even several thousands of kilometers (by intrathermocline lenses). Some numerical estimates of the cross-frontal water exchange by various ordered structures are given. A role of thermoclinicity and baroclinicity of fronts in the formation of frontal intrusions and along-frontal (vertical) movement of alien water approaching to the front is touched on, as well as an influence of frontal phenomena on biological productivity.

1. Introduction

Fronts are natural boundaries in the ocean. Drastic changes in the properties of oceanic waters of evidently frontal origin, like sharp line of interface between warm and cold masses of water or change of current direction, were known to seamen since at least the 15th century. Discrete studies (mainly phenomenological) of surface effects of oceanic fronts relate to the middle of the 19th century. A great contribution to understanding of physical nature of fronts was made by pioneer studies of Japanese oceanographer Michitaka Uda in the 1930s. However, intense investigation of fronts began significantly only in the 1970s as a consequence of accumulation by then of numerous observations in the ocean, their analysis, development of theoretical hydrodynamic concepts and wide use of new measuring devices and methods (especially of aerospace ones), which made it possible to measure oceanic properties with high spatial and temporal resolutions. It became evident that fronts are not only boundaries between different water masses. 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 various eddies, coastal upwelling, intrusions in the intermediate waters, river discharges into coastal zones of the ocean, and so on. In its turn instability of fronts gives rise to formation of eddies and jets with their own frontogenetic mechanisms and lifetime from a day to two-three years that provide cross-frontal water exchange and horizontal mixing in the neighboring waters. So, oceanic fronts are multiscale in both space and time. Marked vertical water inhomogeneities (the thermohaline finestructure) with scales of about meters – hundred meters that contribute to the transfer of heat and salt through the hydrostatically stable pycnocline are frequently observed in frontal zones. Thus, fronts are an integral part of oceanic dynamics, which play an important role in the transfer of energy along a cascade of scales from global oceanic circulation (thousands of kilometers) to small-scale phenomena (meters). Besides, various phenomena and processes accompany fronts, such as high biological productivity and fishery, anomalies in conditions of sound propagation, anomalies of wind wave, high velocity of jet currents, sharp change of sea color, intense vertical movements. Large-scale fronts have important effects on the weather and climate. Therefore, not only scientific interest, but important practical problems are associated with oceanic fronts.

2. Frontal Zones and Fronts

2.1. Manifestation of Fronts at the Ocean Surface

Frontal interfaces, which intersect the ocean surface, can be detected by sharp near-surface changes of the thermodynamic parameters (Figure 1) with corresponding measuring devices (see Section 2.3)

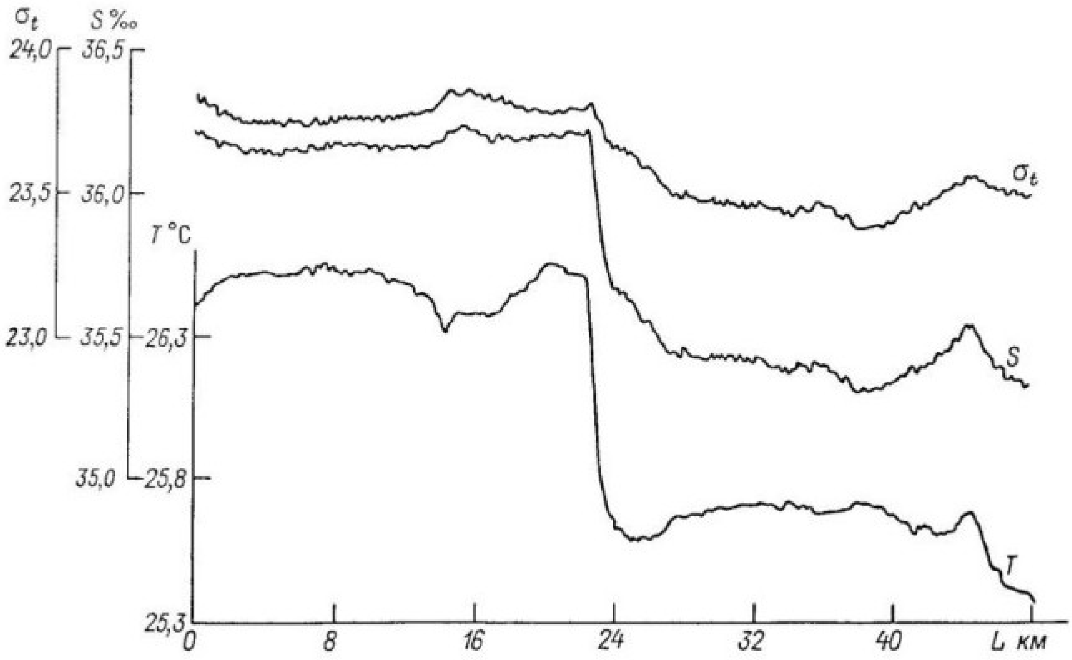

Figure 1. A front in temperature, salinity and density in the Sargasso Sea (Figure 2.10 in the book by Fedorov K.N. (1986) The Physical Nature and Structure of Oceanic Fronts, 333 pp. Germany: Springer-Verlag)

Figure 2. Front between water discharged from the Patos-Mirim Lagoon, Southern Brazil (yellow waters on the left) and coastal water of the Southwestern Atlantic Ocean (Courtesy of O.Moller and P.Zavialov).

Besides, the fronts can be visible at the ocean surface as lines of demarcation expressed by a change of color, debris or foam accumulation, choppy (disturbed, rough) water or, vice versa, slicks (smooth surface), accumulation of plankton or marine animals and birds. Change of color may be associated with optical contrast between oceanic and riverine waters, which are rich with suspended matter of terrestrial origin and phytoplankton (Figure 2), or productive waters of coastal upwelling (see Section 2.4.4).

Accumulation of debris and foam arises from convergence of surface currents at front. Slicks may be caused by damping effect of surfactant films accumulated in the convergence or by turbulence and currents. Choppy water (anomalously steep waves, sometimes disorder or having the form of ordered short standing waves) is frequently observed when a current shear across a front is large, especially in the regions where a strong current flows opposite to strong wind. Agitated water surface produces a characteristic acoustic effect – hissing sound, which is audible several kilometers away that can be associated with the breaking of very steep choppy water. The combination of wave (choppy water) and vortex (whirlpools and small vortices with diameter of several meters) motion, the so-called current rip or tide rip, is also typical for fronts with a current shear and can be observed at complete calm against the background of a calm sea. The velocity shear results in yawing of a ship and change of its wake when crossing a front. A difference mentioned by seamen is not only in wake character, but also in wind speed on either side of fronts. Although frontal current rips are extremely widespread in the coastal and open ocean, they do not always accompany fronts. Certain conditions are likely necessary for the origin of frontal current rips, such as the state of the sea surface not higher than force 3–4, the presence of a sharp density gradient across the front, the presence of a horizontal velocity shear and strong convergence of the surface currents at the front. High biological productivity and the presence of surfactant film as a consequence near the front is likely an additional factor contributing to the appearance of foam in the bands of convergence. On the other hand, bands of foam, slicks and choppy water in areas of surface current convergences can be the surface manifestation of phenomena which are not necessarily associated with fronts: accumulations of foam or plankton frequently mark the lines of convergence of Langmuir cells and internal waves; slicks and current rips (choppy water) may be also a result of modulation of surface waves by internal waves of different origins. It is worth noting also, that oceanic fronts are not always accompanied by surface phenomena and that in specific cases fronts are not followed by temperature or salinity gradients. In particular, solar heating and associated stable thermal stratification in the near-surface layer in light wind summer weather can prevent the emergence at the surface of even quite strong thermal contrasts in the subsurface layers (in seasonal and main thermoclines).
(see: *Waves in the Oceans* and *Air-Sea Interactions*)

2.2. Definitions, Terminology

Due to the diversity of the physical nature, external manifestations and space-time scales characterizing oceanic fronts, it is impossible to establish a brief and universal definition for them. It is not surprising, then, that different definitions of fronts and frontal zones may be found in the literature. According to the most known and frequently used definitions given by the Russian oceanographer Konstantin N. Fedorov, a frontal zone is “a zone in which the spatial gradients of the main thermodynamic characteristics are very high in comparison with the mean uniform distribution between the stable climatic or other extremes”, frontal interface is “a surface within frontal zone, which coincides with the surface of the maximum gradient of one or several characteristics (temperature, salinity, density, velocity, etc.”, and a front is “the result of the intersection of the frontal interface with any given surface, particularly with the free surface of the ocean or with isopycnal surface". As a rule, terms “frontal interface” and “front” are used synonymously, whereas the expression “frontal zone” implies existence of more than one front (frontal zones are multifrontal). Fronts are relatively narrow (about 10 m – 10 km) and characterized by high, although changing within wide limits, horizontal gradients of temperature, salinity and density (see: Section 2.4). Considerably larger width (100 km and more) and lesser mean gradients of the characteristics are typical for frontal zones. For example, the mean horizontal gradients of sea surface temperature (SST) in the frontal zones of the Kuroshio and Gulf Stream are 0.1 – 0.15°C km^{-1}, whereas the local SST gradients at individual fronts within the zones can exceed 1.5°C km^{-1}. Fronts that manifest themselves in temperature (T) or salinity (S) fields are named temperature (or thermal) and salinity (or saline) fronts, respectively. Though purely temperature (without salinity across-frontal change) and purely salinity (without temperature across-frontal change) fronts are found in the ocean, the latter mainly in the regions of river discharges, the total number of thermal fronts (with and without the contribution of salinity) is significantly greater than the total number of purely saline fronts and fronts, in which the salinity contribution $\Delta\rho_S = \rho * \beta * \Delta S$ to the density change exceeds the corresponding temperature contribution $\Delta\rho_T = \rho * \alpha * \Delta T$ in absolute value, so that $|\Delta\rho_S| > |\Delta\rho_T|$. Here $\alpha = -(\rho)^{-1} * \partial\rho/\partial T$ is the thermal expansion coefficient and $\beta = (\rho)^{-1} * \partial\rho/\partial S$ is saline contraction coefficient in the linear state relation of sea water under constant pressure P

$$\rho = \rho_0 * (1 - \alpha * \Delta T + \beta * \Delta S), \qquad (1)$$

where ρ_0 is a reference density. When spatial temperature and salinity gradients practically coincide, front is said to be thermohaline. In cases where the scales of the fronts are large enough and the fronts are well-defined in the density field, a geostrophic balance of motion and the mass field is observed, determined by the velocity and density values on both sides of the front. At the same time, the fronts acquire a slope φ_ρ of isopycnal surfaces (ρ = const) to isobaric (P = const), practically horizontal, ones:

$$\gamma_\rho = \tan \varphi_\rho = \\ f * \rho_1 * (u_1 - u_2) * g^{-1} * (\rho_2 - \rho_1)^{-1}, \qquad (2)$$

where g is the gravitational acceleration, $f = 2 * \omega * \sin\phi$ – the Coriolis parameter, ω – angular Earth rotation velocity, ϕ – latitude, u_1 and ρ_1 – the current velocity along the front and the density in the lighter water, and u_2 and ρ_2 – the current velocity along the front and the density of the denser water. It follows from equation (2), which is known as the Margules formula, that a cyclonic vorticity is observed at oceanic geostrophic fronts. Such fronts, with isopycnal surfaces inclined to isobaric ones, are said to be baroclinic. The most typical slopes of oceanic fronts are 10^{-3}–10^{-2}. Slopes of isothermal (T = const) and isohaline (S = const) surfaces to isobaric, γ_T and γ_S, respectively, are not

necessarily equal and the surfaces can be inclined to isopycnals. The fronts that have marked temperature gradients along isopycnals ($\gamma_T \neq \gamma_\rho$) are characterized as thermoclinic as well. In principle, both purely baroclinic ($\gamma_\rho = \gamma_T = \gamma_S$) and purely thermoclinic ($\gamma_\rho = 0$, $\Delta\rho_T = \Delta\rho_S$, that is horizontal changes of temperature and salinity to the density change compensate each other) situations are possible, however in many cases oceanic fronts are found to have dissimilar degree of baroclinicity and thermoclinicity simultaneously. The degree of baroclinicity and thermoclinicity determines peculiarity of the thermohaline finesrtucture at fronts (see Section 4).
(see: *Sea Water Properties. Water Masses. Global Scale Currents*)

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Bibliography

Belkin I.M., Gordon A.L. (1996). Southern Ocean Fronts from the Greenwich Meridian to Tasmania. Journal of Geophysical Research **101** (C2), 3675-3696. [This contains historical data on positions and parameters of fronts in the Indian Ocean].

Bower A.S., Rossby T. (1989). Evidence of Cross-Frontal Processes in the Gulf Stream Based on Isopycnal RAFOS Float Data. Journal of Physical Oceanography **19**, 1177–1190. [Patterns of vertical and cross-stream motions in Gulf Stream meanders observed with RAFOS floats are presented].

Bowman M., Esais W.E. (Eds.) (1978). Oceanic Fronts in Coastal Processes, 114 pp. Germany: Springer-Verlag. [This presents a variety of fronts in coastal area, associated biological aspects and mixing processes].

Fedorov K.N. (1986). The Physical Nature and Structure of Oceanic Fronts, 333 pp. Germany: Springer-Verlag. [This provides extensive data on characteristic features of fronts and frontal zones in the open and coastal ocean].

Fedorov K.N., Ginsburg A.I. (1992). The Near-surface Layer of the Ocean, 259 pp. The Netherlands VSP,: Utrecht. [This considers various physical processes near the ocean surface and problems of the effectiveness of remote sensing].

Halpern D. (Ed.). (2000). Satellites, Oceanography and Society, 367 pp. Elsevier Oceanographic Series, 63. [This presents recent achievements in the remote sensing of the ocean].

Kazmin A.S., Reinecker M.M. (1996). Variability and frontogenesis in the large-scale oceanic frontal zones. Journal of Geophysical Research **101** (C1), 907-921. [This considers seasonal variability of frontal zones in the Pacific Ocean basing on satellite SST data].

Kostianoy A.G., Nihoul J.C.J., Rodionov V.B. (2004). Physical Oceanography of Frontal Zones in the Subarctic Seas, 316 pp. Elsevier, Elsevier Oceanography Series, 71, Amsterdam. [This provides extensive data and classification of all fronts in the Norwegian, Greenland Barents and Bering seas].

Stevenson R.E. (1989). Oceanography from the Space Shuttle, 200 pp. USA: Office of Naval Research, University Corporation for Atmospheric Research. [This contains pictures of oceanographic phenomena photographed by astronauts in space and comments to them].

Warren B.A., Wunsch C. (Eds.) (1981). Evolution of Physical Oceanography. Scientific Surveys in

Honor of Henry Stommel, 623 pp. The MIT Press, Cambridge, Massachusetts and London, England. [This considers the problems of ocean circulation and mixing processes].

Biographical Sketches

Anna Ginzburg was born 13 March 1941 in Moscow, Russia. In 1958 she finished secondary school and entered Moscow Aviation Institute. In 1964 she graduated from the Institute as an engineer (specialization – electronic devices of aircraft control) and for two years worked at an electronic firm. In 1967–1970 she worked as a researcher in Moscow group of Marine Hydrophysical Institute of the Ukraine Academy of Sciences. Since 1970 to the present day she works in P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences, in Department of Experimental and Space Oceanology. In 1978 A. Ginzburg defended Candidate dissertation “Experimental study of thermal skin layer in the water under its cooling through the free surface” under supervision of Professor K.N. Fedorov. Since 1990 she is a principal scientist.

Field of her scientific interest is mesoscale variability of the ocean (sea) conditioned by various quasistationary and nonstationary elements of circulation (fronts, currents, eddies, vortex dipoles and multipoles, jets). Of particular interest now is coastal/deep-basin water exchange processes with regard to local geographic peculiarities of a region and synoptic atmospheric forcing. Her investigations are based on analysis of satellite information and field measurements.

A. Ginzburg took part in four oceanic expeditions. She is an author of about 140 publications, including the book (in co-authorship with K.N. Fedorov) “The Near-surface Layer of the Ocean” (VSP, The Netherlands, 1992). She participated in 17 International Conferences and was co-convener in two of them.

Andrey G. Kostianoy was born 17 June 1960 in Moscow, Russia. In 1982 he graduated from Moscow Institute of Physics and Technology as an engineer in applied physics (specialization – aerodynamics and thermodynamics) and entered P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences. Since 1982 he has been working in the Department of Experimental and Space Oceanology as post-graduate student (1982-1984), junior scientist (1984-1988), scientist (1988-1991), senior scientist (1991-1997) and principal scientist (1997-present). In 1987 A.G. Kostianoy got a degree of Candidate of Science (Ph.D. in Oceanology) and in 2000 a degree of Doctor of Science in Oceanology. Since 1994 he has a title Senior Scientist and since 1998 – Visiting Professor of Liege University (Belgium). Since 1995 he leads two international projects “Upwelling” and “"Mathematical modeling of the coastal upwelling" in the frame of two Bilateral Cooperation Programs between Russian Federation and French Community of Belgium (CGRI), and SSTC (Belgium). Since 1999 he occupies the post of Scientific Secretary of the Sub-Program "Southern Seas" (the Black, Azov and Caspian Seas) of the Russian Ministry of Science and Technologies Program "World Ocean". He is a member of the Russian National SCOR Committee and of the International Association "Modelenvironment" (Liege University).

Field of his interest is oceanography of coastal zones, fronts, upwellings, mesoscale dynamics, eddies, filaments, cross-frontal mixing in the coastal zones. The regions of interest are the Black Sea, the Aral Sea, the Mediterranean Sea, the Nordic Seas, the Atlantic and Southern Indian Ocean. His research is based on the analysis of remote sensing data and in-situ measurements.

A.G. Kostianoy is the author of more than 160 publications, including two books: one in co-authorship with V.B. Rodionov “Oceanic Fronts of the North-European Basin Seas” (1998), 292 pp., Moscow: GEOS (in Russian) and another in co-authorship with J.C.J. Nihoul and V.B. Rodionov “Physical Oceanography of Frontal Zones in the Subarctic Seas” (2004), 316 pp., Elsevier, Elsevier Oceanography Series, 71, Amsterdam.. He made about 30 scientific visits abroad including the participation of International Conferences. He took part in four sea expeditions.